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TABLE 3.3 CAPITAL COST SUMMARY*

	ESP	VS	FF	T&CI	ADS	ABS	R	F
DIRECT COSTS								
1) PURCHASED EQUIPMENT COSTS								
a) Control Device	As Req'd	----------						
b) Auxiliary Equipment	As Req'd	----------						
c) Instruments & Controls	0.10	----------						
d) Taxes	0.03	----------						
e) Freight	0.05	----------						
TOTAL	1.00	----------						
2) INSTALLATION DIRECT COSTS								
a) Foundations & Supports	0.04	0.06	0.04	0.08	0.08	0.12	0.08	0.12
b) Erection & Handling	0.50	0.40	0.50	0.14	0.14	0.40	0.14	0.40
c) Electrical	0.08	0.01	0.08	0.04	0.04	0.01	0.08	0.01
d) Piping	0.01	0.05	0.01	0.02	0.02	0.30	0.02	0.02
e) Insulation	0.02	0.03	0.07	0.01	0.01	0.01	0.10	0.01
f) Painting	0.02	0.01	0.02	0.01	0.01	0.01	0.01	0.01
g) Site Preparation**	As Req'd	----------						
h) Facilities & Buildings**	As Req'd	----------						
TOTAL	1.67	1.56	1.72	1.30	1.30	1.85	1.43	1.57
INDIRECT COSTS								
3) INSTALLATION INDIRECT COSTS								
a) Engineering & Supervision	0.20	0.10	0.10	0.10	0.10	0.10	0.10	0.10
b) Construction & Field Expenses	0.20	0.10	0.20	0.05	0.05	0.10	0.05	0.10
c) Construction Fee	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
d) Start Up	0.01	0.01	0.01	0.02	0.02	0.01	0.02	0.01
e) Performance Test	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
f) Model Study	0.02	----	----	----	----	----	----	----
g) Contingencies	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
TOTAL	2.24	1.91	2.17	1.61	1.61	2.20	1.74	1.92

* Values based on average of cost factors reduced from cost estimates.(Ref. 148, 160)

TABLE 3.4 BASIS FOR ESTIMATING ANNUALIZED COSTS

DIRECT OPERATING COSTS	COST FACTOR	REFERENCE
1) Operating Labor		
a) Operator	$7.87/man-hour	USDL, BLS average mill workers rate $6.56/h plus fringes of 20%, May 1977.
b) Supervisor	15% of 1a	Ref. 150
2) Operating Materials	As Required	
3) Maintenance		
a) Labor	$8.66/man-hour	Hourly rate of 10% premium over operating labor
b) Material	100% of 3a	
4) Replacement Parts	As Required	
5) Utilities		
a) Electricity	$0.0432/Kwh	USDL, BLS Consumer Price Index for 500/Kw/mo., May, 1977.
b) Fuel Oil	$0.47/gal	USDL, BLS Consumer Price Index, May 1977
c) Natural Gas	$1.98/Mcf	USDL, BLS Consumer Price Index, May 1977
d) Plant Water	$0.25/1000 gal	Ref. 156 updated 1977
e) Water Treatment & Cooling Water	$0.10/1000 gal	Ref. 156 updated 1977
f) Steam	$5.04/Mlb	Fuel @ $4.19/M Lb steam plus ~ 16% oper & Main.
g) Compressed Air	$0.02/1000 cf	Ref. 156 updated 1977
6) Waste Disposal	$5-10/Ton	
INDIRECT OPERATING COSTS		
7) Overhead	80% of 1a + 1b + 3a	Ref. 150
8) Property Tax	1% of capital costs	Ref. 150
9) Insurance	1% of capital costs	Ref. 150
10) Adminstration	2% of capital costs	Ref. 150
11) Capital Recovery Cost	0.16275 (as an example of 10% and an equipment life of 10 years)	
CREDITS		
12) Recovered Product	As Required	

TABLE 3.6 GUIDELINES FOR PARTS AND EQUIPMENT LIFE*

MATERIALS AND PARTS LIFE	LOW (Years)	AVERAGE (Years)	HIGH (Years)
Filter bags	.3	1.5	5
Adsorbents	2	5	8
Catalyst	2	5	8
Refractories	1	5	10
EQUIPMENT LIFE			
Electrostatic Precipitators	5	20	40
Venturi Scrubbers	5	10	20
Fabric Filters	5	20	40
Thermal Incinerators	5	10	20
Catalytic Incinerators	5	10	20
Adsorbers	5	10	20
Absorbers	5	10	20
Refrigeration	5	10	20
Flares	5	15	20

* Based on discussions with manufacturers and operators with corroborating data from refs. 19, 20, 37, 38, 40, 78 and 82.

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PB81-233033

MITIGATION OF WORKER EXPOSURE TO ETHYLENE OXIDE

R. Goldgraben, et al

Mitre Corporation
McLean, Virginia

March 1981

U.S. DEPARTMENT OF COMMERCE
National Technical Information Service
NTIS®

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PREVENTION OF EXPOSURE TO CHEMICAL CARCINOGENS:

ETHYLENE OXIDE

Contract No. NO1-CN-95419
MRI Project No. 4867-T

March 1981

For

Preventive Medicine Branch
Division of Resources, Centers and Community Activities
National Cancer Institute
Bethesda, Maryland 20205

MIDWEST RESEARCH INSTITUTE

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The Costs of Measures Used to Mitigate Worker Exposure to Ethylene Oxide

Renee Goldgraben

August 1981

MTR-81W203

Sponsor: U.S. Environmental Protection Agency
Contract No.: 68-01-5965

The MITRE Corporation
Metrek Division
1820 Dolley Madison Boulevard
McLean, Virginia 22102

10/2/84

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EVALUATION OF THE EFFICIENCY OF AN ETHYLENE OXIDE SCRUBBER

Scott Environmental Services
a division of
Scott Environmental Technology, Inc.

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II - A - 6

Economic Analysis of Candidate Hazardous Organics NESHAP Controls

Draft Report

Prepared for

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EPA Contract Number 68-02-4321
RTI Project Number 2330-3474-11

November 1986

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INDUSTRY PROFILE: STERILIZATION

I. INDUSTRY STRUCTURE

A. Markets Served

A diverse group of companies use 12/88 (ethylene oxide/CFC-12) in sterilization chambers. The users range from libraries and museums that use 12/88 to fumigate old books and archives to contract sterilization facilities that sterilize for profit. The use of emission control devices for ethylene oxide (EO) and/or CFC-12 is mainly limited to the facilities that use large amounts of 12/88, such as medical equipment suppliers and control sterilizers, and to facilities located in States with existing regulations on EO emissions. Some of the large users are recovering and reusing the 12/88 mixture not because of emission regulations but for economic reasons instead.

B. Product Substitutes

Several possible chemical substitutes exist to replace 12/88 as a sterilant gas. These include 10/90 (EO/carbon dioxide), pure EO, and nitrogen/EO mixtures. However, there are drawbacks associated with the use of these substitutes. The 10/90 mixture requires a much higher operating pressure (33 psig) than 12/88 (10 psig) and, therefore, the sterilization chambers have to be ASME pressure vessels (i.e., jacketed and double-welded as compared to the nonjacketed, single-welded vessels used for 12/88 sterilization). This criterion cannot be met by chamber modifications; the chambers must be replaced. In addition, some products to be sterilized cannot withstand the higher operating pressure required for 10/90 sterilization. The use of pure EO and nitrogen/EO mixtures requires a deep vacuum (as low as 1 in. Hg) to rid the sterilization

chamber of oxygen because mixtures of EO greater than 3 percent by volume in air are explosive. Some products to be sterilized cannot withstand the low vacuum required to pure EO sterilization. Also, the chamber instruments must be modified to be explosion-proof. Because of the explosivity of EO, safety considerations are a major consideration for the use of pure EO or nitrogen/EO. In addition, the use of the nitrogen/EO mixture is still in development, and the effectiveness of this mixture as a sterilant has not been proven.

A process substitute for the use of 12/88 is gamma radiation which currently accounts for approximately 40 to 50 percent of the sterilization market. This share is expected to grow within the next few years. However, gamma radiation will probably never control over 50 to 60 percent of the sterilization business because of safety considerations. In addition, radiation discolors plastics and damages Teflon® and acetyl delrin.

C. Technologies Employed

The sterilization chambers, control devices, and ethylene oxide (but probably not CFC-12) could be manufactured in someone's garage. These manufacturing processes are neither capital-intensive nor labor-intensive.

D. Size Distribution of Firms

(See attached list.)

E. Degree of Vertical Integration

This section is not applicable to this industry.

F. Supply/Demand Relationships

In general, the suppliers hold the power because there are only a few companies that manufacture the sterilization chambers and the

chemicals (e.g., the manufacture of hospital sterilization chambers is mainly controlled by two companies, AMSCO and Castle-Sybrno). The suppliers of the control devices have even more power since the manufactures of condensation/reclamation systems is currently limited to two companies. Vacudyne and Union Carbide. In addition, the control device manufactures consider their prices to be confidential and do not release them to the public.

G. Barriers to Entry/Exit

It is relating easy to enter the businesses manufacturing sterilization chambers or of manufacturing the control devices. The capital intensity is rather low and no special technological sophistication is required. However, the startup of a chemical suppliers business would require a large capital investment and might be subject to various government regulations (e.g., regarding EO emissions). Closing a chemical supplier company would probably entail high closing costs and perhaps union obligations as well because of the size of the company required for this type of business.

H. Industry Segmentation

The sterilization chamber and control device industries are segmented. For example, two manufacturers of sterilization chambers, AMSCO and Castle-Sybron, only make chambers for hospitals. Vacudyne and after manufacturers of industrial-size chambers do not make the type of sterilization chambers that hospitals use. The manufacturers of condensation/reclamation systems, to recover CFC-12, currently serve only the large industrial users of 12/88 (EO/CFC-12). The manufacture of acid-water scrubbers (control EO emissions before nonexplosion-proof recovery

of CFC-12) is divided between companies that make small scrubbers for small industrial users of 12/88 and those that manufacture larger capacity scrubbers. Currently, no companies manufacture control devices for CFC-12 recovery at hospitals or hospital-sized scrubbers.

I. Import/Export Relationships

This section is not applicable to sterilization.

II. Industry Trends

A. Market

The markets for sterilization chambers and for 12/88 (EO/CFC-12) gas have been increasing due to an increase in population and thus an increase in products to be sterilized. The markets also increased because certain users, sued as museums and libraries, were forced to change to fumigation with EO when DDT was banned.

The market for the control devices, particularly acid-water scrubbers, has been growing rapidly due to the development of State regulations for EO emissions.

The development of additional State regulations and/or Federal regulations for EO emissions will be important in changing the direction of the current growth in the sterilization chamber industry and in the purchase of 12/88 gas. Additional regulations will probably force smaller users of 12/88 to send their products that need to be sterilized to contract sterilization facilities. Most of the contract sterilizers use pure EO because it is cheaper to use per load) for products that can withstand the low vacuum required. (A lot of facilities that currently use 12/88 do so because it is nonflammable, not because the products cannot tolerate low vacuums). In addition, some companies will send out products for gamma radiation, thus lowering the purchase of 12/88 gas.

B. Technological.

Gamma radiation is a relatively new process that is challenging part of the EO sterilization market. However, this process will not really jeopardize the EO sterilization industry due to safety considerations and other problems (see Section 2.2).

The manufcturers of control devices are funding a lot of research and development work due to the possibility of additional State regulations and/or Federal regulations on EO and CFC-12 emissions.

C. Competitive

The control device industry is a relatively new industry and, therefore, includes only a few companies. However, this field is rapidly growing due to increased EO regulation and potential CFC regulation. Some companies that manufacture control devices do so because they manufacture sterilization chambers (e.g., Vacudyne Corp. and Environmental Techtonics, Inc.), and therefore, have an interest in how future regulations will affect their primary business. One company that has recently entered the CFC control market is Chemrox, Inc. (Chemrox already markets acid-water scrubbers for EO emissions). The possibility of future regulations for EO and/or CFC emissions has led to some agreements between control device manufactures and producers of 12/88 in which the chemical suppliers agree to buy back CFC-12 recovered the control device. The control device market is highly competitive; most manufacturers consider their prices and operating parameters confidential and will not release them to the public.

D. Regulatory

Recently, there have been rapid developments in State regulations of EO emissions. The likelihood of additional State regulations and the

possibility of future Federal regulation for EO emissions will probably significantly affect the future of the EO sterilization industry.

United States
Environmental Protection
Agency

EPA-600/2-83-0[illegible]
July 1983

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FLARE EFFICIENCY STUDY

Prepared for

Office of Air Quality Planning and Standards

Prepared by

Industrial Environmental Research
Laboratory
Research Triangle Park NC 27711

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EPA-600/2-83-052
July 1983

FLARE EFFICIENCY STUDY

by

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EPA Contract 68-02-3541-6

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Washington, DC 20460

3

ABSTRACT

A full-scale experimental study was performed to determine the efficiencies of flare burners as devices for the disposal of hydrocarbon emissions from refinery and petrochemical processes. The primary objectives of the study were to determine the combustion efficiency and hydrocarbon destruction efficiency for both air- and steam-assisted flares under a wide range of operating conditions. Test results indicate that flaring is generally an efficient hydrocarbon disposal method for the conditions as evaluated. The study provides a data base for defining the air quality impact of flaring operations.

The test methodology utilized during the study employed a specially constructed 27-foot sample probe suspended by a crane over the flare flame. The sample extracted by the probe was analyzed by continuous emission monitors to determine concentrations of carbon dioxide (CO_2), carbon monoxide (CO), total hydrocarbons (THC), sulfur dioxide (SO_2), oxides of nitrogen (NO_x), and oxygen (O_2). In addition, the probe tip temperature, ambient air temperature, and wind speed and direction were measured. Integrated samples of the relief gas were collected for hydrocarbon species analysis by gas chromatograph. Particulate matter samples were also collected during the smoking flare tests.

The rigorous test program included flare testing under thirty-four different operating conditions during a three-week period in June 1982. Test variables included Btu content of the relief gas (propylene diluted with nitrogen), relief gas flow rates, steam flow rates, and air flow rates. When flares were operated under conditions representative of good industrial operating practices, the combustion efficiencies at the sampling probe were determined to be greater than 98 percent. Combustion efficiencies were observed to decline under conditions of excessive steam (steam quenching) and high exit velocities of low Btu gases.

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9

LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

AGL	-- Above ground level
Btu	-- British thermal unit
Btu/hr	-- British thermal unit per hour
Btu/min	-- British thermal unit per minute
Btu/SCF	-- British thermal unit per standard cubic foot
FEP	-- fluro elastic polymer
ft/min	-- feet per minute
HP	-- horsepower
ID	-- inside diameter
in^2	-- square inch
lbs/hr	-- pounds per hour
l/g	-- liters per gram
mg/l	-- milligrams per liter
OD	-- outside diameter
PPM	-- parts per million by volume
psia	-- pounds per square inch absolute
psig	-- pounds per square inch gauge pressure
SCFM	-- standard cubic feet per minute @ 14.7 psia and 70°F

SYMBOLS

CO	-- carbon monoxide
CO_2	-- carbon dioxide
N_2	-- nitrogen
NO_x	-- nitrogen oxides
O_2	-- oxygen
SF_6	-- sulfur hexafluoride
SO_2	-- sulfur dioxide
THC	-- total hydrocarbon

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SECTION 1

INTRODUCTION

This document is a report on an experimental study to determine the efficiencies of flare burners as devices for the control of continuous hydrocarbon emissions. The primary objectives of this study were to determine the combustion efficiency and hydrocarbon destruction efficiency for both air- and steam-assisted flares over a wide range of operating conditions that might be encountered in continuous low flow industrial applications. The study excluded abnormal flaring conditions which might represent large hydrocarbon releases during process upsets, start-ups and shutdowns.

Both government and industry environmental officials are concerned with the effects of flaring hydrocarbons on the air quality. However, since flares do not lend themselves to conventional emission testing techniques, few attempts have been made to characterize flare emissions. Flare emission measurement problems include: the effects of high temperatures and radiant heat on test equipment, the meandering and irregular nature of flare flames due to external winds and intrinsic turbulence, the undefined dilution of flare emission plume with ambient air, and the lack of suitable sampling locations due to flare and/or flame heights, especially during process upsets when safety problems would predominate.

Previous flare efficiency studies did not encompass the range of variables encountered in the industrial setting. Limited test conditions of flare types, relief gas types, Btu content, relief gas flow rate, and steam-to-relief gas ratios were explored. This study was intended to add to the available literature on the subject by testing the flaring of an olefin (propylene) in both air- and steam-assisted flares with test variables of relief gas flow rate, relief gas Btu content, and steam-to-relief gas ratio.

Separate elements of this flare efficiency study were sponsored by the U.S. Environmental Protection Agency (EPA) and the Chemical Manufacturers Association (CMA). Other project participants included John Zink Company who provided flares, test facility and flare operation, and Optimetrics, Inc. who operated the EPA's Remote Optical Sensing of Emissions (ROSE) system. Engineering-Science, Inc. (ES) operated the extractive flare sampling and analysis systems and prepared this report.

SECTION 2

CONCLUSIONS

TECHNICAL SUMMARY

Figure 1 is an overview of the equipment used to operate and test the flares. The test methodology utlized during the study employed a specially constructed 27-foot sample probe suspended by a crane over the flare flame. The sample extracted by the probe was analyzed by continuous emission monitors to determine concentrations of carbon dioxide (CO_2), carbon monoxide (CO), total hydrocarbons (THC), sulfur dioxide (SO_2), oxides of nitrogen (NO_x) and oxygen (O_2). In addition, the probe tip temperature, ambient air temperature and wind speed and direction were measured. Integrated samples of the flare plume were collected for hydrocarbon species analysis by gas chromatograph. Particulate matter samples were collected during the smoking flare tests. Sulfur use was attempted as a tracer material in an effort to determine the dilution of the relief gas between the flare burner and the sampling probe location. However, the implementation of this unproven sulfur balance method for determining dilution ratios was unsuccessful.

The term "combustion efficiency" was used during this study as the primary measure of the flares' performance. Conceptually, this term defines the percentage of flare emissions that are completely oxidized to CO_2. Mathematically the combustion efficiency is defined as:

$$\% \text{ CE} = \frac{CO_2}{CO_2 + CO + THC + Soot} \times 100$$

Where:

CO_2 = parts per million by volume of carbon dioxide

CO = parts per million by volume of carbon monoxide

THC = parts per million by volume of total hydrocarbon as methane

Soot = parts per million by volume of soot as carbon*.

Table 1 summarizes the results of the flare efficiency tests. The rigorous test program included flare testing under thirty-four different operating conditions during a three-week period in June 1982. Test variables included Btu content of the relief gas (propylene diluted with nitrogen), relief gas flow rates, steam flow rates and air flow rates. Five of the thirty-four tests were divided into thirteen subtests for purposes of data analysis because the flare operation did not represent steady-state conditions. The Btu content of the relief gas was varied from 2,183 to 192 Btu/SCF for the steam-assisted flare, and from 2,183 to 83 Btu/SCF for the air-assisted flare. The relief gas flow

* In most cases, the "soot" term was zero.

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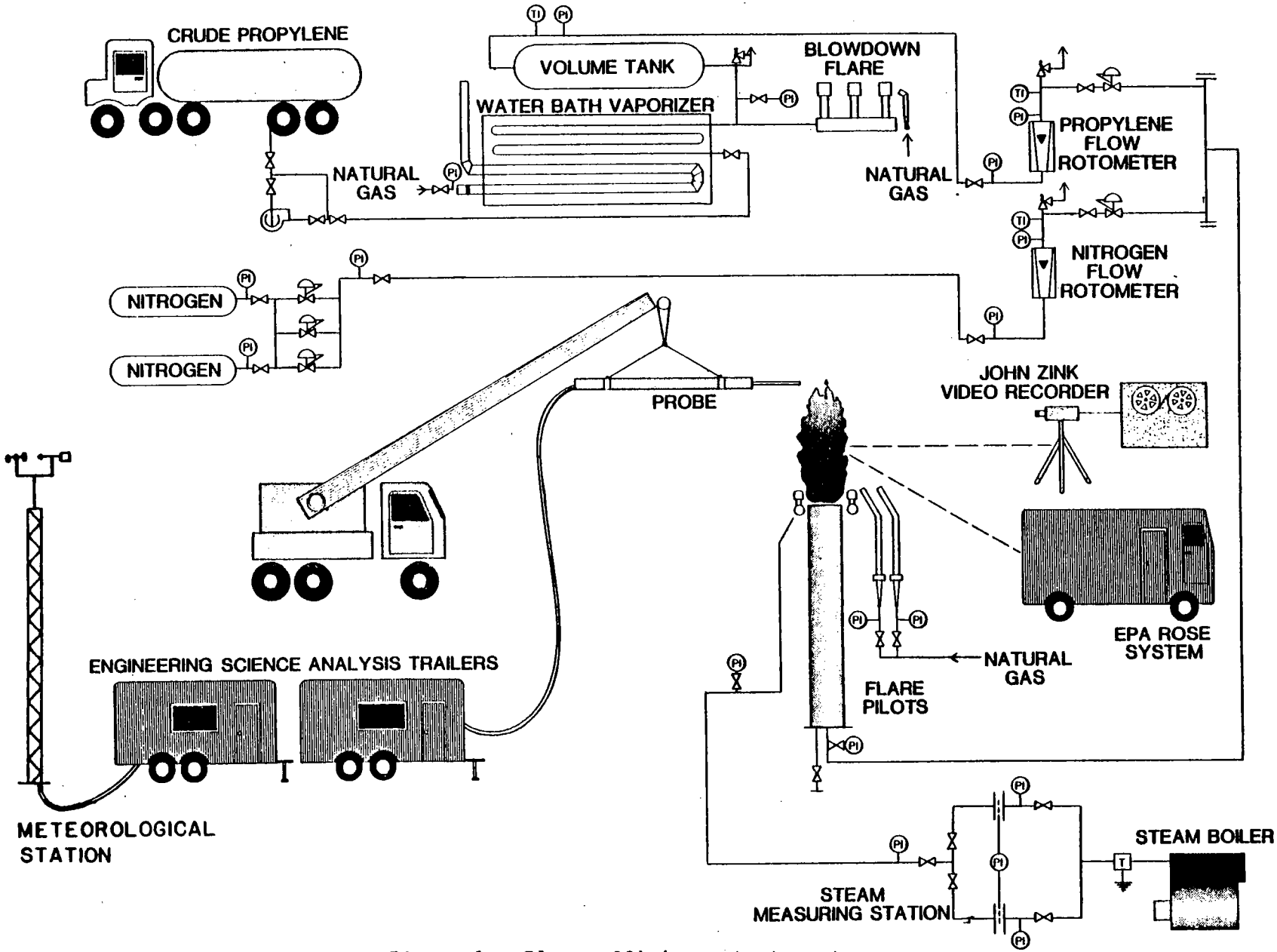

Figure 1. Flare efficiency test systems.

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TABLE 1. FLARE EFFICIENCY TEST RESULTS

Test Number	Relief Gas Flow (SCFM)	Relief Gas Heating Value (Btu/SCF)	Steam-to-Relief Gas Ratio (Lb/Lb)	Combustion Efficiency (%)	Comments
STEAM-ASSISTED FLARE TESTS					
1	473	2183	0.688	99.96	
2	464	2183	0.508	99.82	
3	456	2183	0.448	99.82	Incipient smoking flare
4	283	2183	0	99.80*	Smoking flare
8	157	2183	0	98.81*	Smoking flare
7	154	2183	0.757	99.84	Incipient smoking flare
5	149	2183	1.56	99.94	
67	148	2183	0.725	--	Sampling probe in flare flame
17	24.5	2183	0.926	99.84	
50	24.4	2183	3.07	99.45	
56	24.5	2183	3.45	99.70	
61	25.0	2183	5.67	82.18	Steam-quenched flame
55	24.7	2183	6.86	68.95	Steam-quenched flare
57	703	294	0.150	99.90	
11a	660	305	0	99.79	
11b	599	342	0	99.86	
11c	556	364	0	99.82	
59a	591	192	0	97.95	
59b	496	232	0	99.33	
60	334	298	0	98.92	
51	325	309	0.168	98.66	
16a	320	339	0	99.73	No smoke
16b	252	408	0	99.75	No smoke
16c	194	519	0	99.74	Incipient smoking flare
16d	159	634	0	99.78	Smoking flare
54	0.356	209	0	99.90	
23	0.494	267	0	100.01	
52	0.556	268	77.5	98.82	
53	0.356	209	123	99.40	
AIR-ASSISTED FLARE TESTS			Air Flow, Hi, Low, Off		
26	481.6	2183	Hi	99.97	
65	159	2183	Off	99.57*	Smoking flare; no air assistance
28	157	2183	Hi	99.94	
31	22.7	2183	Low	99.17	
66	639	158	Off	61.94	Detached flame observed
29a	510	168	Low	54.13	Detached flame; no air assistance
29b	392	146	Low	64.03	Detached flame; with air assistance
64	249	282	Low	99.74	
62	217	153	Low	94.18	Flame slightly detached
63	121	289	Low	99.37	
33	0.714	83	Low	98.24	
32a	0.556	294	Low	98.94	
32b	0.537	228	Low	98.82	

* Not accounting for carbon present as soot (see Table 10).

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rates ranged from 703 SCFM to 0.35 SCFM (purge flow rate) for the steam-assisted flare, and from 639 SCFM to 0.54 SCFM (purge flow rate) for the air-assisted flare.

CONCLUSIONS AND OBSERVATIONS

- When flares are operated under conditions which are representative of industrial practices, the combustion efficiencies in the flare plume are greater than 98%.
- Steam- and air-assisted flares are generally an efficient means of hydrocarbon disposal over the range of operating conditions evaluated.
- Varying flow rates of relief gas have no effect on steam-assisted flare combustion efficiencies below an exit velocity of 62.5 ft/sec.
- Varying Btu content of relief gases have no observed effect on steam-assisted flare combustion efficiencies for relief gases above 300 Btu/SCF. A slight decline in combustion efficiency was noted for relief gases below 300 Btu/SCF.
- Flaring low Btu content gases at high exit velocities may result in lower combustion efficiencies for air-assisted flares.
- Smoking flares achieve high gaseous hydrocarbon destruction efficiencies.
- In many cases, where high combustion efficiencies were observed, the carbon monoxide and hydrocarbon concentrations observed in the flare plume were approximately equal to those found in ambient air.
- Concentrations of NO_x emissions in the flare plume were observed to range from 0.5 to 8.16 ppm.
- The combustion efficiency data were insensitive to sampling probe height within the normal operating heights of the probe.
- Further development of a technique to use sulfur or another material as a tracer material to determine the flare dilution ratios is required.
- Steam-assisted flares burning relief gases with less than 450 Btu/SCF lower heating value did not smoke, even with zero steam assistance.
- The meandering of the flame's position relative to the sampling probe with varying wind conditions affected the continuous measurements but had no apparent effect on the combustion efficiency values.
- Higher concentrations of THC and CO were not observed during the purge rate flare tests.

SECTION 3

TESTING METHODOLOGY

EXPERIMENT DESIGN AND FLARE OPERATION

The flare tests were designed to determine the combustion efficiency and hydrocarbon destruction efficiency of flares under a variety of operating conditions. The tests were devised to investigate routine industrial flaring operations. Conditions representative of emergency flaring operations were not investigated. The primary flare operating variables were:

- Flow rate of relief gas;
- Heating value of relief gases; and
- Steam-to-relief gas ratio (steam flare only).

The preliminary test plan called for twenty-seven tests, with each test having a different combination of flare operating variables. The operating variables were defined as follows:

Relief Gas Flow

High – 25 foot flame length.

Intermediate – 1/6 of high flow.

Low – 1/20 of high flow.

The maximum practical flame length that could be tested was approximately 25 feet due to height limitations of the crane boom holding the sampling probe. This was the limiting factor for setting the maximum relief gas flow rate.

Heating Value

High – Heating value of the undiluted relief gas (zero nitrogen flow) (2,200 Btu/ft^3).

Intermediate – Twice the low heating value condition (300-600 Btu/ft^3).

Low – Lowest heating value that will maintain combustion (high nitrogen flow) (less than 200 Btu/ft^3).

Steam Flow

High – Steam-to-relief gas mass ratio of 1.0.

Intermediate – Steam-to-relief gas mass ratio of 0.5.

Low – Steam flow at incipient smoking.

Zero

The preliminary test plan called for determination of the vertical profile of the plume by sampling at least four different heights above the flame. As discussed on page 34, this was not done due to the insensitivity of combustion efficiency to probe height. Following the vertical profile measurements, the flare's efficiency was to be determined at the vertical point where the combustion reactions are complete but prior to further dilution with ambient air.

A technical pretest meeting was held on May 6, 1982 at the John Zink Company flare demonstration facility in Tulsa, Oklahoma to allow the project participants to finalize the test plans. During this meeting, six (6) smoking flare test designs were adopted in addition to the 27 tests previously mentioned, for a total of 33 planned tests. Other items discussed during this meeting included: the division of responsibilities, lines of communication, quality assurance procedures, safety considerations, schedules and testing sequence.

During the early stages of the test program, the participants learned more about the characteristics of flares, and it became apparent that several of the planned tests were not practical and/or did not represent the intended flare operating conditions. Therefore, sixteen of the thirty-three planned tests (numbered 1 through 33) were cancelled and a substitute group of tests (numbered 50 through 67) were formulated in the field and executed in their place. The most common reason for abandoning tests was that many of the planned incipient smoking tests and smoking steam-assisted flare tests would not smoke, even with zero steam flow.

During each test the flows of the flare feed gases were monitored and maintained as close as practical to the target levels. For several tests it was not possible, due to physical constraints, to maintain all the flow rates at constant level. This was particularly true for those tests that called for high nitrogen flow. As the pressure in the N_2 cylinder banks declined during a test, the nitrogen flow would tend to decrease, resulting in higher relief gas heating values.

Sulfur was selected as a tracer material to allow estimation of the dilution of the relief gas from the flare burner tip to the sampling probe. Sulfur was chosen primarily because of the availability of monitoring instrumentation to measure part-per-billion levels of sulfur using flame photometry. Helium was considered as a tracer material. However, this material is difficult to quantify at levels less than several tens of parts per million and thus, would require large quantities of gas. Additionally, helium cannot be detected on a continuous basis as can SO_2. Sulfurhexafluoride (SF_6) was also considered as a tracer material. However, SF_6 is not stable at the elevated temperatures found in a flare flame.

The sulfur in the relief gas originated from three primary sources: 1) naturally occurring reduced sulfur in the crude propylene, 2) sulfur added to the propylene in the form of butyl mercaptan (approximately 1 gallon butyl mercaptan/6,800 gallons crude propylene), and 3) sulfur dioxide gas added to the relief gas stream. All three sources and forms of sulfur are presumably oxidized to SO_2 as the relief gas is burned. The flare emissions were then analyzed for total sulfur as SO_2 using flame photometry.

Crude propylene was selected for the relief gas because it is relativly difficult to burn smokelessly, as compared to paraffins. The availability of propylene and safety considerations also influenced its selection as the relief gas. Lower Btu content relief gases were obtained by diluting the crude propylene with inert nitrogen. Flow rates for both the propylene and the nitrogen were controlled by appropriately sized metering valves and rotameters. Steam flow to the steam-assisted flares was controlled by a metering valve and monitored by an orifice meter. Sulfur dioxide was added to the relief gas during some of the tests to increase the levels of tracer material. The flow of SO_2 was monitored and regulated by a rotameter and metering valve assembly. Figure 2 is a schematic of the flow controls and plumbing used to operate the test flares. Figure 3 presents photographs of the flow control manifold assembly and the nitrogen cylinder manifold arrangement.

SAMPLING AND ANALYSIS

An extractive sampling system was use to collect the flare emission samples and transport these samples to two mobile analytical laboratories. Figure 4 is a diagram of the sampling and analysis system. The extractive sampling system consisted of a specially designed 27-foot sampling probe which was suspended over the flare flame by support cables and a hydraulic crane. This probe consisted of a 5-foot unheated section of 1" stainless steel pipe coupled with a 22-foot heated section of 5/8" stainless steel tubing. The heated section was insulated and housed in a 3" pipe which provided support for the entire probe assembly. Guy wires were attached to both ends of the 3" pipe support to position and secure the probe from ground level. Figure 5 contains photographs of the flare emission sampling probe.

Gaseous flare emission samples entered the sampling system via the probe tip, passed through the particulate filter, through the heated probe section and then were carried to ground level by a 3/8" heated FEP teflon tube sample line. The sampling system temperature was maintained above 100 C to prevent the condensation of water vapor. The flare emission sample was divided into three possible paths. A fraction of the heated sample was passed through an EPA Reference Method 4 sampling train to determine the moisture content of the sample. A second fraction was directed through a moisture removal cold trap and thence, into a sampling manifold in one of the mobile laboratories. Sample gas in this manifold was analyzed by continuous monitors for O_2, CO, CO_2, NO_x and THC on a dry-sample basis. A third fraction of the sample was directed into a heated sampling manifold in the other mobile laboratory. Sample gas in this manifold was analyzed for SO_2 and hydrocarbon species on a wet basis.

TYPES OF FLARE BURNERS TESTED

The steam-assisted flare used for the test series was a John Zink Standard STF-S-8 flare tip with two constant ignition pilots. Overall length was 12'-3 1/2" with the upper 7'-3" constructed of stainless steel and the lower 5'-1/2" made from carbon steel. The maximum capacity of the tip is rated by John Zink Company at approximately 53,300 lbs/hr for crude propylene at 0.8 Mach exit velocity. However, the STF-S-8 would not burn this volume of gas and remain totally smokeless. The capacity of steam flow through the flare steam manifold

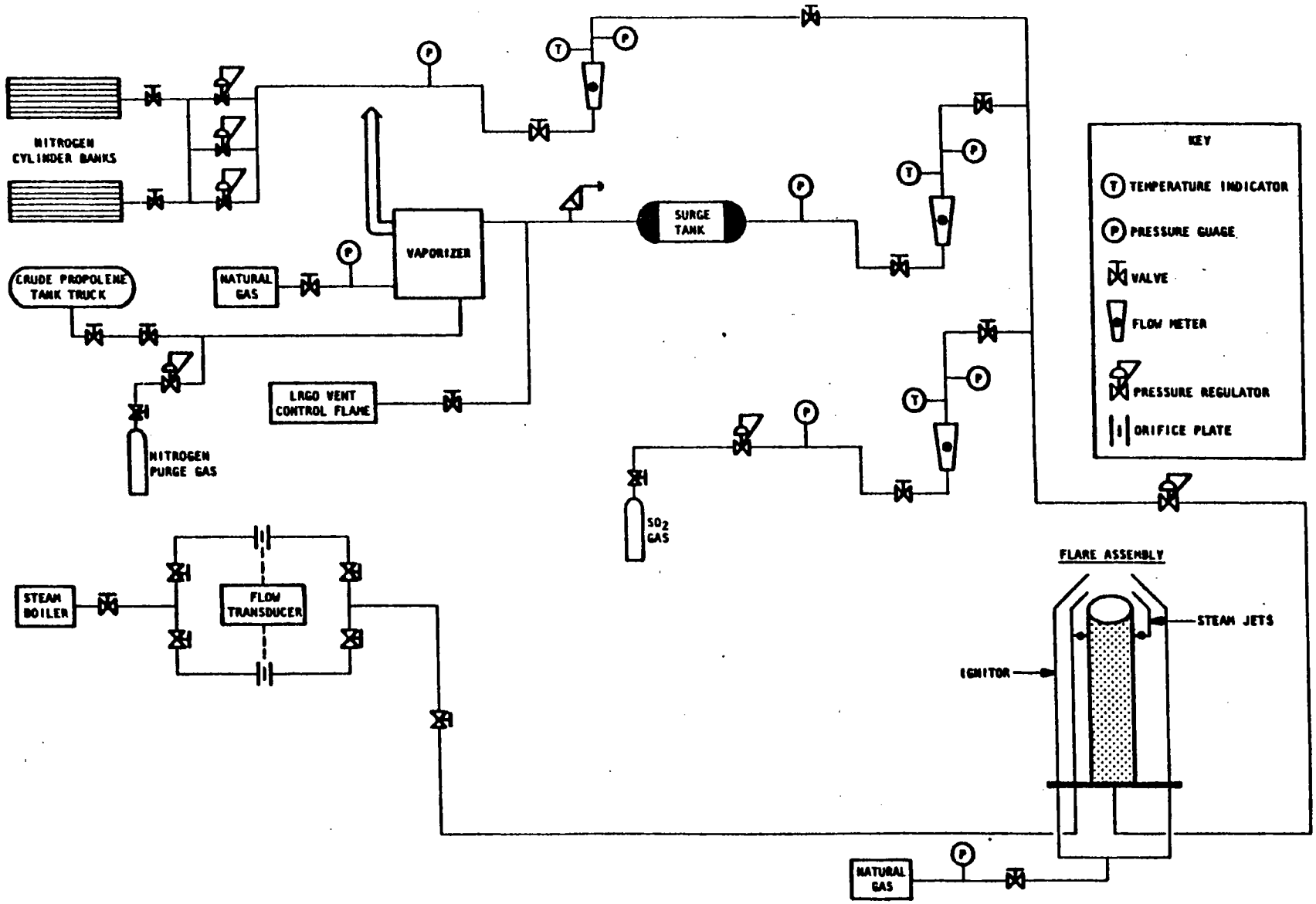
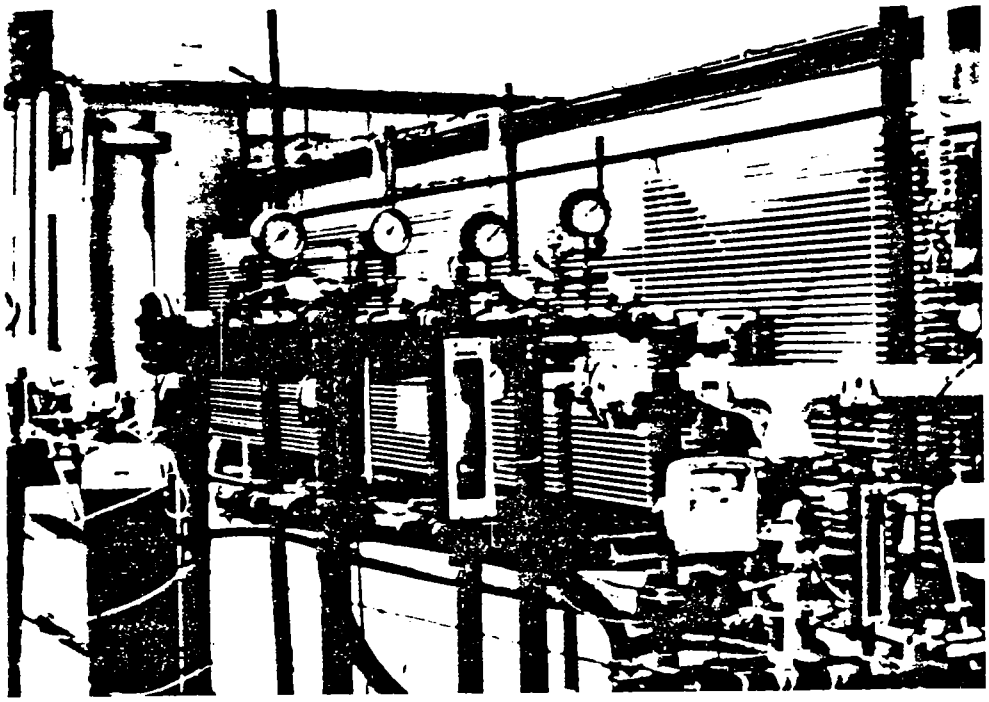
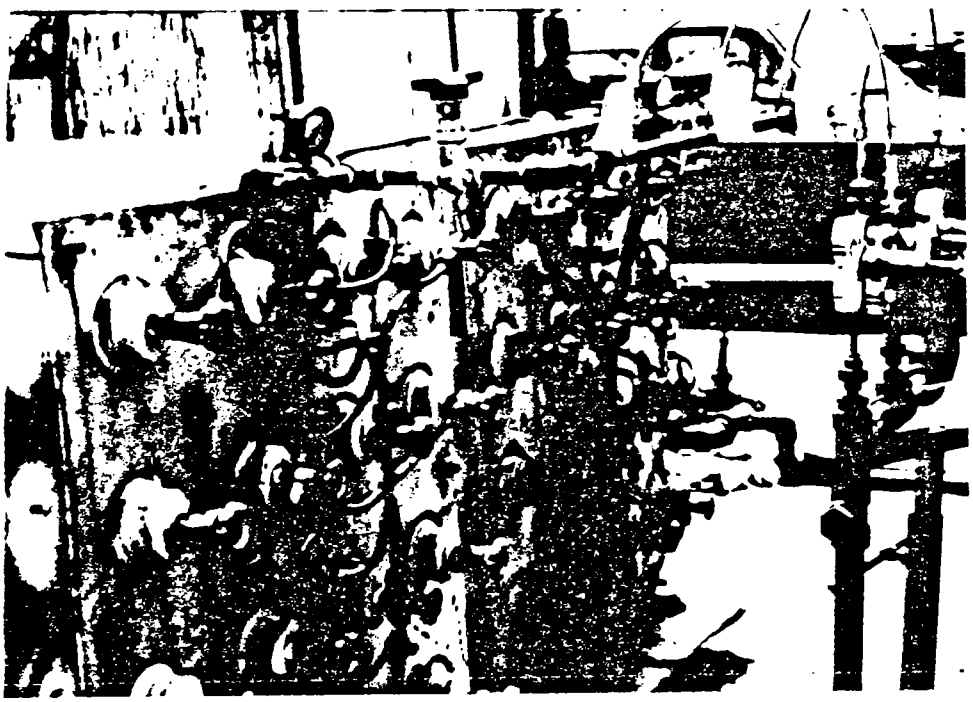


Figure 2. Flare flow control system.



Flow Control Manifold



Nitrogen Cylinder Manifold

Figure 3. Flow control and nitrogen cylinder manifolds.

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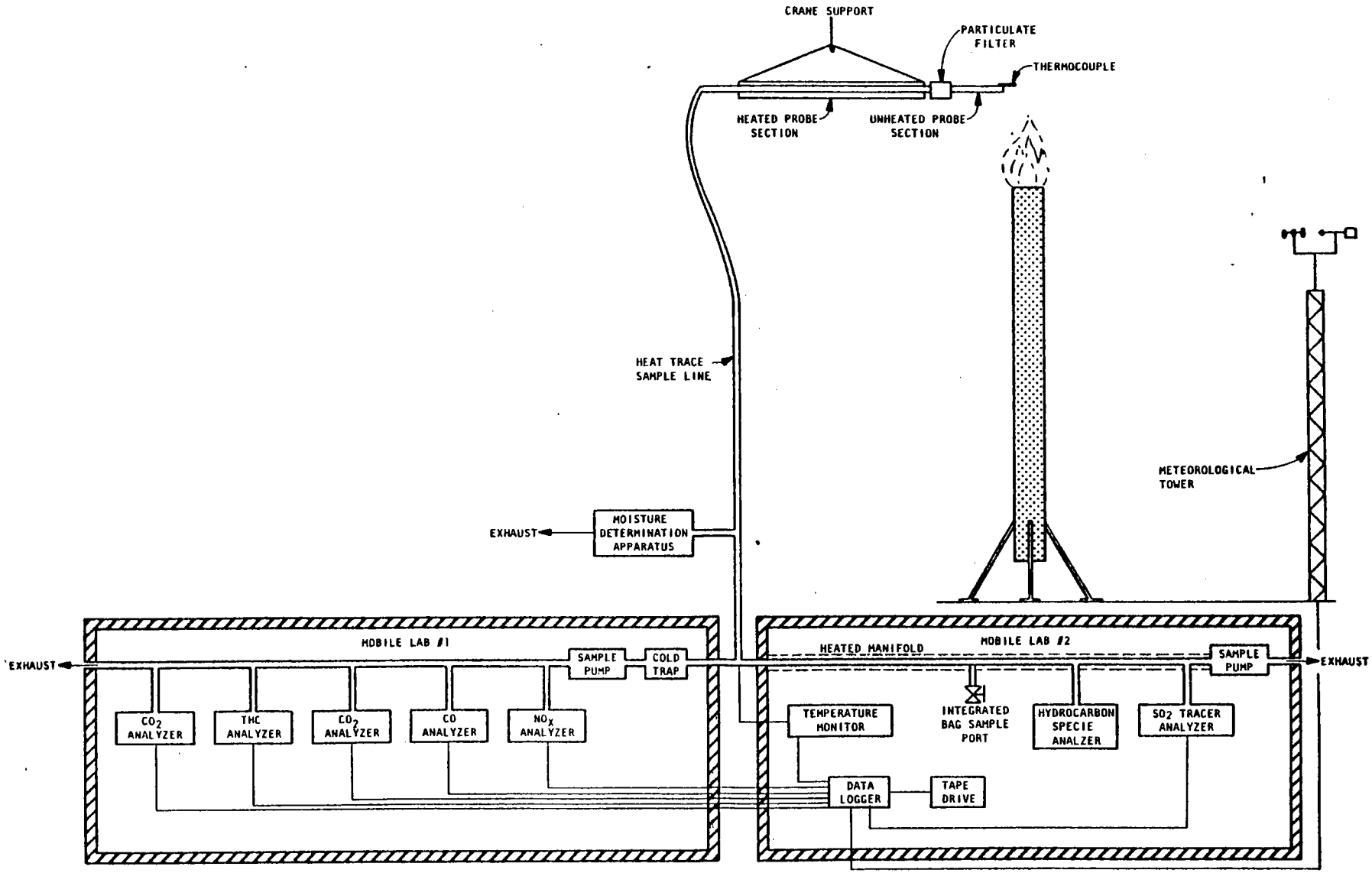

Figure 4. Flare sampling and analysis system.

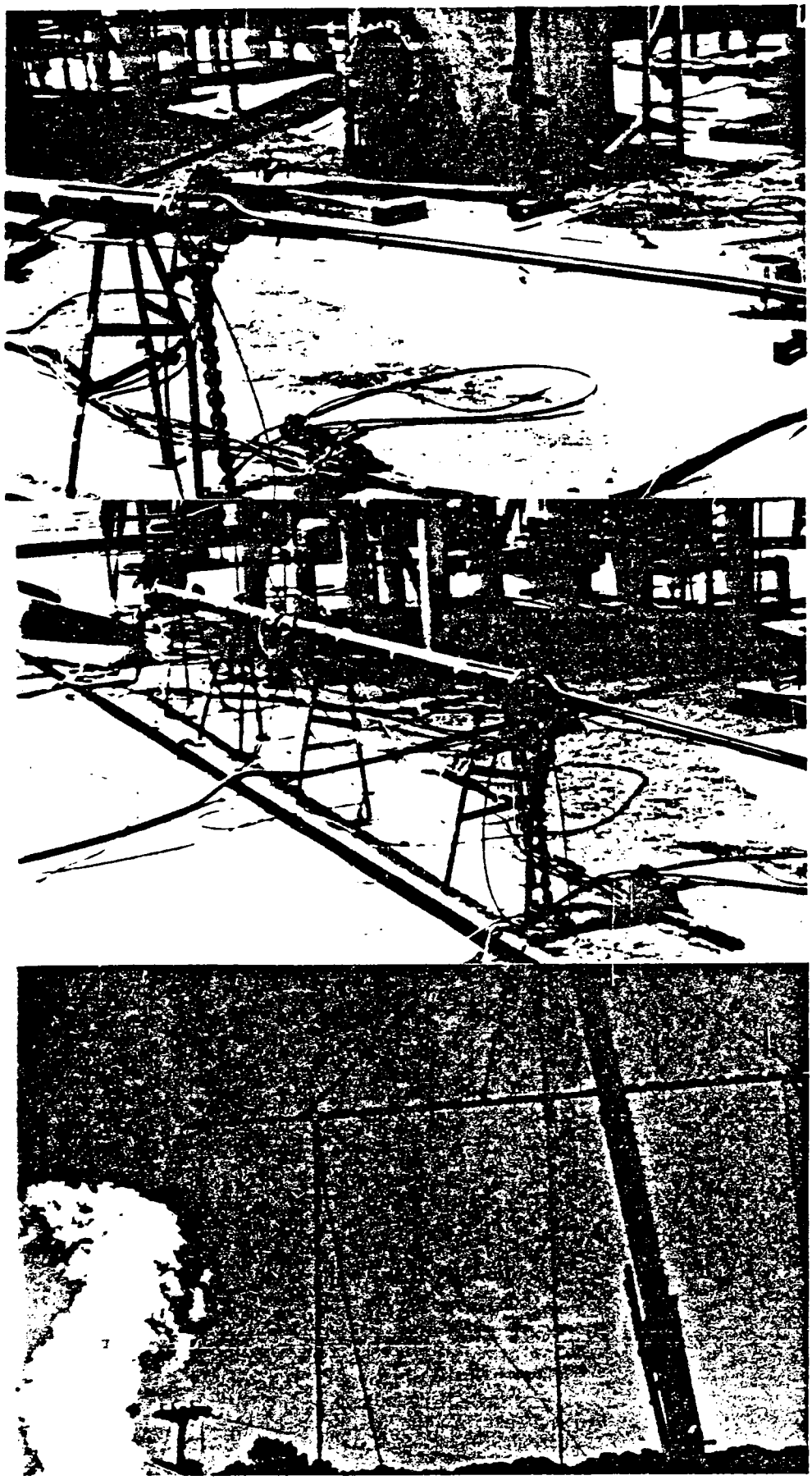

Figure 5. Flare emission sampling probe.

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is 10,080 lbs/hr based on steam conditions of 100 psig and 338°F. The recommended steam flow for this flare is approximately 0.4 pounds of steam per pound of crude propylene. The steam jet total flow area is 1.92 in^2 and the unobstructed flow area at the exit of the 8 5/8" ID steam-assisted flare tip is 27.0 in^2.

The air-assisted flare was the John Zink STF-LH-457-5 flare with two constant ignition pilots. The overall length of this flare was 13'-2". The upper portion of this flare's air plenum and burner are constructed of stainless steel and the lower portion is of carbon steel. The maximum capacity of the air-assisted flare is approximately 23,500 lbs/hr of crude propylene, which can be burned smokelessly through use of an air blower. The blower used for this test series was 7 1/2 HP vane axial fan located in the base of the 18 1/4" ID air riser. The relief gas is delivered to the tip by an 4" OD internal riser with the air supplied around the outside through the air riser and plenum. The relief gas is discharged via a specially designed "spider" on the end of the internal riser. The total area of the relief gas holes in the spider burner was 5.30 in^2 for the tests on high Btu content relief gas and 11.24 in^2 for the tests on low Btu content gases. The air flow and air flow velocity are proprietary information and are not included in this report.

Typical field installations of air-assisted flares utlize two-speed forced draft fans. The blower normally runs at low speed with automatic advancement to high speed upon an increased relief gas flow signal. The blower is also automatically returned to low speed when the increased relief gas condition subsides. Some deadband is normally provided to avoid excessive speed cycling of the blower with oscillating flows. Normal low speed operation handles approximately one-third of the maximum smokeless duty. The air-assisted flare used in these tests employed an adjustable air inlet vane assembly instead of a two-speed fan. Adjustment of the vane assembly allowed duplication of the high and low speed air flow rates without the two-speed fan.

Two different "spider" burner tips were employed during the air-assisted flare tests. The LH burner tip, designated at "A", was used for tests 26, 65, 28 and 31 for high Btu content gases, and the burner tip designated as "B" was used for the low Btu content gas tests 66, 29, 64, 62, 63, 33 and 32.

John Zink Standard STF-6-2 pilots were used for both flare tips. At 15 psig, the pilots were designed to burn 300 SCFH of natural gas. The natural gas burned in the pilots had a lower heating value of 921 Btu/SCF. Two pilots were used on both the air- and steam-assisted flares, resulting in 552,600 Btu/hr being supplied to the flare by the pilots.

FLARE TEST PROCEDURES

All key personnel involved in the execution of the flare tests were in communication with one another via a hard wire intercom system. This communications system included the following: JZ test coordinator, ES instrument operator, CMA test observer, EPA ROSE operator, steam flow operator, rotameter operator, vaporizer operator, crane operator, propylene truck/nitrogen bank operator and video camera operator. All conversations between these persons during tests were recorded on the video tape and on a portable tape

recorder. In addition, the two ES mobile laboratories were in communication via a separate intercom system.

Flaring was not begun until all key personnel were at their stations and verified that they were prepared to initiate a formal test. Then the test coordinator would call for flare ignition and the gas flows to the flare would be adjusted to the previously agreed nominal values. Once the flows were stabilized the probe would be brought into position by manipulating the hydraulic crane and guy wires.

The probe positioning objective was to place the probe tip as close as possible to the flare flame without the probe being in the flame. The intent was to sample the flame emission plume as close as possible to the combustion zone to minimize the of dilution of the plume by ambient air. The probe tip was kept out of the flame so as not to bias the data with gases that were still undergoing combustion reactions.

Probe positioning was directed by the JZ test coordinator. The test coordinator's visual probe positioning was aided by observers located in different quadrants surrounding the flare and the CMA observer who was situated on an elevated platform. Additionally, the ES instrument operator monitored the probe tip temperature, CO, CO_2, and THC.

When the project participants agreed that the probe was positioned as well as was feasible, the test coordinator announced the initiation of the test and data collection ensued. The probe position was adjusted as required during the test to compensate for changes in wind conditions causing movement of the flame and the plume away from the probe tip. These adjustments were both vertical and lateral. The primary criteria for determining the need to adjust the probe position was a decline in probe tip temperature. Short-term declines in temperature (i.e. less than one minute) were common as the flare flame and plume moved with intermittent changes in the wind. However, extended temperature declines (i.e., greater than two minutes) were regarded as a significant shift of the wind and signaled the need to adjust the probe position.

Data collecton continued for each test for a target period of 20 minutes. The actual test duration was dependent on a number of factors which influenced decision of when to terminate the tests. These factors included:

1. The effects of the flare's radiant heat on buildings, personnel and test equipment in the area;

2. The representativeness of the data from the standpoint of being able to maintain good probe positioning during the majority of the test; and

3. The consumption rates of propylene and nitrogen.

BACKGROUND MEASUREMENTS

Ambient air concentrations of the compounds of interest were measured in the test area before and after each test or series of tests. These background

measurements were collected for a minimum period of five minutes. The background measurements collected before the tests were typically initiated fifteen to thirty minutes before the anticipated start of the next test. Background measurements collected after the tests were initiated as soon as all the instruments indicated a complete return to baseline concentrations (typically five to ten minutes after test completion). On occasions when several tests were executed in a relatively short time period (less than four hours), the same pair of before and after background measurements were applied to more than one test. On other occasions a set of background measurements collected after a test would also suffice as the background data set collected before the next test.

CONTINUOUS EMISSION ANALYZERS

Flare emission measurements of carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2), oxides of nitrogen (NO_x), total hydrocarbons (THC) and sulfur dioxide (SO_2) were measured by continuous analyzers that responded to real time changes in concentrations. These analyzers obtained their samples from the sample manifolds in the two mobile laboratories. Table 2 is a summary of the instrumentation used during the tests. The operating principles of these instruments are well known and are not discussed in detail in this report.

The instruments were operated according to the manufacturers' recommendations, utilizing the primary measurement ranges listed in Table 2. The only exceptions to this were the operation of the THC and SO_2 analyzers. During some tests it was necessary to change the operating range of the THC analyzer to higher scales due to elevated levels of these compounds. The Meloy SA 285 SO_2 analyzer was modified to incorporate a 1:5 sample dilution system. This was necessary in order to minimize the effect of variable O_2 content in the flare emissions on the instrument response.

All instruments were housed in air conditioned mobile laboratories to minimize the effects of temperature on instrument response. However, given the high radiant heat effects of some of the flare tests, it was not always possible to maintain a constant temperature within the mobile labs. This factor had the greatest effect on the NO_x and SO_2 analyzers which employed photomultiplier tubes in their detection systems. The effect of rising ambient temperature was noted as a slight shift in the instrument baseline.

HYDROCARBON SPECIES ANALYSIS

Flare emission samples were collected during each test for gas chromatographic analysis for hydrocarbon species. These samples were of two forms: instantaneous samples and time integrated samples. The instantaneous samples were periodically withdrawn directly from the sample manifold during each test and injected into the chromatograph via a gas sample loop. The time integrated samples were transferred from the manifold into a six liter Tedlar® bag over a period of five to ten minutes. Subsequently, the integrated samples were analyzed by gas chromatograph. The analysis techniques for the integrated and instantaneous samples were the same. Only the sampling differed. Table 3 outlines the operating conditions of gas chromatograph.

TABLE 2. FLARE EMISSION ANALYZERS AND INSTRUMENTATION

Make and Model	Parameter	Primary Operating Range	Operating Principle
Thermo Electron Model 10	NO_x	0-25 ppm	Chemiluminescence
Horiba PIR 2000	CO	0-1,000 ppm	Infrared absorption
Horiba PIR 2000	CO_2	0-5%	Infrared absorption
Teledyne 320 AX	O_2	0-25%	Electro catalysis
Scott 116	Total hydrocarbon	0-100 ppm	Flame ionization
Carle 211 Gas Chromatograph	Hydrocarbon Species	N/A	Flame ionization
Meloy SA 285 (ES Modified)	Tracer (SO_2)	0-5 ppm	Flame photometry
Climatronics Electronic Weather Station	Wind Speed Wind Direction Ambient Temperature	0-50 mph 0-540 40-120°F	Photo chopper Precision potentiometer Thermistor
Omega Thermocouple Assembly	Probe Temperature	-300° to 2300°F	Chromel-Alumel exposed bead thermocouple

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TABLE 3. GAS CHROMATOGRAPH OPERATING CONDITIONS

Gas Chromatograph:	Carle 211
Column:	4.9 foot x 1/8 in. stainless steel
Packing:	n-octane/porasil C, 100/120 mesh
Oven Temperature:	35 °C
Sample Loop Temperature:	35 °C
Carrier Gas:	Nitrogen
Carrier Flow:	35 cc/min.
Sample Loop Size:	1 cc
Sample Valve:	Carle 6 port, selonoid activation
Detector Type:	Flame ionization detector
Calibration Basis:	Methane equivalents (parts per million)
Lower Detection Limit:	0.05 ppm as CH_4
Valving Scheme:	Direct injection, no backflush

Elution Times:	Minutes
Methane	1.27
Ethane/Ethylene	1.62
Propane	2.44
Propylene	2.91
Butane	4.68

TEMPERATURE MEASUREMENTS

The temperature at the sampling probe tip was continuously monitored during the tests with a chromel-alumel thermocouple in conjunction with a digital thermometer. The thermocouple selected was an exposed bead type so as to minimize the response time. An open end stainless steel shield protected the thermocouple from the flame's radiant heat and still allowed free circulation of the flare emission around the thermocouple. Thermocouples were also installed in the heat trace line, the heated manifold and the heated probe assembly to allow monitoring of these tempertures during the tests.

PARTICULATE ANALYSES

The probe assembly included an in-line particulate filter housed inside the heated section of the probe about six feet from the probe tip. This in-line particulate filter assembly served two purposes: 1) collection of particulate samples from smoking flares for subsequent analysis, and 2) maintaining the cleanliness of the sampling system. The preweighed filter elements used were of the thimble configuration and constructed of 0.3 micrometer glass fiber.

The filters were changed before and after each of the smoking flare tests. Following the tests the filters were reweighed to determine the mass of particulate collected. This information, combined with the measured flow rate of sample through the probe assembly, allowed the calculation of the gross particulate concentration of the flare emission at the sampling location. It should be noted however, that these particulate samples were not collected isokinetically and thus, represent only gross estimates of the particulate concentration. The flare particulate emissions were not isokinetically sampled because it was not practical to directly measure the plume velocity. Due to small particle sizes, the lack of isokinetic sampling conditions is probably insignificant.

MOISTURE DETERMINATIONS

The moisture content of the sampled flare emissions were determined by the procedures set forth in EPA's Reference Method 4 (40 CFR 60 Appendix A). A gas sample was extracted from the heated sample line and passed through a series of four impingers immersed in an ice bath. The impingers removed the water from the sample stream by condensation and by adsorption on silica gel. The weight gain of the impingers was measured to determine the moisture content of the sample. The only deviation from the published method required by this appication was a reduction in the size of the sample passed through the impingers. Due to the short duration of the test, it was not possible to sample the full 21 SCF volume recommended in the published method. This deviation only slightly affects the accuracy of the moisture determinations.

The purpose of collecting moisture samples was to provide data to allow conversion of concentrations measured on a wet basis to a dry basis and vice versa. This was believed to be important since the instrumental analyses were conducted on both a wet and dry basis. However, the moisture determinations revealed low levels of moisture content by weight (3.8% (volume basis) average

for steam-assisted flare tests and 3.0% average for air-assisted flare tests). Therefore, moisture corrections were not applied to the data because of their low levels and questionable accuracy. It is not believed that moisture corrections would enhance the value of the data.

The results of the moisture determinations may be found in Section 4 of this report.

METEOROLOGICAL MEASUREMENTS

The ambient wind speed, wind direction and temperature was monitored at the flare test facility concurrently with the collection of flare emission data. The meteorological sensors were situated as close as was practical to the test flares at an elevation approximately the same as the flare tip (12 feet, 8 inches AGL).

Due to the numerous air flow obstructions in the test area the wind data are not expected to correspond with the prevailing Tulsa area winds. Rather, the wind data were intended to represent the wind encountered by the subject flare flames.

Testing of the flares was found to be infeasible when wind velocities exceeded 5 miles per hour. Elevated wind velocities prevented sustained and consistent positioning of the probe in the flare plume.

AUDIO AND VIDEO RECORDINGS

Audio and video recordings were made during the flare tests. Video recordings were made to document the flame behavior and the probe position relative to the flame. The video camera was positioned to have an unobstructed view of the flame by placing it on a platform approximately 20 feet above ground level. The distance from the flare to the camera was approximately 50 feet.

Audio recordings were made of the verbal observations of the participants during the tests. The audio recordings were made on the same magnetic tape used for the video recordings. The intercom system served as the source of all audio recordings.

The audio and video recordings were made primarily as means of documentation of the tests and to allow possible future more detailed analyses of the data with respect to flame behavior. These recordings were not generally used in the data analysis contained in this report. The one exception to this is the use of the recordings to identify the point at which smoking began during Test 11 relative to the increasing Btu content of the relief gas.

SECTION 4

DATA COLLECTION AND CALCULATIONS

CONTINUOUS ANALYZERS' DATA ACQUISITION

The outputs of the continuous monitoring instruments used for this study were analog signals that were proportional to the magnitude of the parameter being monitored. These output signals were recorded on both a strip chart recorder and on a data logging system. The strip chart records provided a permanent, continuous record of the analyzer output and a graphical display that aided in the data interpretation. The electronic data logger system provided a convenient means to record and process a large quantity of data. Although the data logger served as the primary means of data acquisition, the strip chart records provided a back-up data acquisition system and documentation for the data logger.

The data logger employed for this project was a Monitor Labs Model 9300. This instrument was coupled with a 9-track magnetic tape recorder (Kennedy Model 9800) and a ten-digit manual data entry system. The functions of the data logger were as follows:

- Scan each instrument output (approximately every 12 seconds);
- Convert the analyzer's analog output to a digital value;
- Scale the digital value to a useful unit of measure (ppm, mph, etc.);
- Record the scaled instantaneous value on the 9-track magnetic tape.
- Average the instantaneous values to one-minute averages;
- Print the one-minute averages on paper tape for on-site review; and
- Label each set of data with the time and the appropriate manually entered status data.

The original test plan called for the data logger to scan each channel once every six seconds. However, this was not possible given the number of input channels to the data logger (10), the required functions, and the speed of the instrument. Each input channel was scanned for instantaneous data approximately once every twelve seconds.

The data logger's internal clock was set as closely as possible to Central Daylight Savings Time (CDST). This clock was used as the standard time for all data acquisition relating to the flare tests.

The printed paper tape output of the data logger provided means to review the data being recorded on-site by the data logger. This data was compared with the strip chart data to ensure integrity in the entire data acquisition system. Likewise, the paper tape output was used to indicate the combined instrument and data logger responses to the routine zero and span calibration gas inputs. An example paper tape output may be found in this report's Appendix.

A 10-digit manual data entry system allowed the labeling of each set of data as it was collected. This system was used to record the following:

Record Digits	Parameter
0, 1	Test number designation
2, 3, 4, 5	Sampling probe height (feet and inches)
6, 7, 8	Spare
9	Status of data 0 = Calibration data 1 = Acceptable test data 2 = Change in test conditions 3 = Questionable data 4 = Ambient background data 5 = Trial test burn 6 = Probe positioned in fire 7, 8 = Spare 9 = Disregard data

HYDROCARBON SPECIES DATA

The gas chromatography data for hydrocarbon species was recorded by a Hewlett-Packard Model 3390 Integrator. This device accepted the analog signal from the gas chromatograph and plotted the peaks which correspond to the hydrocarbon species. The integrator also determined the retention time for each peak and the peak areas which are proportional to the hydrocarbon concentration. This data was recorded by a printer/plotter on a paper tape. The peak area values recorded on this tape were subsequently reduced to units of parts per million by volume of methane equivalents.

DOCUMENTATION

The performance of these tests was documented by the following:

- Logbooks maintained by CMA project participants. These records contain a test chronology, records of field observations, records of flow rates of gases feeding the flare and preliminary field data records copied from the data logger paper tape. These logbooks are stored at CMA's headquarters in Washington, D.C.

- Logbooks maintained by ES test personnel. These records contain a chronology of all events associated with the flare tests that are related to the analysis of flare plume gases. This recorded data includes records of calibrations, zero and span checks, sampling probe heights, test observations, moisture determination data, particulate mass loading data, difficulties encountered and solutions offered. These logbooks are stored at the ES Austin, Texas office.

- Strip chart records. This includes continuous recordings of CO, CO_2, NO_x, THC, SO_2, O_2, probe temperature, wind speed, wind direction, ambient temperature and the gas chromatograph integrator. These records are maintained at the ES Austin, Texas office.

- Video and audio recordings. These magnetic tapes include the audio recordings of the participants' comments and observations made during each test through the intercom system. The video tapes also include a visual record of the flare flame during the tests. Copies of these tapes are stored at the JZ Tulsa, OK facility; the EPA, IERL Office, Research Triangle Park, North Carolina; and the CMA headquarters in Washington, D.C.

- Data tapes. These paper tapes and magnetic computer tape contain all the validated data logged by the data logger during the tests. The paper tapes are stored at the ES Austin, Texas office. Copies of magnetic tape are stored at CMA headquarters, Washington, D.C., and at the ES Austin, Texas office.

CALCULATIONS

The following calculation formulas and constants were employed to reduce the data presented in this report.

Combustion Efficiency

$$\% \text{ CE} = \frac{CO_2}{CO + CO_2 + THC} \cdot 100$$

Where: CO, CO_2 and THC are flare plume concentrations (corrected for background) of these parameters in parts per million by volume. (The THC term is expressed in terms of methane equivalents corrected for background.) Note that soot corrections were made only for Tests 4, 8, and 65 (see pages 43-46).

Gaseous Flows

$$F_t = \frac{\frac{\% \text{ MR}}{100} \cdot \text{MF}}{\sqrt{\frac{MW}{29} \cdot \frac{14.7}{P+14.7} \cdot \frac{T + 460}{530}}}$$ Standard Rotameters (SCFM)

$$F_t = \frac{\text{MR}}{\sqrt{\frac{MW}{29} \cdot \frac{14.7}{P+14.7} \cdot \frac{T + 460}{530}}}$$ Direct Reading Rotameters (SCFH)

Where: F_t = gas flow at time t
% MR = percent of full-scale meter reading for standard flow
MR = meter reading for direct reading rotameters
MF = flowmeter calibration factor (SCFM)

MW = molecular weight of gas in flow meter
P = flowmeter back pressure (PSIG)
T = temperature of gas (^{o}F)

Flow Meter Calibration Factors

Meter Designation	Flow Meter Calibration Factor (SCFM)
699 MT	745.4
391 MT	409.5
R13M-25-3	128.8
R10M-25-3	26.04
R8M-26-2	2.13

Gas Constants

Gas	Density (lbs/ft^3)	Lower Heating Value (Btu/ft^3)	Molecular Weight
Crude Propylene	0.1106	2183	42.4
Nitrogen	0.1700	0	28
Sulfur Dioxide	0.0730	0	64

Steam Orifice Flows

3" orifice maximum flow = 2,250 lbs/hr
1-1/2" orifice maximum flow = 600 lbs/hr
1/2" orifice maximum flow = 200 lbs/hr

$$F_t = F_{Max}\sqrt{\frac{\%\ Chart - 20}{80} \cdot \frac{P_g}{P_o}}$$

Where: F_t = steam flow at time t (lbs/hr)

F_{Max} = maximum steam flow through orifice (lbs/hr)

% Chart = response of recorder coupled with flow transducer

20 = zero offset of recorder

80 = full-scale recorder response

P_g = steam pressure, (psia)

P_o = base pressure, (psia)

Average Flows

$$F_A = \frac{F_{t_1} + F_{t_2} + F_{t_3} + \ldots F_{t_z}}{z}$$

Where: F_A = average flow rate for each test

z = number of flow rate readings during each test

F_{t_z} = flow reading numbered 1...z at time t

SECTION 5

REVIEW OF FLARE TEST RESULTS

The test reviews contained in this section are grouped by the experimental variables of flow rate and Btu content of the relief gas. The test reviews consist of a narrative description of the test conditions and the results by test group. The measured combustion efficiency of the flare is the term which is used in these discussions to evaluate the flare performance.

Statistical data summaries are presented on a test-by-test basis in the appendix to this report (Appendix B). The data presented in these summaries were calculated from the instantaneous data values (collected at approximately 12-second intervals) which have been corrected by subtracting background concentrations. No adjustment was made for moisture. These summaries include average values, standard deviations, number of observations and combustion efficiency calculations for each test. The combustion efficiencies for each test were calculated by two methods: (1) the "average combustion efficiency" values listed in the summaries are the average values of all of the instantaneous combustion efficiency calculations performed on the instantaneous data values; (2) the "overall combustion efficiency" term was calcuclated from the average concentration values of CO, CO_2 and THC for the entire test. The differences between these two calculation methods are not regarded as significant. The "overall combustion efficiency" term is used in this report for comparison between tests.

The chronological order in which the tests were performed minimized piping and equipment changes in the field, and this order is substantially different from the groupings listed here. The test numbering system is not sequential since many tests were added or deleted from the planned sequence. Tests numbered 1 through 33 represent tests which were completed in accordance with the planned test series. Tests numbered 50 through 67 represent test conditions which were planned and implemented in the field in place of the deleted tests.

The results for tests numbered 11, 16, 59, 29 and 32 have been divided into subtests (designated 11(a), 11(b), etc.). These test data were divided into subtests for data analysis because the flare operating conditions significantly changed during the tests. The division into subtests allowed the data to more closely represent steady-state flare operation. All other tests were judged to represent steady-state flare operation. The criteria for steady-state flare operation were that all individual flow readings must be within +10% of the average flow.

STEAM-ASSISTED FLARE TESTS

Twenty-three tests were completed on the John Zink Company (STF-S-8) steam-assisted flare. The flare operating conditions and the results of these tests are summarized in Table 4.

35

TABLE 4. STEAM-ASSISTED FLARE SUMMARY

Test Conditions			Test Number	RELIEF GAS* Flow (SCFM)	Exit Velocity (ft/min)	Lower Heating Value (Btu/SCF)	Propylene Flow (lbs/hr)	Propylene Flow (SCFM)	Nitrogen Flow (lbs/hr)	Nitrogen Flow (SCFM)	Steam Flow (lbs/hr)	Steam-to-Relief Gas Ratio (lb/lb)	Combustion Efficiency Percent
High Btu Content	Decreasing Flow Rate		1	473	2,523	2,183	3,138	473	-	-	2,159	0.688	99.96
			2	464	2,475	2,183	3,078	464	-	-	1,564	0.508	99.82
			3	456	2,432	2,183	3,027	465	-	-	1,355	0.448	99.82
			4	283	1,509	2,183	1,875	283	-	-	-	-	98.80**
			8	157	837	2,183	1,044	157	-	-	-	-	98.81**
			7	154	821	2,183	1,019	154	-	-	722	0.757	99.84
			5	149	795	2,183	991	149	-	-	1,543	1.56	99.94
			67	148	789	2,183	980	148	-	-	711	0.725	See pg. 28.
	Low Flow Rate		17	24.5	131	2,183	162	24.5	-	-	150	0.926	99.64
		Excessive Steam Flow Rates	50	24.4	130	2,183	162	24.4	-	-	498	3.07	99.45
			56	24.5	131	2,183	163	24.5	-	-	562	3.45	99.70
			61	25.0	133	2,183	166	25.0	-	-	941	5.67	82.18
			65	24.7	132	2,183	164	24.7	-	-	1,125	6.86	68.95
Low Btu Content	Decreasing Flow Rate		57	703	3,749	294	629	94.8	2,663	608	497	0.150	99.90
			11(a)	660	3,520	305	612	92.2	2,489	568	-	-	99.93
			11(b)	599	3,195	342	623	93.9	2,210	505	-	-	99.86
			11(c)	556	2,965	364	616	92.8	2,028	463	-	-	99.82
			59(a)	591	3,152	192	345	52	2,361	539	-	-	98.11
			59(b)	496	2,645	232	350	52.7	1,942	443	-	-	99.32
			60	334	1,781	298	212	32	1,325	302	-	-	98.92
			51	325	1,733	309	305	46	1,222	279	256	0.168	98.66
			16(a)	320	1,707	339	329	49.6	1,182	270	-	-	99.74
			16(b)	252	1,344	408	313	47.2	897	205	-	-	99.75
			16(c)	194	1,035	519	307	46.2	650	148	-	-	99.74
			16(d)	159	848	634	307	46.3	496	113	-	-	99.78
	Purge Flow Rate***		54	0.356	1.90	209	0.226	0.0341	1.41	0.322	-	-	99.90
			23	0.494	2.63	267	0.451	0.0680	2.13	0.487	-	-	100.01
		Excessive Steam Flow Rates	52	0.556	2.96	268	0.452	0.0682	2.14	0.488	201	77.5	98.82
			53	0.356	1.90	209	0.226	0.0341	1.41	0.322	201	123	99.40

* All values at standard conditions of 70°F and 29.92 in Hg.

** Not accounting for carbon present as soot (see Table 10).

*** For purge flows the pilot contributed greater than 95% of the total combustible gas to the flare.

High Btu Content Relief Gases

This test group addresses the steam flare's combustion efficiency while burning high Btu content relief gases at variable flow rates and various steam-to-relief gas ratios. Tests numbered 1, 2 and 3 examined the burning of the crude propylene at the normal (high) rate of approximately 3,100 lbs/hr with steam-to-relief gas ratios ranging from 0.688 to 0.448. Test 3 was run at the steam flow which yielded incipient smoking of the flare. No significant change in the combustion efficiency values was noted between these three high flow rate tests. What little hydrocarbons were present were predominately methane. Likewise, the average corrected CO concentrations for these tests were low, ranging from 3.8 to 13.8 ppm.

The CO_2 values reported during the first minute of test 3 are lower than those which were prevalent during the remainder of the test. The combustion efficiency data does not appear to be influenced by this unexplained anomoly.

The background data file applied to test 3 has a negative average value for CO (-0.4 ppm). This was caused by the physical limitations of the CO analyzer. This instrument was operated on the lowest available range (0-1000 ppm). At this range, the practical limit for accurately adjusting the analyzer's zero response was +3.0 ppm. Therefore, it is not surprising that slightly negative background CO values could be recorded during conditions of low ambient CO concentrations.

The average corrected total hydrocarbon value reported for test 1 is -0.7 ppm. This negative value results from the measured ambient background THC concentration being higher than the THC concentration measured above the flare flame.

Tests numbered 4 and 8 were performed with crude propylene relief gas flows of 1,875 and 1,044 lbs/hr without any steam assistance to the flare. These conditions purposely resulted in a heavily smoking flare condition. The relief gas flow rates for test number 4 were reduced from those used in tests 1, 2 and 3 in order to keep the flame length within the probe height constraints.

The combustion efficiencies for these two tests are reported as 98.80% and 98.81%. It should be noted that these combustion efficiency calculations do not account for the carbon lost as soot; only carbon present as gaseous species are considered (CO, CO_2, and THC). Higher levels of CO were observed during these tests (61 to 75 ppm corrected) in comparison to tests 1, 2 and 3. However elevated levels of unburned gaseous hydrocarbons were not detected. The hydrocarbon species data shows the predominant species present to be methane and acetylene.

Particulate samples of the soot were collected during these two tests. This data is addressed later in this section.

Tests numbered 7 and 5 were designed to represent flaring of a high Btu content gas at an intermediate flow rate. The steam-to-relief gas ratio was 1.56 for test 5 and represented the high steam flow case, while the ratio of 0.757 for test 7 yielded incipient smoking. Both of these tests at intermediate

flow rates yielded similar combustion efficiency results to the high flow rate tests (1, 2 and 3). The observed combustion efficiencies were 99.94% and 99.84% for tests 5 and 7 respectively. Methane accounted for the major fraction of the total hydrocarbons present in the flare emissions. The corrected CO levels for both tests were fairly low at 4.1 ppm for test 5 and 7.9 ppm for test 7.

During test 67 the sampling probe was deliberately placed in the flare flame. This is in contrast to the other tests which sought to sample in the flare plume above the flame. The purpose of this short test was to demonstrate the upscale instrument responses to the partially combusted gases in the flame. Concentrations of CO and THC were observed to rise sharply and offscale as the probe was placed in the flame. THC concentrations were observed to be greater than 100 ppm and CO concentrations were observed to be greater than 2,280 ppm. The data collected during this test does not represent the combustion efficiency of the flare since the sample was collected within the flame. The average values for THC and CO reported in the statistical summary are disregarded since these numbers excluded the overrange observations.

Low Flow Rate, High Btu Relief Gases

Tests numbered 17, 50, 56, 61 and 55 examined the effects of increasing steam flows on the flaring of a high Btu content relief gas at a low flow rate (approximately 164 lbs/hr). Test 17 yielded results similar to the high and intermediate flow rate tests. The overall combustion efficiency was calculated to be 99.84% and the corrected average concentrations of THC and CO were low at -0.5 and 6.1 ppm, respectively. (The negative THC value resulted from the measured concentration being lower than the background concentration.) It was determined during this test that a steam-to-relief gas ratio of 0.926 was required for smokeless operation at the designated flow rate.

Tests 50, 56, 61 and 55 were performed at increasing steam flow rates. The steam-to-relief gas ratios used for these tests are regarded as being higher than those that would represent good engineering practice. Steam-to-relief gas ratios for tests 50 and 56 were 3.07 and 3.45 and yielded combustion efficiencies of 99.45% and 99.70%. By contrast the steam-to-relief gas ratios for tests 61 and 55 were 5.67 and 6.86 and resulted in lower observed combustion efficiencies of 82.18% and 68.95%. This data suggests that steam-to-relief gas ratios above 3.5 may cause inefficient combustion.

The total hydrocarbon and CO concentrations for tests 50 and 56 were fairly low in keeping with the high observed combustion efficiencies. However, the hydrocarbon specie data for these two tests show that a larger fraction of the total hydrocarbon was present as unburned propylene (approximately 1/4 of the total hydrocarbon for test 56 and 1/2 of the total hydrocarbon for test 50) in comparison to the previously discussed tests. In tests 61 and 55, with the lower observed combustion efficiencies, the CO and THC concentrations were elevated and propylene represented approximately 3/4 fraction of the total hydrocarbon.

Test 61 was a repeat of Test 55. This repeat test was performed because of uncertainties regarding probe placement during test 55. The flaring of the high heating value relief gas at a low flow with a very high steam rate yielded a low luminosity flame that prevented accurate visual placement of the probe.

Additionally, test 55 was conducted during variable wind conditions. Test 61 was performed at night to aid visual probe positioning and to take advantage of stable wind conditions. The only significant difference between test 61 and test 55 was that the steam-to-relief gas ratio for test 61 was somewhat lower (5.7 versus 6.9). This ratio is still regarded as being very high and not representative of typical industrial operating practices. The effect of steam quenching on the flare combustion efficiency is evidenced in the test data.

Low Btu Content Relief Gases

The flaring of low Btu content relief gases was simulated by diluting the high Btu crude propylene with inert nitrogen. Thus, by changing the relative flow rates of nitrogen and crude propylene to the flare, the heating value of the relief gas could be varied. For this series of tests, the Btu content of the relief gases ranged from 634 Btu/SCF to 192 Btu/SCF, and the relief gas flow rates ranged from 3,292 lbs/hr to 803 lbs/hr.

The original test plan called for the series of tests involving low Btu content relief gases to include variations in the steam flow to achieve incipient smoking and smoking conditions. However, for most of these tests smoking was not observed, even with zero steam flow. Only when the lower heating value rose above 450 Btu/SCF during test 16 was smoking observed.

Tests numbered 11, 59 and 16 in this series were divided into subtests because the flare operation was not steady-state during these tests. Due to physical limitations in the nitrogen flow control system, the flow of nitrogen decreased with respect to time causing a corresponding increase in the lower heating value of the relief gas. The division into subtests allowed the data to more closely represent steady-state flare operation.

Test 57 represented the highest flow rate of a low Btu content gas that was tested. The flare was supplied with 3292 lbs/hr of relief gas with a lower heating value of 294 Btu/SCF and a steam-to-relief gas ratio of 0.150 steam/lb relief gas. Test 51, by comparison, represented flaring of a similar heating value gas (309 Btu/SCF) with a similar steam-to-relief gas ratio (0.168), but at a lower flow rate of 1,527 lbs/hr. Tests 57 and 51 achieved combustion efficiencies of 99.90% and 98.66%, respectively. Corrected hydrocarbon concentrations of 2.0 ppm and 11.5 ppm and CO concentrations of 5.0 ppm and 34.1 ppm were obtained for tests 57 and 51, respectively. The slightly lower combustion efficiency of test 51 is also observed in the hydrocarbon species data. The observed hydrocarbons in test 57 were approximately 20% non-methane species, while the hydrocarbons in test 51 were comprised of 58% non-methane species.

The flames for tests 57 and 51 were of low luminosity and visual positioning of the probe was difficult. These two tests were the only low Btu flare tests where steam was supplied to the flare. The background file as applied to test 51 (and tests 23 and 52) lists probe tip temperatures that are higher than ambient levels. This is believed to be caused by the probe acting as a heat reservoir from the test event that immediately preceded. This anomaly does not effect the combustion efficiency data.

Tests 11, 59, 60 and 16 examined the flaring of relief gases with heating values of 192 Btu/SCF to 634 Btu/SCF at flow rates ranging from 3,101 lbs/hr to 803 lbs/hr with zero steam flow to the flare. The variations in observed combustion efficiencies for this set of tests was fairly narrow, ranging from 99.93% to 98.11%.

Test 59 demonstrated the flaring of a low Btu content gas at a high flow rate with no steam. The nitrogen flow decreased during this test from 2,453 lbs/hr to 1,726 lbs/hr due to declining pressure in the nitrogen cylinders. This resulted in an increase in the Btu content of the relief gas from 182 Btu/SCF to 257 Btu/SCF from the beginning to the end of the test. This corresponds to a slightly lower combustion efficiency for test 59(a) than for test 59(b).

Tests 59(a) and 59(b) had the lowest Btu content relief gases of the group. Likewise, these tests exhibited slightly lower combustion efficiencies. This observation is confirmed in the hydrocarbon species data which shows test 59 to have elevated total hydrocarbon concentrations (as compared with tests 11, 60 and 16), and non-methane hydrocarbons representing 92% of the total. These results indicate that some unburned hydrocarbons were sampled during this test.

Test 11 was to demonstrate the flaring of low heating value gas at a flow rate of approximately 3,100 lbs/hr. No steam was supplied to the flare. The flow rate of nitrogen to the flare declined somewhat during the test, thus, causing a corresponding increase in the heating value of the flare gas. Therefore, this test has been divided into three subtests [11(a), 11(b) and 11(c)] for purposes of data analysis. The data does not indicate any change in the flare combustion efficiency with the change in nitrogen flow.

Test 16 was designed to be a smoking flare test utilizing an intermediate flare gas flow with a low heating value gas. No steam was supplied to the flare. As was the case with Test 11, the nitrogen flow declined during the test and hence, the test was divided into subtests for data analysis [tests 16(a), 16(b), 16(c), 16(d)].

During the initial period of the test, when the heat content of the flare gas was the lowest, the flare did not emit smoke. However, as the nitrogen flow declined and the heat content of the flare gas increased, the flare began to smoke. The smoking began approximately nine and one-half minutes from the start of the test [during subtest 16(b)] when the heating value of the flare gas reached approximately 450 Btu/SCF. The smoking increased with increasing Btu content of the relief gas. The onset of smoking and the change in heating value did not have any obvious effects on the gaseous combustion efficiency data (if carbon lost as smoke is excluded from the combustion efficiency calculations).

Test 60 was similar to Test 16(a) except the Btu content was slightly lower at 298 Btu/SCF instead of 339 Btu/SCF. The flow rates for the two tests were similar with exit velocities of 1781 and 1707 ft/min. The observed combustion efficiency for test 60 was 98.92% as compared with 99.74 for test 16(a). As was the case for test 59, this slightly lower combustion efficiency is believed to be a result of the lower Btu content of the relief gas.

Purge Rate Relief Gas Flows

Tests 54, 23, 52 and 53 examined purge gas flare operations. Purge flows are sometimes used in flare operations to prevent oxygen encroachment into the flare system during the time that no relief gas is provided the flare. It should be noted for these tests that the flow of natural gas from the flare pilots was significantly greater than the flow of the purge gases. The two pilots burned a total of 10 SCFM (9210 Btu/min) of natural gas as compared with purge flows of 0.56 to 0.36 SCFM (149 to 74 Btu/min). Thus, the overall combustion efficiency measurements for these tests were primarily a measure of the flare pilots. During these tests only an occasional flicker of flame could be observed at the flare header.

Tests 54 and 23 were performed without the addition of steam to the flare. These tests yielded high observed overall combustion efficiencies of 99.90% and 100.01%. The calculated combustion efficiency greater than 100% for test 23 resulted from the observed hydrocarbon level above the flare being slightly lower than the measured ambient background hydrocarbon concentrations. The corrected total hydrocarbon concentration for tests 54 and 23 were 0.0 and -5.0 ppm.

Tests 52 and 53 were similar to tests 54 and 23 except 210 lbs/hr steam was supplied for the former. The calculated combustion efficiencies for tests 52 and 53 were 98.82% and 99.40%. This slight decline in the combustion efficiency is believed to be due to steam quenching of the combustion process. Corrected total hydrocarbon values observed for tests 52 and 53 are 15.2 and 10.9 ppm. Correspondingly, the CO concentrations for tests 54 and 23 were lower than for tests 52 and 53 (6.8 and 4.5 ppm versus 16.0 and 23.9 ppm). Likewise, non-methane species represented a larger percentage of the total hydrocarbon for tests 52 and 53 than for tests 54 and 23.

The probe tip temperatures during the first three and one-half minutes of test 53 were not recorded by the data logger. This temperature data was recovered from the strip chart record. The low, steady wind speeds that prevailed during test 54 allowed the collection of twenty minutes of relatively consistent data. However, during the latter part of the test the wind speed was observed to increase with a corresponding decrease in probe tip temperature, CO_2 concentration, and SO_2 concentration.

AIR-ASSISTED FLARE TESTS

Eleven tests were completed on the John Zink Company STF-LH-457-5 air-assisted flare. The flare operating conditions and results are summarized in Table 5.

High Btu Content Relief Gases

Four tests numbered 26, 65, 28 and 31 were conducted on undiluted crude propylene burned in the air-assisted flare. The flow of relief gas for these tests ranged from 3,196 lbs/hr to 150.8 lbs/hr. All these tests achieved observed combustion efficiencies greater than 99.0%.

TABLE 5. AIR-ASSISTED FLARE SUMMARY

Test Conditions		Test Number	RELIEF GAS* Flow (SCFM)	Velocity (ft/min)	Heating Value (Btu/SCF)	Propylene Flow (lbs/hr)	Propylene Flow (SCFM)	Nitrogen Flow (lbs/hr)	Nitrogen Flow (SCFM)	Air Flow	Combustion Efficiency (%)
High Btu Content	Decreasing Flow Rate	26	481.6	13087	2183	3196	481.6	-	-	High	99.97
		65	159	4320	2183	1056	159	-	-	Off	99.57 **
		28	157	4266	2183	1043	157	-	-	High	99.94
		31	22.7	617	2183	151.8	22.7	-	-	Low	99.17
Low Btu Content	Decreasing Flow Rate	66	639	8192	158	308	46.4	2598	593	Off	61.94
		29(a)	510	6538	168	261.9	39.3	2062	471	Low	55.14
		29(b)	392	5025	146	173	26.2	1602	366	Low	65.65
		64	249	3192	282	214	32.2	949	217	Low	99.74
		62	217	2782	153	101	15.3	884	202	Low	94.18
		63	121	1551	289	106	16	464	105	Low	99.37
	Purge Flow Rate	33	0.714	9.1	83	0.181	0.0272	3.01	0.687	Low	98.24
		32(a)	0.556	7.1	294	0.498	0.0750	2.10	0.481	Low	98.91
		32(b)	0.537	6.9	228	0.374	0.0563	2.10	0.481	Low	98.86

* All values at standard conditions of 70°F and 29.92 in Hg.

** Not accounting for carbon present as soot (see Table 10).

The hydrocarbon species data for the higher flow rate tests 26, 65 and 28 show the bulk of the total hydrocarbon present as methane. Test 31 integrated hydrocarbon species data shows only 14% of the total hydrocarbon present as methane. Correspondingly test 31 has the lowest flow rate and combustion efficiency of the group. The data collected during test 28 exhibits more variation than usual due to the unstable wind conditions that were present.

One of the ambient background files that is applied to this data (file 32) shows slightly higher concentrations of CO and CO_2 and lower concentrations of THC during the first minute of data than are prevalent during the majority of the background period. The probable explanation for this is that the probe temporarily was in the plume of another combustion source in the area. This abberation does not significantly effect the test results.

Test 65 represents the combustion of a high Btu content hydrocarbon at an intermediate flow rate and no air assistance. This test essentially represents a repeat of test 28 without the air blower switched on. During the test, the flame was observed to smoke.

Low Btu Content Relief Gases

Five tests were performed on low Btu content relief gases with the air-assisted flare. The relief gas flows for these tests ranged from 2,906 to 570 lbs/hr and the lower heating values varied from 146 to 289 Btu/SCF.

Tests 66, 29 and 62 of this group yielded the lowest combustion efficiencies observed for the air-assisted flare tests. Correspondingly, these tests involved the lowest Btu content relief gases (146 to 158 Btu/SCF) that were tested on the air-assisted flare. The flare flames for these tests were of low luminosity and were observed to be detached from the flare tip. This detached flame condition is not regarded as good engineering practice. Predictably, the major portions of the unburned hydrocarbons present in the flare plume were in the form of propane and propylene. Likewise, elevated CO concentrations were observed during tests 66, 29 and 62.

In contrast to the above low efficiency tests, the air-assisted flaring of 282 and 289 Btu/SCF relief gases during tests 64 and 63 proved to be much more efficient. These higher Btu content relief gases were flared at lower flow rates (1,163 and 590 lbs/hr) than the previously discussed tests and yielded good combustion efficiencies of 99.74% and 99.37%. Methane comprised 61% of the total hydrocarbon for test 64 and only 29% of the total hydrocarbon for the less efficient test 63.

The CO_2 data from test 63 shows a three minute period in the middle of the test with CO_2 concentrations observed near ambient levels. This is believed to have been caused by the flare plume shifting away from the sampling probe due to a wind shift. This is evidenced by shifts in wind speed and direction and a decline in probe tip temperature that corresponds to the decline in CO_2 concentrations. This shift in CO_2 concentrations caused a corresponding decline in the combustion efficiency data. Therefore, the average combustion efficiency data presented for this test is regarded as conservative.

The first thirteen minutes of data collected during test 29 was designated as test 66. The difference between these two tests was that the air-assisted flare's axial fan was turned off for test 66 and turned on for test 29. Both the propylene and the nitrogen flows were observed to decrease during test 29, thus resulting in unsteady flare operation. Therefore, the test was divided into two subtests [29(a) 29(b)] in an effort to make the data within each subtest more closely approximate steady-state flare operation.

Purge Rate Relief Gas Flows

Tests 33 and 32 evaluated the performance of the air-assisted flare in burning purge rate flows of low Btu content gases. As was the case for the steam flare purge gas tests, the overall efficiency of the purge gas combustion is masked by the flare pilots.

The purge flows for tests 33 and 32 are ranged from 0.714 SCFM to 0.537 SCFM as compared with the 10 SCFM flow of natural gas from the pilots. The lower heating values of the purge gases for these tests ranged from 83 Btu/SCF to 294 Btu/SCF. The observed combustion efficiencies for these tests were 98.24% for test 33 and 98.87% for test 32. These values are slightly lower than those observed for the steam-assisted flare purge gas tests. However, the majority of hydrocarbon measured in the flare plume was found to be methane, thus, suggesting that incomplete combustion of the natural gas from the flare pilots may have caused the lower combustion efficiencies.

The flow of crude propylene to the flare did not remain constant throughout test 32. Hence, the test data was divided into two subtests [32(a) and 32(b)] appropriate for data analysis.

SENSITIVITY OF COMBUSTION EFFICIENCY TO PROBE HEIGHT

During the course of the test series the position of the flare sampling probe was frequently adjusted to keep the probe tip as near as possible to the middle of the flare plume and as close to the flame as possible without being in the flame. These changes were necessary to compensate for changes in the wind that occurred during the tests and resulted in changes in the flare flame pattern and location. Not infrequently, the probe was situated at several different locations and heights during a test.

The vertical position of the probe did not have a definable effect on the combustion efficiency data. Figures 6 and 7 are graphs of combustion efficiency versus probe height that demonstrate the insensitivity of the vertical probe position to the combustion efficiency measured at the probe tip.

EFFECT OF STEAM-TO-RELIEF GAS RATIO ON COMBUSTION EFFICIENCY

Steam injection is a technique commonly used in flare operations to enhance the combustion process. The steam-assisted flare tests performed in this project included a wide range of steam flows and steam-to-relief gas ratios.

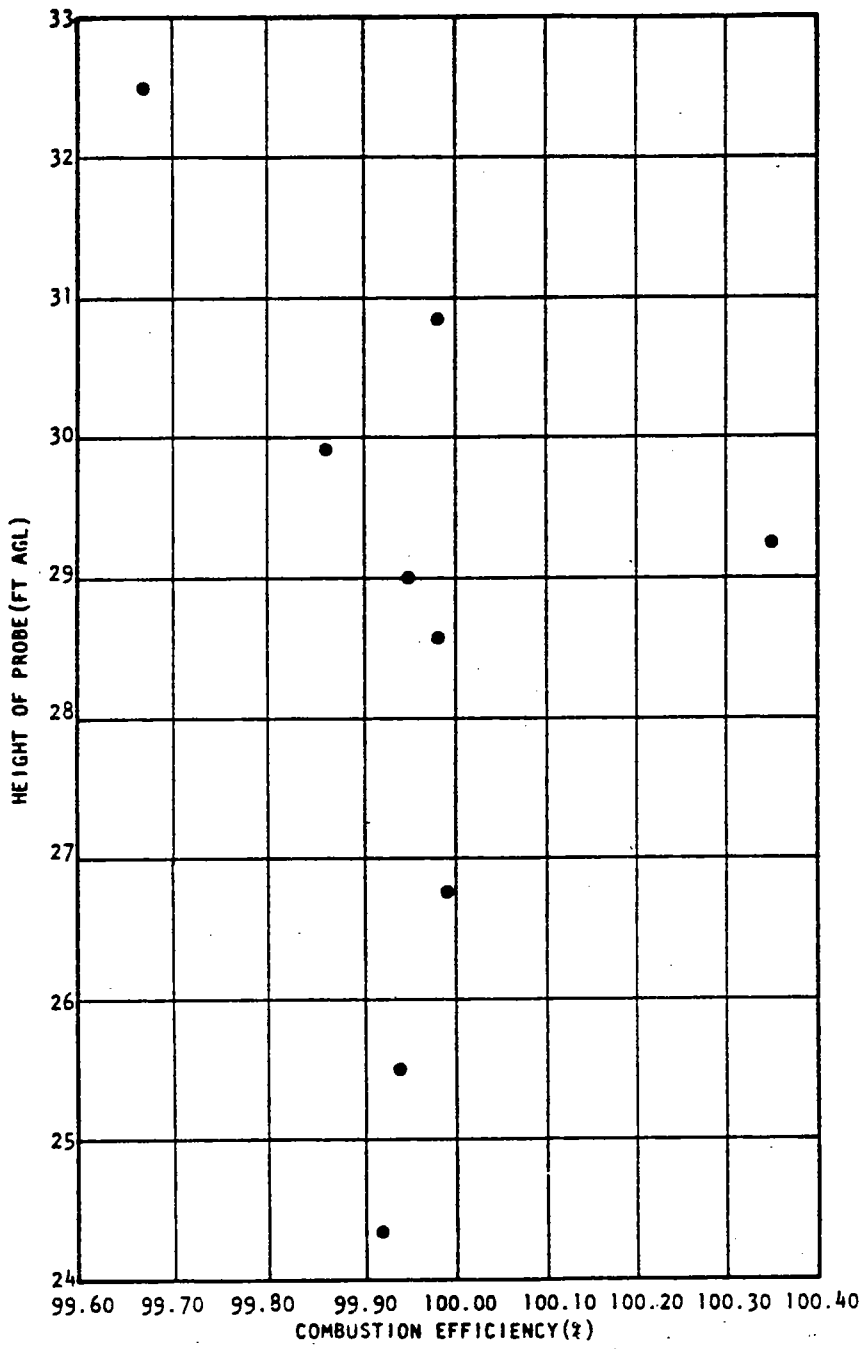

Figure 6. Sensitivity of combustion efficiency to probe height.
Test 28

45

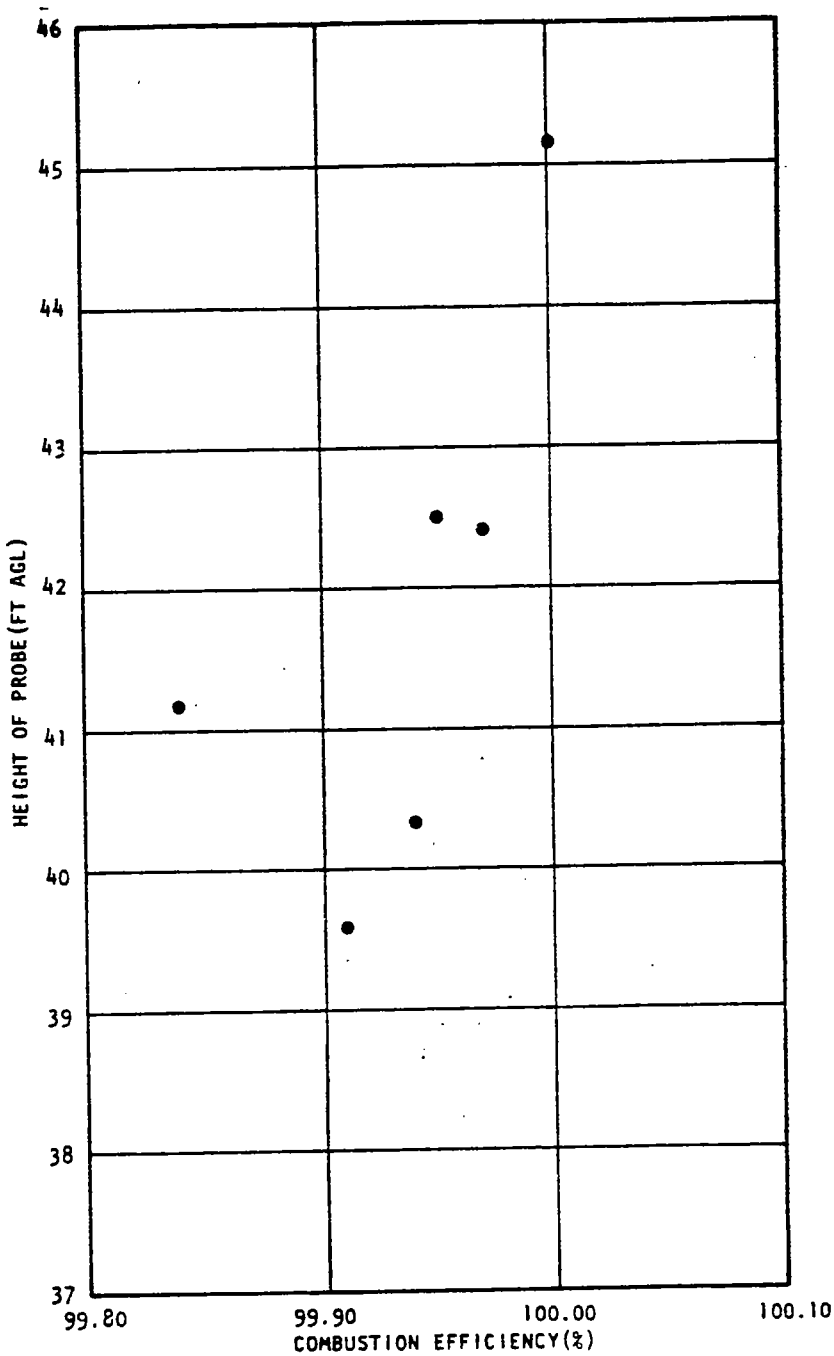

Figure 7. Sensitivity of combustion efficiency to probe height.
Test 57

Figure 8 is a graph of the effect of steam-to-relief gas ratios on the measured combustion efficiencies of high Btu content relief gases. This plot shows general tendencies for combustion efficiencies to decline at higher or lower than normal steam flows. This data suggests that steam-to-relief gas ratios ranging from 0.4 to 1.5 yield the best combustion efficiencies. The smoking flare tests at zero steam flow were observed to have slightly lower combustion efficiencies than the other comparable tests at normal steam flows. Presumably this is due to the lack of steam-induced turbulence and reaction in the combustion process. It should be noted that these combustion efficiency values do not account for carbon lost as smoke.

The steam flows during the low flow rate tests were at too low a velocity to promote good combustion. Likewise, because of the low relief gas flows the steam to hydrocarbon ratios were greater than for the higher flow rate tests. In the case of tests 61 and 55, the excessive steam-to-relief gas ratios are believed to have caused steam quenching of the flame.

FLARE NO_x EMISSIONS

Emissions of NO_x from both steam- and air-assisted flare plumes were measured during this test program. The NO_x concentrations observed during these tests were fairly low in comparison to other types of combustion sources. However, the NO_x concentrations were subject to undefined dilutions of ambient air and steam not normally encountered in other sources. Corrected NO_x concentrations ranged from 0.50 to 8.16 ppm.

The NO_x mass emission rates were estimated from the NO_x and CO_2 data suggested by EPA:

$$E_{NO_x} = \frac{\text{Moles } NO_x}{\text{Moles } CO_2} \cdot \frac{46 \text{ lbs/mole } NO_x}{44 \text{ lbs/mole } CO_2} \cdot \frac{132 \text{ lbs } CO_2 \text{ produced}}{42 \text{ lbs propylene burned}}$$

$$\cdot\ 47.2 \frac{\text{lbs propylene burned}}{10^6 \text{ Btu}}$$

$$E_{NO_x} = \frac{\text{PPM } NO_x \text{ Measured}}{\text{PPM } CO_2 \text{ Measured}} \cdot 155.0 = \text{lb } NO_x/10^6 \text{ Btu}$$

Where:

$$\frac{\text{Moles } NO_x}{\text{Mole } CO_2} = \frac{\text{PPM } NO_x \text{ Measured}}{\text{PPM } CO_2 \text{ Measured}}$$

Assumptions:

1. 100 % combustion of propylene (fuel assumed to be 100% propylene);
2. Equal dilution of NO_x and CO_2 between flare plume and sampling probe;
3. Neglect Btu content of flare pilots (612,600 Btu/hr, gross);*
4. 47.2 lbs/10^6 Btu higher heating value for propylene.

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* For purge tests, this assumption is invalid.

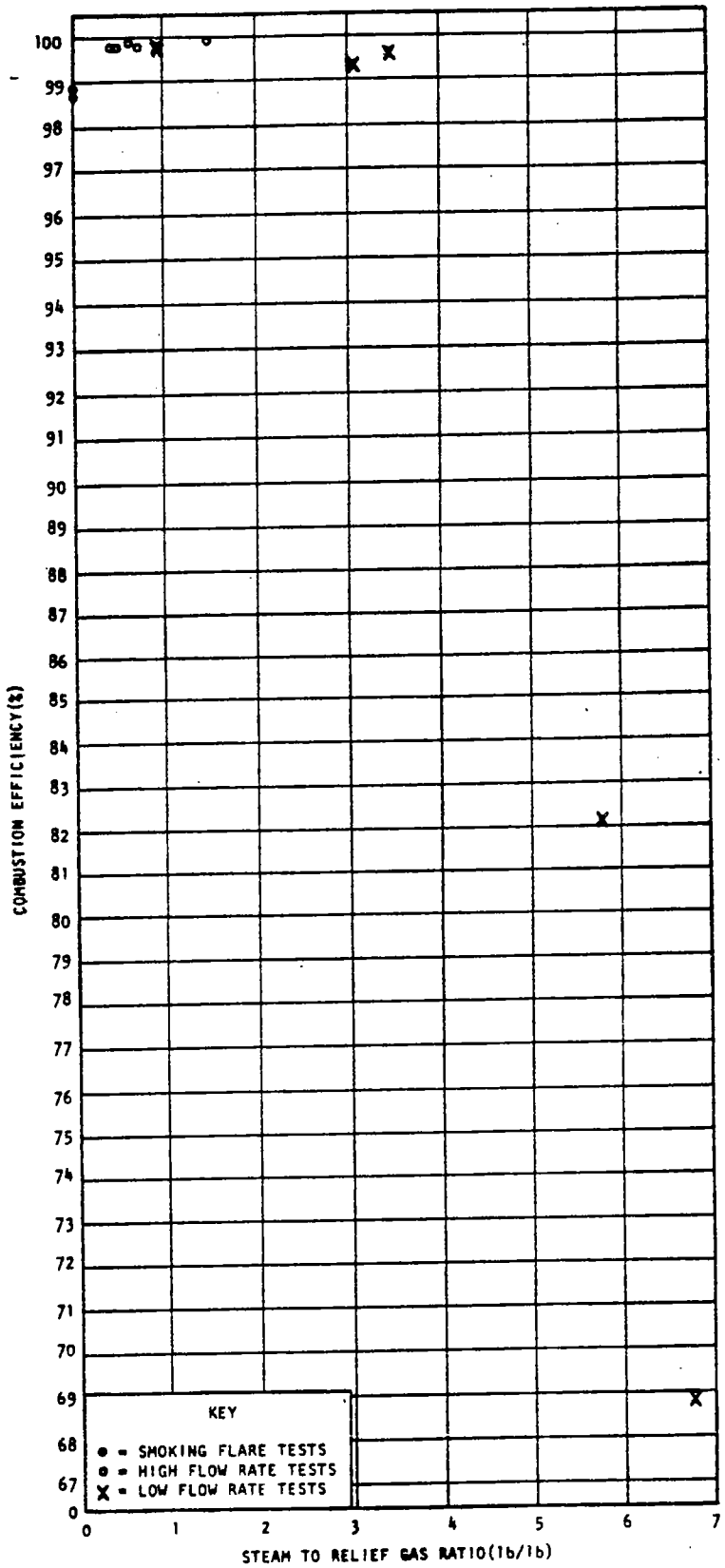

Figure 8. Effect of steam-to-relief gas ratios on flare combustion efficiency. (High Btu content relief gases)

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Table 6 summarizes the NO_x results of these calculations. This treatment of the NO_x data yields NO_x emission rates ranging from 0.018 to 0.208 lbs/10^6 Btu. Examining this data shows no clear patterns of high or low emissions between test groups. One possible exception to this is the high Btu content air-assisted flare tests which yielded the highest calculated NO_x emission rates.

HYDROCARBON ANALYSES

Hydrocarbon analyses were performed both by continuous total hydrocarbon monitor and by gas chromatograph for hydrocarbon species. The samples for the gas chromatograph were taken from the heated sample manifold (wet basis) and either directly injected into the instrument (an instantaneous sample) or collected in a Tedlar® bag over a period of time (integrated bag sample), and subsequently, analyzed by the same gas chromatograph. The continuous hydrocarbon analyzer withdrew its sample from an unheated sample manifold (dry basis) and measured total hydrocarbon (THC) directly. Both the chromatograph and the continuous hydrocarbon analyzer utilized flame ionization detectors. Thus, three sets of hydrocarbon data are available for each test.

Tables 7 and 8 present a summary of the hydrocarbon data collected during the steam- and air-assisted flare tests. All three sets of hydrocarbon data show good agreement between their total hydrocarbon values for those tests with lower THC concentrations (high combustion efficiency tests). In addition, the instantaneous and bag sample values show good agreement (considering the different sampling techniques) throughout the range of values. However, some discrepancies are noted between the continuous THC values and the gas chromatograph THC analyses at the higher concentrations encountered during the lower combustion efficiency tests. These discrepancies at higher THC concentrations are believed due primarily to the absorption of unburned propylene in the cold trap associated with the dry basis sampling system utilized by the continuous THC analyzer. It is believed that the propylene was subject to loss by virtue of its solubility in the water in the cold trap. This may have been the situation despite the precaution of using a minimum-contact design cold trap condenser.

The sample concentrating effect of the cold trap is believed to be negligible due to the low moisture content of the gaseous samples. Variations between the response characteristics of the gas chromatograph's and the continuous THC analyzer's detectors are not thought to be significant. Both instruments were calibrated in terms of parts per million by volume of methane equivalents.

The continuous total hydrocarbon analyzer's data is believed to be the most useful for evaluating the higher combustion efficiency tests where methane was the major fraction of the total hydrocarbon. However, in the case of the lower combustion efficiency tests where water soluble propylene could have been lost in the continuous analyzer's sampling system, the integrated bag samples provide the most representative total hydrocarbon data. Likewise, since the reported combustion efficiency values were based on the continuous total hydrocarbon data, these values may be biased high for the lower combustion efficiency tests due to the potential loss of propylene in the sampling system.

TABLE 6. FLARE NO_x RESULTS

		Test No.	NO_x* Concentration (PPMv)	CO_2* Concentration (PPMv)	NO_x Mass Emission (lbs/10^6 BTU)
Steam-Assisted Flare	High Btu Content	1	3.09	7,052	0.068
		2	2.16	4,719	0.071
		3	1.54	2,496	0.095
		4	1.96	6,616	0.046
		8	1.45	5,400	0.042
		7	1.62	5,224	0.048
		5	2.09	7,052	0.046
		67	3.77	N/A	N/A
		17	1.00	3,499	0.044
		50	0.50	4,220	0.018
		56	0.58	3,120	0.029
		61	1.32	6,273	0.033
		55	0.38	2,012	0.029
	Low Btu Content	57	2.68	6,945	0.060
		11	3.69	5,269	0.108
		59	1.41	5,413	0.040
		60	0.99	3,685	0.042
		51	0.57	3,347	0.026
		16	1.87	4,059	0.071
		54	5.00	7,115	0.109
		23	5.90	8,465	0.108
		52	0.68	2,622	0.040
		53	2.83	5,741	0.076
Air-Assisted Flare	High Btu Content	26	5.34	6,270	0.132
		65	2.40	4,878	0.076
		28	8.16	6,076	0.208
		31	4.02	4,568	0.136
	Low Btu Content	66	0.97	2,432	0.062
		29	1.06	2,179	0.075
		64	1.24	3,282	0.058
		62	0.60	3,076	0.030
		63	1.57	4,184	0.058
		33	0.74	1,857	0.061
		32	1.75	3,702	0.073

* Corrected for background.

TABLE 7. HYDROCARBON ANALYSIS SUMMARY
STEAM-ASSISTED FLARE TESTS

	Test No.	Continuous THC Analyzer Avg. Conc.*	Instantaneous Samples, Average Values*							Bag Samples, Average Values*						
			C_1	$C_2/C_2^=$	$C_2^{\equiv}$	C_3	$C_3^=$	C_4	THC	C_1	$C_2/C_2^=$	$C_2^{\equiv}$	C_3	$C_3^=$	C_4	THC
High Btu Content	1	3.7	2.2	-	-	-	-	-	2.2**	3.0	-	-	-	-	-	3.0**
	2	6.5	3.0	-	-	-	-	-	3.0**	2.8	-	-	-	-	-	2.8**
	3	4.3	2.5	-	-	-	-	-	2.5**	3.5	-	-	-	-	-	3.5**
	4	10.5	4.73	0.68	2.51	0.25	2.66	-	10.8	6.19	0.76	2.95	0.34	0.77	-	11.0
	8	9.5	5.70	0.63	3.00	0.15	1.82	-	11.3	5.87	0.63	1.46	0.18	0.34	-	8.5
	7	9.9	1.79	0.20	0.30	0.12	0.35	-	2.8	2.92	-	0.22	0.23	0.56	-	3.9
	5	4.9	2.4	-	-	-	-	-	2.4**	3.08	-	0.32	0.30	0.29	0.03	4.0
	17	4.7	2.59	0.25	-	0.09	-	-	2.9	3.12	0.59	0.35	0.15	0.06	-	4.3
	50	12.0	5.59	1.08	0.49	1.34	5.65	-	12.1	4.31	1.90	0.95	2.21	7.65	-	12.6
	56	8.2	4.06	0.12	0.10	0.19	1.52	-	6.0	4.91	1.46	1.06	0.88	2.22	-	10.5
	61	964	45.6	143	69.2	635	2,675	-	3,568	24.2	67.4	33.5	282	1,182	1.08	1603
	55	742	14.07	3.35	0.20	268	1,075	-	1,361	16.5	36.6	21.0	259	1,061	-	1402
Low Btu Content	57	7.8	6.72	0.37	0.03	0.29	0.50	-	7.9	7.54	0.53	0.16	0.36	0.82	-	9.4
	11	6.6	4.29	0.24	0.52	0.31	0.71	-	6.1	5.70	1.33	0.35	0.32	0.79	0.02	8.5
	59	36.1	4.00	2.96	1.05	3.30	9.63	-	20.9	4.31	5.17	1.72	13.0	31.4	-	55.6
	60	14.3	3.75	1.28	0.55	1.47	6.22	-	13.3	4.45	3.05	1.31	2.63	14.2	0.08	25.6
	51	22.8	5.82	0.56	0.53	0.50	1.78	-	9.2	8.19	3.73	3.83	1.38	5.92	-	23.1
	16	6.4	6.06	0.49	0.18	0.64	2.16	-	9.5	6.55	0.48	0.25	0.55	1.15	-	9.0
	54	6.5	3.15	0.64	-	1.76	2.42	-	8.0	3.46	0.64	0.33	0.86	1.57	0.02	6.9
	23	6.3	3.47	0.03	-	0.06	-	-	3.6	3.95	0.05	-	0.09	0.11	-	4.2
	52	24.6	7.66	1.74	0.03	5.21	21.24	-	35.9	6.65	2.49	4.23	6.70	27.8	-	47.9
	53	15.6	3.39	0.90	0.31	2.04	6.10	-	12.7	3.97	1.53	0.55	3.22	13.6	-	22.9

* All values are ppm by volume methane equivalents; uncorrected for background THC.

** The gas chromatograph electrometer attenuation was set to a less sensitive scale for these analyses.

KEY: Methane, C_1 — Ethane, C_2 — Ethylene, $C_2^=$ — Propane, C_3 — Propylene, $C_3^=$ — Acetylene, $C_2^{\equiv}$ — Butane, C_4 — Total Hydrocarbon, THC

TABLE 8. HYDROCARBON ANALYSIS SUMMARY
AIR-ASSISTED FLARE TESTS

	Test No.	Continuous THC Analyzer Avg. Conc.*	Instantaneous Samples, Average Values*							Bag Samples, Average Values*						
			C_1	$C_2/C_2^=$	$C_2^{\equiv}$	C_3	$C_3^=$	C_4	THC	C_1	$C_2/C_2^=$	$C_2^{\equiv}$	C_3	$C_3^=$	C_4	THC
High Btu Content	26	11.3	3.36	0.86	0.15	0.67	2.02	-	7.06	3.18	-	-	0.22	0.78	-	4.18
	65	4.8	4.63	0.07	0.18	0.07	0.06	-	5.0	4.50	0.11	0.32	0.16	0.18	-	5.3
	28	6.0	4.15	0.19	0.03	0.18	0.54	-	5.1	3.43	0.09	0.05	0.22	0.77	-	4.6
	31	15.7	4.85	4.93	1.20	3.62	29.0	-	43.6	4.12	3.20	2.19	3.82	15.36	-	28.8
Low Btu Content	66/29	1,238	25.5	69.1	27.4	513	1,992	-	2,627	31.4	47.4	21.1	474	1,965	0.20	2,539
	64	8.7	7.59	0.54	0.06	0.36	0.82	-	9.37	7.35	1.14	0.68	0.85	1.97	-	12.0
	62	109	13.1	14.7	5.64	32.8	249	0.08	315	16.6	16.5	6.16	33.7	139	0.09	214
	63	15.3	5.97	1.57	0.78	1.67	6.45	0.03	16.5	6.18	1.83	0.63	2.60	10.4	-	21.6
	33	32.1	25.1	2.71	0.10	1.44	3.38	10.2	42.9	27.6	12.7	0.10	1.83	5.19	0.11	47.5
	32	34.1	15.6	1.71	0.28	0.93	2.19	-	20.7	29.7	3.96	0.65	1.67	4.31	0.13	40.4

*All values are ppm by volume of methane equivalents, uncorrected for ambient background THC.

KEY: Methane, C_1
Ethane, C_2
Ethylene, $C_2^=$
Propane, C_3
Propylene, $C_3^=$
Acetylene, $C_2^{\equiv}$
Butane, C_4
Total Hydrocarbon, THC

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Figure 9 is an example of a gas chromatograph analysis of the flare emissions.

PARTICULATE MATERIAL ANALYSES

Samples of the particulate material emitted from the flare flame were collected during the flare test series. An in-line fiberglass filter collected these samples for determination of particulate mass loading and subsequent analysis for polynuclear aromatic compounds (PNA's) by gas chromatography/mass spectroscopy. The PNA data is reported in Appendix D.

Table 9 is a summary of the mass particulate concentration data collected during the test series. The data show distinct differences between particulate loadings of nonsmoking and smoking flare tests.

The combustion efficiency calculations used in this report as a measure of the flares' performance did not account for the carbon lost as particulate material in the smoke. Only terms for CO, CO_2 and THC concentrations are used in these combustion efficiency calculations. Therefore, the gaseous combustion efficiency values reported for the smoking flare tests would be expected to be higher than the real combustion efficiency.

The following equation was used to include the carbon lost as particulate material for smoking flare tests 4, 8 and 65.

$$CE\% = \frac{CO_2}{CO_2 + CO + THC + C_p} \times 100$$

Where:

CO_2 = carbon dioxide concentration (PPM_v)

CO = carbon monoxide concentration (PPM_v)

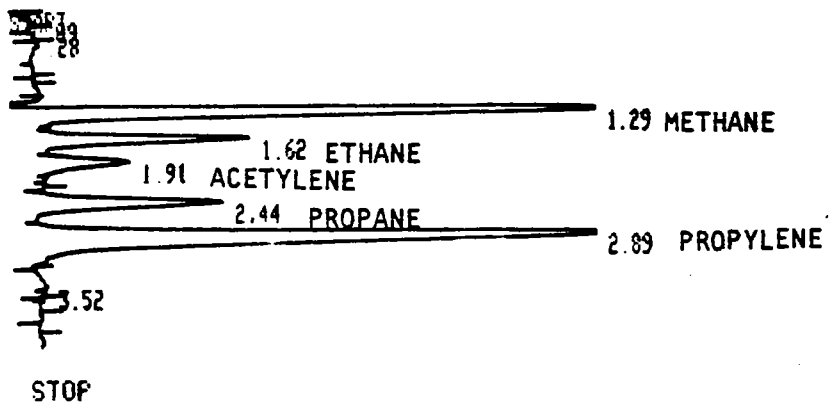
THC = total hydrocarbon concentration (PPM_v as methane)

C_p = particulate concentration (PPM_v assuming smoke particulate as gaseous elemental carbon and ideal gas, 2.03 l/g).

Table 10 outlines the results of calculating the combustion efficiency using this particulate corrected method.

DILUTION RATIO AND DESTRUCTION EFFICIENCY DETERMINATIONS

The attempt to use sulfur as a tracer material for the flare tests yielded disappointing results. The tracer technique was employed in lieu of measuring the volumetric flow rate of the flare plume. Volumetric flow rate determinations in an open combustion system such as a flare are not feasible. The intent was to complete a sulfur balance between the flare burner and the sampling probe in order to calculate the effective dilution of the flare gas due to combustion, steam, forced air and ambient air. By knowing the dilution ratio, estimates of flare destruction efficiency and emission rates can be calculated. Unfortu-



RUN # 194 JUN/21/82 14:11:08
ID 26128.00

ESTD

RT	AREA	TYPE	CAL.	AMOUNT
0.09	291	PB		0.000
0.28	198	PB		0.000
1.29	92868	PV	1.	3.501
1.62	46859	VV		0.000
1.91	23201	VV		0.000
2.44	20129	VP		0.000
2.89	87374	PB		0.000
3.52	1044	PV		0.000

TOTAL AREA= 271960
MUL FACTOR= 1.0000E+00

Figure 9. Example gas chromatogram hydrocarbon analysis. (Test 50)

TABLE 9. PARTICULATE ANALYSIS

Test No.	Filter No.	Wt. gain, (grams)	Sample Time[1] (minutes)	Sample Rate (ℓ/min)	Concentration (μg/ℓ)
2, 3, 1, 5, 7	A-1	0.0063	---	18.51	---
7, 17, 50, 51 23, 52, 53, 54	F-1	0.0071	---	18.51	---
4 (Smoking)	F-2	0.0810	16	18.51	274
8 (Smoking)	F-3	0.0819	25	18.51	177
55, 56, 11, 57 16, 59, 60, 61 28, 31, 26, 29 33, 32, 62, 63 64, (80, 81, 82 83, 84)[2]	F-4	0.0179	---	18.51	---
65 (Smoking)	F-5	0.0183	25	18.51	40

1 Includes time for probe positioning while probe was in the plume but before formal initiation of the test.

2 Separate tests conducted for John Zink Company not reported herein.

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TABLE 10. SMOKING FLARE COMBUSTION EFFICIENCIES

Test	Particulate Concentration (μg/l)	Particulate Concentration (μl/l)	Combustion Efficiency (percent) Particulate Corrected	Combustion Efficiency (percent) Reported
4	274	557	91.21	99.80
8	177	360	92.72	98.81
65	40	81	97.95	99.57

nately, considerable difficulty was encountered in quantifying and maintaining constant levels of sulfur in the relief gas.

The primary source of flare gas for this series of tests was a tank truck of 6,800 gallons of crude propylene to which approximately 4 liters of butyl mercaptan were added. This addition of mercaptan should have yielded a sulfur concentration of approximately 89 ppm (by weight) in addition to the naturally occurring sulfur in propylene (estimated at 2 - 10 ppm). An extremely wide range of results were obtained from these analyses. Thus, there is considerable doubt as to the actual concentration of sulfur in the propylene. Additionally, this data cast doubt on whether or not the concentration of sulfur was stable or if a fraction of the sulfur could have combined with the steel tank, iron pipe or other materials which were in contact with the propylene.

The sulfur content of the nitrogen used for dilution of the propylene and the sulfur content of the steam condensate were found to be very low and did not represent a significant contribution to the overall sulfur balance.

The levels of SO_2 measured during the initial tests were lower than expected, and in some cases, challenged the practical detection limit of the analyzer. After completion of ten of the thirty-four tests, provisions were made to add SO_2 gas into the relief gas stream in order to elevate the sulfur levels in the flare emission into a midrange level. This modification was plagued with mechanical falures that prevented the addition of SO_2 to many of the subsequent tests and was not accomplished at a uniform rate.

The sulfur balance data yielded results that were much higher than would reasonably be expected to occur. In addition, the ratio of SO_2 to CO_2 concentrations in the flare emissions were not constant as was expected, either between tests or within tests. The SO_2 and CO_2 ratio should be constant given that both these gases are subject to the same dilution effects and assuming a constant level of sulfur in the relief gas and no effect due to background concentrations.

Because of the doubts surrounding the sulfur balance dilution ratios, an alternate means of calculating dilution ratios was formulated using the CO_2 data. This technique assumes stoichiometric combustion and is frequently used in evaluating emisions from other combustion sources. However, the CO_2 dilution technique was not well received because: (1) it did not provide a measure of dilution independent of the combustion measurement, and (2) the flare plume did not maintain steady-state conditions relative to the sampling probe.

By making simplifying assumptions, destruction efficiency calculations can be made and are provided in Appendix C. With regard to flare efficiencies, it should be noted that in a smokeless flare, the total hydrocarbon destruction efficiency will always be greater than the combustion efficiency. This is because, by definition, the percentage of hydrocarbon that is converted to CO_2 (combustion efficiency) is equal to or less than the percentage of relief gas that is converted to CO and CO_2 (destruction efficiency).

MOISTURE DETERMINATIONS

The moisture content of the flare emissions was gravimetrically determined using an ice-bath condenser type of moisture trap. Table 11 lists the results of these moisture analyses. The moisture data were lower than expected with an average of 3.0% moisture measured for the air-assisted flares and 3.8% moisture measured in the steam-assisted flare samples. A description of the methodology used for moisture determinations may be found page 18 of this report.

OTHER FLARE TEST ANALYSES

A composite sample of the steam condensate was collected and analyzed for sulfur and hydrocarbon content. The results of these analyses are as follows:

Sulfate	less than 1 mg/l
Sulfide	0.03 mg/l
Hydrocarbon	0.13 mg/l

The crude propylene that was used during the test series as the basis for flare fuel was analyzed by both the propylene vendor and by ES. The results of these analyses are as follows:

Analyst	Propylene	Propane	Ethane/Ethylene
Vendor	80.2	19.8	---
ES	79.4	18.5	1.9%

For the purposes of this test series, the differences between these two analyses is not significant.

The nitrogen used to dilute the crude propylene to a lower heating value gas was analyzed for hydrocarbon content. The nitrogen was found to contain 0.33 ppm by volume of hydrocarbon methane equivalents.

TABLE 11. FLARE EFFICIENCY TEST
MOISTURE CONTENT OF SAMPLES
(EPA METHOD 4)

Test Number	Moisture (Volume %)
2	<1
3	N/A
1	7.1
5	<1
7	3.6
17	2.8
50	2.9
51	3.0
23	3.5
52	5.5
53	7.1
54	4.6
4	3.1
8	3.0
55	4.6
56	3.7
11	1.9
57	2.9
16	4.8
59	N/A
60	N/A
61	N/A
28	2.1
31	3.2
26	3.4
66	3.3
29	3.3
33	2.9
32	2.9
62	2.9
64	2.9
63	2.9
65	3.8

SECTION 6

QUALITY ASSURANCE AND QUALITY CONTROL ACTIVITIES

MULTIPOINT CALIBRATIONS

Before the collection of data was initiated, the continuous analyzers were checked for proper operation. A key element of the operational checks was the multipoint calibrations. These multipoint calibrations consisted of challenging the analyzers with a zero gas and several upscale concentrations of the gaseous compounds of interest. Calibrations were conducted at the concentrations anticipated to be in the flare emission plume. The purpose of these multipoint calibrations was to demonstrate instrument response linearity both within instrument ranges and between instrument ranges. Table 12 lists the analyzer ranges and gas concentration ranges used for these checks. The criteria for calibration curve acceptability was no more than 5% deviation from the input value within a range and no more than a 10% deviation from the reference standard between ranges.

The source of the calibration gases was aluminum compressed gas cylinders certified by their manufacturers to be accurate within + 2% of their listed concentrations. The gas standards for NO_x and CO were traceable to the National Bureau of Standards' standard reference materials. The compressed gas standard for SO_2 calibrations was contained in a Teflon® lined aluminum cylinder and was certified on-site against a graviametrially calibrated SO_2 permeation device.

In addition, the efficiency of the NO_2 to NO converter in the NO_x analyzer was checked using the procedure recommended in EPA Reference Method 20 (40 CFR 60 Appendix A). The converter efficiency was found to be greater than 99% efficiency in the conversion of NO_2 to NO.

The response of the probe tip thermocouple was verified at ambient temperature against the calibrated meteorological station thermistor and was checked for 0^oC response in an ice water bath.

ZERO AND SPAN CHECKS

Before and after each test or series of tests, all the continuous analyzers were challenged with zero gas and a single upscale concentration of the compound of interest. The purpose of these calibration checks was two-fold. First the collection of the zero/span data provided a data base to allow estimation of the analyzer's precision of measurement. Secondly, the gas standards used for the zero and span checks provided points of reference for instrument calibration adjustment between tests. Thus, the zero/span checks provided a mechanism to both monitor and maintain the precision of the data.

Table 13 is a summary of the zero span check data.

TABLE 12. MULTIPOINT CALIBRATION CHECKS

Analyzer	Instrument Ranges Checked	Calibration Gas Levels [1]
CO	0-5,000 ppm 0-3,000 ppm 0-1,000 ppm[2]	3,490 ppm 1,003 ppm 252 ppm[3]
CO_2	0-5%[2] 0-10% 0-15%	5.01%[3] 10.0%
THC[4]	0- 100 ppm[2] 0-1000 ppm 0- 500 ppm	50 ppm[3] 159 ppm 500 ppm
NO_x	0-25 ppm[2] 0-100 ppm 0-250 ppm 9-1000 ppm	3.7 ppm 17 ppm[3] 92 ppm
O_2	0-25%[2]	21.0%[3] 12.1% 2.0%
SO_2	0-1 ppm range (Instrument modified with 1:5 dilution system to yield an effective 0-5 ppm range)	.934 ppm[3] .404 ppm .103 ppm

1 All instruments' zero responses were verified with zero nitrogen.
2 Primary operating range used during tests.
3 Concentrations used for routine span checks and calibration adjustments.
4 THC analyzer calibrated on methane.

TABLE 13. ZERO/SPAN CHECK SUMMARY

Parameter	No. of Checks	Average Deviation of Instrument Response to Span Value	Standard Deviation	Upper 95% Probability Limit	Lower 95% Probability Limit
CO	29	-0.91%	±1.88%	+2.77%	-4.59%
CO_2	30	-1.16%	±3.09%	+4.90%	-7.16%
THC	31	-0.13%	±2.65%	+5.06%	-5.32%
NO_x	29	+2.94%	±4.37	+11.51%	-5.63%
O_2	29	-0.07%	±1.32%	+2.52%	-2.66%
SO_2	34	-3.25%	±4.98%	+6.51%	-13.01%
HC Species	33	-0.80%	±2.20%	+5.11%	-3.51%

During the initial tests, zero/span checks were conducted between each test. As the project progressed, confidence in the reliability of the instruments increased and the frequency of these calibration checks was reduced by allowing two or three tests to be completed between zero/span checks. As a minimum, zero/span checks were conducted at the beginning and end of each test day.

INSTRUMENT RESPONSE TIMES AND THROUGH-PROBE CALIBRATION CHECKS

The response time for each instrument was adjusted to allow comparision of individual data values. The goal was to ensure that all the instruments were analyzing a fraction of the same sample at the same time. The synchronization of the instrument responses permitted data calculations to be performed on the instantaneous data as well as on the one-minute and test averages. For example, the combustion efficiency calculations, which included data from three separate instruments, could be performed on each set of instantaneous data because the three analyzers were simultaneously sampling the same flare emission gas.

The instrument synchronization was accomplished by adjusting the sample tubing length and volume between the sample manifold and the instrument and adjusting the sample flow rate to the analyzer. In this manner, the transit time of the sample between the manifold and the instrument could be adjusted. These adjustments were made in reference to the instruments' initial upscale response time.

The upscale and downscale response times of the instruments were checked by introducing calibration gases through the probe and timing the subsequent response of the instrument. Table 14 summarizes the results of these response time checks.

An adaptor fitting was attached to the probe tip to allow the introduction of the calibration gases. This 1/4" tube to 1" pipe adapter fitting presented a flow restriction on the entire sampling system that was not present during the normal sampling. Thus, the response times reported in Table 14 may be somewhat slower than the actual response times encountered during the sampling.

The introduction of calibration gases through the probe tip also served to verify the integrity of the sampling system. There were no significant differences observed in instrument responses to calibration gases introduced directly into the analyzers as compared to calibration gases which were passed through the probe. This evidence suggests that the sampling assembly did not alter the composition of the flare emissions during the sampling.

Leak checks of the sampling system were performed on several occasions during the test series. The procedure followed was to introduce zero nitrogen in the probe tip and monitor the oxygen content of the sampling system. If leaks were present in the sample system, they would be evidenced by elevated oxygen levels in the sampling system. Table 15 presents the results of these leak checks. This leak check data is believed to be conservative since the installation of the required adapter fitting on the probe tip during these

TABLE 14. INSTRUMENT RESPONSE TIMES

	(Up Scale (Seconds)		Down Scale (Seconds)	
	Initial	90% Response	Initial	90% Response
CO	32	115	30	115
CO_2	30	123	25	120
THC	35	147	34	125
NO_x	32	77	25	69
O_2	30	123	25	120
SO_2	29	90	32	80

TABLE 15. SAMPLING SYSTEM LEAK CHECKS

Date	Input	O_2 Analyzer Response	Percent Leakage [1]
6/17/82	N_2	0.80%	3.8%
6/17/82	N_2	0.25%	1.2%
6/18/82	N_2	0.31%	1.5%
6/19/82	N_2	0.24%	1.1%
7/ 1/82	N_2	0.30%	1.4%

[1] Assuming 20.95% oxygen in ambient air.

checks caused an increase in the vacuum present in the sampling system as compared to during normal flare emission sampling.

The zero response of the other continuous analyzers to zero nitrogen passed through the sampling system was also verified during the leak checks.

BACKGROUND MEASUREMENTS

Ambient air component concentrations of CO, CO_2, THC, NO_x, O_2 and SO_2 were collected immediately before and after each of the tests or series of tests. The collection of this background data documented the influence of local ambient air concentrations on the flare emission measurements. The background concentrations of these compounds of interest could have had a significant effect on the data given the dilution effects of ambient air in both steam- and air-assisted flare emissions. This is especially true in this situation since other combustion sources were present and operating in the test area. A complete listing of the background concentration measurements is contained in the data volume (Volume II) of this reort.

The background data was applied to the flare emission data by subtraction. The average background values were subtracted from each raw flare emission concentration values to determine the corresponding corrected value. This subtraction removed any data bias between tests that was caused by variable ambient concentrations. Additionally, the subtraction of the average of the background concentrations before and after each test helped to compensate the data for instrument calibration drift that may have occurred between these periods. It is recognized that to properly account for background concentrations, a dilution factor correction is required. As discussed previously, dilution factors were not obtained in this study. Calculations indicate that an error of less than 0.1% in combustion efficiency (for CE's greater than 98%) is caused by the background correction method employed herein. As shown below, this error is less than the sampling and analysis error. Therefore, the background correction described above is suitable for this study.

COMBUSTION EFFICIENCY ERROR ANALYSIS

It is assumed that accuracy of the combustion efficiency calculations is dependent on two primary sources of error: (1) the accuracy of the listed concentrations of the calibration gases, and (2) the accuracy of the instruments' measurements of the gaseous samples (instrument drift, interference, repeatability, etc.). Other systemic errors due to sampling, data acquisition, etc. are assumed to be negligible.

Table 16 lists estimates of the magnitude of these two primary types of error for each of the continuous analyzers. The instrument error data in this table was calculated from the instrument responses to the routine span calibration checks. The calibration gas error data are nominal values supplied by the vendors of the calibration gases.

Although these two types of errors are independent of each other, it is assumed for this worst-case error analysis that they reinforce and are additive. Likewise, it should be noted that the measurement errors of variables in the

TABLE 16. ERROR ESTIMATES

Parameter	Instrument Precision Standard Deviation of Span	Instrument Error	Calibration Gas Accuracy Error	Total Worst Case Accuracy Error
CO	1.88%	±4.7 ppm	±5.0 ppm	±9.7 ppm
CO_2	3.09%	±1545 ppm	±1000 ppm	±2545 ppm
HC	2.65%	±1.3 ppm	±1.0 ppm	±2.3 ppm
NO_x	4.37%	±0.7 ppm	±0.3 ppm	±1.0 ppm
O_2	1.32%	±0.27%	±0.42%	±0.69%
SO_2	4.98%	±0.046 ppm	±0.019 ppm	0.065 ppm

combustion efficiency calculations are independent of one another. However, for this worst-case analysis it is assumed that the errors in the measurements of CO, CO_2 and THC concentrations reinforce.

For this worst-case analysis two sets of concentration values for CO, CO_2 and THC were selected: (1) for the high combustion efficiency case, and (2) for the low combustion efficiency case. The total worst-case accuracy error values were applied to these two sets of concentration values to determine the effects on the combustion efficiency calculations.

	High Efficiency Test	Low Efficiency Test
CO Observation (ppm)	8	1000
CO_2 Observation (ppm)	7000	5000
THC Observation (ppm)	4	90
% CE Best Estimate	99.83	82.10
% CE Highest Estimate	100	87.49
% CE Lowest Estimate	99.46	69.02

This exercise shows that the high combustion efficiency test data are less sensitive to accuracy errors than are the low combustion efficiency test data. This analysis also provides worst-case estimates of the magnitudes of the combustion efficiency accuracy errors. It should be noted that the real accuracy errors (which were not directly measured) are expected to be less than those listed above since the sources of error are independent and do not necessarily reinforce.

Another mechanism for examining the quality of the combustion efficiency determinations is to examine the variance of repetitive determinations based on consecutive measurements of CO, CO_2 and THC within each test. The data listing and analysis program used to compile the data from these tests incorporated routines to calculate the combustion efficiency from each set of data collected every twelve seconds. The variance (and standard deviation) of the average combustion efficiency value was determined from this data set as an indicator of the precision of the data. The standard deviations of the consecutive measurements of combustion efficiency ranged from + 0.1% to +11.1%. As in the worst-case error analysis, the largest variances occurred with the low combustion efficiency tests and the smallest variances were obseved with the high combustion efficiency tests.

APPENDIX A

GRAPHICAL REVIEW OF SELECTED TESTS

Five of the thirty-four flare efficiency tests completed during this project were selected for more detailed data analysis via graphical aids. The selected tests are as follows:

Test	Flare Type	Flare Gas Flow (SCFM)	Heating Value (Btu/SCF)	Steam-to-Flare Gas Ratio (lb/lb)	Combustion Efficiency Percent
3	Steam-assisted	456	2183	0.45	99.8
55	Steam-assisted	24.7	2183	6.9	68.9
57	Steam-assisted	703	294	0.15	99.9
28	Air-assisted	157	2183	--	99.4
33	Air-assisted	0.714	83	--	98.2

These tests were selected because they represented a fairly wide range of flow rates, heating values and combustion efficiencies. Figures A-1 and A-2 are photographs of the flare taken during these tests.

Three types of graphical test data plots were compiled from the digitized instantaneous data collected on magnetic tape via a data logger. A detailed listing of these data may be found in a separate data volume to this report (Volume II). The plots chosen for this exercise are as follows:

SO_2 and Probe Temperature versus Time;

THC and CO versus Time; and

CO and Combustion Efficiency versus time.

Figures A-3 through A-17 are the graphical plots of this data.

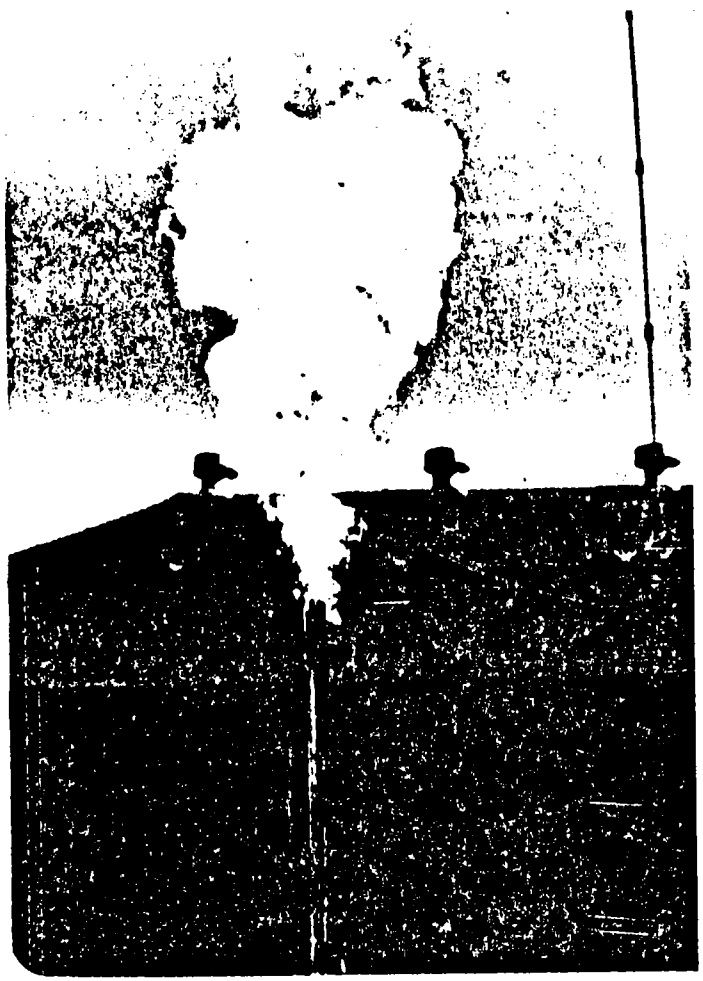
The plots of SO_2 and probe temperature show a positive correlation between these two parameters. The temperature values are observed to lead the SO_2 values by about 0.3 minutes. This time lead indicates the difference in response times between the thermocouple/digital thermometer assembly and the sampling system/SO_2 analyzer. The positive correlation between these two parameters is due to both parameters being indicators of probe position relative to the flame.

The graphical presentations of THC and CO_2 versus time show variable amounts of positive correlation between these two species. Theoretically,

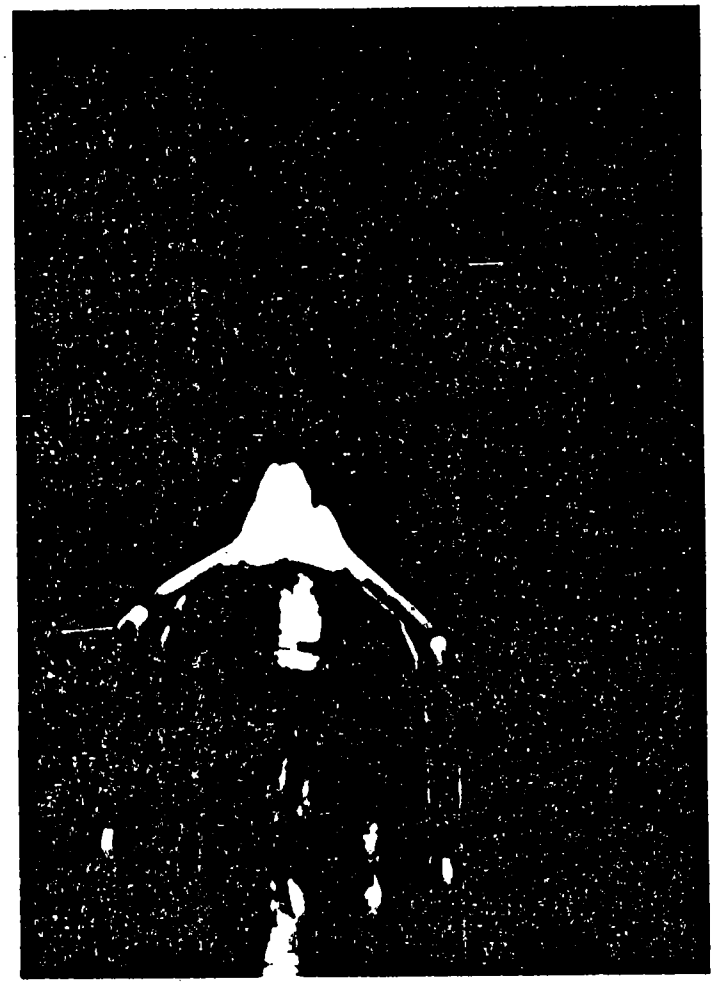
given a flare burning with constant combustion efficiency, the ratio of THC to CO_2 should be constant regardless of flame postion relative to the probe. This is shown to be the case in the plot for Test 55 and to a lesser extent Test 57. Tests 3, 28 and 33 show little or no correlation between concentrations of THC and CO_2.

The graphs of combustion efficiency and CO versus time show an inverse relationship between CO and concentrations on the combustion efficiency. This demonstrates the importance of the CO term in the combustion efficiency calculations and the usefulness of CO measurements as a primary indicator of relative combustion efficiency.

These plots of the test data also serve to graphically show the typical range and variation of concentrations and temperature observed during the flare tests.



Test 3



Test 33

Figure A-1. Photographs of flare taken during tests.

Test 57

Test 28

Figure A-2. Photographs of flare taken during tests.

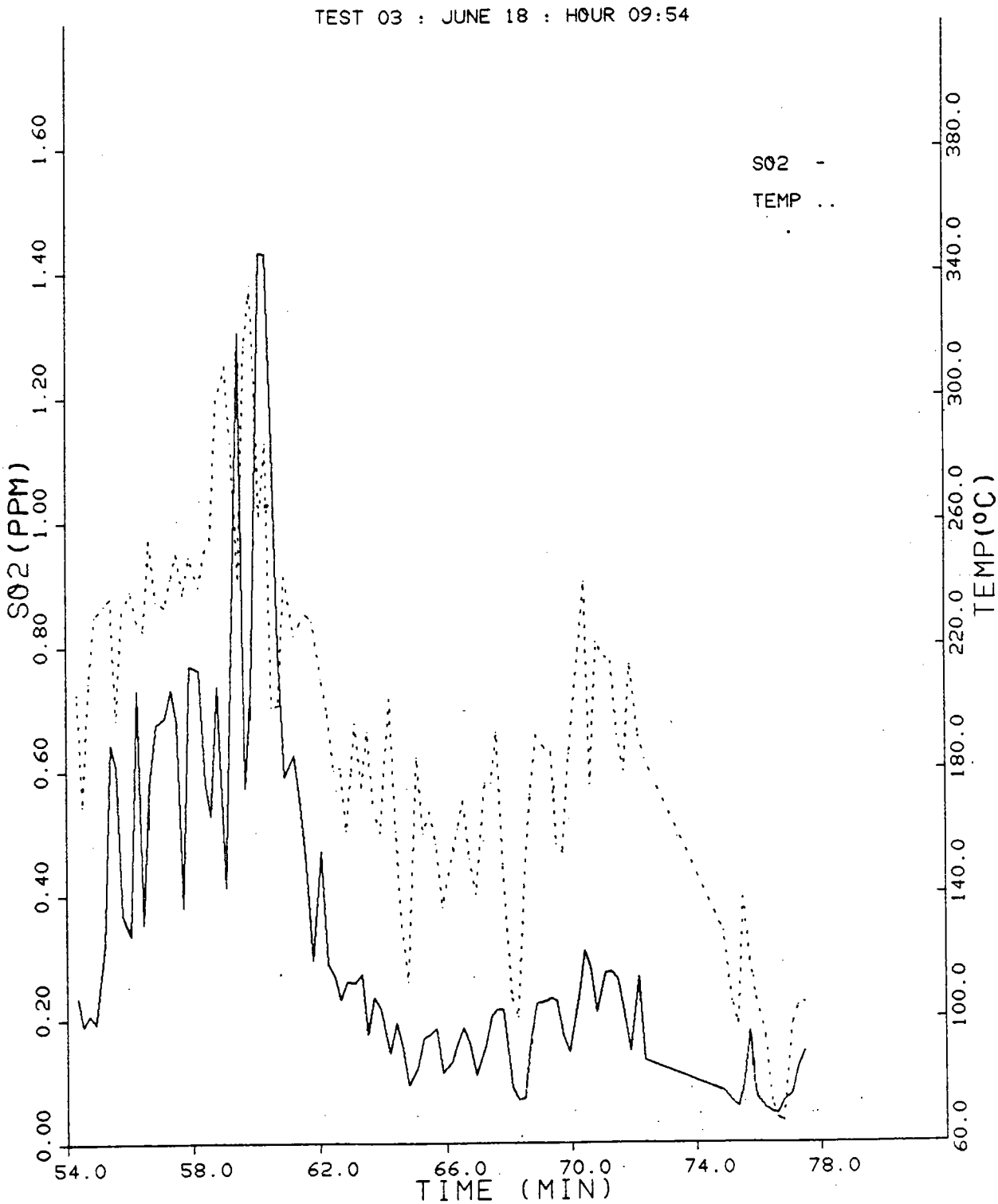


Figure A-3. SO_2 and temperature vs. time.

73

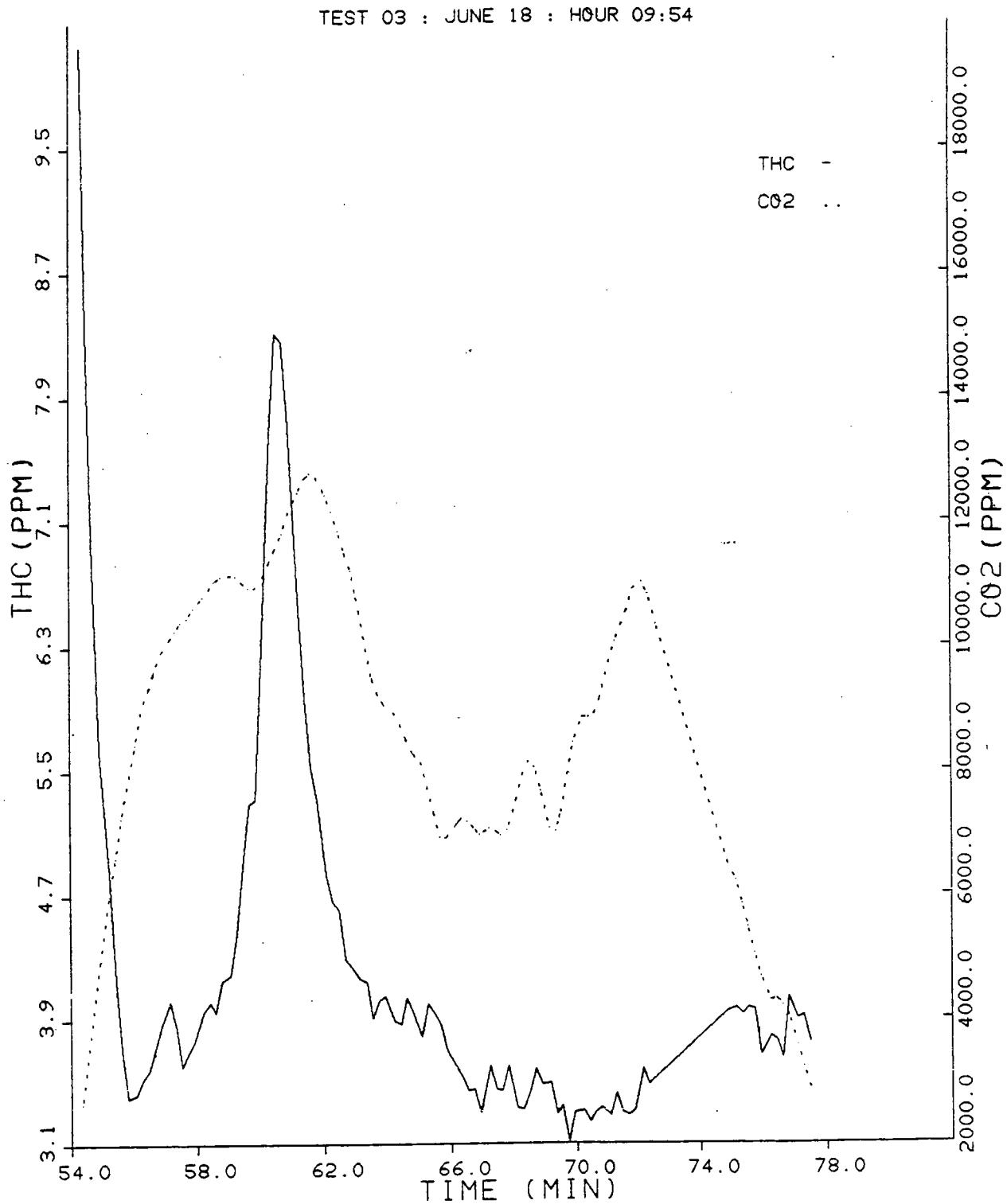


Figure A-4. THC and CO_2 vs. time.

74

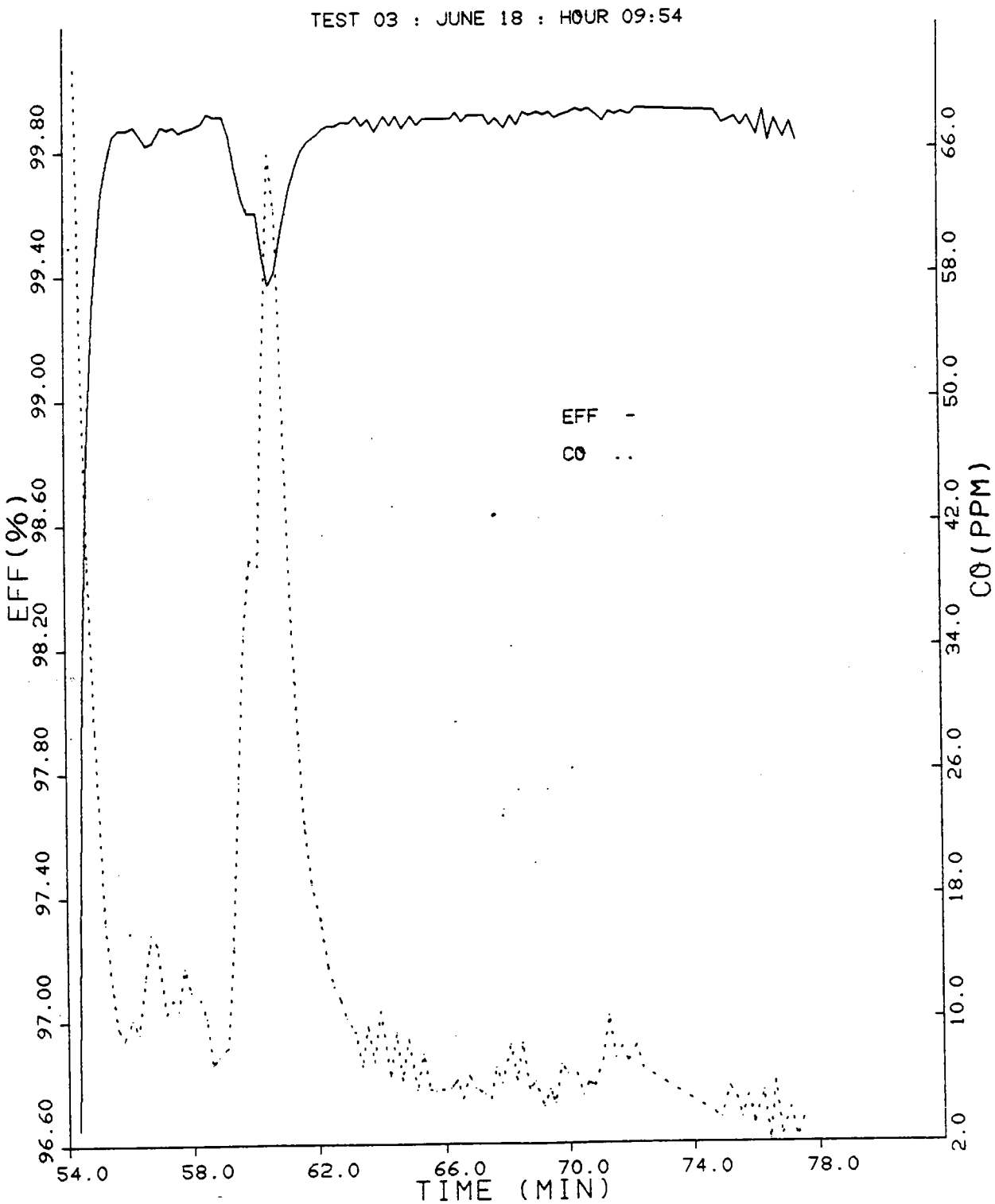


Figure A-5. Efficiency and CO vs. time.

75

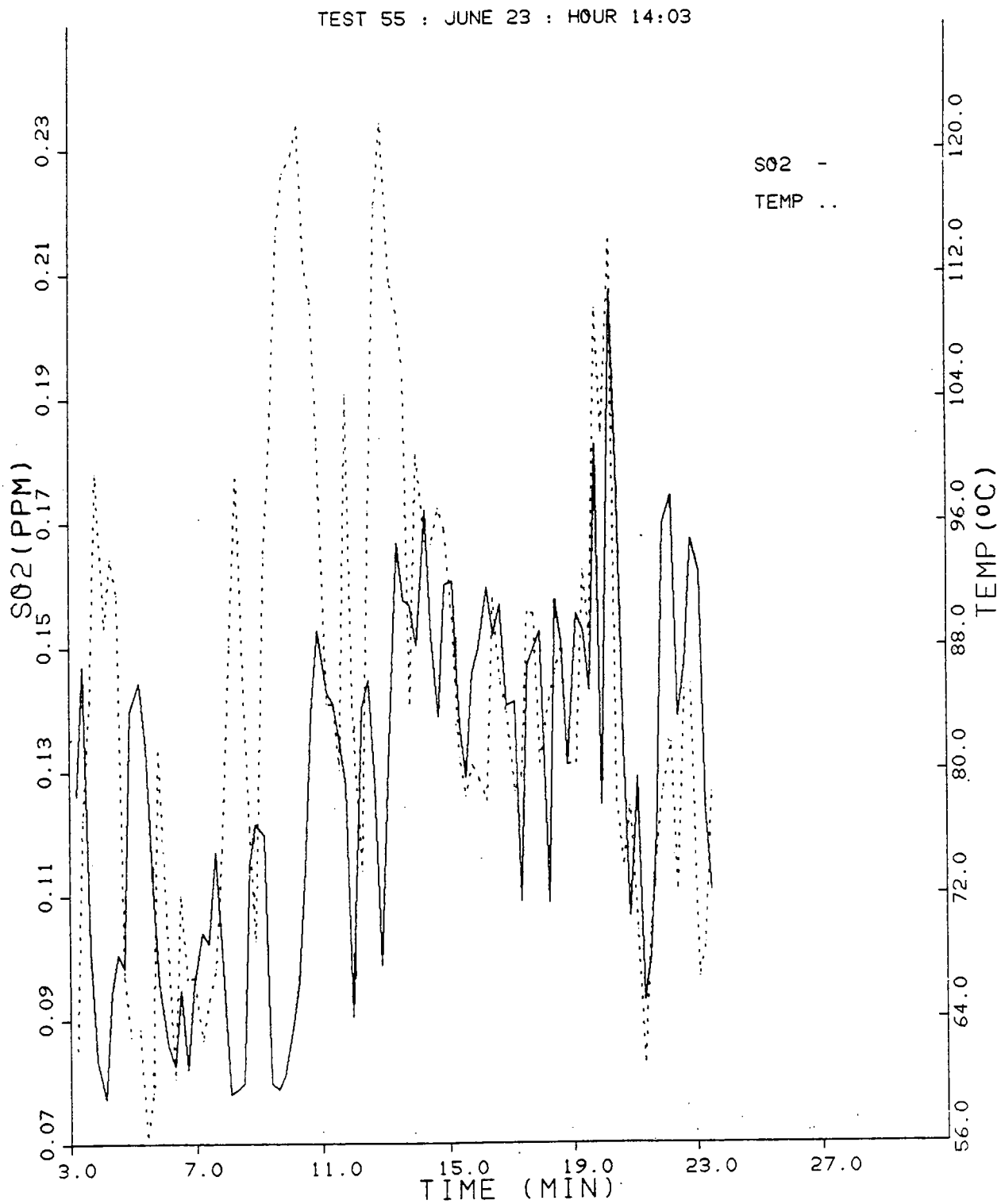


Figure A-6. SO_2 and temperature vs. time.

76

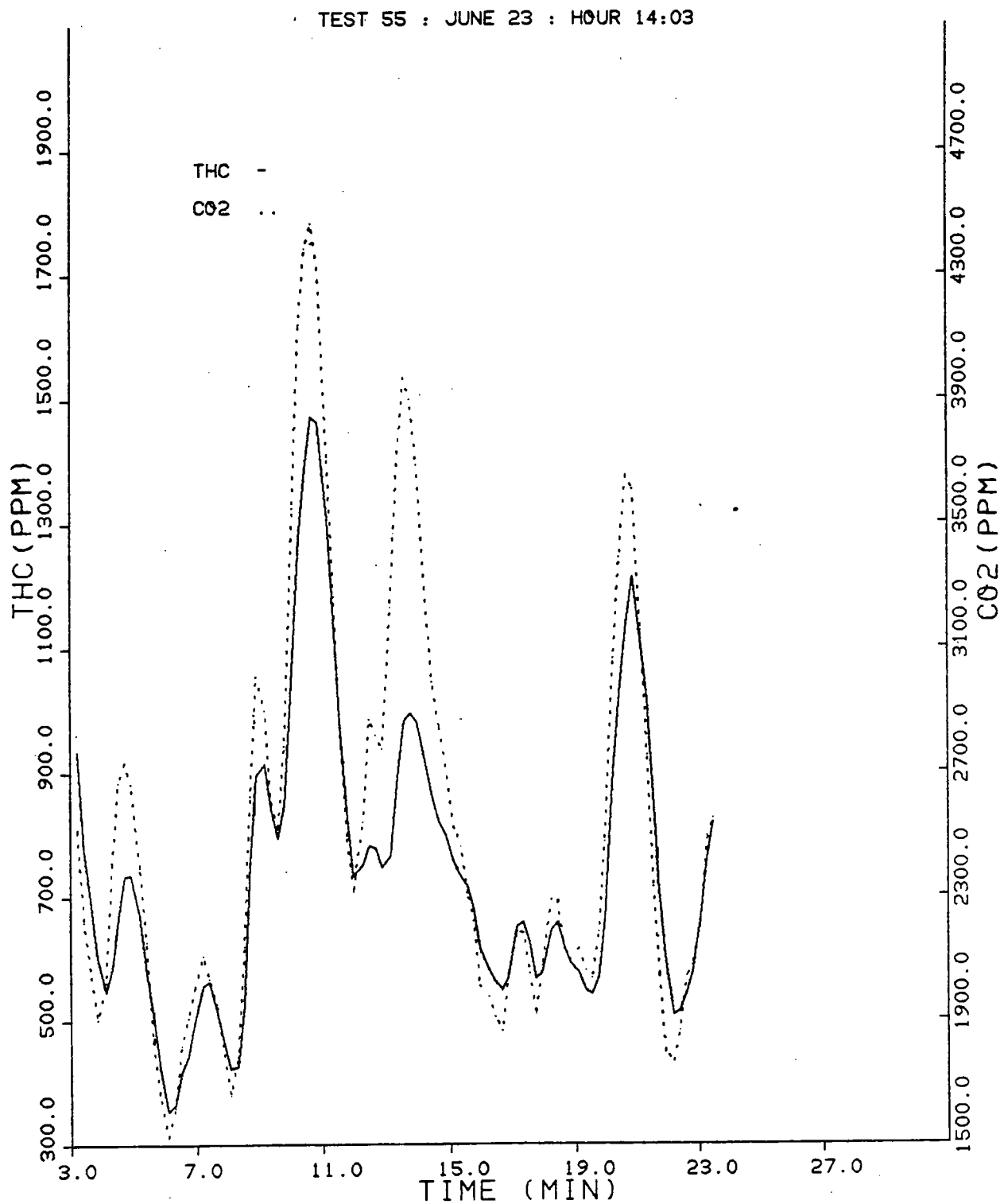


Figure A-7. THC and CO_2 vs. time.

77

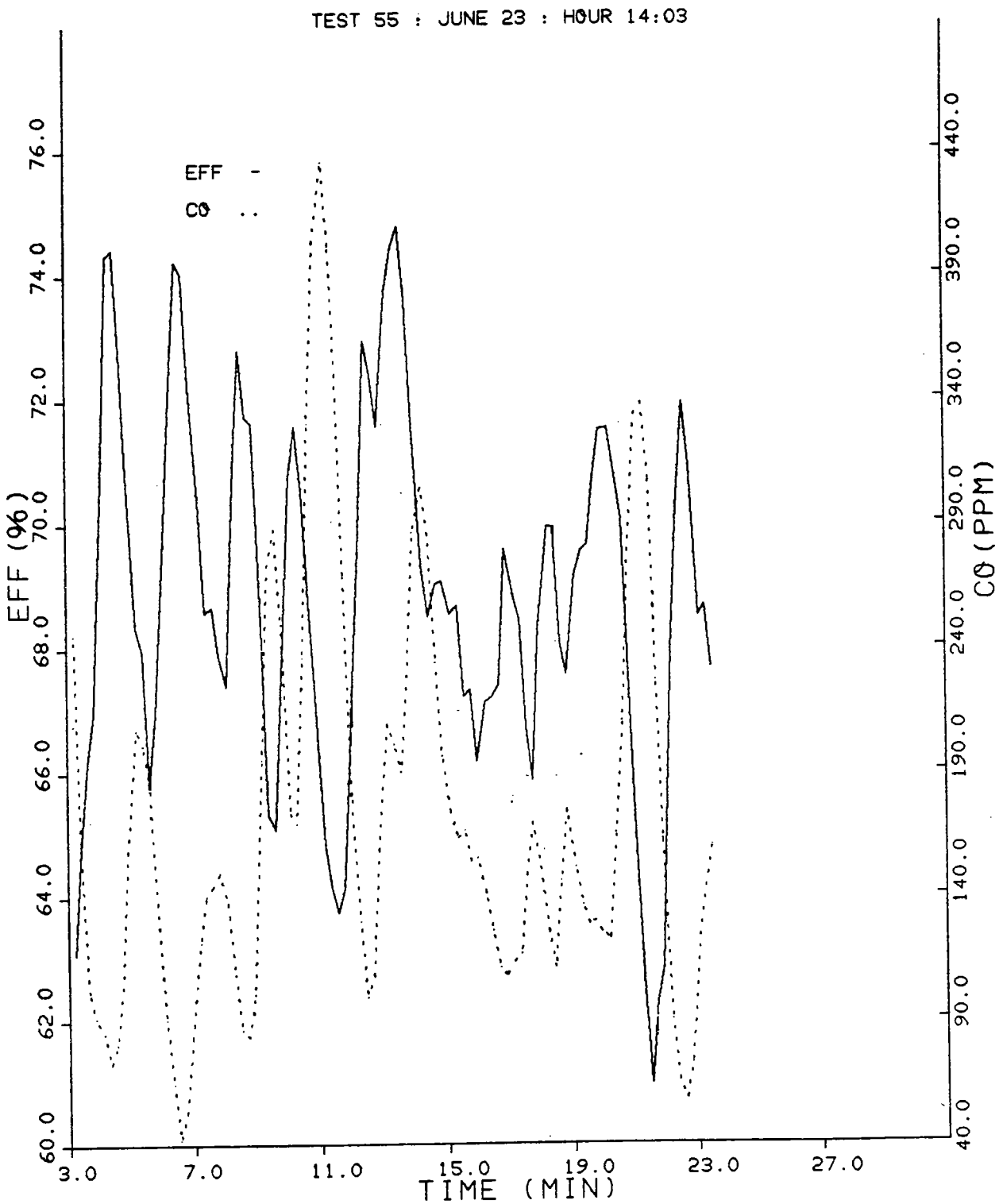


Figure A-8. Efficiency and CO vs. time.

78

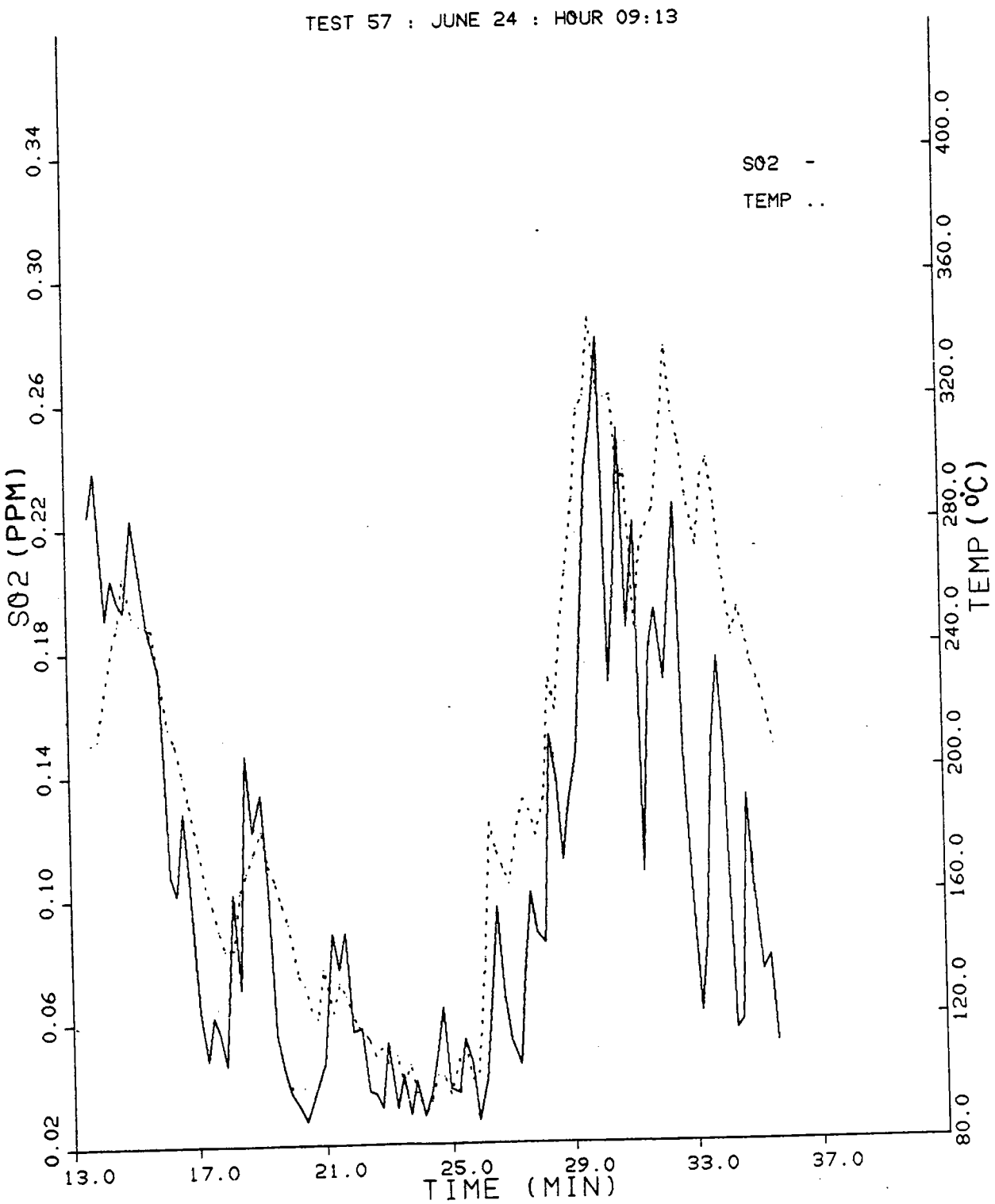


Figure A-9. SO_2 and temperature vs. time.

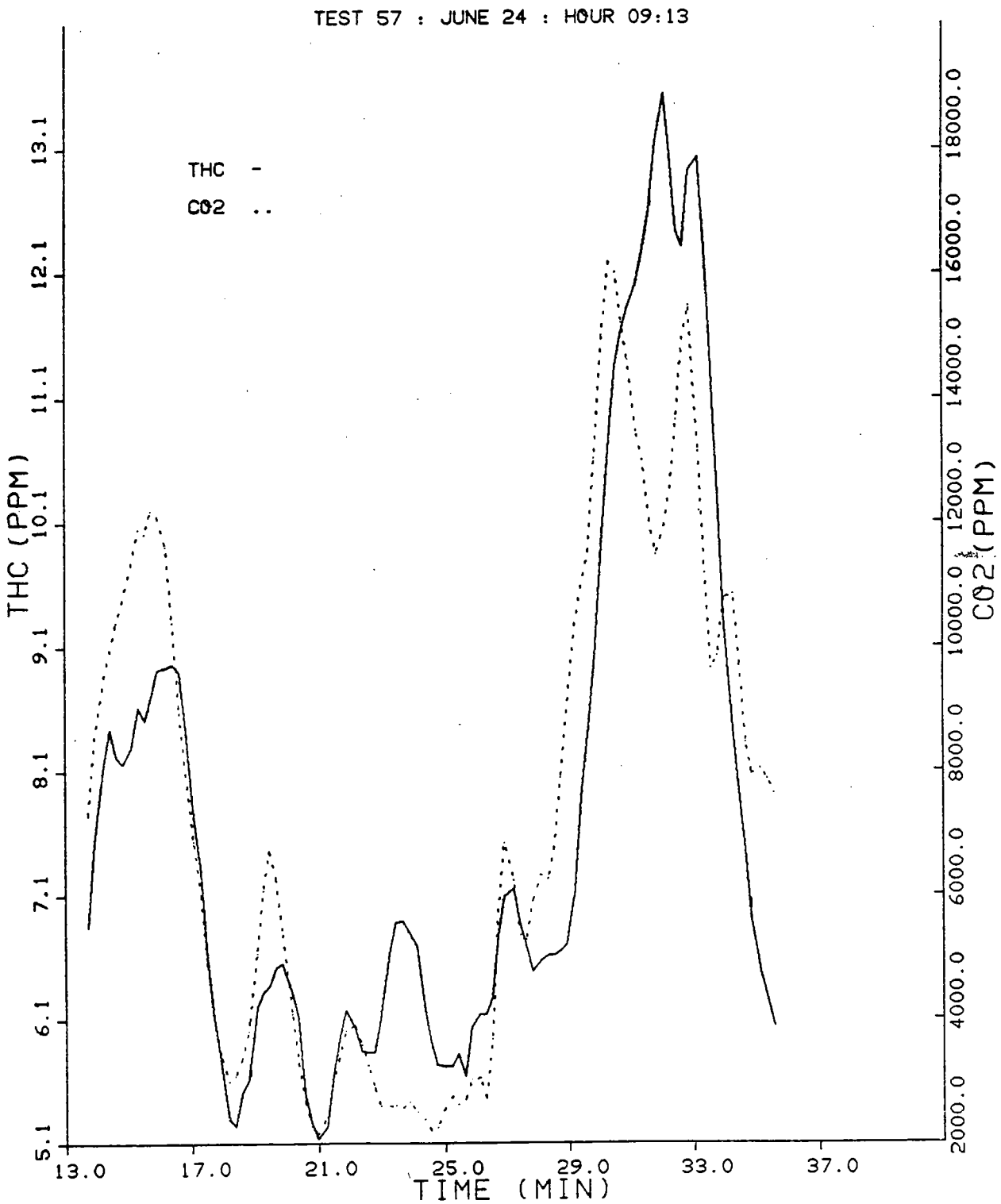


Figure A-10. THC and CO_2 vs. time.

80

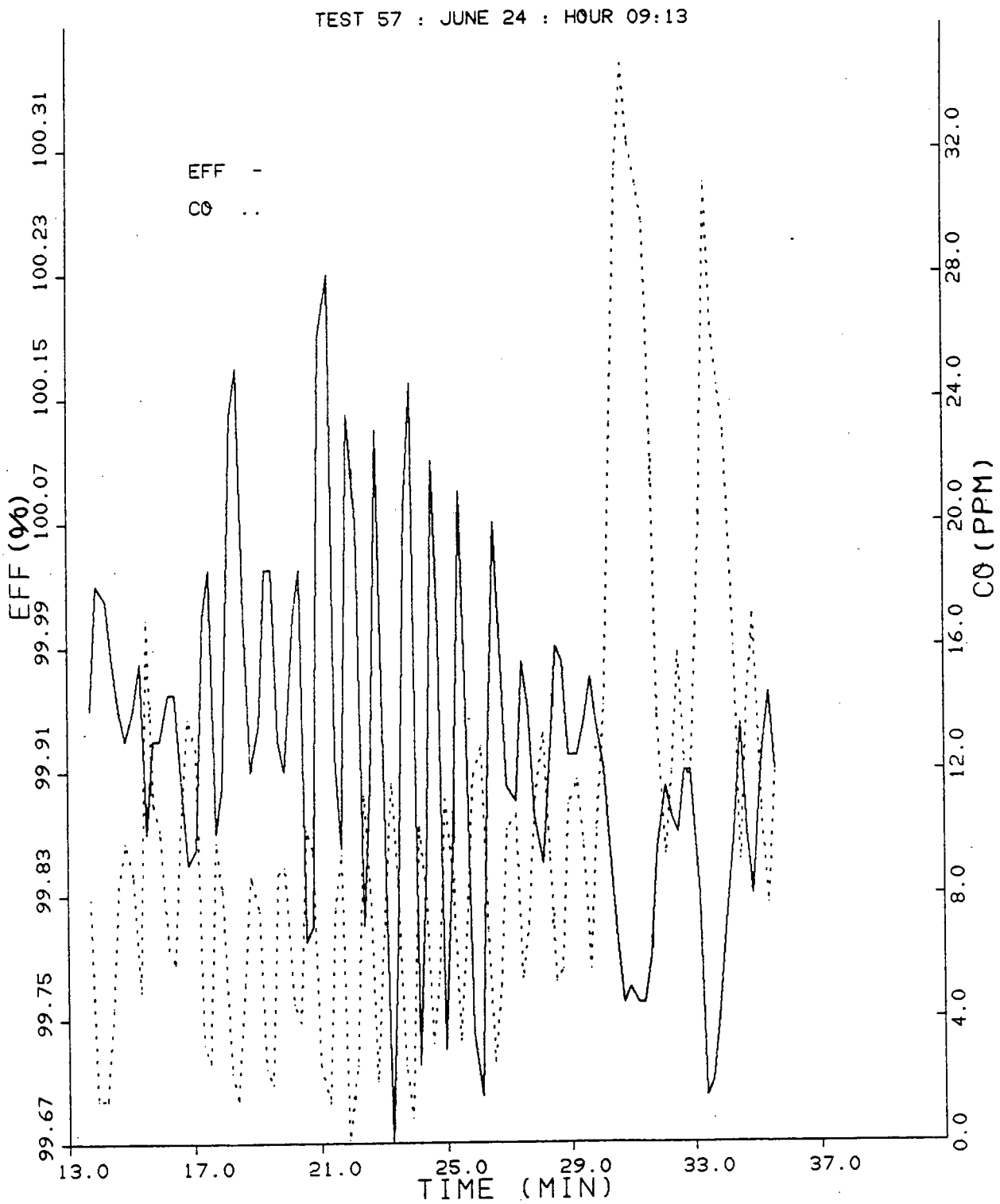


Figure A-11. Efficiency and CO vs. time.

81

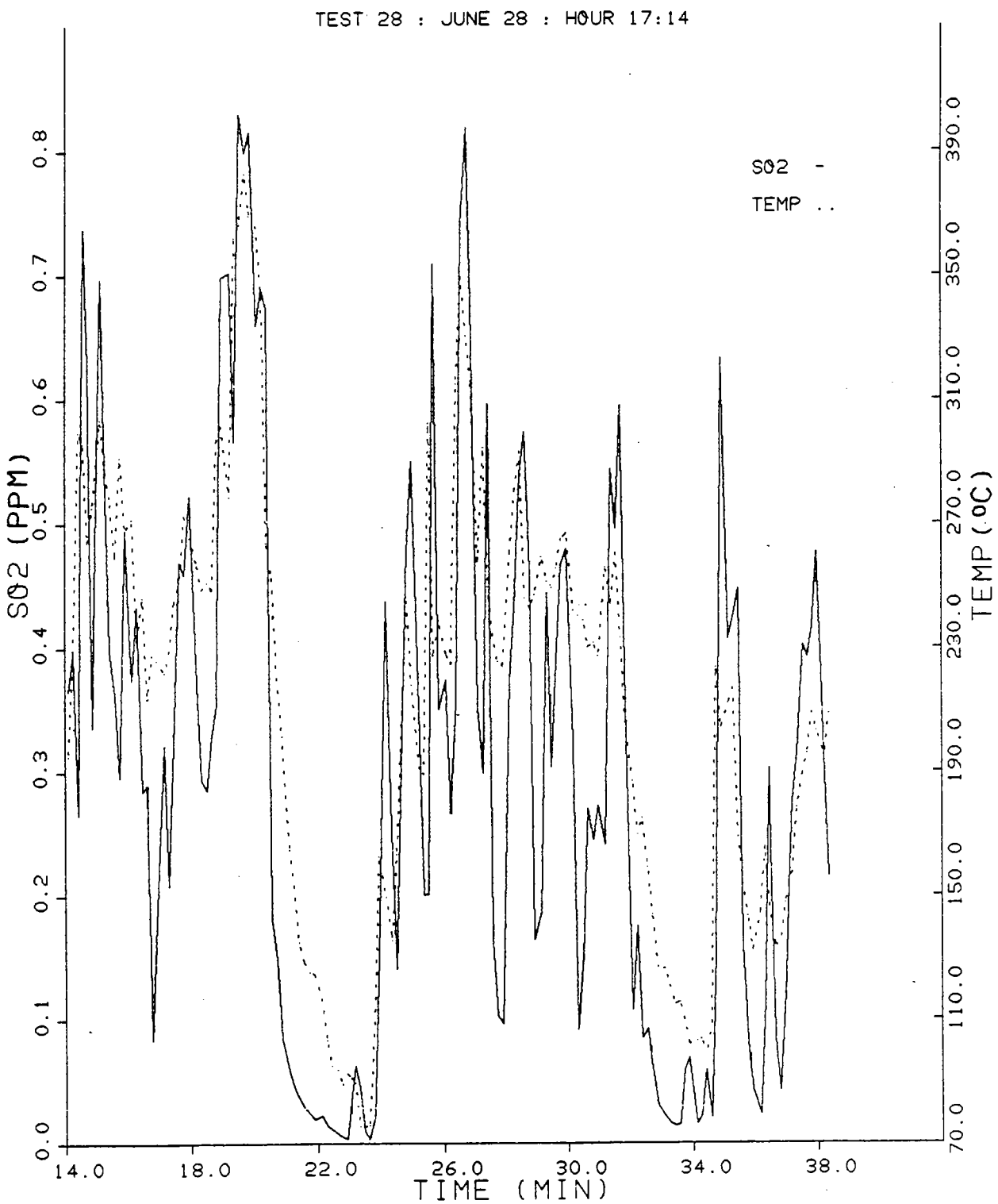


Figure A-12. SO_2 and temperature vs. time.

82

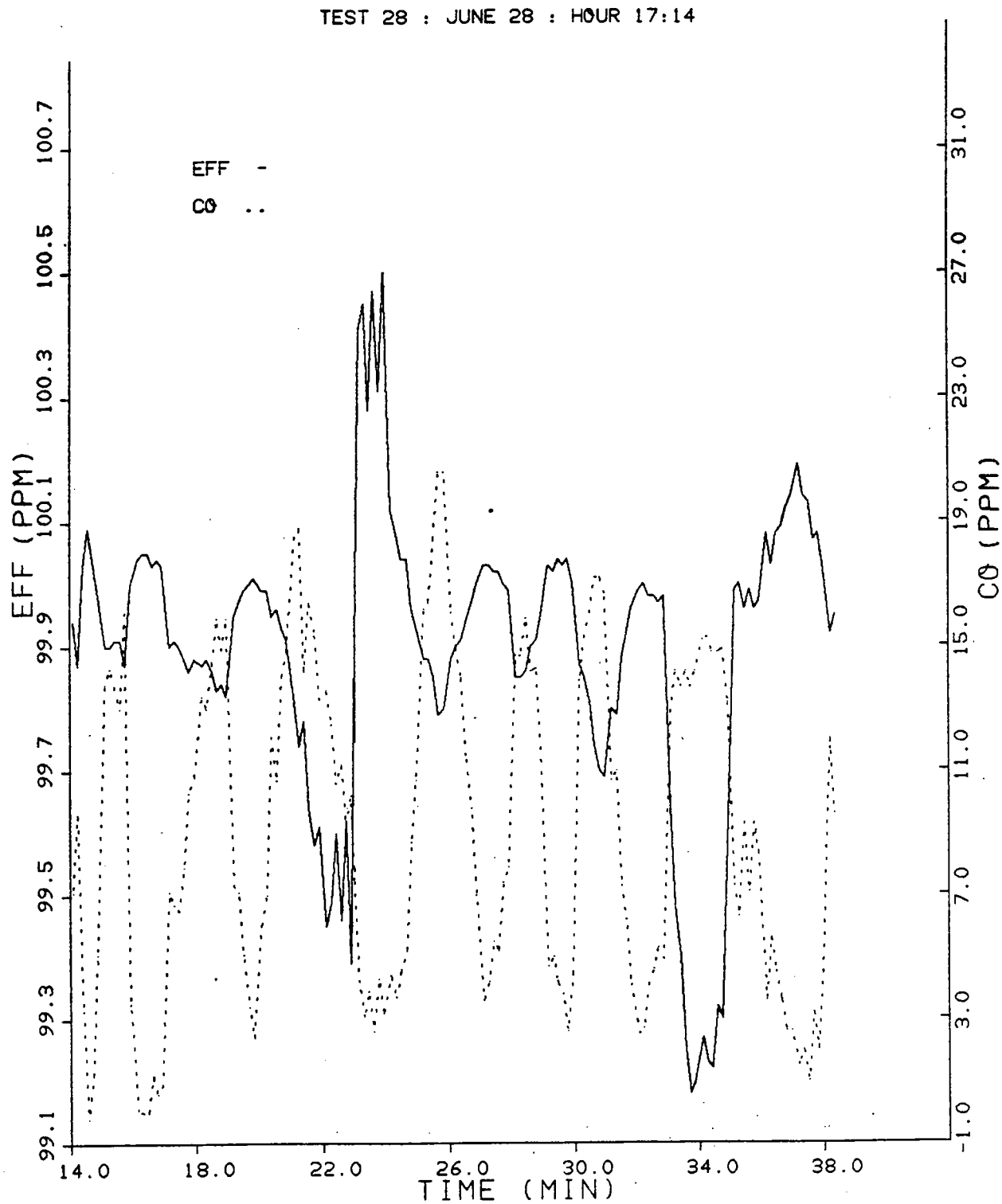


Figure A-13. Efficiency and CO vs. time.

83

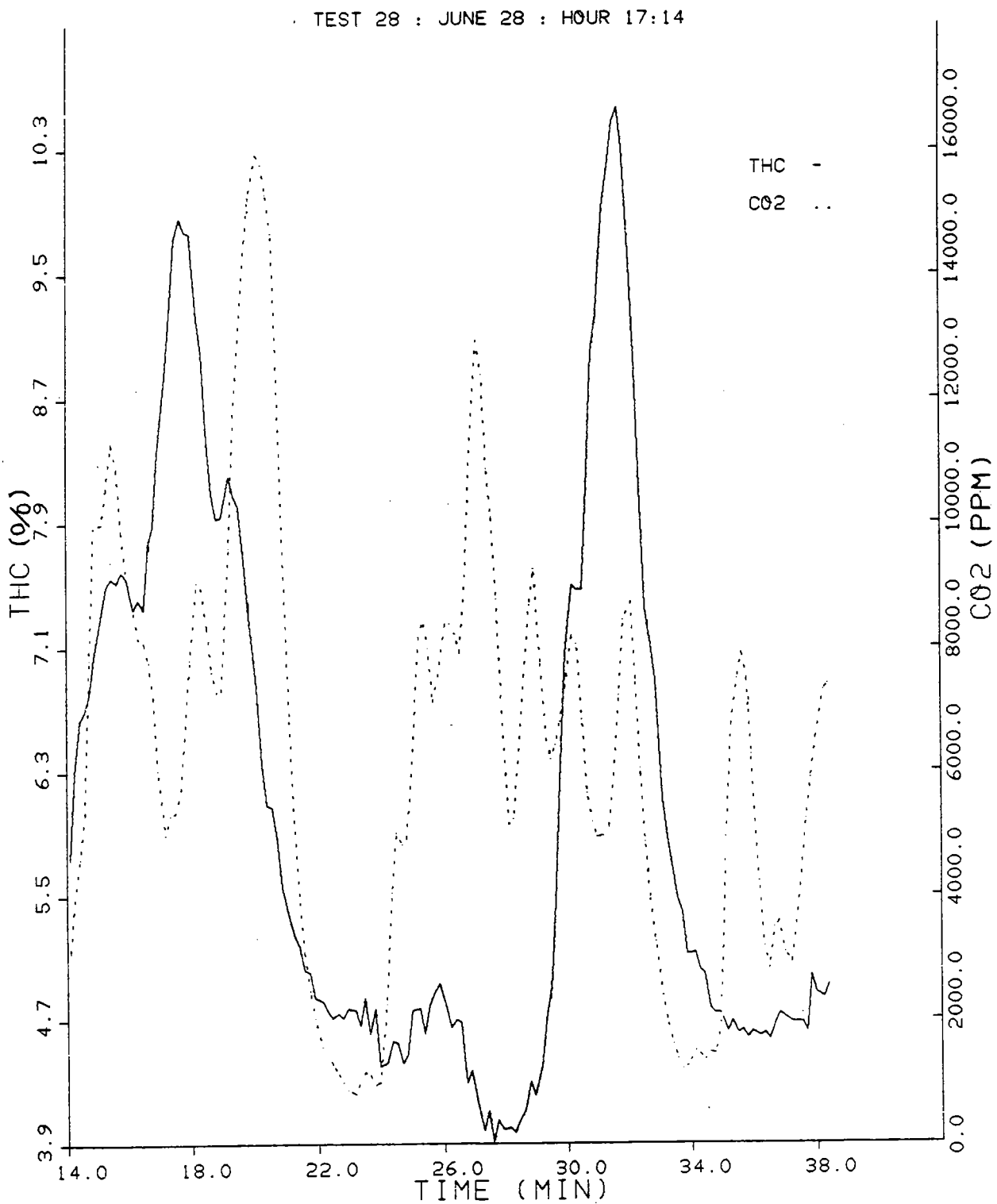


Figure A-14. THC and CO_2 vs. time.

84

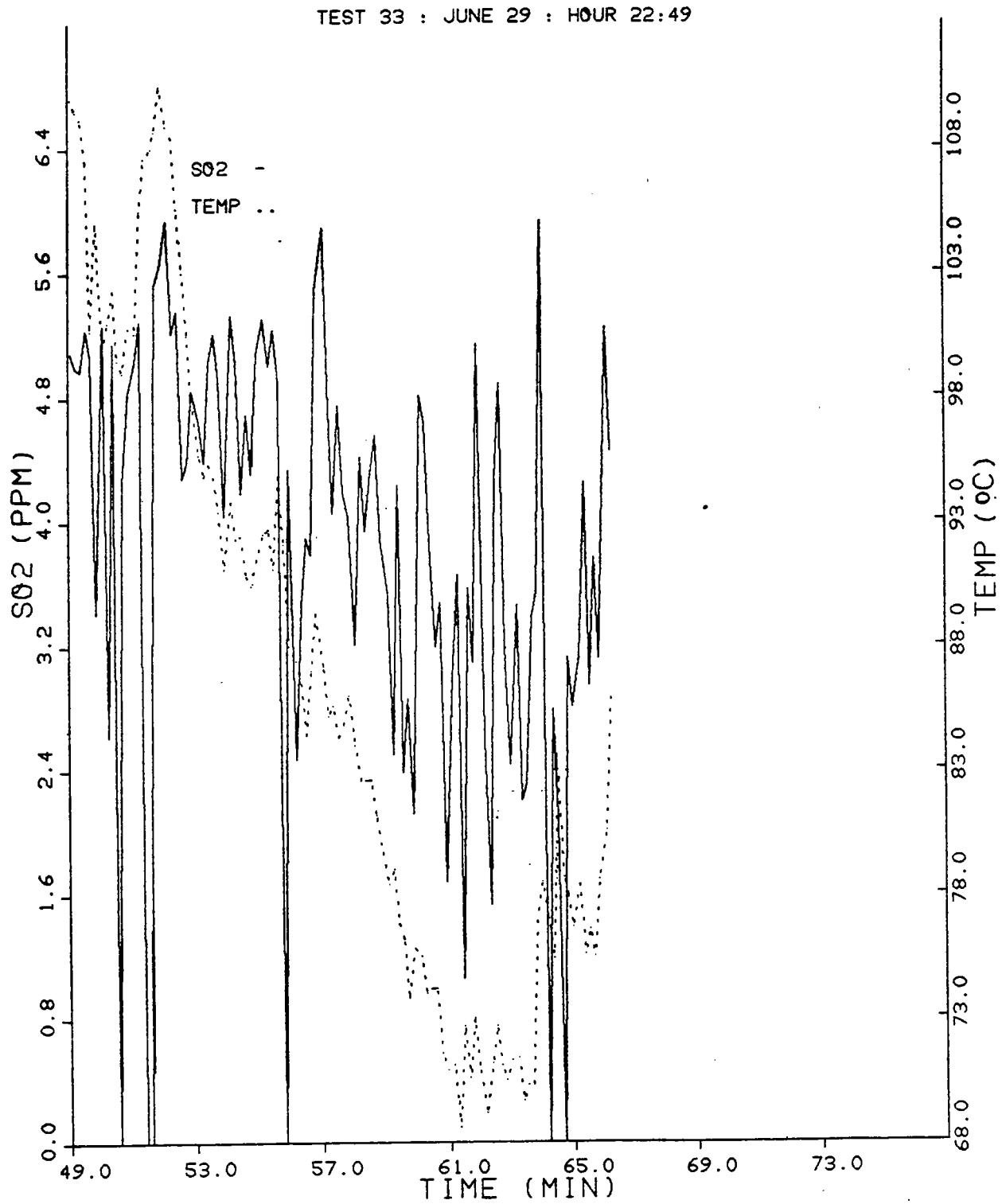


Figure A-15. SO_2 and temperature vs. time.

85

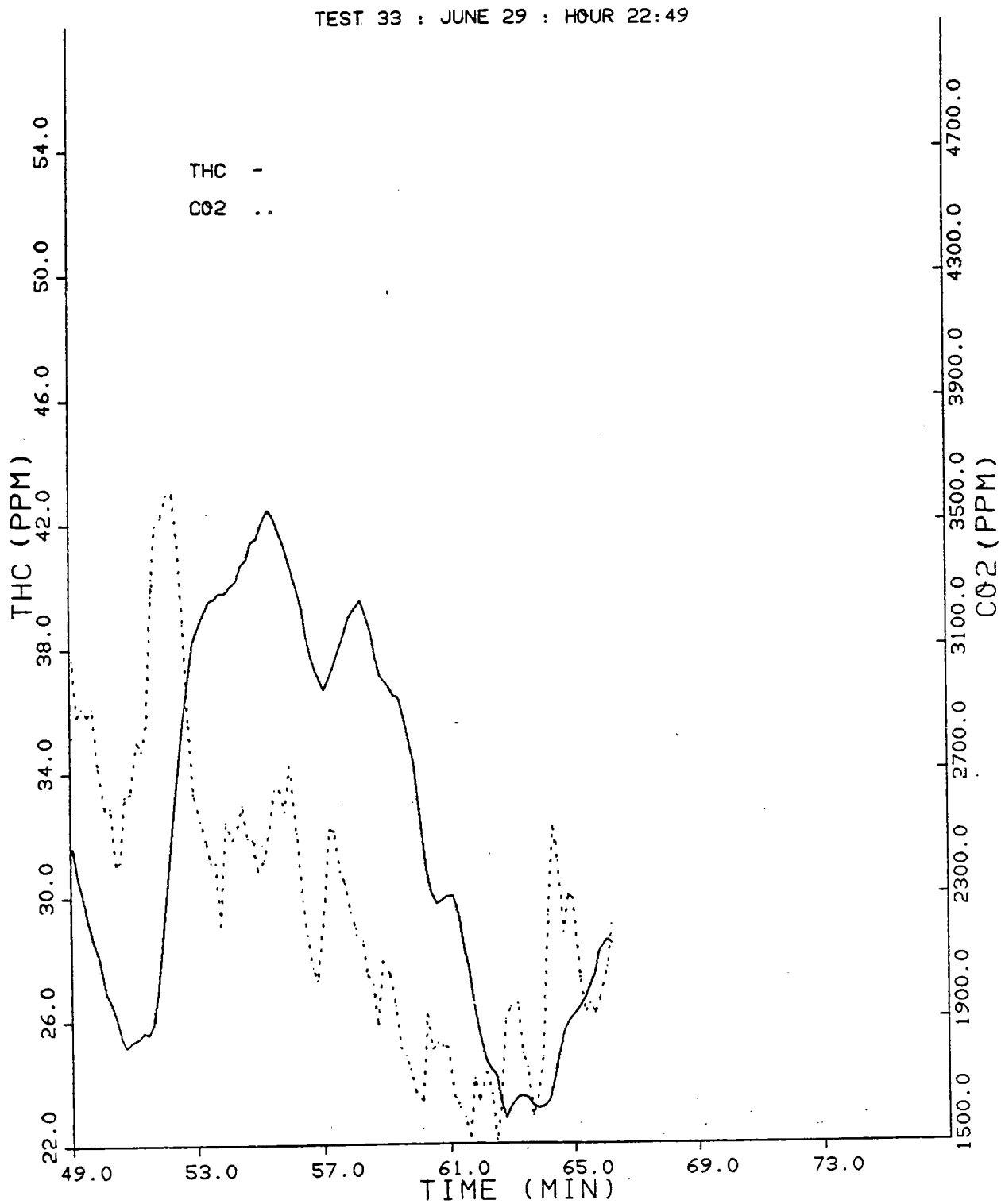


Figure A-16. THC and CO_2 vs. time.

86

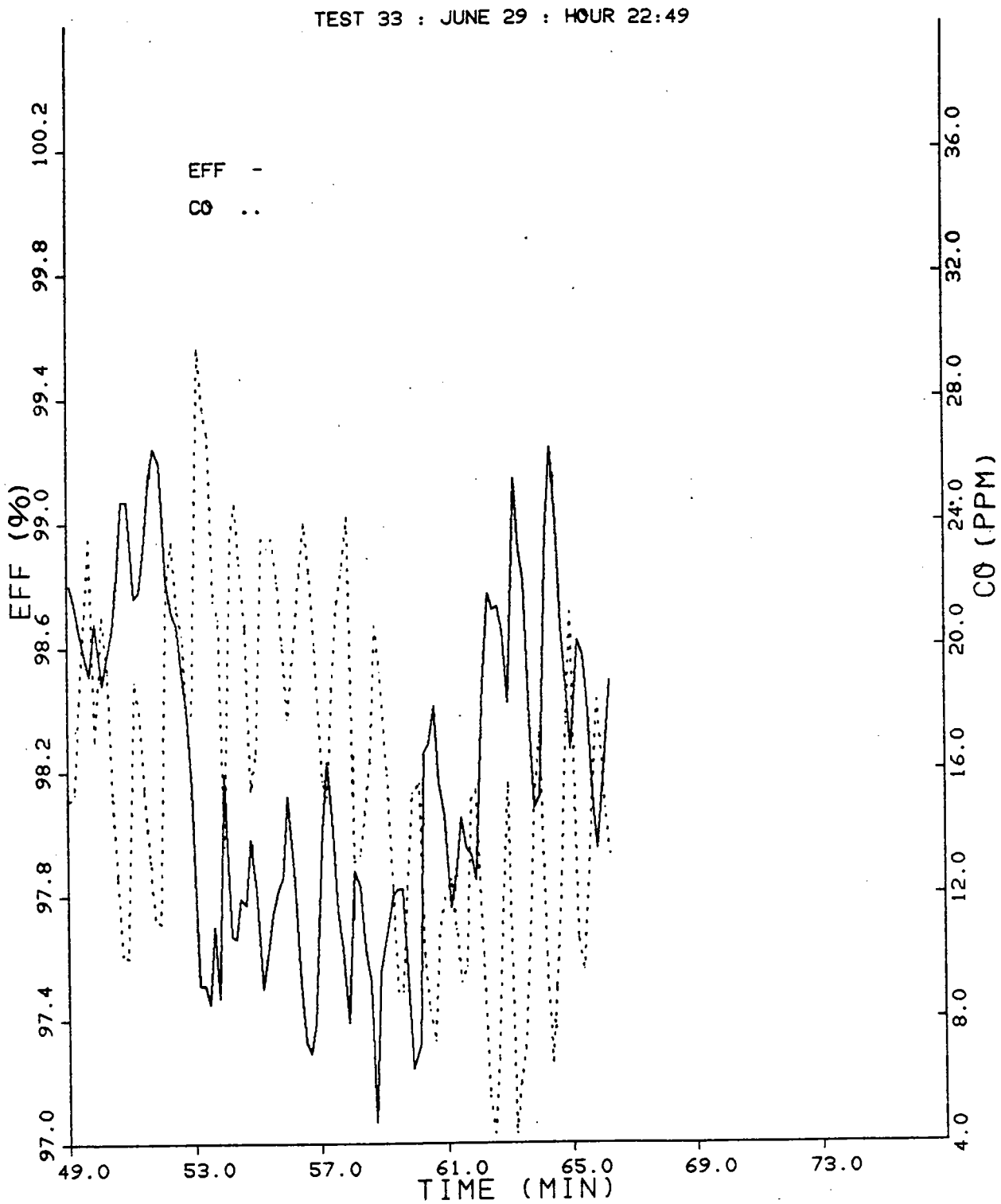


Figure A-17. Efficiency and CO vs. time.

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APPENDIX B
TEST 1
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE*	175.3	0.053	3.09	19.46	3.8	7052.	-0.7	3.5	267.	30.1	99.9
STANDARD DEVIATION	73.8	0.047	2.12	0.62	1.4	3498.	0.2	1.2	24.	0.6	0.1
NUMBER OF OBSERVATIONS	117	117	117	117	117	117	117	117	117	117	117
AVERAGE BACKGROUND	28.2	0.073	0.45	20.43	4.7	373.	4.4	2.9	285.	28.0	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 4	18/13:17:29	18/13:32:10
BACKGROUND 5	18/14:14:22	18/14:22:07

OVERALL COMBUSTION EFFICIENCY = 99.96%

* All concentrations here and throughout Appendix B have been corrected via subtraction. Thus, the actual measured value (i.e., uncorrected) is the "average" plus the "average background" (last row).

TEST 2
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	158.7	0.197	2.16	19.73	8.5	4719.	0.2	2.8	199.	33.6	99.8
STANDARD DEVIATION	45.6	0.152	1.31	0.42	12.9	1684.	1.3	0.9	33.	0.6	0.2
NUMBER OF OBSERVATIONS	84	84	84	84	84	84	84	84	84	84	84
AVERAGE BACKGROUND	38.2	-0.008	1.41	20.26	6.3	388.	5.2	2.7	198.	31.5	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 1	17/16:52:27	17/16:55:38
BACKGROUND 2	17/17:25:51	17/17:30:47

OVERALL COMBUSTION EFFICIENCY = 99.82%

TEST 3
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	189.4	0.336	3.46	19.48	13.8	8159.	1.2	3.0	221.	30.5	99.8
STANDARD DEVIATION	56.1	0.296	1.64	0.49	14.5	2567.	1.3	0.9	27.	0.4	0.4
NUMBER OF OBSERVATIONS	98	98	98	98	98	98	98	98	98	98	98
AVERAGE BACKGROUND	29.6	0.005	0.33	20.58	-0.4	394.	3.1	3.2	218.	27.2	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 3	18/10:26:06	18/10:29:29

OVERALL COMBUSTION EFFICIENCY = 99.82%

TEST 4
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	153.4	0.153	1.96	20.05	75.3	6616.	5.3	1.4	184.	32.8	98.8
STANDARD DEVIATION	38.6	0.080	0.96	0.52	35.5	3004.	2.9	0.2	8.	0.2	0.2
NUMBER OF OBSERVATIONS	57	57	57	57	57	57	57	57	57	57	57
AVERAGE BACKGROUND	24.9	0.003	0.11	21.09	3.1	497.	5.2	0.8	186.	26.3	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 18	22/21:21:17	22/21:27:29
BACKGROUND 19	22/22:48:09	22/22:54:34

OVERALL COMBUSTION EFFICIENCY = 98.80%

16

TEST 8
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	127.0	0.066	1.45	20.30	61.1	5400.	3.7	0.9	185.	32.2	98.9
STANDARD DEVIATION	33.2	0.040	0.96	0.52	36.1	3094.	3.9	0.3	11.	0.9	0.3
NUMBER OF OBSERVATIONS	84	84	84	84	84	84	84	84	84	84	84
AVERAGE BACKGROUND	31.4	0.008	0.12	21.12	3.8	495.	5.8	0.6	153.	26.6	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 19	22/22:48:09	22/22:54:34
BACKGROUND 20	22/23:27:41	22/23:32:10

OVERALL COMBUSTION EFFICIENCY = 98.81%

TEST 7
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	138.4	0.044	1.62	20.13	7.9	5224.	0.3	3.1	262.	26.7	99.8
STANDARD DEVIATION	39.7	0.026	0.96	0.41	3.4	2254.	1.0	0.9	24.	0.5	0.1
NUMBER OF OBSERVATIONS	103	103	103	103	103	103	103	103	103	103	103
AVERAGE BACKGROUND	24.0	0.002	0.06	20.87	0.1	396.	9.6	2.4	280.	24.5	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 8	21/10:55:50	21/11:04:28
BACKGROUND 9	21/11:55:06	21/12:01:30

OVERALL COMBUSTION EFFICIENCY = 99.84%

TEST 5
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	172.8	0.070	2.09	19.42	4.1	6115.	-0.1	2.9	294.	30.8	99.9
STANDARD DEVIATION	54.6	0.060	1.25	0.49	1.6	2908.	0.2	1.0	59.	0.6	0.1
NUMBER OF OBSERVATIONS	165	165	165	165	165	165	165	165	165	165	165
AVERAGE BACKGROUND	32.8	0.022	1.00	20.28	3.4	368.	5.0	2.7	289.	29.9	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 6	18/16:23:48	18/16:39:05
BACKGROUND 7	18/17:45:33	18/17:49:39

OVERALL COMBUSTION EFFICIENCY = 99.94%

TEST 67
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	470.9	0.018	3.77	20.19	N/A	3758.	N/A	6.6	77.	25.8	N/A
STANDARD DEVIATION	160.0	0.001	4.32	0.69	N/A	2241.	N/A	2.0	13.	0.3	N/A
NUMBER OF OBSERVATIONS	21	21	21	21	N/A	21	N/A	21	21	21	N/A
AVERAGE BACKGROUND	22.2	-0.002	0.18	20.92	5.4	362.	3.3	3.1	131.	22.1	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 51	19/10:13:18	19/10:32:57

TEST 17
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	124.8	0.023	1.00	20.38	6.1	3499.	-0.5	1.8	255.	26.9	99.8
STANDARD DEVIATION	35.1	0.011	0.84	0.40	3.9	2274.	0.6	0.9	77.	0.4	0.2
NUMBER OF OBSERVATIONS	135	135	135	135	135	135	135	135	135	135	135
AVERAGE BACKGROUND	29.4	0.005	-0.05	20.86	0.2	434.	5.2	1.8	276.	26.3	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 9	21/11:55:06	21/12:01:30
BACKGROUND 10	21/13:26:34	21/13:38:58

OVERALL COMBUSTION EFFICIENCY = 99.84%

TEST 50
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	131.5	0.031	0.50	20.19	16.7	4220.	6.6	2.2	269.	27.7	99.4
STANDARD DEVIATION	43.9	0.013	0.30	0.38	11.0	2179.	5.8	0.8	91.	3.5	0.3
NUMBER OF OBSERVATIONS	103	103	103	103	103	103	103	103	103	103	103
AVERAGE BACKGROUND	33.2	0.009	0.12	20.91	0.1	415.	5.4	2.0	229.	28.0	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 10	21/13:26:34	21/13:38:59
BACKGROUND 11	21/14:19:40	21/14:29:33

OVERALL COMBUSTION EFFICIENCY = 99.45%

TEST 56
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	120.4	0.252	0.58	20.67	7.8	3120.	1.6	2.4	148.	31.8	99.7
STANDARD DEVIATION	40.4	0.221	0.43	0.44	6.3	2190.	1.6	1.0	40.	0.4	0.3
NUMBER OF OBSERVATIONS	134	134	134	134	134	134	134	134	134	134	134
AVERAGE BACKGROUND	32.9	0.016	0.78	21.23	0.2	515.	6.6	2.3	177.	30.8	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 21	23/13:09:36	23/13:19:44
BACKGROUND 22	23/15:18:53	23/15:26:12

OVERALL COMBUSTION EFFICIENCY = 99.70%

TEST 61
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	166.8	0.039	1.32	19.47	398.4	6273.	961.7	1.7	68.	21.1	81.6
STANDARD DEVIATION	32.6	0.012	0.47	0.34	117.0	1823.	251.4	0.6	12.	0.1	3.8
NUMBER OF OBSERVATIONS	58	58	58	58	58	58	58	58	58	58	58
AVERAGE BACKGROUND	21.2	0.003	0.11	20.46	-0.6	397.	3.5	0.4	70.	21.2	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 30	24/22:18:40	24/22:30:09
BACKGROUND 31	25/00:08:59	25/00:17:09

OVERALL COMBUSTION EFFICIENCY = 82.18%

TEST 55
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	85.6	0.112	0.38	20.83	171.0	2012.	735.5	2.2	187.	30.9	68.9
STANDARD DEVIATION	16.0	0.030	0.32	0.21	83.9	686.	242.1	0.8	39.	0.4	3.1
NUMBER OF OBSERVATIONS	93	93	93	93	93	93	93	93	93	93	93
AVERAGE BACKGROUND	32.9	0.016	0.78	21.23	0.2	515.	6.6	2.3	177.	30.8	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 21	23/13:09:36	23/13:19:44
BACKGROUND 22	23/15:18:53	23/15:26:12

OVERALL COMBUSTION EFFICIENCY = 68.95%

TEST 57
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	199.7	0.113	2.68	19.80	5.0	6945.	2.0	1.5	168.	23.7	99.9
STANDARD DEVIATION	72.5	0.067	2.05	0.89	7.6	4163.	2.3	0.5	25.	0.3	0.1
NUMBER OF OBSERVATIONS	100	100	100	100	100	100	100	100	100	100	100
AVERAGE BACKGROUND	23.3	-0.004	0.19	21.11	5.3	424.	5.8	1.0	156.	22.7	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 25	24/08:40:29	24/08:54:22
BACKGROUND 26	24/09:44:11	24/09:50:57

OVERALL COMBUSTION EFFICIENCY = 99.90%

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TEST 11
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	159.7	0.163	3.69	20.03	7.1	5269.	1.6	1.2	135.	23.3	99.8
STANDARD DEVIATION	31.6	0.057	1.18	0.33	5.2	3156.	1.9	0.4	24.	0.3	0.2
NUMBER OF OBSERVATIONS	63	63	63	63	63	63	63	63	63	63	63
AVERAGE BACKGROUND	21.4	-0.003	0.22	21.34	3.6	512.	5.0	1.1	88.	21.0	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 23	24/07:07:06	24/07:14:22
BACKGROUND 24	24/07:55:07	24/08:04:46

OVERALL COMBUSTION EFFICIENCY = 99.83%

TEST 11A
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	139.8	0.135	3.31	20.10	4.7	6677.	0.2	1.2	130.	23.2	99.9
STANDARD DEVIATION	30.4	0.042	1.02	0.35	4.2	1446.	1.4	0.4	24.	0.3	0.1
NUMBER OF OBSERVATIONS	33	33	33	33	33	33	33	33	33	33	33
AVERAGE BACKGROUND	21.4	-0.003	0.22	21.34	3.6	512.	5.0	1.1	88.	21.0	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 23	24/07:07:06	24/07:14:22
BACKGROUND 24	24/07:55:07	24/08:04:46

OVERALL COMBUSTION EFFICIENCY = 99.93%

TEST 11B
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	181.5	0.198	4.17	19.92	8.6	8158.	3.0	1.1	149.	23.4	99.9
STANDARD DEVIATION	7.7	0.028	0.74	0.21	4.9	608.	0.9	0.3	16.	0.1	0.1
NUMBER OF OBSERVATIONS	18	18	18	18	18	18	18	18	18	18	18
AVERAGE BACKGROUND	21.4	-0.003	0.22	21.34	3.6	512.	5.0	1.1	88.	21.0	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 23	24/07:07:06	24/07:14:22
BACKGROUND 24	24/07:55:07	24/08:04:46

OVERALL COMBUSTION EFFICIENCY = 99.85%

TEST 11C
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	181.4	0.189	4.00	19.98	11.6	8210.	3.3	1.4	125.	23.5	99.8
STANDARD DEVIATION	19.2	0.081	1.73	0.38	4.6	1108.	1.5	0.4	25.	0.1	0.1
NUMBER OF OBSERVATIONS	12	12	12	12	12	12	12	12	12	12	12
AVERAGE BACKGROUND	21.4	-0.003	0.22	21.34	3.6	512.	5.0	1.1	88.	21.0	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 23	24/07:07:06	24/07:14:22
BACKGROUND 24	24/07:55:07	24/08:04:46

OVERALL COMBUSTION EFFICIENCY = 99.82%

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TEST 59
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	139.3	0.060	1.41	19.53	49.9	5413.	33.3	0.9	94.	22.2	98.4
STANDARD DEVIATION	26.3	0.024	0.50	0.39	26.4	1481.	24.7	0.6	67.	0.1	1.0
NUMBER OF OBSERVATIONS	57	57	57	57	57	57	57	57	57	57	57
AVERAGE BACKGROUND	20.4	0.002	0.18	20.61	0.0	421.	2.9	0.5	93.	21.8	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 29	24/21:16:12	24/21:31:11
BACKGROUND 30	24/22:18:40	24/22:30:09

OVERALL COMBUSTION EFFICIENCY = 98.49%

TEST 59A
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	142.4	0.052	1.30	19.44	62.1	5575.	45.3	1.0	72.	22.1	97.9
STANDARD DEVIATION	29.9	0.025	0.53	0.40	23.8	1659.	21.7	0.6	46.	0.1	0.9
NUMBER OF OBSERVATIONS	38	38	38	38	38	38	38	38	38	38	38
AVERAGE BACKGROUND	20.4	0.002	0.18	20.61	0.0	421.	2.9	0.5	93.	21.8	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 29	24/21:16:12	24/21:31:11
BACKGROUND 30	24/22:19:40	24/22:30:09

OVERALL COMBUSTION EFFICIENCY = 98.11%

TEST 599
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	133.1	0.076	1.62	19.71	25.4	5090.	9.4	0.7	140.	22.3	99.3
STANDARD DEVIATION	15.9	0.014	0.35	0.30	7.9	1002.	3.1	0.6	79.	0.0	0.1
NUMBER OF OBSERVATIONS	19	19	19	19	19	19	19	19	19	19	19
AVERAGE BACKGROUND	20.4	0.002	0.18	20.61	0.0	421.	2.9	0.5	93.	21.8	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 29	24/21:16:12	24/21:31:11
BACKGROUND 30	24/22:18:40	24/22:30:09

OVERALL COMBUSTION EFFICIENCY = 99.32%

TEST 60
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	99.7	0.052	0.99	19.70	28.3	3685.	11.8	1.3	65.	21.7	98.8
STANDARD DEVIATION	20.7	0.014	0.47	0.33	9.5	1290.	2.9	0.4	12.	0.0	0.4
NUMBER OF OBSERVATIONS	97	97	97	97	97	97	97	97	97	97	97
AVERAGE BACKGROUND	21.2	0.003	0.11	20.46	-0.6	397.	3.5	0.4	70.	21.2	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 30	24/22:18:40	24/22:30:09
BACKGROUND 31	25/00:08:59	25/00:17:09

OVERALL COMBUSTION EFFICIENCY = 98.92%

TEST 51
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	119.6	0.039	0.57	19.85	34.1	3347.	11.5	2.3	193.	30.1	98.5
STANDARD DEVIATION	45.4	0.017	0.66	0.60	32.3	2564.	12.1	0.8	27.	0.2	0.9
NUMBER OF OBSERVATIONS	78	78	78	78	78	78	78	78	78	78	78
AVERAGE BACKGROUND	35.1	-0.003	0.42	20.45	0.6	410.	11.3	2.3	186.	29.6	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 13	21/18:30:47	21/18:37:39

OVERALL COMBUSTION EFFICIENCY = 98.66%

TEST 16
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	129.5	0.121	1.87	20.43	7.7	4059.	2.4	1.7	149.	22.7	99.7
STANDARD DEVIATION	20.7	0.056	1.02	0.38	3.5	1501.	1.5	0.6	22.	0.2	0.1
NUMBER OF OBSERVATIONS	103	103	103	103	103	103	108	103	103	103	103
AVERAGE BACKGROUND	24.7	-0.002	0.26	21.17	0.6	394.	6.0	0.8	188.	22.3	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 27	24/11:26:05	24/11:35:44

OVERALL COMBUSTION EFFICIENCY = 99.75%

TEST 16A
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	113.0	0.082	1.39	20.55	6.1	3236.	2.3	1.8	136.	22.8	99.7
STANDARD DEVIATION	22.4	0.033	1.02	0.44	3.5	1657.	1.8	0.8	13.	0.1	0.1
NUMBER OF OBSERVATIONS	34	34	34	34	34	34	34	34	34	34	34
AVERAGE BACKGROUND	24.7	-0.002	0.26	21.17	0.4	394.	6.0	0.8	188.	22.3	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 27	24/11:26:05	24/11:35:44

OVERALL COMBUSTION EFFICIENCY = 99.74%

TEST 16B
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	148.6	0.168	2.42	20.20	9.6	5291.	3.5	1.4	151.	22.9	99.8
STANDARD DEVIATION	11.7	0.050	0.98	0.36	3.7	1183.	0.7	0.5	24.	0.1	0.1
NUMBER OF OBSERVATIONS	28	28	28	28	28	28	28	28	28	28	28
AVERAGE BACKGROUND	24.7	-0.002	0.26	21.17	0.4	394.	6.0	0.8	188.	22.3	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 27	24/11:26:05	24/11:35:44

OVERALL COMBUSTION EFFICIENCY = 99.75%

113

TEST 16C
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	125.0	0.107	1.57	20.59	7.3	3419.	1.4	1.9	164.	22.4	99.7
STANDARD DEVIATION	8.7	0.052	0.77	0.24	2.8	896.	0.8	0.4	14.	0.1	0.1
NUMBER OF OBSERVATIONS	22	22	22	22	22	22	22	22	22	22	22
AVERAGE BACKGROUND	24.7	-0.002	0.26	21.17	0.4	394.	6.0	0.8	188.	22.3	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 27	24/11:26:05	24/11:35:44

OVERALL COMBUSTION EFFICIENCY = 99.74%

114

TEST 16D
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	136.3	0.138	2.28	20.36	7.9	4458.	2.0	1.9	155.	22.4	99.8
STANDARD DEVIATION	7.4	0.045	0.81	0.24	2.5	627.	1.3	0.6	26.	0.1	0.1
NUMBER OF OBSERVATIONS	19	19	19	19	19	19	19	19	19	19	19
AVERAGE BACKGROUND	24.7	-0.002	0.26	21.17	0.4	394.	6.0	0.8	188.	22.3	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 27	24/11:26:05	24/11:35:44

OVERALL COMBUSTION EFFICIENCY = 99.78%

115

TEST 54
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	197.1	0.559	5.00	19.15	6.8	7115.	0.0	1.5	225.	31.6	99.9
STANDARD DEVIATION	48.1	0.478	2.29	0.51	3.8	2757.	0.8	0.6	31.	0.4	0.1
UMBER OF OBSERVATIONS	92	92	92	92	92	92	92	92	92	92	92
AVERAGE BACKGROUND	34.4	0.085	0.22	20.35	0.8	354.	6.5	1.4	211.	31.4	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 16	22/16:52:39	22/17:09:36
BACKGROUND 17	22/17:41:43	22/17:46:36

OVERALL COMBUSTION EFFICIENCY = 99.90%

TEST 23
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	233.1	0.018	5.93	18.72	4.5	8465.	-5.0	1.5	160.	28.4	100.2
STANDARD DEVIATION	111.5	0.017	5.31	1.31	4.5	6646.	0.9	0.5	21.	0.1	0.5
UMBER OF OBSERVATIONS	103	103	103	103	103	103	103	103	103	103	103
AVERAGE BACKGROUND	35.1	-0.003	0.42	20.45	0.6	410.	11.3	2.3	186.	29.6	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 13	21/18:30:47	21/18:37:33

OVERALL COMBUSTION EFFICIENCY = 100.01%

TEST 52
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	118.2	0.001	0.68	19.92	16.1	2622.	15.2	0.9	165.	28.0	98.7
STANDARD DEVIATION	14.3	0.003	0.31	0.17	5.0	851.	4.8	0.3	20.	0.2	0.4
NUMBER OF OBSERVATIONS	80	80	80	80	80	80	80	80	80	80	80
AVERAGE BACKGROUND	39.9	-0.004	0.02	20.46	-0.5	380.	9.4	1.5	179.	28.5	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 13	21/18:30:47	21/18:37:39
BACKGROUND 14	21/20:15:10	21/20:20:44

OVERALL COMBUSTION EFFICIENCY = 98.82%

TEST 53
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	160.6	0.729	2.83	19.22	23.9	5741.	10.9	2.0	235.	30.4	99.3
STANDARD DEVIATION	47.1	0.264	1.89	0.68	12.4	3489.	6.4	0.8	33.	0.3	0.4
NUMBER OF OBSERVATIONS	112	112	112	112	112	112	112	112	112	112	112
AVERAGE BACKGROUND	30.5	0.050	0.14	20.50	0.3	375.	5.7	2.2	225.	30.6	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 15	22/13:13:56	22/13:18:48
BACKGROUND 16	22/16:52:39	22/17:09:36

OVERALL COMBUSTION EFFICIENCY = 99.40%

119

TEST 26
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	194.0	0.356	5.34	19.62	5.5	6270.	-3.9	3.1	250.	37.7	100.0
STANDARD DEVIATION	42.5	0.220	2.93	0.44	2.1	2646.	0.9	1.0	29.	0.9	0.1
NUMBER OF OBSERVATIONS	124	124	124	124	124	124	124	124	124	124	124
AVERAGE BACKGROUND	32.8	0.013	0.80	20.63	0.2	375.	7.4	2.4	244.	33.5	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 35	29/13:34:20	29/14:01:22
BACKGROUND 36	29/14:44:11	29/14:58:17

OVERALL COMBUSTION EFFICIENCY = 99.97%

TEST 65
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	111.3	0.062	2.40	20.33	20.3	4878.	0.6	2.1	172.	31.0	99.5
STANDARD DEVIATION	26.6	0.024	1.82	0.35	5.1	2168.	1.4	0.5	12.	0.2	0.3
NUMBER OF OBSERVATIONS	83	83	83	83	83	83	83	83	83	83	83
AVERAGE BACKGROUND	26.4	0.001	0.15	21.14	4.1	399.	4.2	1.8	179.	26.9	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 47	30/23:31:27	30/23:36:34
BACKGROUND 49	1/00:10:30	1/00:14:28

OVERALL COMBUSTION EFFICIENCY = 99.57

121

TEST 28
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	212.1	0.329	8.16	19.66	3.2	6078.	0.7	3.5	290.	31.6	99.9
STANDARD DEVIATION	71.9	0.224	5.92	0.62	5.4	3562.	1.8	1.5	87.	0.7	0.3
NUMBER OF OBSERVATIONS	143	143	143	143	143	143	143	143	143	143	143
AVERAGE BACKGROUND	30.7	0.008	0.73	20.51	5.9	250.	5.3	3.0	324.	30.2	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 32	28/16:23:13	28/16:38:57
BACKGROUND 33	28/17:57:13	28/18:04:50

OVERALL COMBUSTION EFFICIENCY = 99.94%

TEST 31
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	159.3	1.226	4.02	19.83	27.9	4568.	10.1	2.8	315.	31.1	99.1
STANDARD DEVIATION	37.6	0.751	2.34	0.56	12.1	2258.	3.7	1.1	43.	0.3	0.4
NUMBER OF OBSERVATIONS	121	121	121	121	121	121	121	121	121	121	121
AVERAGE BACKGROUND	30.4	0.022	0.59	20.53	0.5	327.	5.6	3.0	317.	30.2	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 33	28/17:57:13	28/18:04:50
BACKGROUND 34	28/18:56:54	28/19:05:46

OVERALL COMBUSTION EFFICIENCY = 99.17%

TEST 66
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	102.2	0.935	0.97	20.05	229.4	2432.	1265.0	0.6	144.	29.7	60.6
STANDARD DEVIATION	25.5	0.395	0.53	0.39	114.2	1177.	510.7	0.2	23.	0.1	11.1
NUMBER OF OBSERVATIONS	69	69	69	69	69	69	69	69	69	69	69
AVERAGE BACKGROUND	28.9	0.026	0.00	21.01	2.4	337.	12.7	1.1	173.	29.1	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 38	29/20:52:49	29/20:56:53
BACKGROUND 39	29/21:46:23	29/21:55:10

OVERALL COMBUSTION EFFICIENCY = 61.94%

124

TEST 29
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	86.3	1.365	1.06	20.23	180.9	2179.	1177.6	0.6	190.	29.3	60.0
STANDARD DEVIATION	14.3	0.502	0.40	0.23	46.3	789.	296.4	0.3	19.	0.2	10.9
NUMBER OF OBSERVATIONS	57	57	57	57	57	57	57	57	57	57	57
AVERAGE BACKGROUND	28.9	0.026	0.00	21.01	2.4	337.	12.7	1.1	178.	29.1	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 38	29/20:52:49	29/20:56:53
BACKGROUND 39	29/21:46:20	29/21:55:10

OVERALL COMBUSTION EFFICIENCY = 61.60%

125

TEST 29A
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	75.1	1.236	1.09	20.34	146.6	1529.	1097.1	0.6	191.	29.5	54.1
STANDARD DEVIATION	8.1	0.509	0.40	0.22	28.6	476.	243.0	0.3	21.	0.1	10.8
NUMBER OF OBSERVATIONS	28	28	28	28	28	28	28	28	28	28	28
AVERAGE BACKGROUND	28.9	0.026	0.00	21.01	2.4	337.	12.7	1.1	178.	29.1	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 38	29/20:52:48	29/20:56:53
BACKGROUND 39	29/21:46:20	29/21:55:10

OVERALL COMBUSTION EFFICIENCY = 55.14%

126

TEST 298
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	97.2	1.489	1.04	20.12	213.9	2808.	1255.4	0.7	189.	29.2	65.6
STANDARD DEVIATION	9.9	0.470	0.41	0.18	34.6	440.	325.6	0.3	15.	0.1	7.7
NUMBER OF OBSERVATIONS	29	29	29	29	29	29	29	29	29	29	29
AVERAGE BACKGROUND	28.9	0.026	0.00	21.01	2.4	337.	12.7	1.1	178.	29.1	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 38	29/20:52:48	29/20:56:53
BACKGROUND 39	29/21:46:20	29/21:55:10

OVERALL COMBUSTION EFFICIENCY = 65.6%

TEST 64
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	105.0	0.051	1.24	20.42	8.6	3282.	-0.1	0.9	185.	25.3	99.7
STANDARD DEVIATION	10.1	0.014	0.47	0.20	3.7	896.	1.9	0.3	23.	0.1	0.2
NUMBER OF OBSERVATIONS	67	67	67	67	67	67	67	67	67	67	67
AVERAGE BACKGROUND	29.0	0.032	0.03	21.11	-1.7	428.	8.8	0.7	184.	25.1	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 40	30/00:10:08	30/00:15:14
BACKGROUND 41	30/02:01:53	30/02:08:14

OVERALL COMBUSTION EFFICIENCY = 99.74%

TEST 62
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	108.3	0.841	0.60	20.39	90.2	3076.	99.8	0.9	175.	25.2	93.8
STANDARD DEVIATION	22.1	0.667	0.36	0.39	32.0	1206.	30.6	0.2	15.	0.1	1.6
NUMBER OF OBSERVATIONS	113	113	113	113	113	113	113	113	113	113	113
AVERAGE BACKGROUND	29.0	0.032	0.03	21.11	-1.7	428.	8.8	0.7	184.	25.1	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 40	30/00:10:08	30/00:15:14
BACKGROUND 41	30/02:01:53	30/02:08:14

OVERALL COMBUSTION EFFICIENCY = 94.18%

TEST 63
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	123.4	0.057	1.57	20.13	19.9	4184.	6.5	1.4	97.	24.8	99.1
STANDARD DEVIATION	30.4	0.037	1.06	0.48	9.8	2204.	6.7	0.7	44.	0.6	1.2
NUMBER OF OBSERVATIONS	106	106	106	106	106	106	106	106	106	106	106
AVERAGE BACKGROUND	29.0	0.032	0.03	21.11	-1.7	428.	8.8	0.7	184.	25.1	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 40	30/00:10:04	30/00:15:14
BACKGROUND 41	30/02:01:53	30/02:08:14

OVERALL COMBUSTION EFFICIENCY = 99.37%

TEST 33
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	86.6	3.793	0.74	20.66	15.8	1857.	17.5	1.0	181.	26.9	98.2
STANDARD DEVIATION	12.5	1.440	0.29	0.11	5.6	500.	6.4	0.2	11.	0.2	0.5
NUMBER OF OBSERVATIONS	102	102	102	102	102	102	102	102	102	102	102
AVERAGE BACKGROUND	27.5	0.044	-0.03	21.23	0.1	436.	14.6	1.0	175.	26.9	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 39	29/21:46:20	29/21:55:10
BACKGROUND 40	30/00:10:08	30/00:15:14

OVERALL COMBUSTION EFFICIENCY = 98.24%

TEST 32
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	120.9	3.281	1.75	20.49	22.7	3702.	19.5	0.8	189.	26.3	98.9
STANDARD DEVIATION	36.7	1.098	1.00	0.36	11.0	1732.	11.8	0.2	12.	0.1	0.3
NUMBER OF OBSERVATIONS	121	121	121	121	121	121	121	121	121	121	121
AVERAGE BACKGROUND	27.5	0.044	-0.03	21.23	0.1	436.	14.6	1.0	175.	26.9	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 39	29/21:46:20	29/21:55:10
BACKGROUND 40	30/00:10:08	30/00:15:14

OVERALL COMBUSTION EFFICIENCY = 98.87%

TEST 32A
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	80.3	2.204	0.63	20.90	12.2	1761.	7.3	0.9	199.	26.3	98.9
STANDARD DEVIATION	9.7	0.827	0.25	0.11	6.3	520.	5.4	0.2	7.	0.1	0.4
NUMBER OF OBSERVATIONS	44	44	44	44	44	44	44	44	44	44	44
AVERAGE BACKGROUND	27.5	0.044	-0.03	21.23	0.1	436.	14.6	1.0	175.	26.9	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 39	29/21:46:20	29/21:55:10
BACKGROUND 40	30/00:10:08	30/00:15:14

OVERALL COMBUSTION EFFICIENCY = 98.91%

TEST 329
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	144.1	3.896	2.39	20.27	28.8	4811.	26.5	0.7	184.	26.3	98.9
STANDARD DEVIATION	23.9	0.680	0.63	0.22	8.2	1077.	8.3	0.2	11.	0.1	0.2
NUMBER OF OBSERVATIONS	77	77	77	77	77	77	77	77	77	77	77
AVERAGE BACKGROUND	27.5	0.044	-0.03	21.23	0.1	436.	14.6	1.0	175.	26.9	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 39	29/21:46:20	29/21:55:10
BACKGROUND 40	30/00:10:08	30/00:15:14

OVERALL COMBUSTION EFFICIENCY = 98.86%

APPENDIX C

CALCULATION OF DESTRUCTION EFFICIENCY (DE)

While dilution factors are required for an accurate determination of destruction efficiency (DE), estimates of DE can be made for total hydrocarbons (THC) and for individual hydrocarbon species. Assuming:

(a) All carbon resulting from combustion is accounted for in the measurements,

(b) Dilution is neglected, and

(c) The relief gas is 80% propylene and 20% propane.

One can calculate DE's as follows:

$$DE_{THC} = \frac{CO_2 + CO + Soot}{CO_2 + CO + Soot + THC} \times 100$$

$$DE_{Propylene} = \frac{0.8(CO_2 + CO + Soot + THC) - C_{Propylene}}{0.8(CO_2 + CO + Soot + THC)} \times 100$$

$$DE_{Propane} = \frac{0.2(CO_2 + CO + Soot + THC) - C_{Propane}}{0.2(CO_2 + CO + Soot + THC)} \times 100$$

where:
- DE_{THC} = Total Hydrocarbon DE (%)
- $DE_{Propylene}$ = Propylene DE (%)
- $DE_{Propane}$ = Propane DE (%)
- $C_{Propylene}$ = Measured Propylene Concentration (ppmv)
- $C_{Propane}$ = Measured Propane Concentration (ppmv)

and all other variables as previously defined.

Tables C-1 and C-2 provide calculated values for DE_{THC}, $DE_{Propylene}$, $DE_{Propane}$ for each of the tests. Note that a Combustion Efficiency (CE) value is also provided, and in some cases, it differs from CE values reported in previous tables. This is due to the method of calculating CE:

(a) THC, $C_{Propylene}$, and $C_{Propane}$ values from the integrated bag samples (Tables 7 and 8) were used instead of the continuous THC data used in previous calculations. As noted in the report, there are differences between the continuous and integrated bag THC results.

TABLE C-1. DESTRUCTION EFFICIENCY ESTIMATES
STEAM-ASSISTED FLARE TESTS

Test Number	CE (%)	DE_{THC} (%)	$DE_{Propylene}$ (%)	$DE_{Propane}$ (%)
High Btu Tests				
1	99.85	99.96	-	-
2	99.66	99.95	-	-
3	99.80	99.96	-	-
4	91.67	99.86	99.99	99.98
8	93.15	99.87	99.99	99.99
7	99.79	99.93	99.99	99.98
5	99.82	99.94	99.99	99.98
17	99.73	99.89	100.00	99.98
50	99.37	99.73	99.80	99.76
56	99.49	99.71	99.92	99.88
61	76.92	81.51	82.96	83.74
55	61.63	65.81	67.65	68.42
Low Btu Tests				
57	99.73	99.87	99.99	99.98
11	99.67	99.85	99.98	99.97
59	98.22	99.06	99.34	98.91
60	98.71	99.38	99.59	99.68
51	98.48	99.39	99.81	99.82
16	99.61	99.80	99.97	99.94
54	99.81	99.91	99.97	99.91
23	99.84	99.93	100.00	99.99
52	97.93	98.44	98.87	98.91
53	99.24	99.63	99.72	99.74

TABLE C-2. DESTRUCTION EFFICIENCY ESTIMATES
AIR-ASSISTED FLARE TESTS

Test Number	CE (%)	DE_{THC} (%)	$DE_{Propylene}$ (%)	$DE_{Propane}$ (%)
High Btu Tests				
26	99.85	99.94	99.99	99.98
65	97.95	99.90	100.00	99.99
28	99.78	99.93	99.98	99.98
31	98.84	99.42	99.61	99.61
Low Btu Tests				
66	49.98	54.17	55.66	57.22
29	48.03	51.53	53.11	54.76
64	99.49	99.68	99.93	99.89
62	92.05	94.38	95.44	95.57
63	99.14	99.54	99.72	99.72
33	97.31	97.98	99.72	99.61
32	98.50	99.04	99.87	99.80

(b) Since the integrated bag sample hydrocarbon data were used and no background data were available for propane and propylene, the measured values for hydrocarbons in the flare plume were not "corrected" by subtracting background concentrations. Thus, the CE and DE values in the following tables were calculated from a consistent set of data.

(c) Did not segment tests 11, 16, 29, and 32 due to lack of hydrocarbon species data.

APPENDIX D

SOOT COMPOSITION

ES ENGINEERING-SCIENCE

3109 NORTH INTERREGIONAL • AUSTIN, TEXAS 78722 • 512/477-9901

CABLE ADDRESS: ENGINSCI
TELEX: 77-6442

February 1, 1983

Dr. Bruce Tichenor
Industrial Processes Branch (MD-63)
U.S. Environmental Protection Agency
Research Triangle Park, North Carolina 27711

Dear Dr. Tichenor:

In response to your letter dated December 9, 1982, and our subsequent telephone conversation, I am providing a summary of the procedures used for the PNA analyses of soot collected during the flare efficiency test.

The sample probe assembly included an in-line particulate filter housed inside the heated section of the probe about six feet from the probe tip. This in-line particulate filter assembly served two purposes: 1) collection of particulate samples from smoking flares for subsequent analysis, and 2) maintaining the cleanliness of the sampling system. The preweighed filter elements used were of the thimble configuration and constructed of 0.3 micrometer glass fiber.

The filters were changed before and after each of the smoking flare tests. Following the tests the filters were reweighed to determine the mass of particulate collected. This information, combined with the measured flow rate of sample through the probe assembly, allowed the calculation of the gross particulate concentration of the flare emission at the sampling location. It should be noted however, that these particulate samples were not collected isokinetically and thus, represent only gross estimates of the particulate concentration. The flare particulate emissions were not isokinetically sampled because it was not practical to directly measure the plume velocity.

Table 1 is a summary of the mass particulate concentration data collected during the test series. Although these samples were not collected isokinetically, the data shows distinct differences between particulate loadings of nonsmoking, lightly smoking (Test 65) and heavily smoking (Test 4) flare tests.

Samples were prepared for PNA analysis by Soxhlet extraction of the air filters as received with 200 mL of methylene chloride for 24 (+2) hours. The condenser water was chilled to 1 - 4°C and no solvent loss (bp 40°C) was noted. The samples were transferred to bottles and the glassware washed with additional methylene chloride which was added to sample. Samples were dried for several days over anhydrous sodium sulfate which had been kiln-fired at 450°C to remove organic compounds. Sample extract volumes were carefully reduced to 1 mL using Kuderna-Danish flasks and three-ball Snyder columns.

Sample extracts were analyzed by GC/MS using a 60 meter J & W fused-silica DB-1 bonded SE-30 capillary column, using d_{12}-Chrysene as an internal standard. Individual compound response factors were obtained by running a standard mix prepared from EPA standard solution concentrates, and spiked with d_{12}-chrysene. Quantitation was based on integrated peak areas and was performed by the GC/MS data system.

As a further quality assurance measure, a solvent blank was run, spiked with d_{12}-chrysene, and was found to be free of interfering peaks. No recovery efficiency data can be given, since there was only one of each sample. Ideally, one should consider collecting at least one replicate sample which could be spiked (directly onto the soot) with a known addition of a surrogate PNA. By this means, an indication of the efficiency of recovery of PNA's from the soot matrix could be obtained. Tables 2 and 3 summarize the results of the PNA analyses.

As I indicated in our telephone conversation, I am unable to calculate these results in terms of mass emission rates (e.g., mg/10^6 Btu, mg/hr, etc.) because of the lack of isokinetic sampling and a measure of the dilution between the reaction zone and the sampling probe.

If you have any questions, please call me at 512/444-5830.

Sincerely,

Marc McDaniel

Attch.

/kg

Table 1. Flare Efficiency Study Particulate Analysis.

Test No.	Filter No.	Wt. gain, (grams)	Sample Time[1] (minutes)	Sample Rate (ℓ/min)	Concentration (μg/ℓ)
2, 3, 1, 5, 7	A-1	0.0063	---	18.51	---
7, 17, 50, 51 23, 52, 53, 54	F-1	0.0071	---	18.51	---
4 (Smoking)	F-2	0.0810	16	18.51	274
8 (Smoking)	F-3	0.0819	25	18.51	177
55, 56, 11, 57 16, 59, 60, 61 28, 31, 26, 29 33, 32, 62, 63 64, 80, 81, 82 83, 84	F-4	0.0179	---	18.51	---
65 (Smoking)	F-5	0.0183	25	18.51	40

[1] Includes time for probe positioning while probe was in the plume but before formal initiation of the test.

Table 2. Total Polynuclear Aromatic Hydrocarbons in Filter Samples, in Micrograms[1].

E.S. Sample #	F_1	F_2	F_3	F_4	F_5
napthalene	(0.05)[2]	1.9	1.8	-[3]	-
acenapthylene	-	3.3	6.2	-	-
acenapthene	-	-	0.25	-	-
fluorene	-	(0.02)	0.61	-	-
phenanthrene	0.35	4.7	11.	(0.02)	(0.06)
anthracene	-	0.24	1.5	0.32	-
pyrene	0.77	6.0	17.	0.25	0.38
fluoranthene	0.96	8.3	21.	0.93	0.63
benzanthracene	0.13	0.18	4.7	1.0	0.21
chrysene	0.12	0.28	5.6	1.2	0.17
benzo(a)pyrene	-	1.2	4.4	2.6	-
1,2;5,6 dibenzanthracene	-	-	-	-	-
1,12 benzoperylene	-	-	-	1.2	-

1 - Also equal to concentration in final 1 mL extract, in μg/mL (ppm).

2 - The calculated amount is given in parenthesis if it is below twice the stated detection limit in the extract (0.05ppm). Note that some compounds were detected at concentrations below the stated detection limit.

3 - a dash indicates that the compound was not present above the stated detection limit.

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16. ABSTRACT

The report gives results of a full-scale experimental study to determine the efficiencies of flare burners for disposing of hydrocarbon (HC) emissions from refinery and petrochemical processes. With primary objectives of determining the combustion efficiency and HC destruction efficiency for both air- and steam-assisted flares under a wide range of operating conditions, it provides a data base for defining the air quality impact of flaring. Test results indicate that flaring is generally an efficient HC disposal method for the conditions evaluated. Test methodology involved a special 27-ft sample probe suspended by a crane over the flare flame. The sample extracted by the probe was analyzed by continuous emission monitors to determine concentrations of CO2, CO, total HC, SO2, NOx, and O2. In addition, the probe tip temperature, ambient air temperature, and wind speed and direction were measured. Integrated samples of the relief gas were collected for HC species analysis by gas chromatograph. Particulate matter samples were collected during the smoking flare tests. When flares were operated under conditions representing good industrial operating practice, combustion efficiencies at the sampling probe were greater than 98 percent. Combustion efficiencies declined under conditions of excessive steam (steam quenching) and high exit velocities of low-Btu content gases.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution Flares Burners Hydrocarbons Refineries Petrochemistry Combustion Efficiency	Pollution Control Stationary Sources Petrochemical Industry	13B 21B 19A 13A 07C 13I 08G

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Table 3. Analytical Results for Polynuclear Aromatics in Filter Samples.

E.S. Sample #	F_1	F_2	F_3	F_4	F_5
SumX Sample #	1767	1768	1769	1770	1771
Sample weight, g	0.0071	0.0810	0.0819	0.0179	0.0183
Compound	PNA concentrations, µg/g soot (ppm)				
napthalene	< 14	23	22	nd [2]	nd
acenapthylene	nd	41	76	nd	nd
acenapthene	nd	nd	3.1	nd	nd
fluorene	nd	<1	7.4	nd	nd
phenanthrene	49	58	130	<5	<5
anthracene	nd	3.0	18	18	nd
pyrene	110	74	210	14	21
fluoranthene	140	100	260	52	34
benzanthracene	18	2.2	57	56	11
chrysene	17	3.5	68	67	9.3
benzo(a)pyrene	nd	15	54	145	nd
1,2;5,6 dibenzanthracene	nd	nd	nd	nd	nd
1,12-benzoperylene	nd	nd	nd	67	nd
Detection Limit[1]	7	0.6	0.6	3.	3.

1 - Dependent on sample size. Corresponds to 0.05ppm in 1 mL extract. Concentrations of substances found but less than twice the detection limit are reported as less than (<) twice the detection limit.

2 - nd = none detected at or above the stated detection limit.

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Sources of Ethylene Oxide Emissions

David W. Markwordt
Emission Standards and Engineering Division

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Air and Radiation
Office of Air Quality Planning and Standards
Research Triangle Park, North Carolina 27711

April 1985

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16. ABSTRACT

The objective of this report is to present the results of a preliminary source assessment study conducted for ethylene oxide in which emission, cost, and dispersion data were developed that will aid in evaluating the need for further regulatory development for ethylene oxide.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air Pollution Pollution Control Ethylene Oxide	Air Pollution Control	13/b

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Table 4. Model Plant Dispersion Parameters

Source	Emission Factor ($kg/10^3$ kg capacity)		Ht./D (m)	Vel. (m/sec)	Temp. (K)
	Air	O_2			
Process Vent(s)	0.017	.034	25.4/ .23	17	346
Cooling Tower	N/A	.07	16 /5.98	11.7	314
Effluents	.0035	.0	N/A	0.01	273
	(Mg/yr)				
Equipment Leaks	113	61.5	N/A	0.01	273

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TABLE 2.

DISPERSION MODELING PARAMETERS[a]
Ethylene Oxide/Ethoxylator, Sterilizer, and Fumigator Facilities

Model Plant/Emission Source		Emission Rate (Kg/yr)	Stack/vent Height (meters)	Source Area (m^2)	Stack (0) Vent(1)	Stack/vent Diameter (meters)	Emission Velocity (m/s)	Emission Temp. (k)
Ethoxylators/Equipment Leaks		6,100	--	20,000	--	--	0.01	273
Sterilizers/Vent Emissions and Fumigators	1[c] (Low)	7,000	25.4	--	1	0.23	17	273
	2[d] (High)	30,000	25.4	--	1	0.23	17	273

[a]All parameters are assumed.

[b]10% of 61.5 Mg/yr

[c]Assumes 450 facilities.

[d]Assumes 100 facilities.

Table 3. Ethylene Oxide Plant Production Capacity

Plant Number	Plant	Location	Capacity (10^3kg EO)
1	BSAF	Geismar, LA	218,000
2	Celanese	Clear Lake, TX	193,000
3	Dow	Freeport, TX	136,000
4	Dow	Plaquemine, LA	205,000
5	ICI Americas	Bayport, TX	227,000
6	Northern Petrochemical	Morris, IL	105,000
7	Olin	Brandenburg, KY	50,000
8	PPG	Beaumont, TX	77,000
9	Shell	Geismar, LA	318,000
10	Sun Olin	Claymont, DA	50,000
11	Texaco	Port Noches, TX	318,000
12	Texas Eastman	Longview, TX	87,000
13	Union Carbide	Ponce, P. R.	295,000
14	Union Carbide	Seadrift, TX	418,000
15	Union Carbide	Taft, LA	590,000

TABLE 1. (cont'd)

Dispersion Modeling Parameters
Ethylene Oxide/Production Facilities

Plant/Emission Source	North Latitude (deg/min/s)	West Longitude (deg/min/s)	Urban 0 Rural 1	Emission Rate (kg/yr)	Stack/vent Height (meters)	Source Area (m^2)	Stack(0) Vent(1)	Stack/Vent diameter (meters)	Emis. Velo-city (m/s)	Emis. Temp. (K)
6 Process	41 24 30			3,600	25.4	--	1	0.23	17	346
Cooling Tower				7,300	16	--	1	5.98	11.7	314
Equipment Leaks				61,500	--	76,000	-	--	0.01	273
Effluent				0	--	--	-	--	--	--
7 Process	38 00 10	86 07 16		1,700	25.4	--	1	0.23	17	346
Cooling Tower				3,500	16	--	1	5.98	11.7	314
Equipment Leaks				61,500	--	76,000	-	--	0.01	273
Effluent				0	--	--	-	--	--	--
8 Process	30 3 38	94 2 53		2,600	25.4	--	1	0.23	17	346
Cooling Tower				5,400	16	--	1	5.98	11.7	314
Equipment Leaks				61,500	--	76,000	-	--	0.01	273
Effluent				0	--	--	-	--	--	--
9 Process	30 11 12	90 59 28		10,800	25.4	--	1	0.23	17	346
Cooling Tower				22,300	16	--	1	5.98	11.7	314
Equipment Leaks				61,500	--	76,000	-	--	0.01	273
Effluent				0	--	--	-	--	--	--
10 Process	39 48 20	75 25 40		1,700	25.4	--	1	0.23	17	346
Cooling Tower				110,000	16.8	--	1	7.3	40	283
Equipment Leaks				61,500	--	76,000	-	--	0.01	273
Effluent				0	--	--	-	--	--	--

TABLE 1. (cont'd)

Dispersion Modeling Parameters
Ethylene Oxide/Production Facilities

Plant/Emission Source	North Latitude (deg/min/s)	West Longitude (deg/min/s)	Urban 0 Rural 1	Emission Rate (kg/yr)	Stack/vent Height (meters)	Source Area (m^2)	Stack(0) Vent(1)	Stack/Vent diameter (meters)	Emis. Velo-city (m/s)	Emis. Temp. (K)
11 Process				5,400	25.4	--	1	0.23	17	346
Cooling Tower				--	--	--	-	--	--	--
Equipment Leaks				113,000	--	20,000	-	--	0.01	273
Effluent				1,100	--		-	--	0.01	273
12 Process	32 26 44	94 41 17		3,000	25.4	--	1	0.23	17	346
Cooling Tower				6,200	16.8	--	1	7.3	40	283
Equipment Leaks				61,500	--	76,000	-	--	0.01	273
Effluent				0	--	--	-	--	--	--
13 Process	17 59 36	66 44 46		5,000	25.4	--	1	0.23	17	346
Cooling Tower				--	--	--	-	--	--	--
Equipment Leaks				113,000	--	20,000	-	--	0.01	273
Effluent				1,000	--		-	--	0.01	273
14 Process	28 30 30	96 46 15		7,100	25.4	--	1	0.23	17	346
Cooling Tower				--	--	--	-	--	--	--
Equipment Leaks				113,000	--	20,000	-	--	0.01	273
Effluent				1,500	--		-	--	0.01	273
15 Process	29 59 27	90 26 50		10,000	25.4	--	1	0.23	17	346
Cooling Tower				--	--	--	-	--	--	--
Equipment Leaks				113,000	--	20,000	-	--	0.01	273
Effluent				2,000	--	--	-	--	0.01	273

APPENDIX B

Dispersion Modeling Parameters

HUMAN EXPOSURE MODEL

EPA's Human Exposure Model (hEM) is a general model capable of producing quantitative expressions of public exposure to ambient air concentrations of pollutants emitted from stationary sources. The input data needed to operate this model include source data that are typically required for the operation of dispersion models (e.g. plant location, height of emission release point, and velocity of stackgases). Based on the source data, the model estimates the magnitude and distribution of ambient air concentrations of the pollutant in the vicinity of each source.

The dispersion model used is a Gaussian diffusion model that uses the same basic dispersion algorithm as EPA's Climatological Dispersion Model (CDM), but has been simplified to improve overall efficiency. In general, CDM determines long-term (seasonal or annual) quasi-stable pollutant concentrations at any ground level receptor using average emission rates from point and area sources and joint frequency distribution of wind direction, wind speed, and stability for the same period.

Stability array (STAR) summaries are the principal meteorological input to the HEM dispersion model. STAR data are standard climatological frequency-of-occurrence summaries formulated for use in EPA models and available for major U.S. meteorological monitoring sites from the National Climatic Center. A STAR summary provides a frequency-of-occurrence of wind speed, atmospheric stability, and wind direction, classified according to Pasquill's categories.

Estimates of human exposure are developed using dispersion modeling of emissions that pairs population density estimates with predicted pollutant concentrations from the concentration grid described above. Estimates of

the number and distribution of people residing within 50 km of each plant are based on a slightly modified version of the Census Bureau's "Master Enumeration District List--Extended" (MED-X) data base.

Dispersion results for ethylene oxide production facilities are presented below:

DISPERSION RESULTS

Production Plants	Maximum Annual Average Concentration (ppm)	Maximum Annual Average Concentration ($\mu g/m^3$)
1	0.002	3.59
2	0.002	3.05
3	0.0006	0.98
4	0.004	6.37
5	0.004	6.30
6	0.001	2.29
7	0.0001	0.22
8	0.001	2.15
9	0.003	4.92
10	0.011	18.8
11	0.004	7.54
12	0.002	2.96
13	0	0
14	0.0002	0.29
15	0.005	9.12

TABLE 1.

Dispersion Modeling Parameters
Ethylene Oxide/Production Facilities

Plant/Emission Source	North Latitude (deg/min/s)	West Longitude (deg/min/s)	Urban 0 Rural 1	Emission Rate (kg/yr)	Stack/Vent Height (meters)	Source Area (m^2)	Stack(0) Vent(1)	Stack/Vent Diameter (meters)	Emis. Velo-city (m/s)	Emis. Temp. (K)
1 Process	30 11 22	90 59 43		7,400	25.4	--	1	0.23	17	346
Cooling Tower				15,300	16	--	1	5.98	11.7	314
Equipment Leaks				61,500	--	76,000	-	--	0.01	273
Effluent				0	--	--	-	--	--	--
2 Process	29 37 24	95 03 34		6,600	25.4	--	1	0.23	17	346
Cooling Tower				13,500	16	--	1	5.98	11.7	314
Equipment Leaks				61,500	--	76,000	-	--	0.01	273
Effluent				0	--	--	-	--	--	--
3 Process	28 59 34	95 24 22		4,600	25.4	--	1	0.23	17	346
Cooling Tower				--	--	--	-	--	--	--
Equipment Leaks				61,500	--	76,000	-	--	0.01	273
Effluent				0	--	--	-	--	--	--
4 Process	30 19 00	91 16 20		34,800	25.4	--	1	0.23	17	346
Cooling Tower				--	--	--	-	--	--	--
Equipment Leaks				113,000	--	20,000	-	--	0.01	273
Effluent				0	--	--	-	--	--	--
5 Process	29 37 44	95 03 04		7,700	25.4	--	1	0.23	17	346
Cooling Process				15,900	16	--	1	5.98	11.7	314
Equipment Leaks				61,500	--	76,000	-	--	0.01	273
Effluent				0	--	--	-	--	--	--

TABLE 10. RELIEF VALVE CONTROL COSTS
(October 1983 $)

(1) Rupture disk systems with block valves — Total Capital Cost = $2,509 relief valve

	Annualized Costs	Capital Costs
Rupture disk	$165	$ 283
Holders, etc.	363	2,226
Maintenance & Misc.	226	
TOTAL ($/year)	$754	$2,509

(2) Rupture disk systems with 3-way valve

Assembly

One 7.6 cm stainless steel rupture disk	$ 282
One 7.6 cm carbon steel disk holder	471
One 0.6 cm dial face pressure gauge	22
One 7.6 cm safety/relief valve	1,800
Two 7.5 cm elbows	36
SUBTOTAL	$2,612

Three-way Valve

One 7.6 cm, 3-way, 2 port valve	$1,624
Installation	783
SUBTOTAL	$2,407

TOTAL COST $5,019

	Annualized Costs
Rupture disk	$ 164
holder, valve, etc.	772
Maintenance & Misc.	552
TOTAL ($/year)	$1,488

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TABLE 8 COSTS OF CONTROLLING FUGITIVE VOC EMISSIONS USING EQUIPMENT CONTROLS (Oct 83$)

Source	Control Technique	Capital Cost, $/Source	Amortization Period, Years	Capital Recovery Factor[a]	Factor for Other Capital Charges[b]	Annualized Cost, $/Source
Pump (LL)	Seal system/flare	4,690[e]	2/10[c]	0.58/0.163[c]	0.09	1,650
	Seal system/enclosed device	8,400[e]	2/10[c]	0.58/0.163[c]	0.09	2,590[e]
Safety/Relief Valves (G)	RD/block valves	2,510[f]	2/10[d]	0.58/0.163[d]	0.09	750[f]
	RD/3-way valve	5,020[f]	2/10[d]	0.58/0.163[d]	0.09	1,490[f]
	Soft-seals (O-rings)	290[g]	10	0.163	0.09	73
	Connection to flare	2,840[g]	10	0.163	0.09	720
Open-ended Lines	2nd valve	65[g]	10	0.163	0.09	16
Compressors	Seal system	9470[g]	10	0.163	0.09	2,400
Sampling Connections	Closed purge system	670[g]	10	0.163	0.09	170

[a]Capital recovery factor (CRF) is computed using the 10 percent interest rate (i) and the amortization period (n):

$$CRF = \frac{i\ (1 + i)^n}{(1 + i)^n - 1}$$

[b]Other capital charges include maintenance, taxes, insurance, etc.; 9 percent of the capital cost is used for those charges.

[c]A 2-year period is used for the seal; a 10-year period is used for piping and installation charges.

[d]A 2-year period is used for the disk; a 10-year period is used for piping and installation charges.

[e]From Table 9

[f]From Table 10.

[g]Apply CE plant cost index ration (Oct 1983/1978) 318.2/218.8 = 1.45 to figures in Table 2 of Memo: Subject: Procedure to Compile Control Cost, From: John Stelling, To: SOCMI Fugitive NSPS File, March 11, 1983

Table 9. EQUIPMENT COST FOR CONTROL OF EMISSIONS FROM A PUMP SEAL
(October 1983 dollars)

	Degassing Reservoir Vented to a Flare	Degrassing Reservior Vented to an Enclosed Combustion Device
Capital Costs		
Dual seal[a]	1490[h]	1490[h]
Barrier fluid[b]	2160	2160
Vent system	1015[c]	4730
Total	4665	8380
Annual Costs		
Dual seal[d]	707	707
Barrier fluid[e]	365	365
Vent system[e]	165	770
Maintenance & Miscellaneous charges[f]	421	756
Total[g]	1648	2598

[a]Based on $1250/seal (1980 dollars) average cost quoted by industry. 1978 cost = $1030 (seal cost = $1015, installation cost = $240, single seal credit = $225). See Table 10 for 1983 dollars.

[b]From Chapter 6 of the BID.

[c]Based on installed capital cost of 20m of 5.1cm piping ($650), one 5.1cm check valve ($125), and one 5.1cm block valve ($415) per vent system and one vent per pair of pump seals (1978 Dollars).

[d]Based on 2 year seal life and 10 percent interest (CRF = 0.58) for dual seal and 10 year amortization period and 10 percent interest (CRF = 0.163) for installatin charges.

[e]Based on 10 year equipment life and 10 percent interest (CRF = 0.163).

[f]Based on 9 percent of total capital costs (Chapter 6 of the BID).

[g]Costs do not include credits for recovered product.

Table 7a. COSTS OF EQUIPMENT CONTROL IN MODEL UNIT (OCT 1983$)
Ethylene Oxide Production Plants
(Oxygen Oxidation Process)

Source	Number Of Components	Component Captial Cost, $ Source	Capital Cost, $	Component Annualized Cost $/Source	Annualized Cost, $
Safety/Relief Valves (G)[a]	7[b]	3,765[e]	26,355	1,120[e]	7,840
Open-Ended Lines	0[c]	65[e]	0	16[e]	0
Compressors	3	9,470[e]	28,410	2,400[e]	7,200
Sampling Connections	10[d]	670[e]	6,700	170[e]	1,700
TOTAL			61,465		16,700

[a]Component control costs are comprised of 50 percent RD/block valve and 50 percent RD/3-way valve.

[b]75 percent of gas service safety/relief valves are assumed to be controlled at baseline; therefore, the emissions reduction and costs of control are based on 7 valves instead of 26.

[c]All open-ended lines (in model unit) are assumed to be controlled at baseline; therefore, there are no associated costs of control or emissions reduction.

[d]75 percent of sampling connections are assumed to be controlled at baseline; therefore, the emissions reduction and costs of control are based on 10 out of 40 sampling connections.

[e]From Table 8.

TABLE 7b.

COSTS OF EQUIPMENT CONTROL IN MODEL UNIT (OCT 1983$)
Ethylene Oxide Production Plants
(Air Oxidacion Process)

Source	Number Of Components	Component Captial Cost, $ Source	Capital Cost, $	Component Annualized Cost $/Source	Annualized Cost, $
Safety/Relief Valves (G)[a]	15[b]	3,765[e]	56,475	1,120[e]	16,800
Open-Ended Lines	0[c]	65[e]	0	16[e]	0
Compressors	6	9,470[e]	56,820	2,400[e]	14,400
Sampling Connections	36[d]	670[e]	24,120	170[e]	6,120
TOTAL			137,415		37,320

[a]Component control costs are comprised of 50 percent RD/block valve and 50 percent RD/3-way valve.

[b]75 percent of gas service safety/relief valves are assumed to be controlled at baseline; therefore, the emissions reduction and costs of control are based on 15 valves instead of 60.

[c]All open-ended lines (192 in model unit) are assumed to be controlled at baseline; therefore, there are no associated costs of control or emissions reduction.

[d]75 percent of sampling connections are assumed to be controlled at baseline; therefore, the emissions reduction and costs of control are based on 36 out of 145 sampling connections.

[e]From Table 8.

Table 6a. COSTS OF INITIAL LEAK DETECTION AND REPAIR OF VALVES
ETHYLENE OXIDE PRODUCTION: OXYGEN OXIDATION

	Service	
	Gas	Light Liquid
Number of Valves	177	693
Initial Leak Frequency[a]	x 0.114	x 0.065
Estimated Number of Leaks	20	45
Repair Time, Man-Hour/Leak[a]	x 1.13	x 1.13
Labor Hours Requires	22.6	51
Labor Charge Rate, $/Man-Hour	x 21	x 21
Initial Leak Repair	475	1,071
Admin. & Support Costs (0.4 x Initial Leak Repair)	+ 190	+ 428
	665	1,499
Total Capital Costs	665	1,499
Capital Recovery Factor[b]	x 0.163	x 0.163
Annualized Cost of Capital	108	244

[a]"Fugitive Emission Sources of Organic Compounds--Additional Information on Emissions, Emission Reductions, and Costs," EPA-450/3-82-010, p. 5-7.

[b]Capital Recovery Factor is based on a 10 percent interest rate over a 10-year period.

Table 6b. COSTS OF INITIAL LEAK DETECTION AND REPAIR OF VALVES
ETHYLENE OXIDE PRODUCTION: AIR OXIDATION

	Service	
	Gas	Light Liquid
Number of Valves	200	58.1
Initial Leak Frequency[a]	x 0.114	x 0.065
Estimated Number of Leaks	23	38
Repair Time, Man-Hour/Leak[a]	x 1.13	x 1.13
Labor Hours Requires	26	43
Labor Charge Rate, $/Man-Hour	x 21	x 21
Initial Leak Repair	546	903
Admin. & Support Costs (0.4 x Initial Leak Repair)	+218	+ 361
	764	1,264
Total Capital Costs	764	1,264
Capital Recovery Factor[b]	x 0.163	x 0.163
Annualized Cost of Capital	125	206

[a]"Fugitive Emission Sources of Organic Compounds--Additional Information on Emissions, Emission Reductions, and Costs," EPA-450/3-82-010, p. 5-7.

[b]Capital Recovery Factor is based on a 10 percent interest rate over a 10-year period.

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Table 5a. ANNUAL COSTS OF A LEAK DETECTION AND REPAIR PROGRAM
VALVES--MONTHLY MONITORING: OXYGEN-OXIDATION

Monitoring	Instrument
Number of Valves	870
Monitoring Time, Man-Min/Source	x 10
Monitoring Time Per Interval, Min.	8,700
Number of Times Monitored Annually	x 12/60
Monitoring Time Total, Man-hours	1,740
Repairs	
Number of Valves	870
Fraction of Leaks Found Annually[a]	x .191
Estimated Number of Repairs Annually	166
Labor Hours Per Repair[a]	x 1.13
Repair Times Total, Man-Hours	188
Aggregation of Costs	
Instrument Monitoring Hours	1,740
Repair Hours	+ 188
Total Labor Hours	1,928
Labor Charge Rate, $/Man-Hour	21
Labor Charges	40,488
Admin. & Support Costs (0.4 x Labor Charges)	16,195
Annualized Charges for Initial Repairs	+ 352[b]
TOTAL ANNUAL COSTS	57,035

[a]"Fugitive Emission Sources of Organic Compounds--Additional Information on Emissions, Emission Reductions, and Costs," EPA-450/3-82-010, P.5-8.
% Leaks=(#Leaks/yr)/(#Valves)
[b]From Table 6a.

Table 5b. ANNUAL COSTS OF A LEAK DETECTION AND REPAIR PROGRAM
VALVES--MONTHLY MONITORING: AIR-OXIDATION

Monitoring	Instrument
Number of Valves	781
Monitoring Time, Man-Min/Source	x 10
Monitoring Time Per Interval, Min.	7,810
Number of Times Monitored Annually	x 12/60
Monitoring Time Total, Man-hours	1,562
Repairs	
Number of Valves	781
Fraction of Leaks Found Annually[a]	x .191
Estimated Number of Repairs Annually	149
Labor Hours Per Repair[a]	x 1.13
Repair Times Total, Man-Hours	168
Aggregation of Costs	
Instrument Monitoring Hours	1,562
- Repair Hours	+ 168
Total Labor Hours	1,730
Labor Charge Rate, $/Man-Hour	x 21
Labor Charges	36,330
Admin. & Support Costs (0.4 x Labor Charges)	14,532
Annualized Charges for Initial Repairs	+ 331[b]
TOTAL ANNUAL COSTS	51,193

[a]"Fugitive Emission Sources of Organic Compounds--Additional Information on Emissions, Emission Reductions, and Costs," EPA-450/3-82-010, P.5-8.
% Leaks=(#Leaks/yr)/(#Valves)
[b]From Table 6b.

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Table 4a. COSTS OF INITIAL LEAK DETECTION AND REPAIR OF PUMP SEALS
ETYLENE OXIDE MODEL UNIT : OXYGEN-OXIDATION

Number of Pump Seals	30
Initial Leak Frequency	x 0.088
Estimated Number of Leaks	2.64
Repair time, man-hour/leak	x 16
Labor hours required	42.2
Labor charge rate, $/man-hour	x 21
Initial leak repair	886
Admin. & Support Costs (0.4 x Initial leak repair)	+ 354
SUBTOTAL	1,240
Seal costs, $/single seal[a]	164
Estimated Number of Leaks	2.64
Materials Cost	433
Subtotal (from above)	1,240
TOTAL CAPITAL COSTS	1,673
Capital recovery factor[b]	x .163
ANNUALIZED COST OF CAPITAL	$ 273

[a]Fraction of sources repaired annually is an output of the LDAR model.
[b]The number of times monitored annually is divided by "60" to convert from man-minutes to man-hours.

TABLE 4b. COSTS OF INITIAL LEAK DETECTION AND REPAIR OF PUMP SEALS
ETHYLENE OXIDE MODEL UNIT : AIR OXIDATION

Number of Pump Seals	27
Initial Leak Frequency	x 0.088
Estimated Number of Leaks	2.4
Repair Time/Man-Hour/Leak	x 16
Labor Hours Required	38.4
Labor Charge Rate, $/Man-Hour	x 21
Initial Leak Repair	806
Admin. & Support Costs (0.4 x Initial Leak Repair)	+ 323
Sub-Total (Labor Charges)	1,129
Seal Costs, $/Single Seal[a]	164
Estimated Number of Leaks	x 2.4
Materials Cost	394
Subtotal (from above)	1,129
TOTAL CAPITAL COSTS	$1,523
Capital Recovery Factor[b]	x 0.163
ANNUALIZED COST OF CAPITAL	248

[a]Cost of single seal (replacement) includes a 50 percent credit for the old seal.

[b]Capital recovery factor is based on a 10 percent interest rate over a 120-year period.

Table 3a. ANNUAL COSTS OF A LEAK DETECTION AND REPAIR PROGRAM FOR PUMP SEALS--MONTHLY MONITORING: OXYGEN-OXIDATION

Monitoring	Instrument	Visual
Number of Pump Seals	30	30
Monitoring Time, Man-Min/Source	x 10	x .5
Monitoring Time Per Interval, Min	300	15
Number of Times Monitored Annually[a,b]	x 12/60	x 52/60
Monitoring Time Total, Man-hours	60	13
Repairs		
Number of Pump Seals	30	
Fraction of Leaks Found Annually[a]	x 0.408	
Estimated Number of Repairs Annually	12.2	
Labor Hours Per Repair	x 16	
Repair Times Total, Man-Hours	195	
Estimated Number of Repairs Annually	11.8	
Seal Costs, $/Single Seal	x 164	
Annual Materials Cost	1,935	
Aggregation of Costs		
Instrument Monitoring Hours	60	
Visual Monitoring Hours	13	
Repair Hours	+ 195	
Total Labor Hours	268	
Labor Charge Rate, $/Man-Hour	x 21	
Labor Charges	5,628	
Admin. & Support Costs (0.4 x Labor Charges)	2,251	
Materials Costs	1,935	
Annualized Charges for Initial Repairs	+ 273[c]	
TOTAL ANNUAL COSTS	$10,087	

[a]Fraction of sources repaired annually is an output of the LDAR model.
[b]The number of times monitored annually is divided by "60" to convert from man-minute to man-hours.
[c]From Table 4a.

Table 3b. ANNUAL COSTS OF A LEAK DETECTION AND REPAIR PROGRAM FOR PUMP SEALS--MONTHLY MONITORING: AIR OXIDATION

Monitoring	Instrument	Visual
Number of Pump Seals	27	27
Monitoring Time, Man-Min/Source	x 10	x 0.5
Monitoring Time Per Interval, Min	270	13.5
Number of Times Monitored Annually[a,b]	x12/60	x52/60
Monitoring Time Total, Man-hours	54.0	2.7
Repairs		
Number of Pump Seals	27	
Fraction of Leaks Found Annually[a]	x 0.408	
Estimated Number of Repairs Annually	11.0	
Labor Hours Per Repair	x 16	
Repair Times Total, Man-Hours	176	
Estimated Number of Repair Annually	11.0	
Seal Costs, $/Single Seal	x 164	
Annual Materials Cost	1,804	
Aggregation of Costs		
Instrument Monitoring Hours	54.0	
Visual Monitoring Hours	2.7	
Repair Hours	+ 176	
Total Labor Hours	232.7	
Labor Charge Rate, $/Man-Hour	x 21	
Labor Charges	$4,887	
Admin. & Support Costs (0.4 x Labor Charges)	1,955	
Materials Costs	1,804	
Annualized Charges for Initial Repairs	+ 248[c]	
TOTAL ANNUAL COSTS	$8,894	

[a]Fraction of sources repaired annually is an output of the LDAR model.
[b]The number of times monitored annually is divided by "60" to convert from man-minute to man-hours.
[c]From Table 4b.

Table 2a. Emissions and Emission Reduction Estimates
Ethylene Oxide Production: Oxygen Oxidation
Model Plant

Emissions Source	Number of Sources	Emission Factor, kg/day/source	Adjustment Factor[a]	Annual Emissions, Mg/yr[b]	Control Efficiency	Emission Reductions, Mg/yr
Pump Seals						
Light Liquid	30	1.19	.5	6.5	0.61	3.9
Heavy Liquid	--	--	--	--	--	--
Valves						
Gas	177	0.13	.5	4.2	0.73	3.0
Light Liquid	693	0.17	.5	21.5	0.59	12.6
Heavy Liquid	--	--	--	--	--	--
Safety/Relief Valves						
Gas	26	2.5	.5	11.8	1.0	11.8
Open-ended Lines	0	0.04	.5	0	1.0	0
Compressors	3	5.47	.5	2.9	1.0	2.9
Sampling Connections	10	0.36	.5	0.6	1.0	0.6
Flanges	1,738	0.02	.5	6.4	--	--
TOTAL				53.9		34.8

[a]The emission factor assumes 100 percent organic in stream and must be adjusted for ethylene oxide emission estimates to account for the different percent of ethylene oxide in various streams. Assumed the average stream contains 50 percent ethylene oxide.

[b]For estimating purposes, one operating year was assumed to be 365 days.

Table 2b. Emissions and Emission Reduction Estimates
Ethylene Oxide Production: Air Oxidation
Model Plant

Emissions Sources	Number of Sources	Emission Factor, kg/day/source	Adjustment Factor[a]	Annual Emissions, Mg/yr[b]	Control Efficiency	Emission Reductions, Mg/yr
Pump Seals						
Light Liquid	27	1.19	.5	5.8	0.61	3.5
Heavy Liquid	--	--	--	--	--	--
Valves						
Gas	200	0.13	.5	4.8	0.73	3.5
Light Liquid	581	0.17	.5	18.0	0.59	10.6
Heavy Liquid	--	--	--	--	--	--
Safety/Relief Valves						
Gas	60	2.5	.5	27.4	1.0	27.4
Open-ended Lines	2	0.04	.5	0	1.0	0
Compressors	6	5.47	.5	5.9	1.0	5.9
Sampling Connections	36	0.36	.5	2.4	1.0	2.4
Flanges	1,214	0.02	.5	4.4	--	
TOTAL				68.7		53.3

[a]The emission factor assumes 100 percent organic in stream and must be adjusted for ethylene oxide emission estimates to account for the different percent of ethylene oxide in various streams. Assumed the average stream contains 50 percent ethylene oxide.

[b]For estimating purposes, one operating year was assumed to be 365 days.

APPENDIX A

Equipment Leak Control Costs

for

Ethylene Oxide Model Plants

TABLE 1. EQUIPMENT LEAK CONTROL COSTS[a] ETHYLENE OXIDE PRODUCTION

Source/Process	Model Plants Total Annual Cost (Oct 1983 $) Oxygen Oxidation	Air Oxidation
Pumps	10,090[a]	8,890[a]
Valves	57,040[b]	51,200[b]
Safety/Relief Valves	7,840[c]	16,800[c]
Open-Ended Lines	0	0
Compressors	7,200[c]	14,400[c]
Sampling Connections	1,700[c]	6,120[c]
Monitoring Instruments	7,270	7,270
TOTAL COST	91,140	104,680
Product Recovery Credit	+ (26,800)[d]	(41,040)[d]
NET ANNUAL COST	64,340	63,640

[a]From Table 3a and 3b.
[b]From Table 5a and 5b.
[c]From Table 7a and 7b.
[d]Value of product recovered = $.35/lb or $770/Mg. Letter from D. C. Macauley, Union Carbide Corporation, to Susan R. Wyatt, U.S. EPA, October 5, 1984.

Table 5-5 COST EFFECTIVENESS
DEOXX™ SYSTEM

Cost	1983 $	Annual Cost
Capital Cost (installed)	217,350[a]	25,500[b]
Operating Cost	--	9,300[c]
Local Taxes, Insurance	--	3,500[d]
Administration & Contingency	--	800[e]
Total Annual Costs		39,100
Emission Reduction (Mg/yr)		87[f]
Cost Effectiveness ($/mton)		$ 450

[a]Letter from Anthony Buonicore of Chemrox, Inc. to David Markwordt U. S. EPA dated January 20, 1984. Plant: 87 metric tons of ethylene oxide from 8 sterilizers

[b]Capital Charges assume i = 10% and 20 years equipment life

[c]Letter from Anthony Buonicore of Chemrox, Inc. to David Markwordt, U.S. Environmental Protection Agency, dated August 27, 1984.

[d]1.6% fixed-capital costs

[e]6% of total operating cost (9,300 + 3,500)

[f]Assumed no value for recovered chemical by-product

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8. Detergent Alcohols, Chemical Economics Handbook. SRI International, February 1981, p. 601. 5022 T.

9. Letter from Anthony J. Buonicore of Chemrox Inc. to David W. Markwordt of U. S. Environmental Protection Agency, RTP, N. C. January 20, 1984.

10. Letter from Anthony J. Buonicore of Chemrox Inc. to David W. Markwordt of U. S. Environmental Protection Agency, RTP, N. C. August 27, 1984.

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TABLE 5-3b

EQUIPMENT LEAKS

EMISSIONS AND EMISSION REDUCTION ESTIMATES
ETHYLENE OXIDE PRODUCTION: AIR-OXIDATION
Model Plant

Emissions Source	Number of Sources	Annual Emissions, Mg/yr[a]	Control Technique NSPS	Present Control Efficiency	Emission Reductions, Mg/yr
Pump Seals					
Light Liquid	27	5.8	LDAR	0.61	3.5
Heavy Liquid	--	--		--	--
Valves					
Gas	200	4.8	LDAR	0.73	3.5
Light Liquid	581	18.0		0.59	10.6
Heavy Liquid	--	--		--	--
Safety/relief valves Gas	60	27.4	Performance Standard	1.0	27.4
Open-ended lines	0	0.0	CAPS	1.0	0.0
Compressors	6	5.9	Seal System	1.0	5.9
Sampling connections	36	2.4	Closed Purge System	1.0	2.4
Flanges	1,214	4.4	--	--	--
TOTAL		68.7			53.3

[a]From Table 3.4

TABLE 5-4. EQUIPMENT LEAK CONTROL COSTS: ETHOXYLATION
Model Plant[a]

Source/Process	Total Annual Cost, $
Pumps	950
Valves	5,400
Safety/Relief Valves	1,200
Open-ended Lines	0
Compressors	1,080
Sampling Connections	390
Monitoring Instruments	7,270
TOTAL COST	16,290
Product Recovery Credit	(3,850)[b]
NET ANNUAL COST	12,440

[a]Component counts assumed to be 10% of production facility components. Costs are then 10% of average costs for oxygen and air oxidation model plants (except for monitoring instrument costs).
[b]Emission reduction = 5 mton/yr.

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TABLE 5-2. EQUIPMENT LEAK CONTROL COSTS[a] ETHYLENE OXIDE PRODUCTION

Source/Process	Model Plants Total Annual Cost (Oct 1985 $) Oxygen Oxidation	Air Oxidation
Pumps	10,090	8,890
Valves	57,040	51,200
Safety/Relief Valves	7,840	16,800
Open-Ended Lines	0	0
Compressors	7,200	14,400
Sampling Connections	1.700	6,120
Monitoring Instruments	7,270	7,270
TOTAL COST	91,140	104,680
Product Recovery Credit	+(26,800)	+(41,040)
NET ANNUAL COST	64,340	63,640

[a]Detailed costs are provided in Appendix.

TABLE 5-3a

EQUIPMENT LEAKS
EMISSIONS AND EMISSION REDUCTION ESTIMATES
ETHYLENE OXIDE PRODUCTION: OXYGEN-OXIDATION
Model Plant

Emissions Source	Number of Sources	Annual Emissions, Mg/yr[a]	Control Technique NSPS	Present Control Efficiency	Emission Reductions, Mg/yr
Pump Seals					
Light Liquid	30	6.5	LDAR	0.61	3.9
Heavy Liquid	--	--		--	--
Valves					
Gas	177	4.2	LDAR	0.73	3.0
Light Liquid	693	21.5		0.59	12.6
Heavy Liquid	--	--		--	--
Safety/relief valves					
Gas	26	11.8	Performance Standard	1.0	11.8
Open-ended lines	0	0.0	CAPS	1.0	0.0
Compressors	3	2.9	Seal System	1.0	2.9
Sampling connections	10	0.6	Closed Purge System	1.0	0.6
Flanges	1,738	6.4	--	--	--
TOTAL		53.9		TOTAL	34.8

[a]From Table 3.5

5. CONTROL TECHNIQUE COSTS

Annualized control costs, emission reductions, and cost effectiveness for each emission source are summarized in Table 5-1. The cost analysis was calculated on a model plant basis for equipment leak sources.

5.1 Equipment Leaks

5.1.1. Ethylene Oxide Production

Total annual equipment leak control costs are provided in Table 5-2 for both the oxygen and air oxidation model plants. Model plant emission sources, emissions, and emission reductions are summarized in Table: 5-3a and 5-3b. The annualized cost per metric ton of ethylene oxide reduced is $1,800 for oxygen - oxidation plants and $1,200 for air-oxidation facilities. These costs and emission reductions reflect the new source performance standard level of control; detailed costs are provided in the Appendix A.

5.1.2. Ethoxylation

Ethoxylation equipment leak control costs are provided in Table 5-4. Equipment counts were assumed to be 10 percent of ethylene oxide production facilities. Annualized cost per metric ton of ethylene oxide reduced is approximately $2,500.

5.2 Sterilization/Fumigation

Capital costs, annualized costs, and cost effectiveness for a DEOXX™ system treating approximately 90 metric tons of ethylene oxide is summarized in Table 5-5. Annualized costs per metric ton of ethylene oxide reduced is approximately $450.

Table 5-1.

Preliminary Control Efficiency and Cost Effectiveness
Ethylene Oxide Emission Sources

Facility/Source	Control Technique	% Emission Reduction	Model Plant Annual Cost (1983 $)	Model Plant Emiss. Reduction (Mg/yr)	Model Plant Cost Effect ($/Mg)
I. Production					
A. Equipment Leaks	NSPS SOCMI Std for Equipment Leaks				
1. Oxygen Oxidation		65	64,300[a]	35[b]	1,800
2. Air Oxidation		80	63,600[a]	54[b]	1,200
B. Cooling Towers	Repacking stripper column	80	unknown	20	unknown
C. Vents					
1. Argon	Boiler/Incinerator	99.9		- Baseline -	
2. CO_2 Stripper	Carbonate Flasher and Vent Condenser	92		- Baseline -	
3. E.O. Stripper, Reabsorber, or Purification	Recycle to Process	99.9		- Baseline -	
II. Ethoxylation/Equipment Leaks	NSPS SOCMI Std for Equipment Leaks	70	12,400[c]	5[c]	2,500
III. Sterilizers & Fumigators	DEOXX™	99	39,800[d]	87	450

[a]From Table 5-2

[b]From Table 5-3

[c]From Table 5-4

[d]From Table 5-5

4.2.2.3. Emission Reduction

An emission reduction of roughly 80 percent appears possible for new facilities utilizing both optimum tray and packing design. Existing facilities with only new packing intervals would experience less than an 80 percent emission reduction.

4.3 Vents

As discussed in section 2.1.3., nearly all vent streams from ethylene oxide production facilities are recycled to the process or combusted. In the oxygen oxidation process the CO_2 stripper or regenerator vent is processed to recover CO_2. Present (baseline) control levels are summarized in Table 6 and 7 of Section 3.

4.4 Sterilization and Fumigation

Ethylene oxide emissions vented from sterilizer and fumigator chambers may be combusted or processed for recovery.

4.4.1 DEOXX™

The DEOXX™ system was designed by Chemrox, Inc. to chemically process ethylene oxide vapors to saleable ethylene glycol. The system has been certified by New York State as best available control technology (BACT) and appears to have established the 99 percent efficiency level as BACT in New York. The DEOXX™ system is under patent review. DEOXX™ ethylene oxide emission control systems have been or are scheduled to be installed in the states of New York, Maryland, Michigan, Utah, Hawaii, California, Florida, Connecticut, Texas, Rhode Island, Illinois, Pennsylvania, Puerto Rico, South Carolina, and Minnesota.[10]

Table 4-2. Control Efficiencies: CTG & NSPS

Equipment Components

Emissions Source	Emission Factor[a] (kg/day/source) (uncontrolled)	Present Control Efficiency	
		CTG	NSPS
Pump Seals Light Liquid	1.19	0.33	0.61
Valves			
Gas	0.13	0.64	0.73
Light Liquid	0.17	0.44	0.59
Safety/relief valves Gas	2.5	0.44	1.0
Open-ended lines	0.04	1.0	1.0
Compressors	5.47	0.33	1.0
Sampling connection	0.36	0.0	1.0

4.2. Cooling Towers

Two basic techniques are available for controlling cooling tower emissions. Emissions can be reduced by either using a sealed heat exchanger or using a more efficient stripper column(s).

4.2.1. Heat Exchanger

A heat exchanger used in place of a cooling tower would virtually eliminate ethylene oxide emissions. It was assumed that the incremental cost of utilizing a heat exchanger in place of a conventional cooling tower is prohibitive. Therefore, heat exchangers are not considered a viable approach to reducing cooling tower emissions.

4.2.2. Stripper Column Design

4.2.2.1. New Sources

Recirculated effluent from the ethylene oxide stripper column to the cooling tower results in ethylene oxide emissions when water contacts the atmosphere. Emission can be reduced by utilizing higher efficiency trays and packing internals to increase stripper column effectiveness. More efficient stripper columns require less energy for processing; this energy saving may off-set the cost of additional trays or more costly packing.

4.2.2.2. Existing Sources

Although existing stripper columns can be redesigned to incorporate additional trays, it is most likely too costly. Because packing trays are welded in place, a retrofit of an existing column requires cutting out old trays to replace with new ones.

A stripping efficiency of existing towers can be increased by replacing packing materials with more efficient packing.

4. CONTROL TECHNIQUES

4.1 Equipment Leaks

Primary control methods for equipment leaks include leak detection and repair (LDAR) methods and control equipment. Leak detection methods are used to identify equipment components that are emitting significant amounts of volatile organic chemicals. Emission from leaking sources may be reduced by three general methods: repair, modification, or replacement of source. In the case of open-ended lines, however, equipment leaks are treated more effectively by installation of control equipment.

The U.S. Environmental Protection Agency has proposed new source standards (NSPS) and published control guidelines (CTG) for new and existing facilities in the synthetic organic chemical industry. Both the NSPS and CTG are applicable to ethylene oxide production and ethoxylator facilities. A summary of the CTG and NSPS control levels are included in Table 1 for comparison. The CTG and NSPS background information document, can be consulted for a detailed description of the individual component control techniques (see Table 4-1 footnotes).

Control efficiencies for individual equipment components under the CTG and NSPS level of control are provided in Table 4-2.

Table 4-1 EQUIPMENT LEAKS

CONTROL TECHNIQUES

Emission Source	Control Technique	
	CTG[1]	NSPS[2]
Pump Seals (Light Liquid)	LDAR[3] (quarterly monitoring)	LDAR (monthly monitoring)
Valves (Gas) (Light Liquid)	LDAR (quarterly monitoring)	LDAR (monthly monitoring)
Safety/relief valves (Gas)	LDAR (quarterly monitoring)	Performance standard+
Open-ended Lines	Caps	Caps
Compressors	LDAR (quarterly monitoring)	Seal System
Sampling connections	none	Closed Purge System

1 "Control of Volatile Organic Compound Leaks From Synthetic Organic Chemical and Polymer Manufacturing Equipment," EPA-450/3-83-006, March 1984.

2 "VOC Fugitive Emissions in Synthetic Organic Chemicals Manufacturing Industry - Background Information for Proposed Standards, "EPA-450/3-80-033a, November, 1980.

3 LDAR - Leak Detection and Repair Model

4 No detectable emissions

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caustic scrubber is utilized emitting approximately 39 Mg per year.

3.2 Ethoxylation

Most ethoxylation facilities produce surface active agents (surfacants). Ethylene oxide is received by pressurized railcar, stored, then reacted with various chemicals in a closed process. The primary source of ethylene oxide emissions is assumed to be equipment leaks, although minimal data has been collected. Other emissions sources at these facilities are assumed to be negligible. Control techniques specified in both the synthetic organic chemical manufacture industry (SOCMI) fugitive emissions NSPS and CTG would effectively reduce ethylene oxide emissions by approximately 75 and 40 percent respectively.

It was assumed that component counts at these facilities (minus flanges) were approximately 10 percent of those at ethylene oxide production facilities.

3.3. Fumigation/Sterilization

Ethylene oxide emissions result from fumigation and sterilation operations when chambers are purged to the atmosphere. Emissions from these facilities is based on estimates of ethylene oxide used by these facilities. Approximately 2,800 metric tons of ethylene oxide is used in these industries and ultimately vented to the atmosphere.

QUESTIONS FOR DAVE MARKWORDT

① Emission factors for gas valves, gas safety valves, and compressors were modified for the Louisiana case by applying the effectiveness of quarterly monitoring (450/3-83-006, CEG).
- Why weren't all emission factors modified?
  Ex: LL valves have annual monitoring, LL pump seals have weekly inspections and annual leak measurement

assumed part of baseline

Look into it

② How were the control efficiencies determined? Following the example in the SOCMI NSPS, I get higher efficiencies.

③ If the emission factors for Louisiana equipment reflect the Louisiana regulation, shouldn't the control efficiency be the difference between the Louisiana reg and SOCMI? If not, doesn't this effectively double the true emission reduction?

Other, relatively minor points:
- How was the control efficiency for Louisiana pump seals determined? It has annual measurements and weekly visual inspections.
- Should the control efficiency for compressors in Louisiana be 72%, rather than 100%? La has an LDAR requirement, whereas SOCMI has an equipment specification.

		Correction Factors A	B	C	D	Lyric	Uncertainty ABCD		Corr. em.	CAF Nuc Avail	D Nuc Avail
Pumps (LL)	No	0.97	.95	.98	.92	.81	.75	SOCMI	.61	.61	.75
	[illegible]	0.97	.90	"	.92	.76	.70			.32	.43
	[illegible]	0.87	.80		.92	.69	.63				
Valves											
Gas	No	0.99	.95	.98	.92	.91	.8	SOCMI	.73	.73	.85
	[illegible]	0.99	.90	"	.92	.86	.86	LA/HC		.6	.7
	[illegible]	0.99	.90		.92	.77	.77				
Liq											
	No	0.84	.95	.98	.94	.79	.73	SOCMI	.59	.59	.75
	[illegible]	0.84	.90	"	.94	.74	.70			.4	.59
	[illegible]	0.84	.80	"	.94	.66	.62	LA/HC			
Safety relief valves	No	0.69	.95	.98	.92	.64	.63				
	[illegible]	0.69	.90	"	.92	.61	.60				
	[illegible]	0.69	.80		.92	.54	.53				
Compressors	No	0.84	.95	.98	.92	.78	.76				
	[illegible]	0.84	.90	"	.92	.74	.72	LA/HC		.3	
	[illegible]	0.84	.80		.92	.66	.64				

Weekly [illegible]

More than 99 percent of the CO_2 from the CO_2 absorber is processed to recover CO_2. Also, a carbonate flasher followed by a vent condenser is being used to reduce atmospheric emissions. The average ethylene oxide emission rate from the CO_2 vent is approximately 0.06 Kg per 1000 Kg of ethylene oxide capacity (Table 3-7).

The ethylene oxide stripper purge vent is composed of inert gas, ethylene, and ethylene oxide that were dissolved in the main absorber water during the recovery of ethylene oxide from the reaction gases. After ethylene oxide is desorbed from the water, the purge vent gases are stripped from the ethylene oxide. Typically, ethylene oxide in this stream is scrubbed with water via an absorber and recyled to the process.

An alternative to stripping inerts from the ethylene oxide stream is to vent these gases from the reabsorber tower when ethylene oxide is reabsorbed in water. The process sequence is reactor, scrubber, stripper (ethylene oxide stripped from water), and ethylene oxide reabsorber. The vent stream from the reabsorber can be incinerated.

Inert gases are also purged from the ethylene oxide purification tower. This stream can be scrubbed, vented to an absorber, and recycled to a reabsorber; atmospheric emissions from this vent are negligible (Table 3-7).

3.1.4 Storage & Loading

Ethylene oxide is a gas at ambient termeratures. Therefore, ethylene oxide is stored at approximately 10°C in insulated or underground tanks to maintain it as a liquid. Tanks are generally blanketed with nitrogen for safety purposes. Vapors displaced during storage and railcar loading operations are recycled to the process or scrubbed prior to flaring or incineration at most facilities. Emissions from storage and loading are reduced to negligible amounts with the exception of one producer facility where a

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Table 3-7 . CONTROL TECHNIQUES & EMISSION RATES[a]
OXYGEN OXIDATION

Principal Source	Control Units	Control Efficiency (%)	E.O.: Flow Rate ($kg/10^3 kg$ Capacity) Control Unit	
			Inlet	Outlet
I. VENT SOURCES:				
A. Argon	a. Boiler	100	.0011	0
	b. Boiler	100	.0016	0
	c. Incinerator	99.9	.002	0
			Avg. .0016	0
B. CO_2 Stripper	a. Carbonate Flasher and Vent Condenser	92	.75	.06
	b. CO_2 Recovery	100	.009	0
	c. Methanol Unit	100	.00063	0
CO_2 Regenerator	a. N.A. (to sale)	100	.002	
			Avg. .19	.06
C. E.O. Stripper	a. Uncontrolled	N.A.	.04	---
	b. Recylce to reabsorber	---	---	---
	c. Cooling tower	0	unknown	unknown
E.O. Reabsorber	a. Recycle	100	.002	0 or .002[a]
	b. Incineration	99.95	.065	0
E.O. Purification	a. H_2O Scrubber	85	unk	trace
	b. Vent absorber	99.99+	11.4	.0004
	c. Recycle to reabsorber	---	---	---
			Avg. 2.9	.0004 - .0024

[a]based on data provided by ethylene oxide producers

1.2 SOURCE ASSESSMENT METHODOLOGY

This section describes the general methodology used for the source assessment for the EO production, EO captive-feed uses, ethoxylate production, and sterilization/fumigation processes. These areas are addressed below, followed by a brief discussion of the uncertainties involved in emission and cost estimates.

1.2.1 Ethylene Oxide Production/Capitive-Feed Uses

Detailed emission data and corresponding process parameters from each EO oxide production site were provided to the EPA from each operator. EO flow rates (Kg EO/10^3 Kg EO capacity), both inlet and outlet to control devices, were developed for each vent source based on plant data. This information provides control efficiencies, a means of comparing the relative magnitude of each emission source, and the basis for emission rates for dispersion analysis.

The cost of equipment leak control assumed the new source performance standard level of control and cost assumptions; costs are in October 1983 dollars and were estimated on a model plant basis consistent with the emission estimates. Detailed costs are provided in Appendix A.

1.2.2 Ethoxylate Production

Data from only one plant forms the basis for emission estimates for ethoxylation production. It was assumed that the major source of emissions is equipment leaks. The model plant for ethoxylate producer facilities was based on comparison of equipment counts from the one ethoxylate plant and the EO production sites. For emission estimates it was assumed that

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1. INTRODUCTION

1.1 OVERVIEW

This report provides preliminary information on sources of air emissions of ethylene oxide to assist EPA in regulatory decision-making. Potentially significant sources are identified and described, including ethylene oxide production, its captive end-use in ethylene glycol, glycol ether, and ethanolamine production, linear alcohol ethoxylate production, and sterilization/fumigation processes. Source descriptions include general information on each industry and production process, as well as emission estimates, and control technology.

This report also presents emission estimates of EO and control costs for each emission source. Emission parameters were developed to model ambient dispersion concentrations of EO; these parameters are summarized in Appendix B. Emissions were estimated for two control levels: Level 1 represents the baseline level of emission control which would be expected without further regulatory activity, and Level 2 consists of estimated emission control for each emission source beyond baseline levels.

The EO emissions, control data, and costs of control in this report are based on information obtained from formal information requests to operating companies, existing EPA reports and other reports published on the EO manufacturing industry, and from telephone contacts with control equipment vendors. Emission estimates are based on emission data provided by industry and emission factors developed by EPA.

Table 2-1

Ethylene Oxide Facilities

Facility	Number of Facilities	End-Use (Mg/year)	National Emissions (Mg)
Producer (Captive Use)	15	2.5×10^6	1.6×10^3
Sterilizers/Fumigators	100-450	2.8×10^3	2.8×10^3
Ethoxylators	50	0.4×10^6	0.2×10^3

Carbon dioxide and water are the only significant by-products formed, according to the following reactions:

$$CH_2 = CH_2 + 3\ O_2 \longrightarrow 2\ CO_2 + 2\ H_2O + 1323\ kJ^* \quad (2)$$

$$\underset{\diagdown\ O\ \diagup}{CH_2 \quad CH_2} + 5/2\ O_2 \longrightarrow 2CO_2 + 2H_2O \quad (3)$$

(ethylene oxide)

The main reaction also produces small amounts of acetaldehyde (less than 0.1 percent of EO product) and trace amounts of formaldehyde.

Both the ethylene reaction rate and purge losses increase with higher concentrations of ethylene and oxygen. Thus, depending on the process and the oxidant, the ethylene concentration in the reactor inlet will vary between 5 and 40 volumn percent. The inlet oxygen concentrations will be controlled between 5 and 9 volume percent to stay out of the explosive range. Normally, air-based reactors operate at the low end of this concentration range while oxygen-based reactors operate at the high end.

By controlling the appropriate operating conditions, modern reaction systems are able to maintain selectivities (mols ethylene oxide formed per

*Calculated at 250°C, 15 atm.

2. INDUSTRY PROFILE

Twelve companies at 15 locations produce ethylene oxide in the United States; 2.5 million megagrams were produced in 1983. Most ethylene oxide is used at the production site to produce ethylene glycols, glycol ethers, and ethanolamines. Nameplate ethylene oxide captive feed requirements are 80 percent of nameplate ethylene oxide production capacity. Captive feed levels are approximately 90 percent of actual ethylene oxide production rates.

Of the ethylene oxide that is not used by producers (< 12 percent production), approximately 99.9 percent is sold to detergent manufacturers where ethylene oxide is ethoxylated for use in making surfactants. Less than .1 percent of ethylene oxide is used in the sterilizer and fumigator industries.

The number of facilities involved in production and consumption of ethylene oxide is summarized in Table 1. A complete breakdown of ethylene oxide derivations is provided in Table 2.[1]

2.1 Production. Name plate capacity for the 15 production sites totalled 3.3 million megagrams (7.3×10^9 lbs.) in 1983. Production site locations, capacities, and captive uses are summarized in Table 3.[2,3]

2.1.1. Process Description.[4] Ethylene oxide is produced by the direct, vapor phase oxidation of ethylene over a silver catalyst at 10 to 30 atm. pressure and 200 to 300°C. The main reaction is as follows:

$$CH_2 = CH_2 + 1/2\ O_2 \xrightarrow[\text{Ag Cat}]{} \underset{\underset{O}{\diagdown\ \diagup}}{CH_2 - CH_2} + 106.7\ \text{kJoules}^* \quad (1)$$

(ethylene oxide)

*Calculated at 250°C, 15 atm.

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Cooling towers contribute approximately 13 percent of emissions and may be reduced by approximately 80 percent with appropriate control techniques.

Vents, storage and loading operations, and effluent treatment facilities together contribute approximately 10 percent of total production/captive use site emissions. These sources appear to be well-controlled; additional control may not be necessary.

1.3.2 Ethoxylation

Emissions from equipment leaks may be reduced by 42 to 75 percent, depending on the degree of control implemented.

1.3.3 Sterilization/Fumigation

Add-on control devices may reduce emissions by as much as 99+ percent.

Table 1-1. EMISSION CONTROL LEVELS

Source	Emission Impacts		
	Baseline (Mg/yr)	Controlled (Mg//yr)	Reduction (%)
A. Production/Captive Use	1,540	900 - 500	42 - 68
1. Equipment Leaks	1,200	700 - 300	42 - 75
2. Cooling Towers	190	40	80
3. Vents	100	100	0
4. Storage and Loading	40	40	0
5. Effluents	10	10	0
B. Ethoxylation	200	85 - 50	58 - 75
C. Sterilization/Fumigation*	2,800	32	99
	4,540	1,020 - 580	78 - 87

*(Excluding medical facilities)

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ethoxylate producers have about 10 percent of the components of EO production sites (based on data from one facility); the estimate probably overstates emissions from these facilities. Data are needed for a more accurate estimate.

Costs were calculated by averaging the equipment leak control costs for oxygen and air oxidation plant sites and multiplying by 10 percent; costs are in October 1983 dollars.

1.2.3 Sterilization/Fumigation Processes

It was assumed that the typical sterilization and fumigation facility emits all the EO used in the process to the atmosphere. Emission estimates were then based on national estimates of the EO consumed in these processes.

The DEOXX™ system manufactured by Chemrox Inc. is the control technique considered for sterilization/fumigation processes. Information including control efficiency and costs were provided by the vendor; control costs are based on one industrial application.

1.3 NATIONAL EMISSIONS

National emissions of EO are estimated at approximately 5,000 megagrams per year (see Table 1-1). Production/captive use, ethoxylation, medical facilities, and sterilization/fumigation sites account for 31, 4, 8, and 57 percent of the total emissions, respectively. Emissions associated with growth in the industry were not estimated.

1.3.1 Production/Captive Use

Equipment leaks contribute approximately 75 percent of EO emissions at production/captive use sites. Control techniques are summarized in this document which may reduce these emissions by 42 to 75 percent (see Table 1-1).

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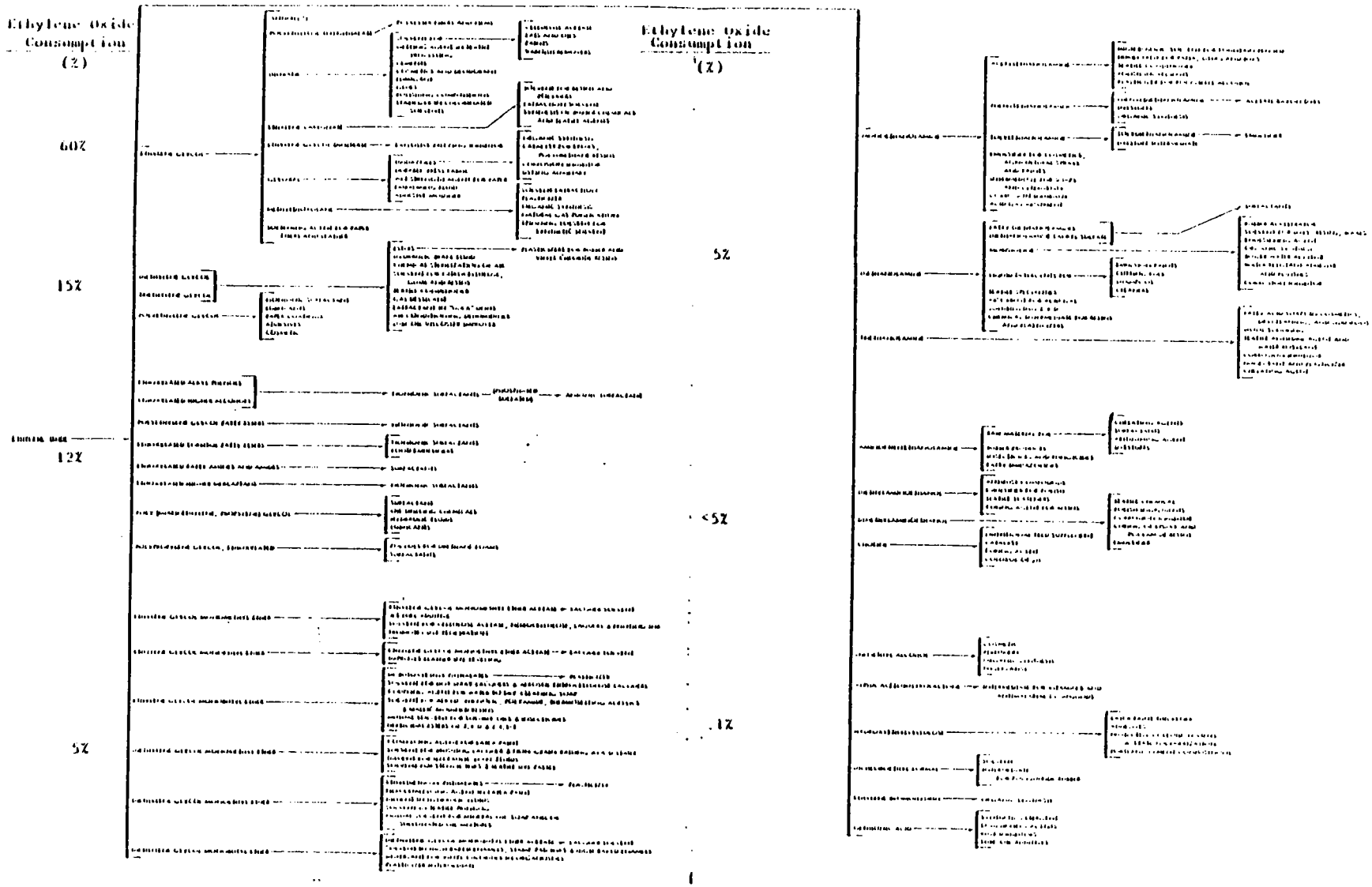
TABLE 2-3. ETHYLENE OXIDE (EO) PRODUCTION SITES*
CAPACITY AND CAPTIVE USES

Producer	Location	Ethylene Oxide	1982 Production Capacity (MM lbs/yr)				
			Ethylene Glycol	Diethylene Glycol	Triethylene Glycol	Glycol Ethers	Ethanol-amines
BASF	Geismar, LA	480	325	35	-	-	-
Celanese	Clear Lake, TX	425	400	50	10	-	-
Dow	Freeport, TX	300	300	30	50	-	-
Dow	Plaquemine, LA	450	450	50	-	120	125
ICI Americas	Bayport, TX	500	450	50	-	-	25
Northern Petrochemical	Morris, IL	230	350	35	-	-	-
Olin	Bradenburg, KY	110	50	5	5	70	30
PPG	Beaumont, TX	170	200	20	2	13	-
Shell	Geismar, LA	700	350	30	10	50	-
Sun Olin	Claymont, DE	110	-	-	-	-	-
Texaco	Port Noches, TX	700	500	50	20	40	240
Texas Eastman	Longview, TX	195	180	20	2	230	-
Union Carbide	Ponce, P.R.	650	840	75	75		-
Union Carbide	Seadrift, TX	920	850	75	-	490	230
Union Carbide	Taft, LA	1,300	1,350	120	-		-
	TOTALS	7,200	6,600	645	174	1,013	650
NAMEPLATE EO CAPTIVE FEED CAPACITY REQUIREMENTS		6,900	4,700	540	150	1,070	470

*As reported in the literature.

TABLE 2-2. Ethylene Oxide Derivatives



preferentially absorbed and vented with a minimum loss of ethylene. The reduced purge permits the O_2-based reactor to operate at a high ethylene concentration without excessive vent losses and allows the use of different diluent gases.

In the air based process, nitrogen must be used as the diluent for the oxygen and ethylene since any other diluent would be vented together with the nitrogen. The oxygen process can, however, use other diluents (such as methane) which allow the safe use of high concentrations of both ethylene and oxygen, thus leading to increased productivity at high selectivities.

Both the air- and oxygen-based processes use shell and tube reactors with the catalyst contained in the tubes and a cooling medium in the shell. Boiling water is now the preferred shell-side coolant for new reactors because of improved safety over non-boiling heat transfer oils and boiling kerosene, which were used in the past.

2.1.2 Air Oxidation.[5] Figure 2-1 is a typical flow diagram for a continuous air-oxidation process. Ethylene and air (S1 and S2) are added to a recycle ethylene stream (S3), which feeds one or more primary reactors operated in parallel. The air:ethylene feed ratio, usually about 10:1, is varied with the recycle gas to ensure an optimum oxygen:ethylene ratio. Oxidation takes place over a silver catalyst packed in tubes. The reactor is surrounded by a heat transfer fluid to control the temperature; the reaction temperature and pressure are maintained at 220 to 280°C and 1 to 3 MPa (42>° to 536°F; 10-30 atm). The unreacted ethylene is separated from the reaction products and recycled through the reactor until consumed.

The effluent from the primary reactor (S4) is cooled by the recycle stream from the main absorber (S3) to about 38°C in a shell-and-tube heat

*S1 = Steam 1

100 mols ethylene reacted) between 65 and 75 percent for air-based processes and between 70 and 80 percent for oxygen-based processes. The selectivity range for the air process is lower because of the purge reactors which, of necessity, operate with low ethylene concentrations and at high conversions per pass. These high reaction efficiencies are achieved by operating with low ethylene conversions per pass and adding controlled, trace amounts of chlorinated inhibitors to moderate the reaction.

Since the reactor exit gas contains substantial amounts of unconverted ethylene, it must be recycled back to the reactor to achieve a high overall ethylene conversion in both the air and oxygen-based processes. The exit gas to be recycled is first scrubbed using water to absorb the ethylene oxide, which if not removed from the feed, would inhibit the reaction and also result in excessive oxidation losses (to CO_2 and H_2O).

In the air-based process, a considerable amount of nitrogen is introduced in the air feed to the reaction. Accordingly, a large portion of the scrubbed reactor exit gas must be withdrawn to remove this nitrogen. This purge stream is usually mixed with additional air to increase the oxygen concentration and then passed through a secondary (or purge) reactor, similar to but smaller than the first (or main) reactor to convert most of the contained ethylene. In large plants, a third stage of reaction is used to achieve an overall ehtylene conversion well in excess of 95 percent of the total feed.

In the oxygen-based process, since high-purity oxygen is used, much less inert gas is introduced into the reaction system. As a result, only a limited purging is required and the unconverted ethylene can be more completely recycled. To avoid a build-up of by-product carbon dioxide, a portion of the recycled gas is first sent to a carbon dioxide removal system where CO_2 is

exchanger; it is then compressed before entering the main absorber. The effluent passes up the main absorber countercurrent to cold water, in which the EO, along with some of the carbon dioxide from the stream, dissolves. The water solution is removed from the base of the main absorber (S5).

Unabsorbed gas passing overhead from the main absorber is split into two unequal portions. The larger portion (S3) recycles through the reactor effluent cooler and joins fresh reactor feed. The smaller portion (S6) is passed through a heat exchanger to raise its temperature and then enters the purge reactor (secondary ethylene conversion reactor). The effluent from the purge reactor (S7) is cooled by the incoming feed to the purge reactor and enters the purge absorber, where ethylene oxide is removed from the stream with water, as in the main absorber. The overhead gas (VA) is vented from the purge absorber. There can be more than one stage of purge reaction, depending on the economics of the value of ethylene recovered versus cost.

The dilute water solutions containing ethylene oxide, carbon dioxide, and other volatile organic chemicals from both absorbers are combined (S8). The mixture is fed to the top of the desorber, where the crude ethylene oxide (S9) is distilled off the top and compressed for further refining. A stripper removes carbon dioxide and inert gases overhead (VB), and the EO, stripped of carbon dioxide (S10), is fed to the midsection of the refiner, where it is distilled overhead to 99.5 mole % EO. The product (S11) is stored under a nitrogen atmosphere. The secondary reaction of ethylene that produces CO_2 represents not only a loss of ethylene but also a release of more than 13 times as much energy as the primary product reaction, i.e., 50.4 vs 3.7 MJ/kg of ethylene.

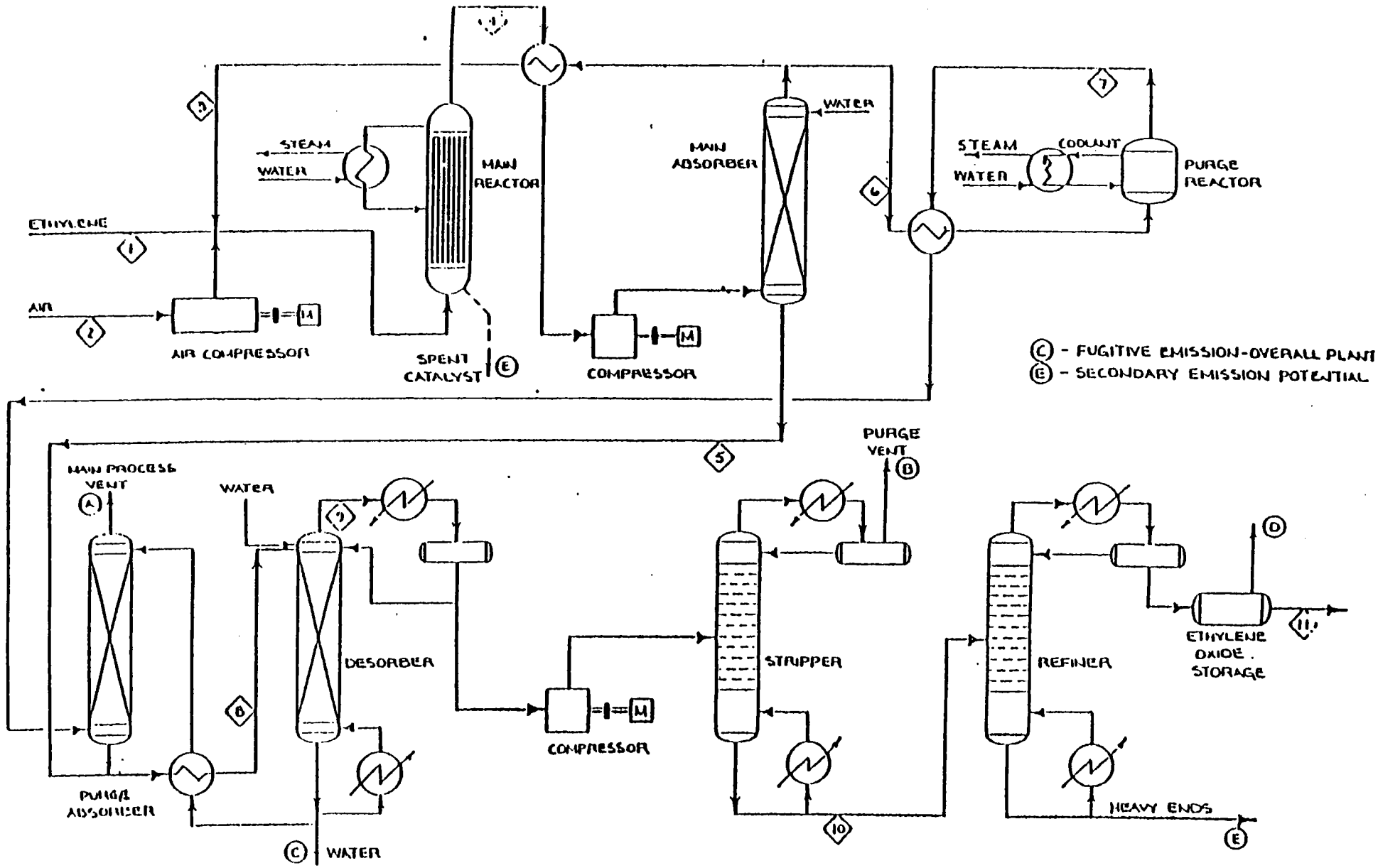


Figure 2-1. Production of Ethylene Oxide by Continuous Air-Oxidation Process[5]

2.1.3 Oxygen Oxidation.[6] Figure 2-2 is a typical flow diagram for a continuous oxygen-oxidation process. A higher concentration of ethylene allows more ethylene to be converted per pass without exceeding the 30% ethylene conversion favorable for optimum selectivity for EO formation. The oxygen-oxidation process also allows recirculation of the unabsorbed gas through the reactor to achieve a higher conversion. The higher ethylene conversion eliminates the need for the purge-reactor absorber system required by the air-oxidation process.

As shown by the oxygen-oxidation flow diagram, Fig. 2-2, the purge reactor and purge absorber of the air-oxidation process are replaced by a CO_2 absorber and reactivator. EO, along with some CO_2, is dissolved in the water stream leaving the base of the main absorber (S6) and is fed to the top of the desorber. The desorption, stripping, and refining steps are similar to those of the aqueous effluent from the main absorber of the air-oxidation process (S8, Fig. 2-1).

Part of the unabsorbed gas overhead from the main absorber of the oxygen-oxidation process (S7) passes through a CO_2 absorber before being recycled back to the reactor feed (S8). Carbon dioxide must be removed to maintain favorable catalyst activity and favorable conversion to EO. The CO_2 absorbent, usually potassium carbonate (S9), is heated by the bottoms from the reactivator and then fed to the top of the reactivator, where it is stripped of carbon dioxide and recycled to the CO_2 absorber.

Small amounts of gaseous impurities in the feed, such as argon, must be removed since they will accumulate in the closed system. Some of the recycle gas stream is purged through the argon purge vent (V8). This emission flow rate is automatically regulated by the argon concentration.

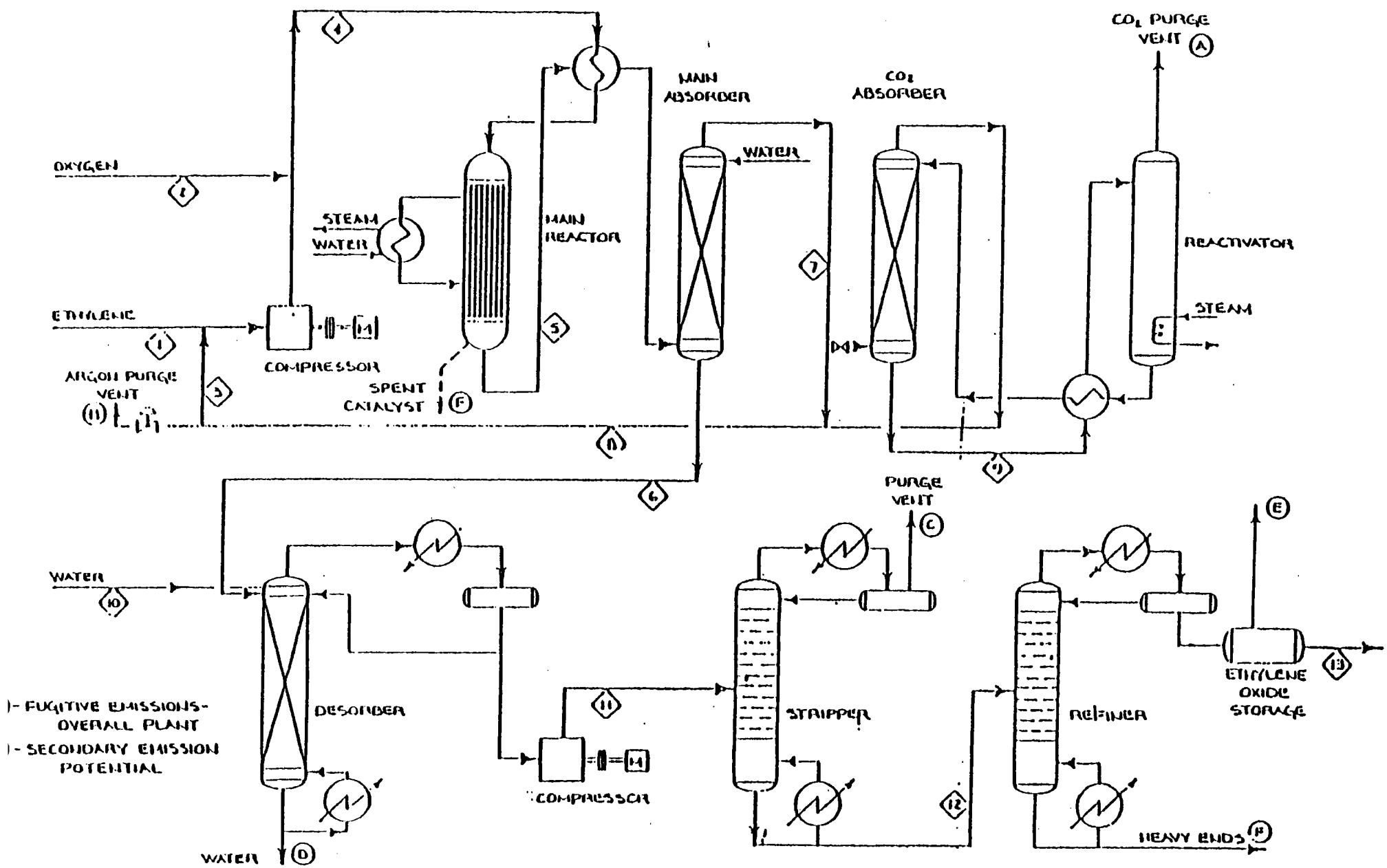


Figure 2-2. Production of Ethylene Oxide by Continuous Oxygen-Oxidation Process[5]

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feasible technologies, were assessed to define what constituted effective control for EO emissions from the various sources. The controls assessment included an examination of control device applicability and effectiveness and control device cost.

Application of available control techniques for all EO emission sources (excluding medical facilities) could reduce emissions by approximatley 87 percent. The control costs per megagram of EO emissions range from 460 to 2,500 depending on the emission source and applied technique.

The decision to initiate regulatory development will depend to some extent on the estimated health effects attributed to exposure to ambient levels of EO. Emission parameters developed for EO dispersion modeling are summarized in Appendix B.

Table 1. NATIONAL EMISSIONS - ETHYLENE OXIDE (Mg/yr)

Source	Baseline Emissions	% Total	Potential Controlled Emissions
A. Production/Captive Use	1,540	31	900-500
1. Equipment Leaks	1,200		700-300
2. Cooling Towers	190		50
3. Vents	100		100
4. Storage and Loading	40		40
5. Effluents	10		10
B. Ethoxylation	200	4	85-50
C. Medical Facilities	400	8	400
D. Sterilization/Fumigation	2,800	57	30
	4,940	100	1,420-980

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EXECUTIVE SUMMARY

The objective of this report is to present the results of a preliminary source assessment study conducted for ethylene oxide (EO) in which data were developed that will aid in evaluating the need for further regulatory development for EO.

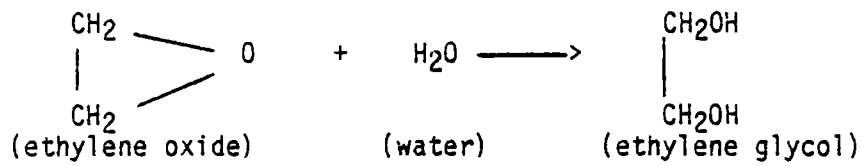
The EO source assessment was focused primarily on air emissions of EO. Processes which could potentially produce air emissions were identified and the levels of total EO generated were quantified. The EO emitted to air was estimated for individual sources from EO production sites (including captive use), ethoxylation sites, and major sterilizer/fumigator facilities. Emission categories included leaking equipment, cooling towers, vents, storage and loading operations, and effluent treatment facilities. Data were obtained from formal information requests to operating companies.

National emissions of EO are estimated at approximately 5,000 megagrams per year. Production/captive use, ethoxylation, medical facilities, and sterilization/ fumigation sites account for 31, 4, 8, and 57 percent of total emissions, respectively (see Table 1). Currently, 15 plants produce approximately 2.5 million megagrams of EO annually. Approximately, 80-90 percent of EO production is captively used on site. The bulk of emissions from producer and ethoxylator sites are from equipment leaks. Less than 0.1 percent of EO production is used in sterilizer/fumigator process, but nearly all of the uncontrolled EO is emitted to the atmosphere.

Control technologies currently used to reduce air emissions of EO were identified and evaluated to estimate what level of control exists at EO sources. The technologies currently applied, along with other potentially

2.2 Captive Feed Use[5,6,7]

2.2.1 Process Description/Ethylene Glycol. Ethylene glycol is manufactured by the addition of water to ethylene oxide (EO) in a noncatalyzed pressure hydration process. The ethylene glycol (EG) formed will react with additional ethylene oxide to form diethylene glycol (DEG), triethylene glycol (TEG), and other higher homologs. The chemical equations are as follows:



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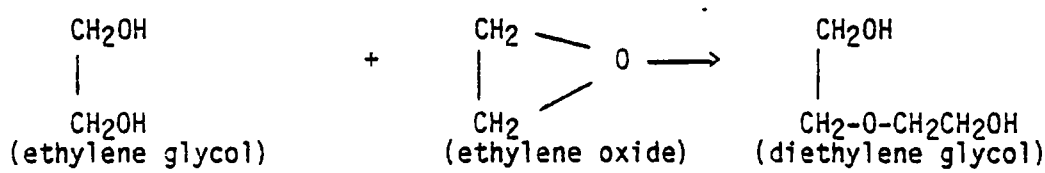

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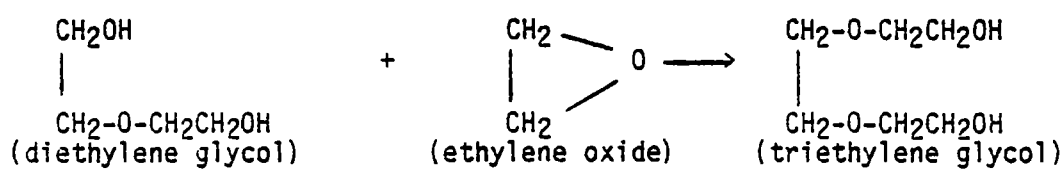


(3)

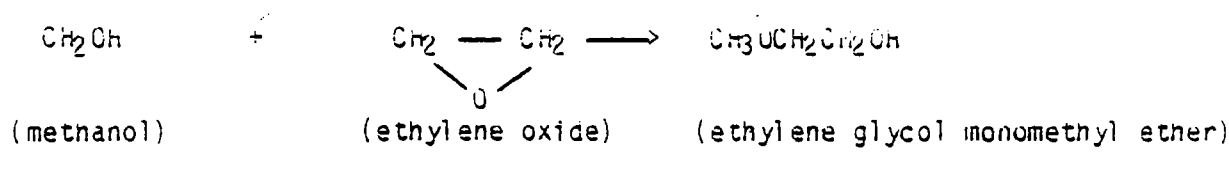
The normal weight ratios of co-products formed are 87 to 88.5 wt. percent ethylene glycol, 9.3 to 10.5 wt. percent diethylene glycol, and 2.2 to 2.5 wt. percent triethylene glycol. These three products constitute an overall yield of 92.5 to 95.5 percent of theoretical, based on the ethylene oxide feed.

Figure 2-3 represents a typical noncatalyzed ethylene oxide hydration process. The continuous process is carried out in the liquid phase, and the reactions are strongly exothermic. Theoretically, 0.71 kg of EO is required to produce 1 kg of EG; 0.83 kg of EO is required to produce 1 kg of DEG; and 0.88 kg of EO is required to produce 1 kg of TEG.

Refined liquid EO (S1), makeup water (S2), and recycle water are mixed under pressure (1.380 kPa), preheated, and fed to the hydrolyzer. The feed solution (S3) contains approximately 8 kg of water per kg of EO. The reactor effluent, heated by the exothermic heat of hydration, exists (S4) the hydrolyzer at 200°C and enters a multiple-effect evaporator system for removal of water.

A portion of the vapor from the first evaporator effect is purged (S5) to remove light impurities from the system. The remainder of the vapor and the vapors from the remaining evaporator effects are condensed and recycled (S6). The evaporator calandria and the condenser on the final evaporator effect are vented (A) to remove noncondensable gases.

2.2.2 Process Description/Glycol Ethers. The ethylene glycol monoethers are produced by the following sodium hydroxide catalyzed chemical reactions. Only the reactions with methanol are shown; however, the primary alcohols, ethanol, and butanol, react similarly to produce the ethyl and butyl ethers.



3. NATIONWIDE EMISSIONS

Chapter 3 provides nationwide ethylene oxide emission estimates from each of the processes described in Chapter 2. Estimates are provided for the following emission sources: Equipment leaks (valves, pumps, compressors, etc.) cooling towers, vents, storage and loading operations, ethoxylation, sterilization/fumigation, and effluents. These estimates represent baseline (present) emission levels.

Detailed emission data and corresponding process parameters from each ethylene oxide production site were provided to the EPA from each operator. Information was provided including emission stream characteristics (flow rate, temperature, composition, etc.) to and from control devices and vents to atmosphere where no device was used. Data were provided for all process vent emission sources, storage and loading operations, and effluents for the entire plant site including captive uses. Equipment component counts for pump seals, compressors, flanges, valves, pressure relief devices, sample connections, and open ended lines were provided for all equipment handling streams with any ethylene oxide present.

The equipment leak component counts from all the plants were used to develop model plants for both the oxygen and air oxidation processes. Emission factors for the synthetic organic chemical manufacturers industry (SOCMI) were applied to these model plants to establish baseline emissions and controlled emission levels. This approach assumes standard industry practice for control of equipment leaks for the baseline case.

National emissions for cooling towers, vents, storage and loading facilities, and effluents for production facilities are the emissions reported by the plants to EPA. Equipment component leak emissions were estimated using EPA emission factors. Ethylene oxide flow rates (kg E.O./10^3 kg E.O.

capacity), to and from control devices, were developed for each emission source based on plant data. This information provides control efficiencies and a means of comparing the relative magnitude of each emission source.

Data from only one plant forms the basis for emission estimates for ethoxylation produciton. It was assumed that the major source of emissions is from leaking equipment. The model plant for ethoxylate producer facilities was based on comparison of equipment counts from the one ethoxylate plant and the ethylene oxide production sites. For rough emission estimates it was assumed that ethoxylate producers have about 10 percent of the components of ethylene oxide production sites; the estimate probably overstates emissions from these facilities. Data is needed for a more accurate estimate.

It was assumed that the typical sterilization and fumigation facility vents all the ethylene oxide used in process to the atmosphere. Emission estimates were then based on national estimates of the ethylene oxide consumed in these processes.

Total nationwide ethylene oxide emissions from production, ethoxylation, and fumigant/sterilant uses are summarized in Table 3-1. Approximately 5,000 metric tons of ethylene oxide are being emitted per year. The average producer, sterilizer/fumigator, medical facility, and ethoxylator facilities emit approximately 100, 6 to 28, 0.06, and 4 metric tons per year of ethylene oxide respectively (see Table 3-2).

3.1 Production Facilities

Emission sources at production facilities include equipment leaks, cooling towers, vents, storage and loading, and effluent treatment facilities.

2.4 Sterlization/Fumigation. The type of equipment used for EO fumigation/sterilization varies with the application. The basic types of equipment are discussed in the following sections.

Vacuum Chambers. Vacuum chambers are pressure vessels with a vacuum pump to remove air from the chamber before sterilization begins and to remove some of the EO/air mixture after sterilization. Though the units vary widely in size and design features, the operating procedure is essentially as follows:

1. Contaminated material is loaded into the chamber.

2. The hermetically sealed door is closed.

3. Air is vacuumed from the chamber.

4. The sterilant pure (100%) EO, 12 percent EO/88 percent Freon, or 10 percent EO/90 percent carbon dioxide is introduced into the chamber to a set pressure or concentration and for a specified time period. Pure (100%) EO is used with negative pressure; EO mixtures are used with positive pressure. Pressure, concentration of sterilant, and time period are adjusted for the individual situation.

5. An exhaust vacuum removes the EO or EO/gas mixture from the chamber. The EO or EO/gas mixture is vented through a vent line to the atmosphere or to a sewer drain.

6. Fresh air is drawn into the chamber until atmospheric pressure is reached.

7. The door is opened and the treated material removed.

8. The treated material may be transferred to an aeration cabinet which circulates heated air around the material until residual EO has escaped. (Aeration cabinets are used almost exclusively in hospitals).

Small countertop models with capacities less than $0.1m^3$ ($<4ft^3$) are most commonly used in health care and health diagnosis facilities. In hospitals they are used in areas such as operating rooms. One industrial use is in the manufacture of contact lenses. EO is supplied either in single-dose cartridges of pure (100%) EO or in pressurized cylinders of 12 percent EO/88 percent Freon. Small chambers generally vent directly into the atmosphere through a length of tubing. Some models vent into a sponge kept damp in a bucket of water.

Intermediate-sized chambers of from 0.1 to $2.8m^3$ (4-100 ft^3) are used primarily in hospital central supply facilities. They are also used in research and industrial facilities, libraries, museums, and beehive fumigation facilities. An EO mixture is supplied in pressurized cylinders. Intermediate-sized chambers of this type may vent emissions to the atmosphere or the emissions may be mixed with water which is routed to a sewer drain.

Large chambers with capacities greater than 2.8 m^3 (100 ft^3) are used primarily for industrial sterilization of medical products, spices, and other products. They may be as large as 85 m^3 (3000 ft^3) in capacity and are custom-made. In such large capacity custom chambers, an EO mixture or pure (100%) EO is fed from pressurized cylinders or from large tanks. Emissions from large sterilizers are typically evacuated using once-through water-ring vacuum pumps. For these pumps, the amount of ethylene oxide absorbed in the water is generally less than 30 percent due to the relatively low gas retention time. Ethylene oxide absorbed in the water can desorb to the workplace above the break between the liquid pipe and drain.

ammonia scrubber with recycle water (S7) and is vented (A). Inert gases enter the system with the ethylene oxide feed, which is stored under a nitrogen pressure pad.

The ammonia stripper bottoms (S9) are vacuum distilled in a series of distillation columns to sequentially remove overhead water (S7), which is recycled, and MEA, DEA, and TEA (S10, 11, 12), which are products. Noncondensables from the vacuum distillation columns are vented (B) from the vacuum-jet discharges, and the vacuum-jet waste waters are discarded to waste treatment. The bottoms residue (S13) from the triethanolamine column is sent to waste treatment or is sold. the product storage tanks are ordinarily equipped with steam-heating coils to keep the products liquid and are padded with a dry inert gas such as nitrogen to prevent product discoloration.

2.3 Ethoxylation.[3] Detergent alcohol ethoxylates are produced by reacting detergent linear alcohols with ethylene oxide in the presence of a base catalyst such as potassium hydroxide. The general reaction may be represented as follows:

$$ROH + n\,\underset{\underset{O}{\diagdown\!\diagup}}{CH_2 - CH_2} \xrightarrow{KOH} RO(CH_2CH_2O)_nH$$

(ethylene oxide)

The molar ratio of ethylene oxide to alcohol in the final product may vary from 2 to 40. Ethoxylates produced for subsequent conversion to alcohol ether sulfates usually contain 3 moles of ethylene oxide per mole of alcohol. Products made for direct use as nonionic surfactants usually contain 6 to 12 moles of ethylene oxide per mole of alcohol.

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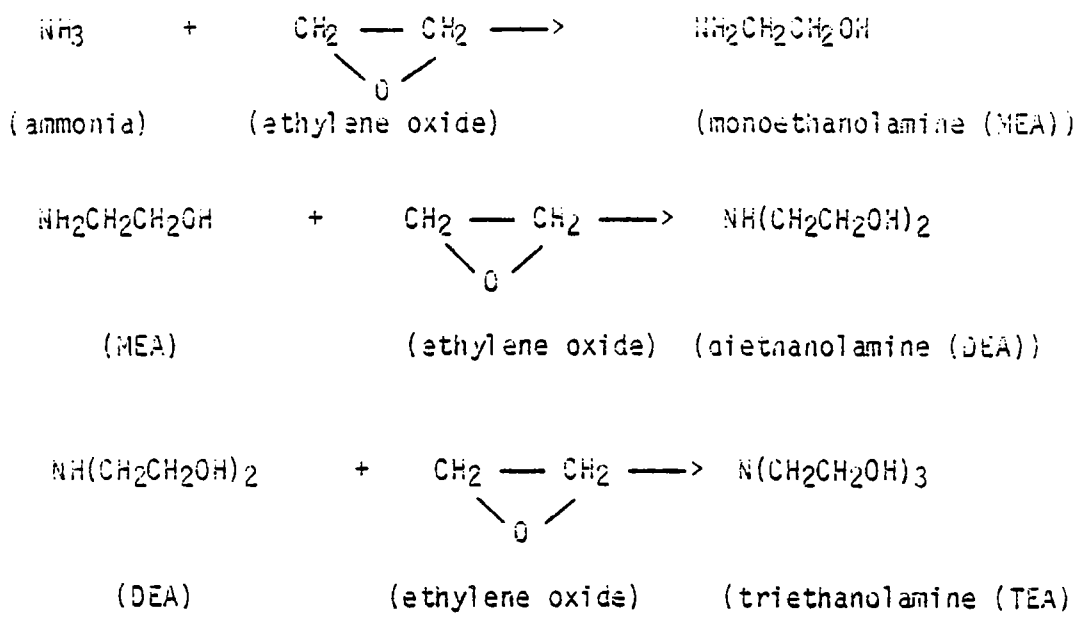
Large chambers with capacities greater than 2.8 m^3 (100 ft^3) are used primarily for industrial sterilization of medical products, spices, and other products. They may be as large as 85 m^3 (3000 ft^3) in capacity and are custom-made. In such large capacity custom chambers, an EO mixture or pure (100%) EO is fed from pressurized cylinders or from large tanks. Emissions from large sterilizers are typically evacuated using once-through water-ring vacuum pumps. For these pumps, the amount of ethylene oxide absorbed in the water is generally less than 30 percent due to the relatively low gas retention time. Ethylene oxide absorbed in the water can desorb to the workplace above the break between the liquid pipe and drain.

2.2.3 Process Description/Ethanolamines. Ethanolamines are produced by the following series:



The process is noncatalytic, strongly exothermic, and is carried out in the liquid phase in the presence of water. The distribution of products is dependent on the ratio of ammonia to ethylene oxide used; excess ammonia favors MEA formation.

The continuous manufacture of ethanolamines is shown schematically in Figure 2-5. Ethylene oxide (S1) and aqueous ammonia (S2) are fed to a reactor. The reaction conditons usually are a temperature range of 50 to 100°C, a pressure of 1 to 2 MPa, and an excess of 28 to 50 percent aqueous ammonia. The reactor effluent (S3) is stripped of unreacted ammonia and some water (S4) in an ammonia stripper operated under pressure. This ammmonia, together with fresh feed (S5), is absorbed in recycled water in the ammonia absorber and fed back to the reactor (S2). The noncondensable overhead gas (S6) from the ammonia stripper is scrubbed of amonia in an

86

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capacity), to and from control devices, were developed for each emission source based on plant data. This information provides control efficiencies and a means of comparing the relative magnitude of each emission source.

Data from only one plant forms the basis for emission estimates for ethoxylation produciton. It was assumed that the major source of emissions is from leaking equipment. The model plant for ethoxylate producer facilities was based on comparison of equipment counts from the one ethoxylate plant and the ethylene oxide production sites. For rough emission estimates it was assumed that ethoxylate producers have about 10 percent of the components of ethylene oxide production sites; the estimate probably overstates emissions from these facilities. Data is needed for a more accurate estimate.

It was assumed that the typical sterilization and fumigation facility vents all the ethylene oxide used in process to the atmosphere. Emission estimates were then based on national estimates of the ethylene oxide consumed in these processes.

Total nationwide ethylene oxide emissions from production, ethoxylation, and fumigant/sterilant uses are summarized in Table 3-1. Approximately 5,000 metric tons of ethylene oxide are being emitted per year. The average producer, sterilizer/fumigator, medical facility, and ethoxylator facilities emit approximately 100, 6 to 28, 0.06, and 4 metric tons per year of ethylene oxide respectively (see Table 3-2).

3.1 Production Facilities

Emission sources at production facilities include equipment leaks, cooling towers, vents, storage and loading, and effluent treatment facilities.

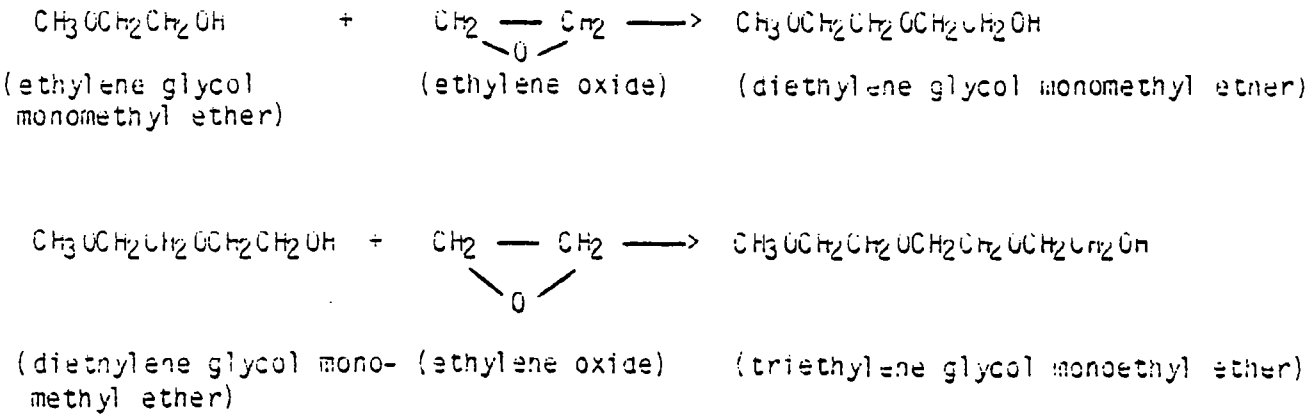

Figure 2-4 represents a continuous process for the manufacture of the glycol ethers. The sodium hydroxide catalyst (S1) and one of the anhydrous primary alcohols (S2) - are blended in the mix tank. The material from the alcohol catalyst storage tank is combined with ethylene oxide (S3) and with the recycled alcohol (S4) and is then fed to the reactor. The exothermic reaction is carried out at an elevated pressure (2.5×10^6 to 4.6×10^6 Pa) and temperature (200 to 230°C).

The product (S5) exits the reactor and is sent to the alcohol distillation column, where excess alcohol is distilled overhead and recycled (S6) for future reaction. The alcohol column bottoms (S7) are then sent to the monoethylene glycol ether column, where monoethylene glycol ether is vacuum distilled and sent (S8) to product storage. Diethylene glycol ether and triethylene glycol ether are vacuum distilled consecutively in two more distillation columns. The diethylene glycol ether product (S9) and triethylene glycol ether product (S10) streams are sent to their respective storage tanks.

Table 3-2. AVERAGE FACILITY EMISSIONS

(Mg of EO/yr)

Facility	Number of Facilities	National Emissions (Mg)	Emissions Per Facility (Mg)
Production	15	1,520	100
Sterilizers/Fumigators	100-450	2,800	6-28
Medical Facilities	6,000-10,000	400	<0.06
Surfactant Production	50	200	- 4
	Total	4,920	

TABLE 3-1. NATIONAL EMISSIONS
ETHYLENE OXIDE
(Mg/Yr)

Source		Emissions Mg/Yr	Emissions % Subtotal
A. Ethylene Oxide Production Facilities[1]			
1. Equipment Leaks		1,180	78
2. Cooling Towers		190	13
3. Vents		100	6
4. Storage & Loading		40	3
5. Effluents		10	< 1
	Subtotal	1,520	100
B. Surfactant Production (Equipment Leaks)	Subtotal	< 200	100
C. Fumigant/Sterilant Use[2]	Subtotal	2,600-3,900[3]	100
	TOTAL	4,320-5,620	

1 Includes captive use of ethylene oxide in production of (a) ethylene, diethylene, and triethylene glycol, (b) glycol ethers, (c) ethanolamines (d) polyethylene glycol and nonionic surface active agents

2 Assumes all ethylene oxide is emitted to atmosphere

3 Reinhart, Joe. Officer of Pesticides Programs, U.S. Environmental Protection Agency. Memo to Carolyn Smith, Radian Corporation, May 1983.

Table 3-3. Model Plant Components for Ethylene Oxide Production Facilities

		Number of Components [1]	
		O_2 - Oxidation[2]	Air - Oxidation[3]
Pump Seals	Packed	4	0
	Mechanical	16	11
	D - Mechanical	10	16
Compressors		3	6
Flanges		1738	1214
Valves	Gas	177	200
	Liquid	693	581
Press. Rel. Dev.	Gas	26	60
	Liquid	15	40
Sample Conn	Gas	18	55
	Liquid	22	90
Open Ended Lines	Gas	38	70
	Liquid	122	122

1 Includes captive feed processing components

2 Average of six facilities component counts: Average EO capacity = 1×10^5 mtons/yr

3 Average of five facilities component counts: Average EO capacity = 3.6×10^5 mtons

3.1.1 Equipment Leaks

Equipment leaks are those emissions that result when process fluid (either liquid or gaseous) leaks from plant equipment. There are many potential sources of equipment leaks in a typical synthetic organic chemical plant. The following sources are considered in this report: pumps, compressors, in-line process valves, pressure relief devices, open-ended valves, sampling connections, and flanges. Emissions which result from leaks in these types of equipment are generally random occurrences which cannot be predicted.

A complete description of each type of equipment leak is addressed in the background information document: "VOC Fugitive Emissions in Synthetic Organic Chemicals Manufacturing Industry - Background Information for Proposed Standards," EPA-450/3-80-033a, November 1980. The number of equipment components subject to leakage for both the oxygen and air oxidation model plants are summarized in Table 3-3. Emission factors, component emissions, and total model plant emissions are summarized for both oxygen and air oxidation model plants in Tables 3-4 and 3-5.

3.1.2 Cooling Towers

Cooling towers are found in the oxygen-oxidation plants where more heat is released than in the air oxidation process. The purpose of these towers is to cool the plant's recirculated effluent from the ethylene oxide stripper column. The cooling process is achieved by evaporation when the process cooling water and air are contacted. The emission rate is inversely proportional to the efficiency of the stripper column in removing ethylene oxide. Approximately 0.07 Kg of ethylene oxide are emitted for each 1000 Kg of ethylene oxide capacity.

Table 3-5. Ethylene Oxide Equipment Leak Emissions
Ethylene Oxide Production: Oxygen-Oxidation
Model Plant

Emissions Source	Number of Sources	Emission Factor [a] (kg/day/source)	Adjustment Factor[b]	Annual Emissions, (Mg/yr)[c]
Pump Seals				
Light Liquid	30	1.19	.5	6.5
Heavy Liquid	--	--	--	--
Valves				
Gas	177	0.13	.5	4.2
Light Liquid	693	0.17	.5	21.5
Heavy Liquid	--	--	--	--
Safety/relief valves Gas	26	2.5	.5	11.8
Open-ended lines	160	0.04	.5	0.0[d]
Compressors	3	5.47	.5	2.9
Sampling connections	40	0.36	.5	0.6[e]
Flanges	1,738	0.02	.5	6.4
TOTAL				53.9

[a]"Control of Volatile Organic Compound Leaks from Synthetic Organic Chemical and Polymer Manufacturing Equipment," EPA-450/3-83-006, March 1984, p. 2-21.

[b]The emission factor assumes 100 percent organic in stream and must be adjusted for ethylene oxide emission estimates to account for the different percent of ethylene oxide in various streams. Assume the average stream contains 50 percent ethylene oxide.

[c]For estimating purposes, one operating year was assumed to be 365 days.

[d]All open-ended lines (in model unit) are assumed to be controlled at baseline; therefore, there are no associated emissions.

[e]Seventy-five percent of sampling connections are assumed to be controlled at baseline; therefore, the emissions are based on 5 of 40 sampling connections.

Table 3-4. Ethylene Oxide Equipment Leak Emissions
Ethylene Oxide Production: Air-Oxidation
Model Plant

Emissions Source	Number of Sources	Emission Factor [a] (kg/day/source)	Adjustment Factor[b]	Annual Emissions, (Mg/yr)[c]
Pump Seals				
Light Liquid	27	1.19	.5	5.8
Heavy Liquid	--	--	--	--
Valves				
Gas	200	0.13	.5	4.8
Light Liquid	581	0.17	.5	18.0
Heavy Liquid	--	--	--	--
Safety/relief valves Gas	60	2.5	.5	27.4
Open-ended lines	192	0.04	.5	0.0[d]
Compressors	6	5.47	.5	5.9
Sampling connections	145	0.36	.5	2.4[e]
Flanges	1,214	0.02	.5	4.4
TOTAL				68.7

[a]"Control of Volatile Organic Compound Leaks from Synthetic Organic Chemical and Polymer Manufacturing Equipment," EPA-450/3-83-006, March 1984, p. 2-21.

[b]The emission factor assumes 100 percent organic in stream and must be adjusted for ethylene oxide emission estimates to account for the different percent of ethylene oxide in various streams. Assume the average stream contains 50 percent ethylene oxide.

[c]For estimating purposes, one operating year was assumed to be 365 days.

[d]All open-ended lines (in model unit) are assumed to be controlled at baseline; therefore, there are no associated emissions.

[e]Seventy-five percent of sampling connections are assumed to be controlled at baseline; therefore, the emissions are based on 36 of 145 sampling connections.

Table 3-6. CONTROL TECHNIQUES & EMISSION RATES[a]

AIR OXIDATION

Principal Source	Control Units	Control Efficiency (%)	E.O.: Flow Rate ($kg/10^3 kg$ Capacity) Control Unit	
			Inlet	Outlet
VENT SOURCES:				
A. Main Process	a. Thermal Oxidation	80	.2	.04
	b. Catalytic Oxidation	100	.005	0
			Avg. .10	.02
B. Vent Absorber	a. Boiler	100	4×10^{-5}	0
	b. Plant Flare	99	0	-
			Avg. 4×10^{-5}	0
C. E.O. Stripper	Boiler	100	unknown	unknown

[a]Based on data provided by ethylene oxide producers

3.1.3 Vent Emission Sources

3.1.3.1 Air Oxidation

The main process vent is the largest vent source of ethylene oxide emissions in the air oxidation plant. The vent gases also contain nitrogen, unreacted oxygen from the air feed, ethane and ethylene from the ethylene feed, and by-product CO_2. The main process gases are vented to a thermal or catalytic oxidizer; inlet and outlet (to atmosphere) mass flow rates of ethylene oxide are summarized in Table 3-6.

The ethylene oxide stripper vent releases inert gases and ethylene which were absorbed into the main and purge absorber waters. The stripper vent stream is combusted in a boiler resulting in approximately 100 percent control of ethylene oxide.

In some plants, vent streams are routed to an absorber to recover ethylene oxide. The vent stream from the absorber is then fed to a boiler or plant flare; emission levels are approximately zero.

3.1.3.2 Oxygen Oxidation

The volume of the main process vent or argon vent of the oxygen oxidation process is much less than that of the corresponding vent in the air process. This vent contains mainly argon and nitrogen from the oxygen feed, ethane from the ethylene feed, and very small amounts of ethylene oxide (< 0.01 mole %). The ethylene content of the main process vent is sufficient to support combustion and is routinely routed to a boiler or incinerator; ethylene oxide emissions are approximately zero from this source. Inlet and outlet mass flow rates of ethylene oxide are summarized in Table 3-7.

A-88-03

United States
Environmental Protection
Agency

Office of Air Quality
Planning and Standards
Research Triangle Park NC 27711

EPA-450/5-86-001
June 1986 II A 010

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USER'S MANUAL FOR THE HUMAN EXPOSURE MODEL (HEM)

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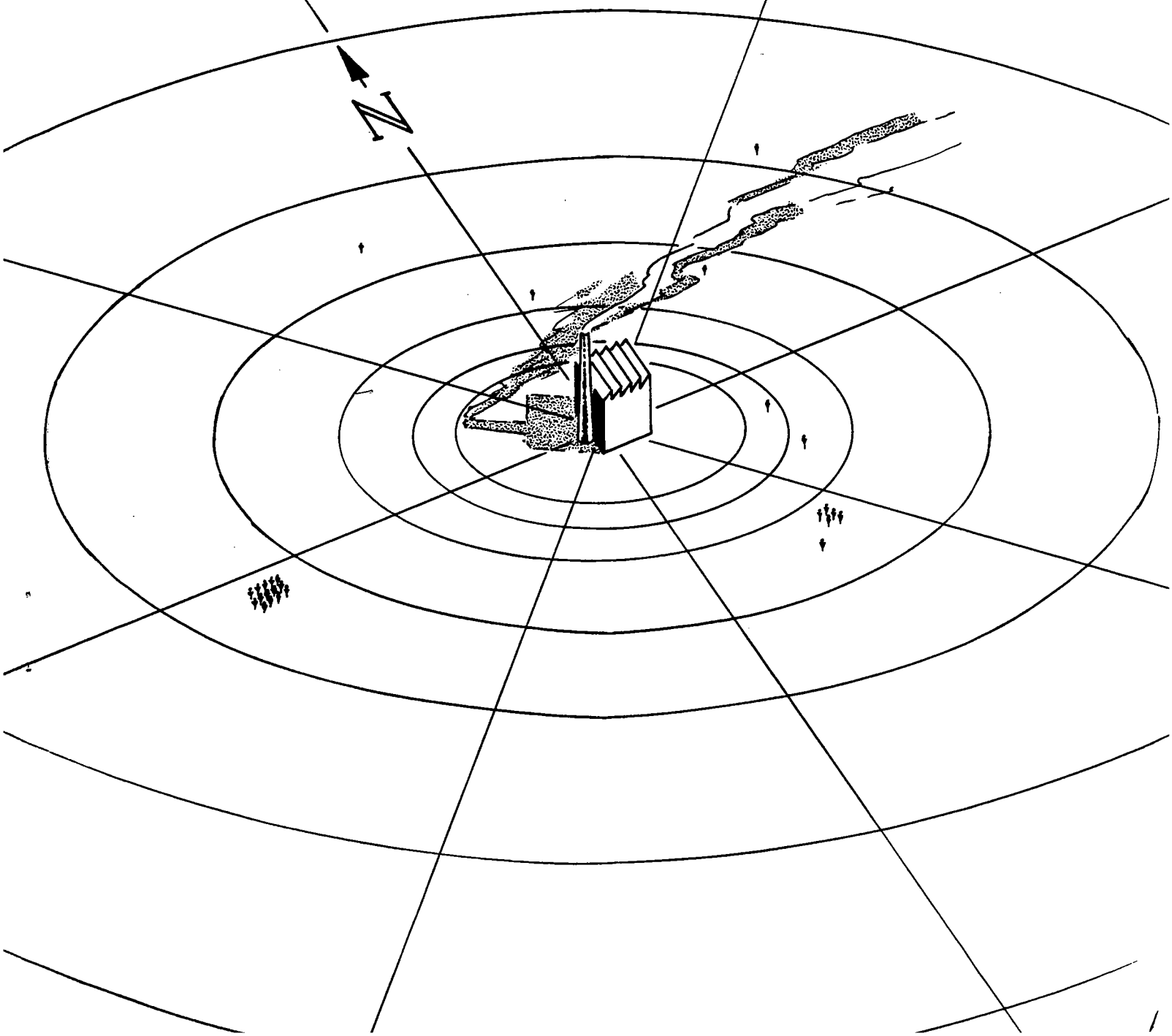

USER'S MANUAL

FOR

THE HUMAN EXPOSURE MODEL (HEM)

Pollutant Assessment Branch
Office of Air Quality Planning and Standards
May 1986

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Chapter 1

1-1. Introduction.

The Human Exposure Model (HEM) is a general model designed to estimate the population exposed to air pollutants emitted from stationary sources and the carcinogenic risk associated with this exposure. The HEM is comprised of (1) an atmospheric dispersion model, with included meteorological data, (2) a population distribution based on Bureau of Census data and (3) a procedure for estimating risks due to the predicted exposure. The only inputs needed to operate this model are source data, e.g., plant location, height of the emission release point, the temperature of the off gases, etc. Based on source data, the model estimates the magnitude and distribution of ambient air concentrations of the pollutant in the vicinity of the source. These concentration estimates are coupled with the population to estimate public exposure to the pollutant. The HEM then predicts population risks if a unit risk number determined from health data is input for the pollutant.

Within HEM there are two basic models, the Systems Applications Human Exposure and Dosage (SHED) model and the Systems Applications Human Exposure And Risk (SHEAR) model. The SHED model was developed to access sources on a nationwide source category basis, e.g., all primary copper smelters. It is generally faster and more economical to run SHED than SHEAR for major point sources (large producers and users). The SHEAR model was developed from SHED to model hot spots, or smaller regions with more than one source. In addition to modeling major point sources, SHEAR can also be used to model prototype sources (model plants) and area sources. Since the applications and actual data input of SHED and SHEAR vary, these aspects will be discussed in separate chapters of this manual.

1-2. When to Use SHED or SHEAR.

As explained above, SHED and SHEAR are two models within HEM which differ slightly in their purpose and scope. Table 1-1 summarizes the differences between the two models. This summary yields the following conclusions of which model should be used in a particular analysis:

1. Use SHED when addressing national exposure from one chemical.
2. Use SHEAR when addressing multiple chemicals from a source or group of sources and the assumption is valid that risks to human health can be approximated simply by adding together the risks from each chemical studied.
3. Use SHEAR when the source is located near uninhabitable areas such as large bodies of water and where the nearest population centroid is close (less than 1.0 km) to the plant.
4. Use SHEAR to assess the impact of area or prototype sources in small geographical areas.

These guidelines should assist in determining which model to use for a particular analysis. To show the possible differences which could be expected with SHED and SHEAR, the same plant was modeled using SHED and SHEAR. The results are outlined in Table 1-2. For more detail on the model differences please refer to Chapters 2 and 3.

Certain components of SHED and SHEAR are similar, for example, the meteorological and population data bases. The subsequent sections of this chapter will address those features common to both models.

1-3. Permanent Data Bases

Four major types of data are essential for assessing exposures to and dosages of atmospheric chemicals:

TABLE 1-1. THE SHED AND SHEAR MODELS

AREA EVALUATED	SHED	SHEAR
SCOPE	NATIONAL (MAJOR POINT SOURCES)	LIMITED GEOGRAPHICAL AREA ANALYSIS (MAJOR POINT, PROTOTYPICAL*, AND AREA** SOURCES)
POLLUTANTS	SINGLE POLLUTANT RUNS ONLY	MULTIPLE POLLUTANTS
NUMBER PEOPLE EXPOSED	DOUBLE COUNTS IF SOURCES SITED NEAR EACH OTHER	NUMBER OF PEOPLE EXPOSED HELD CONSTANT
INDIVIDUAL RISK	MORE REALISTIC ESTIMATE (GENERALLY OVERESTIMATES SLIGHTLY)	UNDERESTIMATE
RESOURCES	INEXPENSIVE TO RUN	MORE EXPENSIVE

* ASSIGNS MODEL PLANTS RANDOMLY TO BG/ED CENTROIDS

** EMISSIONS ASSIGNED TO POPULATION OR ASSUMED TO BE UNIFORMLY DISTRIBUTED OVER AREA SPECIFIED

TABLE 1-2. COMPARISON OF SHED AND SHEAR RESULTS

2 Plants Modeled in New York City (50 Km Radius)

MEASURES	SHED	SHEAR	RATIO SHED/SHEAR
Maximum Lifetime Risk	2.4×10^{-3}	5.9×10^{-4}	4.1
Annual Incidence	1.0	1.0	1
Total No. of People Exposed	27,400,000	13,700,000	2
No. of People Exposed to Incremental Risk			
$>10^{-3}$	1,285	0	
$>10^{-4}$	32,270	43,900	
$>10^{-5}$	927,000	1,380,000	
$>10^{-6}$	13,700,000	9,460,000	
$>10^{-7}$	27,000,000	13,500,000	
$>10^{-8}$	27,400,000	13,700,000	
Maximum Concentration Modeled	8.0×10^{-1} (.2 Km, NE)	8.0×10^{-1} (.2 Km, NE)	
Cost (1986)	$ 6.63	$ 61.50*	

* This is the cost of running the point source portion of SHEAR only. To run point source, you must first run a population routine called XTRACT which would cost additional dollars. The exact amount depends largely on the population density of the area modeled. New York City is >$100.

> Emissions inventories of chemicals

> Atmospheric reactivities of chemicals

> Meteorological data

> Population distribution data

The first two of the four types of data bases are data specific for each chemical. These data must be input for each risk assessment for SHED or SHEAR. These data bases are covered under each section entitled "Input Data" in the SHED and SHEAR chapters.

Meteorological data and population distributions do not vary with the specific chemical but depend on geographic location. These are permanent data bases in the program. The remainder of this section provides further detail on these data bases. Systems Applications, Incorporated (March 1983 and May 1983) provide more detail on the creation of these data bases.

Health data are essential to derive population risks from population exposure. However, these data are provided in the form of a unit risk estimate, which is derived external to the exposure model. This health data type will not be discussed in this manual.

Meteorological Data

The dispersion computations carried out by the HEM require data on wind speed, wind direction, and the intensity of atmospheric turbulence. The turbulence intensity is represented by the atmospheric stability class. These data are provided by a permanent data base in the program known as the Stability Array or STAR data set.

Acquisition and Processing of STAR Data

Martin and Tikvart (1968) developed the STAR program from routinely collected meteorological data to generate frequencies and percentage frequencies of wind direction by speed classes for each stability category.

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The specifications of stability categories depending on wind speed and sky cover were set up by Pasquill (1961) and were modified by Turner (1964). The program was adopted for use at the National Climatic Center (NCC), where archived records of all national reporting weather stations are kept. The most up-to-date version of the STAR data from all STAR stations in the country was obtained on magnetic tape from NCC, and the matrices of STAR frequencies used in the program were taken from these tapes.

The data sets on the NCC tapes were reprocessed into a format which includes 16 wind directions, six wind speed classes, and seven stability categories with categories A, B, C, and D_{day} in the daytime and categories D_{night}, E, and F in the nighttime. There are data sets for 312 stations in this reprocessed STAR data file. Figure 1-1 shows the locations of these STAR sites.

STAR Station Selection

By default, meteorological data recorded at the STAR station nearest to the source are used in the dispersion modeling for SHED. The nearest station is typically input for SHEAR, as well. (See Appendix A for location of the nearest STAR station.) However, local meteorological trends and topographic features may be more important factors in selecting a STAR station than is the absolute distance between the source and the station. A STAR station with climatological conditions most similar to those of the source of emissions may not be the nearest station, so the STAR stations may be manually selected to account for such situations.

Detailed STAR Selection Process

As stated previously, STAR stations can be manually selected such that they are in similar local meteorological regimes and are influenced by

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Figure 1-1. Locations of STAR Stations

similar orographic (topography on the scale of mountain ranges) conditions as the emission sources. Major features which should be considered include the following:

> Surface thermal patterns, which can affect the local wind. For example, the local sea-land breeze wind system is usually limited to surface-based layers several hundred meters thick. Since this region is the atmospheric layer into which chemicals are emitted, consideration of these winds is important for chemical plants located on ocean coasts or adjacent to large lakes. Another example concerns foehn winds (winds flowing down mountains), the influence of which should be considered for emissions sources located in Montana (Chinook wind) and in Los Angeles County (the Santa Ana wind).

> Wind patterns may be obtained from the Climatic Atlas (U.S. Environmental Data Service, 1968) and from maps of the U.S. Geological Survey (1:500,000; 1:125,000).

> Topographical effects, such as that of mountain-valley wind. The behavior of the wind in ridge-valley topography depends both on the relationships between the wind direction and the solar azimuth, and on the orientation of the ridge lines and valleys. These local wind effects should be taken into consideration in the selection process, especially for emissions sources located in the valleys of the Cascades and coastal ranges (northwestern states) or the Appalachian Mountains (eastern states).

> Urban effects, including wind, low disturbances by urban thermal or frictional elements such as organized patterns of urban skyscrapers (Chicago, New York City, Los Angeles metropolitan, etc.). Such

features substantially influence airstream and, consequently, the diffusion of air contaminants. If an emission source is located in a small city, and if STAR stations in a large city and in a small city are equidistant from the emission source, then preference should be given to the STAR station in the small city.

Population Distribution Data Base

The HEM program uses the latitude and longitude from the input data in determining the population of the study area. The permanent data base is comprised of the 1980 Census Data Base broken down by Block Group/Enumeration District (BG/ED). Further information on this data base and the manner in which it is accessed is covered in the following sections.

Population Data Processing

The population data base contains the population centroid coordinates (latitude and longitude) and the 1980 population of each BG/ED in the country (about 300,000 centroids in 50 states plus the District of Columbia) as found in Master Area Reference File 2 (MARF2). In addition, the data base contains large arrays of descriptive and summary population statistics. While these data may be a valuable adjunct in certain types of exposure analyses, the size of the complete file interferes with efficient access to the small subset of information needed for most exposure calculations. For this reason, the permanent data base contains only the essential information in a form that permits rapid access to the relevant study area.

1-4. Computer Access

The HEM program is currently run on the National Computer Center's (NCC) UNIVAC computer system located at Research Triangle Park, N.C. The computer may be easily accessed by terminals located at Research Triangle

Park and at EPA's facilities in the NC Mutual Building in Durham, NC. Terminals in the Mutual Building are presently located in Rooms 934, 624, 654, 653 and 646A.

Access can also be obtained via the EPA regional offices or through any organization using the NCC system. To gain access to the computer, users must have an account to which the computer time will be charged and a user ID. Within the Environmental Protection Agency, user IDs and accounts are obtained through the ADP coordinator by contacting Pete Carter at (919) 541-3522. For information concerning interagency agreements contact Jim Obenchain at (919) 541-2122. To set up a contract for the NCC UNIVAC outside of EPA, contact Ms. Weaver of National Technical Information Service (NTIS) at (703) 487-4805. Ms. Weaver can send the appropriate forms which must be completed and returned. Ms. Weaver will also upon receipt of the completed paperwork, contact EPA to obtain an account number and user ID. To establish equipment compatability call TELE Communications at (919) 541-4506, FTS 629-4506 or (800) 334-0741.

The HEM is frequently under revision to ensure that the best information is incorporated. This manual will thus soon become outdated. Therefore, before attempting to operate HEM, please contact Michael Dusetzina, Brenda Riddle or George Duggan of the Pollutant Assessment Branch, at (919) 541-5645 or FTS 629-5645. These personnel can alert you to changes in the model and can help in deciding which version of the model may be most appropriate for your application. Once one of these is contacted and you have an account number and a compatible terminal, HEM may be run by following the instruction detailed in sections 2-5 and 3-5.

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1-5. Risk Estimates

The HEM produces estimates of annual incidence and maximum individual lifetime risk. These numbers, however, should not be construed as the absolute health risks. HEM was designed to screen, 1) substances to be regulated, 2) source cagtegories to be regulated and 3) alternative control techniques. To produce results inexpensively with limited data (as required by screening techniques), HEM makes many simplifying assumptions. Since these assumptions are common among HEM runs, the results can be compared. Therefore, HEM results should be used only to compare within similar substances, scenarios, etc. for decision-making and <u>not</u> be presented as absolute values of risk.

The assumptions required to estimate the health risk with HEM involve both estimating the exposure to a substance and estimating the health effects due to this exposure. These assumptions are outlined below.

<u>Exposure Assessment</u>

The HEM estimates concentrations of a substance in the ambient air at specific points around a source. It is known, however, that pollutant exposure occurs for exposures other than ambient air exposures (i.e., food, water) and populations move through different microenvironments. This model also employs a number of simplifying assumptions including:

1. It is assumed that most exposure occurs at population weighted centers (centroids) of block group and enumeration districts (BG/ED) as the locations of actual residences are not contained in available databases. The model relies on information provided in a database developed by the U.S. Census Bureau.

2. It is assumed that people reside at these centroids for their entire lifetimes (assumed to be 70 years for calculating cancer risk).

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3. It is assumed that indoor concentrations are the same as outdoor concentrations.

4. It is assumed that plants emit pollutants at the same emission rate for 70 years.

5. It is assumed that the only source of exposure is the ambient air and resuspension of pollutants via dust is not considered.

6. It is assumed that there is no population migration or growth.

7. The model does not provide for descriminating exposure situations that may differ with age, sex, health status, or other situations.

8. The model is designed to model for flat terrain.

Table 1 presents the directional impact some of these assumptions may have on the risk results. It is important to note that these estimates may not be universally applicable to all pollutants and source categories. Nevertheless, they should serve as a useful qualitative description of the effect each assumption may have on the risk estimates.

There is also uncertainty associated with various specifications required for running the HEM as well as uncertainty associated with the variables specified. These model specifications and variables include:

1. Given the variations in meteorology each year and with each location, there is uncertainty as to the extent to which the meteorological station used to model the site modeled is representative. This includes the selection of urban or rural for stability.

2. There is uncertainty associated with the emission estimates and the plant parameters used to characterize the emission source.

3. If the plant is not correctly located, there will be a problem in the matching of population census data with concentrations, which alters

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TABLE 1. DIRECTIONAL IMPACT OF SIMPLIFYING ASSUMPTIONS ON RISK ESTIMATES

MODEL ASSUMPTION	MAXIMUM INDIVIDUAL RISK	AGGREGATE RISK	COMMENT
Exposure at centroids	Underestimates	Minimal underestimate	SHEAR underestimates risk close to the plant due to this assumption
Exposure at receptors	Overestimates occasionally	Minimal overestimate	SHED can overestimate with this assumption if no one lives at the highest concentration level
Indoor exposure equals outdoor	Overestimates	Overestimates	This assumes no indoor sources of the pollutant
Immobile population	Overestimates	No effect	Aggregate is unaffected because population leaving are replaced at the same rate
No individual behavior patterns	Underestimates	Underestimates	Individuals are at a higher risk due to outdoor or closer activities
Flat terrain	Underestimates	Underestimates	Unless the source is higher than the surrounding area, the plume impacts on rough terrain

risk estimates.

Table 2 presents some of the specifications required by HEM and the directional impact of selecting one specification rather than another. Again, these impact estimates may not apply to all situations and sources but may provide useful information for the general trend.

Unit Risk Value

The unit risk value constitutes all of the health risk information input required by the HEM. The uncertainty involved with the unit risk estimate depends on the amount, type and quality of data used in its development. For instance, when only animal data is available, a statistical upper bound is used to calculate the unit risk. When human data is available, a maximum likelihood estimate is used to estimate the unit risk. Although these are similar, the upper bound is often higher than the maximum likelihood estimate by a factor of 2 or 3. There are several areas that contribute to the uncertainty associated with the unit risk or cancer potency estimates developed by the Carcinogen Assessment Group. These areas are divided in a number of different ways but the following grouping is reasonable:

1. Extrapolation: Animal-to-man or route-to-route.

2. Absorption: When route-to-route extrapolation is employed it is necessary to examine, if available, absorption estimates that have been derived from controlled exposure studies using concentrations that are reasonably similar to the ambient exposures.

3. Model Specifications: The consistency of model specifications used in calculating the cancer unit risk estimates.

4. Pharmacokinetics: The consideration of pharmacokinetics especially for studies requiring route-to-route extrapolation.

TABLE 2. COMPARISON OF RISK ESTIMATES BASED ON VARIOUS HEM SPECIFICATIONS

MODEL ASSUMPTION	MAXIMUM INDIVIDUAL RISK	AGGREGATE RISK	COMMENT
Urban vs rural	Higher estimates	Lower estimates	Rural setting results in more stable meteorology and higher distant concentrations. Urban setting is less stable but generally produces higher maximum individual risk.
Stack height (low vs high)	Higher estimates	Somewhat higher estimates	Taller stacks cause greater dispersion within the 50 km area and hence lower concentrations
Exit velocity (low vs high)	Higher estimates	Higher estimates	Higher velocities cause more dispersion and lower concentrations
Emissions	Proportional	Proportional	Concentrations and risk are proportional to emissions
Diameter (small vs large)	Higher estimates	Higher estimates	Only affects the risk occasionally
Location			
Small city	Higher/lower	Higher/lower	Location of sources determines affected BG/EDs. Large cities are more likely to have consistent population density. Location can have a very large impact for small and medium cities.
Medium city	Higher/lower	Higher/lower	
Large city	Minimal	Minimal	

Chapter 2

2-1. Introduction to SHED

SHED is a model within HEM that is used primarily for major (specific) point sources (usually producers or large users of specified chemicals) on a nationwide basis. Each source in SHED must be specifically located by longitude and latitude. For each source the release parameters must be described, these include stack height, exit velocity, emission rate, etc.

SHED is relatively fast to run. After input of the data, the program may take only ten minutes of computer time to run as many as one hundred sources. This rapid processing causes SHED to be relatively inexpensive to run.

2-2. Input Data

As discussed in Section 1-2, the meteorological data and population data are part of the internal computer data base. The necessary input data falls into four categories:

> Source Location

> Emissions Data

> Vent Parameter Data

> Atmospheric Reactivities of Chemicals

Source location, emissions data and vent parameter data are always necessary to analyze sources. The atmospheric reactivities, however, are only necessary when the chemical is extremely reactive. For example, the atmosphere half-life should be specified for those chemicals with half-lives of less than three or four hours. The following section provides additional guidance on the information needed and possible sources of the information. How to input the data into a file for use by the program is discussed in Section 2-5.

To link the computed exposures to the cancer risk of the population, the unit risk estimate must also be included. Generally, these estimates are obtained from the Carcinogen Assessment Group in a Health Assessment Document (HAD) for the chemical. A unit risk estimate is the estimated risk of cancer to an individual if that individual is exposed to one $\mu g/m^3$ of the chemical for their entire lifetime. Hence it is expressed in units of $(\mu g/m^3)^{-1}$. If the unit risk is unknown, HEM assumes a risk of 1.0. The results then merely reflect the concentrations and the number of people exposed to those concentrations without estimating the health risk from that exposure. The "annual incidence" and "maximum individual risk" numbers reported using a unit risk of one may simply be multiplied by the correct unit risk number when it becomes availabale.

Source Location

The geographic location of the source must be identified in order to run the SHED portion of HEM. Specific point source locations may be determined generally from a variety of published sources. These include:

> Directory of Chemical Producers and Chemical Economics Handbook, published by Stanford Research Institute.

> "Chemical Marketing Reporter."

> U.S. Government publications, such as the U.S. Tariff Commission's Synthetic Organic Chemical Production and Sales."

> Reference guides, such as the "Kline Guide to the Chemical Industry."

> Other sources, such as trade associations, trade journals and periodicals, and technical journals and periodicals.

> Existing EPA exposure and risk reports.

Once the general locations (company name, city and state) of the point source are determined, geographic coordinates must be assigned. Geographic coordinate information can also be determined from a variety of sources. These include:

> Personal communication with state air agencies and/or EPA regional offices.

> Emissions inventory files (e.g., the National Emissions Data System (NEDS).

> United States Geological Survey Maps (U.S.G.S).

> Existing EPA exposure and risk reports.

In some instances, these sources will be able to provide geographic coordinates in Universal Tranverse Mercator (UTMs) units. These may be converted by use of a computer program on the UNIVAC system to geodetic coordinates (latitude/longitude). To use this program, please refer to Appendix B.

Emissions Data

Emission factors can be developed to estimate the emissions from the production, consumption, and incidental formation of the various chemicals assessed. The emission factor is expressed as the total kilograms of a specific chemical lost to the atmosphere per kilogram of the chemical produced or used. Multiplication of the emission factor by the quantity of the chemical produced or used at an individual site or in a specific geographic region during a specific time period yields the estimated emissions of the chemical, in kilograms, for that location.

The total emissions resulting from the production of a chemical or chemical intermediate use of a specific chemical are a summation of process, storage, and fugitive emissions losses:

> Process emissions are discrete losses that occur at process vents from reactors, columns, and other types of plant equipment.

> Storage emissions include losses from the raw material feed, in-process and final product storage tanks, as well as from loading and handling losses.

> Fugitive emissions are losses that result from plant equipment leaks, visual openings, evaporation from waste products, and other non-discrete sources.

If possible, emission factors should be determined for each of these types of emissions. To develop specific chemical emission factors various methods are available. Each method produces its own level of reliability of the resulting data. Below are listed some of these methods, in decreasing order of reliability:

> Plant Site Visits: Data are collected by actual site visits or from letters to producers. In certain instances this actual data from a few producers may be useful for preparing model plant parameters for a large number of producers.

> State Air Emission Inventory Questionaires (EIQs): The air EIQs for most manufacturing sites are on file at various state air agencies throughout the United States.

> Other Published Sources: A variety of published reports for different chemicals and types of sources have been prepared by EPA and for EPA by contractors. The most recent publications should be used.

> Engineering Estimates: Occasionally certain pollutants are produced or used in a similar manner. In such cases, estimates from an unknown process can be made by generalizing from a similar, previously defined process. In other instances, an emission factor for an unknown chemical intermediate use of a specific chemical can be calculated based on a weighted average factor of all other known chemical intermediate uses of the same chemical.

Once the emission factor is determined it must be multiplied by the plant's consumption to determine the emission rate required for input to the HEM.

Vent Parameter Data

Vent parameter data are necessary for dispersion modeling of the chemical emissions. The vent parameter data in each of the chemical summaries include the number of process and storage tank vents, vent height, vent diameter, gas discharge temperature, gas emission velocity, fugitive discharge area, and building cross-sectional area. These data can be obtained from the same four source levels discussed above, under emission factors. Some data are supplied by producers during site visits, some data are obtained from EIQs, and some from other published reports or text books.

Atmospheric Reactivities of Chemicals

A variety of studies have reported the lifetime or atmospheric residence time of many listed chemicals. Often, however, the basis for the decay rates are not given and reconciliation between studies tends to be impossible. In this instance, all available data and best engineering judgment should be used.

Most chemical destruction of gaseous compounds in the atmosphere occurs by one of the following three mechanisms:

> Photolysis

> Reaction with free radicals (chiefly hydroxyl)

> Reaction with atmospheric oxidants (chiefly ozone)

The process of photolysis and reaction with hydroxyl radicals occur only during daylight hours. Hydroxyl radicals have a short atmospheric residence time and require a continuing photolytic source to maintain their concentrations. Thus, if no source for the hydroxyl radical exists, no reaction will occur.

The HEM is generally constrained to a study area in a 50 km radius of the source. In most instances, the reactivity of a chemical is not sufficiently high to cause significant removal before the material is dispersed to this distance. Therefore, this input to the HEM can be left blank with the model assuming no atmospheric decay. Some chemicals, however, do have high reactivity (e.g., formaldehyde) and should be analyzed for this behavior.

2-3. Dispersion Modeling

The previous section discussed the information necessary to run the SHED model. This section explains how that data is used to give the resulting exposure/dosage estimation.

The concentration patterns caused by major point source emissions depend most strongly on four factors.

> Emission rate

> Source elevation above terrain (stack height); effective plume elevation may, in turn, depend on meteorological factors

> Wind vectors (speed and direction)

> Dispersive effects (intensity of atmospheric turbulence)

The dispersion model in SHED is a Gaussian model in the climatological form of the EPA's Climatological Dispersion Model (CDM) in that it uses the same basic dispersion algorithm, is coded and used to estimate the annual average ground-level concentrations resulting from emissions of major point sources. Flat terrain is assumed.

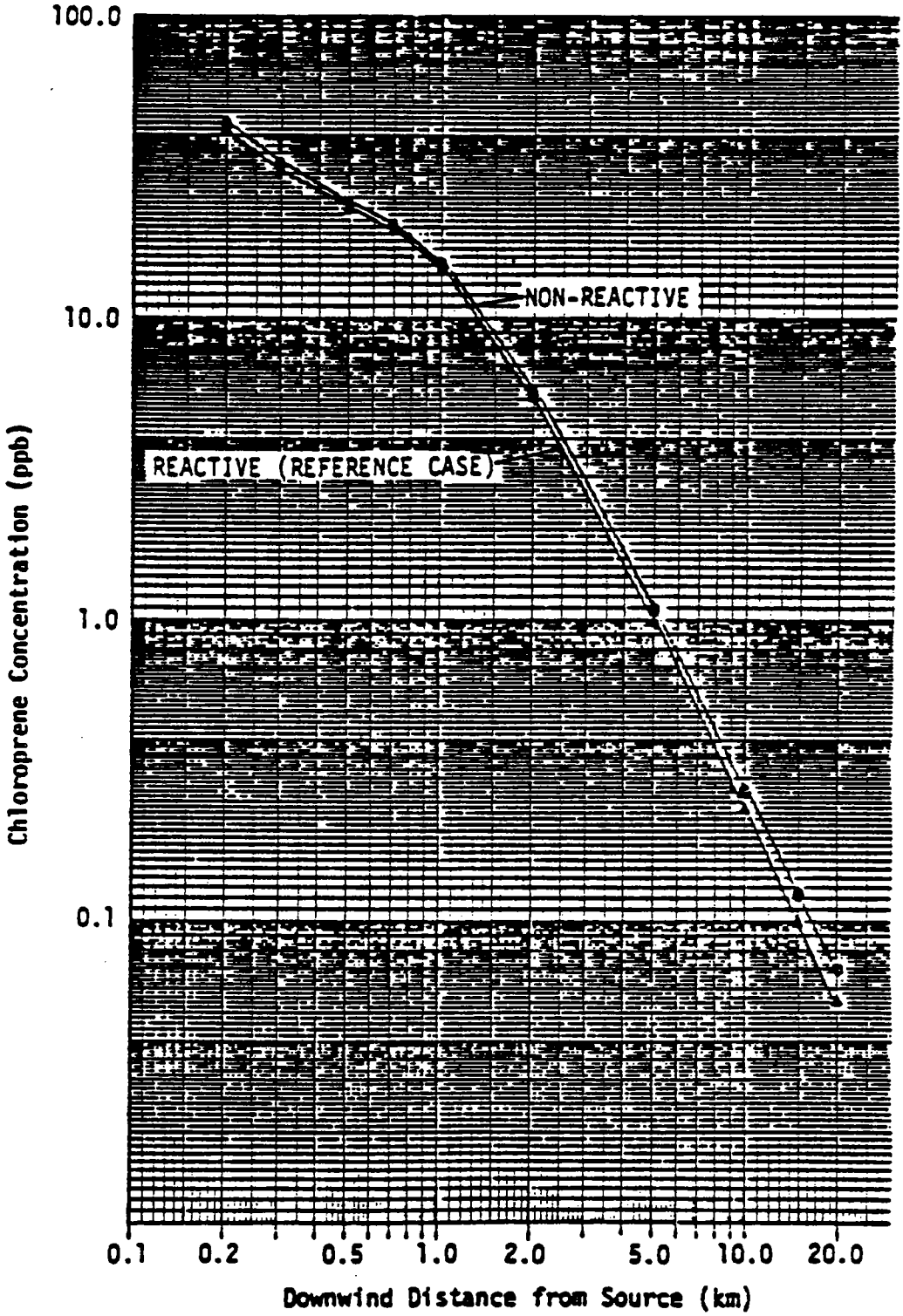
The maximum radius generally considered in the exposure/dosage estimation is set as 50 km for major point sources. Concentrations are estimated for 10 receptors--0.2, 0.5, 1.0, 2.0, 5.0, 10.0, 20.0, 30.0, 40.0, and 50.0 km from the source--along each of the 16 wind directions. In some instances

there may be more than one type of point source (each with its characteristic release height, emissions rate, etc.) within a single plant. Fugitive emissions (valve and flange leaks, etc.) that are random and indeterminate but not negligible can be approximated by an area or volume approximation at a reasonable level above the ground (1-10m). This is the height range typical of outdoor plumbing. Each emissions category is modeled individually, and the total ground-level concentrations resulting from plant emissions are then computed by summing the individual estimates.

The dispersion algorithm can also treat chemical formation and decay, enhanced dispersion caused by building wake effects, and release or stack height. These features are discussed in the following subsections.

Chemical Reactivity

The detailed approach adopted in estimating the effect of chemical reactions on ambient concentrations is shown with chloroprene as an example. Chloroprene is an organic compound that is decidedly photoreactive in the atmosphere. Based on preliminary calculations conducted with the estimated chloroprene atmospheric decay rate, approximately 90 percent of the chloroprene emitted into the sunlit urban atmosphere would be removed within an hour through reaction with hydroxyl radicals and ozone molecules. However, the chemical decay rates are much lower in the nighttime or under overcast conditions. Figure 2-1 displays a comparison between the resulting concentrations along a single wind direction with and without the chemical decay computed for a chloroprene example. Because the atmospheric reactions change atmospheric concentrations over time, the reactivity of a compound has less impact on the concentrations near the emissions source than further downwind. The difference in concentrations between the two curves of



Source: Systems Applications, Incorporated computations using SAI dispersion model and SAI reactivity estimates.

FIGURE 2-1 EFFECTS OF CHEMICAL REACTIVITY ON CONCENTRATION DISTRIBUTION OF CHLOROPRENE

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Figure 2-1 at 200 meters from the source is about 3 percent (43.2/41.9 - 1); at 20 km from the source the difference is about 30 percent (0.070/0.054 - 1).

Building Wake Effect

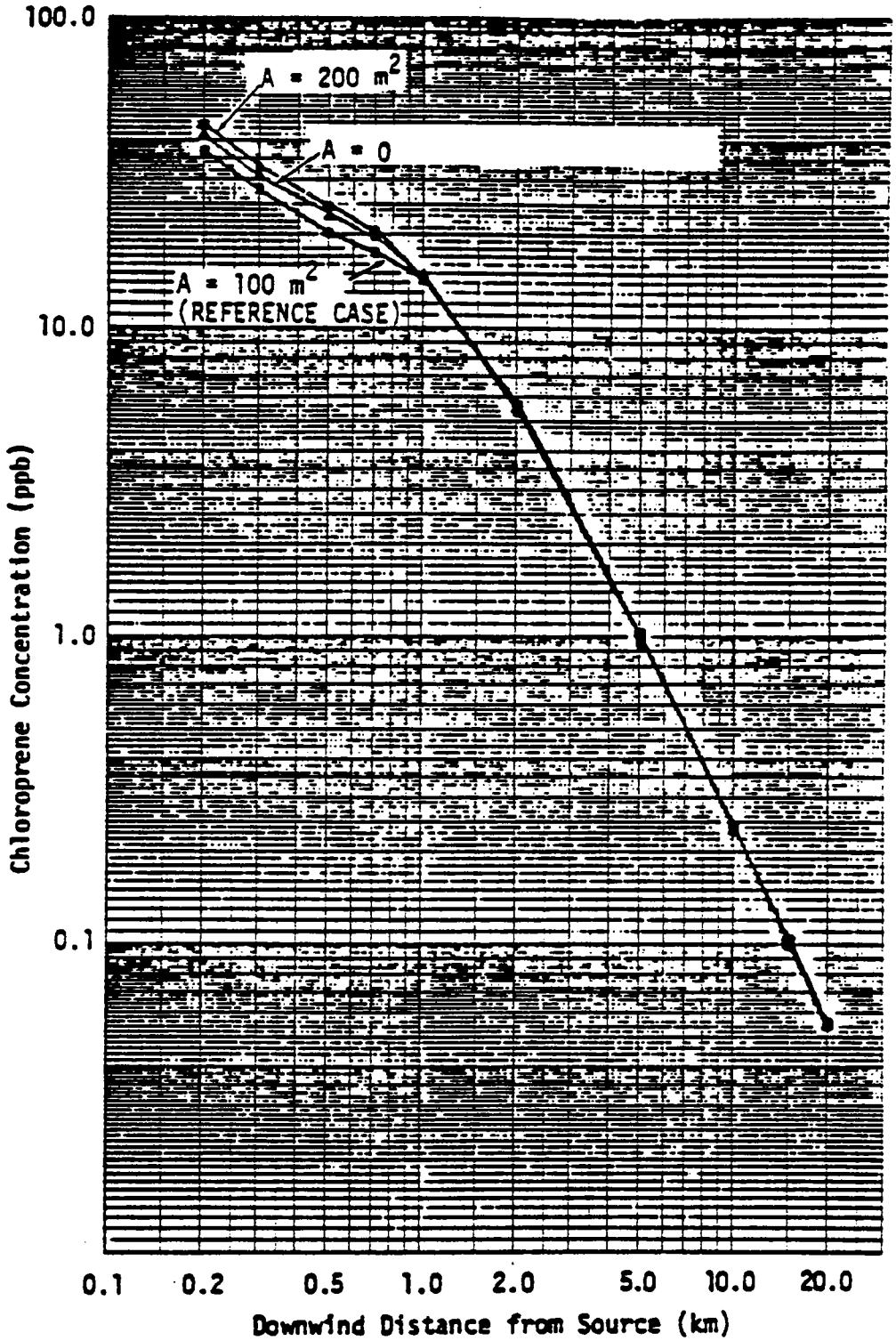
Pollutants emitted into the wake of a building are subject to an enhanced dispersion (e.g., the concentration is reduced very quickly by the turbulence on the lee side of the building). If a dispersion analysis ignored this effect, the occurrence of high concentrations would be overestimated.

The ground-level concentrations that result from different building structure dimensions are depicted in Figure 2-2, where the major parameters for estimating these concentrations are the same as those of the reference case. Clearly, the building wake effect would have insignificant impacts on ground-level concentrations at points further downwind from the source than 1.0 km. However, sources with larger building effects would result in larger ground-level concentrations near the sources. Additional analyses that assess the precise impacts of building wake effect may be required to determine the extent to which the example in Figure 2-2 is site-specific.

Release Height

The exact release height of a source can have a great effect on ground-level concentrations. As Figure 2-3 shows, concentrations resulting from ground-level emissions (H = 0) can be more than 10 times as great as those resulting from emissions at a moderate height (H > 20 m). However, these differences become insignificant further downwind (R > 5 km).

Figures 2-1, 2-2, and 2-3 indicate that groundlevel concentrations decrease approximately log-log linearly with distance at receptors more



Source: Systems Applications, Incorporated computations using SAI dispersion model and SAI building wake algorithms.

FIGURE 2-2 EFFECT OF BUILDING WAKE ON CONCENTRATION DISTRIBUTION OF CHLOROPRENE

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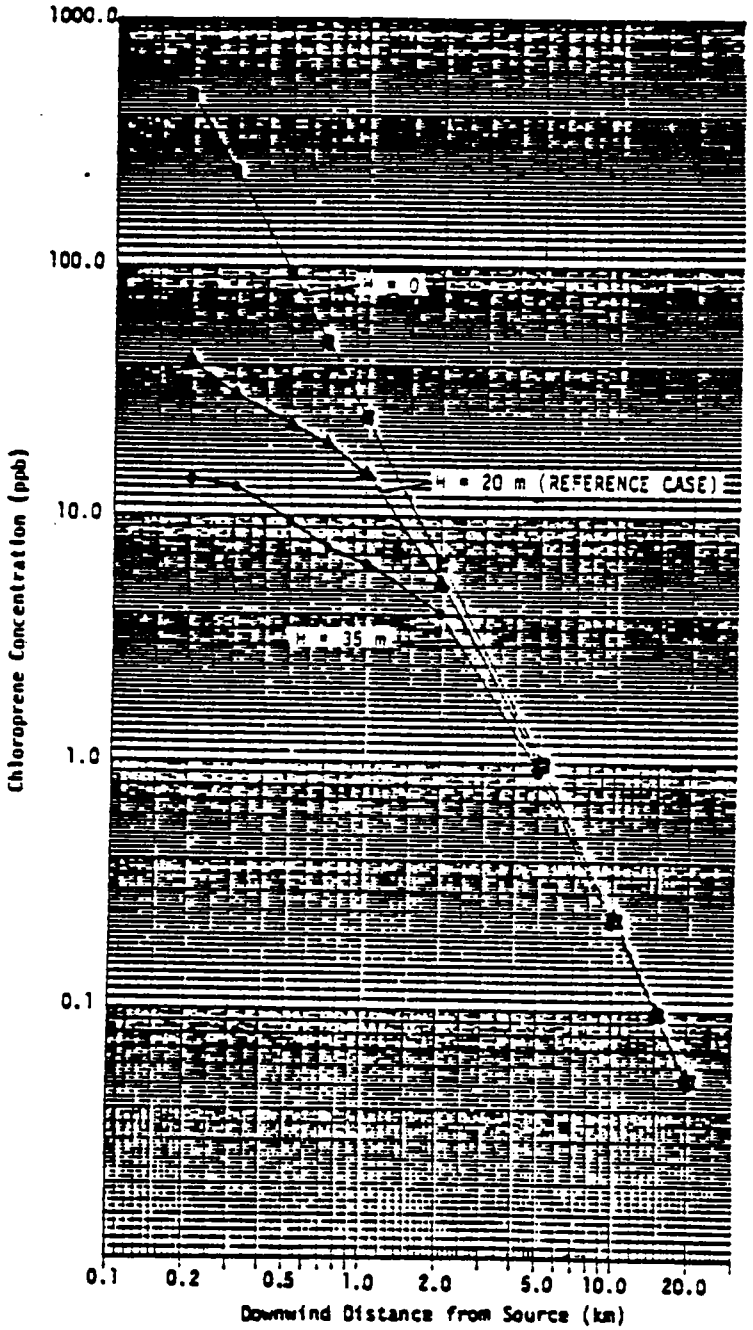


Source: Systems Applications, Incorporated computations using SAI dispersion model and Briggs' plume rise formulas

FIGURE 2-3 IMPACTS OF RELEASE HEIGHT ON CONCENTRATION DISTRIBUTION OF CHLOROPRENE

than 2 km from the source. A plot of this log-log linear relationship could be used to interpolate concentrations at specific locations within the range of 2 to 50 km from the source.

Exposure and Dosage Estimation Scheme

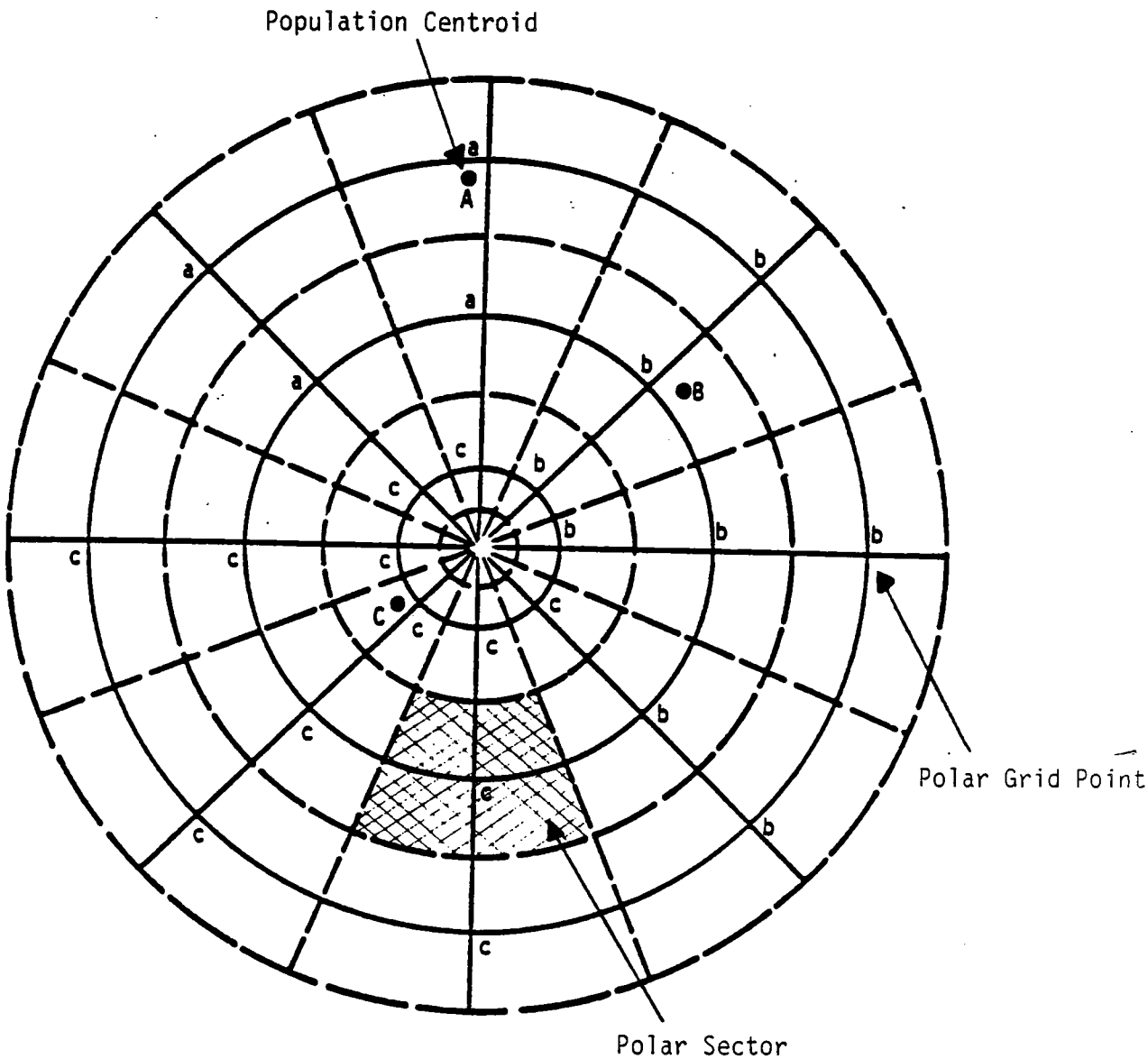
The dispersion modeling approach is coded in a standard Fortran program. The output of the program is a concentration array for 160 receptors around the plant (10 receptors along each of the 16 wind directions). These are the sum of concentration patterns resulting from all sources within a plant. This subsection outlines the basic approach used in combining the concentration pattern with the population distribution pattern around a plant. Three terms are defined here that will be used frequently in the following discussion. A polar grid point is one of the 160 receptors at which concentrations are estimated by the dispersion modeling. A population centroid is the population-weighted geographical center of a BG/ED for which geodetic coordinates are known. A grid cell is defined as the area bounded by two radial arcs and two wind directions.

Exposure is the product of the population and the concentration to which that population is exposed. To form this product, both the concentration and the population must be known at the same location or point. The SHED model uses a two-level interpolation scheme to pair the concentrations with populations prior to the compution of dosages and exposures. The two-level approach is appropriate because the concentrations are defined on a radius-azimuth (polar) grid pattern with non-uniform spacing. This means that at small radii the grid cells are much smaller than BG/EDs while at larger radii the grid cells are much larger than BG/EDs. Interpolation techniques are most appropriately applied by interpolating values of the factor defined on a coarse network (larger) at the locations of the finer (smaller) network, thus

maximizing the resolution and minimizing the uncertainties of interpolation. As previously mentioned, the fine/course relationship between polar grid cells and BG/EDs varies with radius. Hence, the two level approach allows the BG/ED population to be interpolated to the grid point when the BG/EDs are larger than the grid cells and allows the grid point concentration to be interpolated to the BG/ED centroid when the reverse is true. The details of this approach are outlined below. The numbers used assume the analysis is to be completed for a 50 km radius. If the maximum radius changes, so will the radii of the grid points.

For BG/ED centroids located between 0.2 km and 3.5 km from the source, populations are apportioned among neighboring polar grid points. There are 64 (4 x 16) polar grid points within this range. Associated with each of these grid points, at which the concentration is known, is a smaller polar sector bounded by two concentric arcs and two radial lines. The boundary concentric arcs are defined by radii of .10, .35, .75, 1.5, and 3.5 km and the boundary radial lines are drawn right in the middle of two wind directions. These boundary lines are represented by the dashed lines in Figure 2-4. Each of the polar grid points are assigned to the nearest BG/ED centroid identified from the census data set. The population at each centroid is then apportioned among all polar grid points assigned to that centroid according to the area of the polar sector associated with the grid point. For example, all of the polar grid points (labeled b) nearest population centroid B would be assigned a certain proportion of the people in B. The ratio between the area of the polar sector and the area assigned to the population centroid determine the proportionment. Thus, the population density is assumed to be the same for all polar sectors assigned to a single centroid. Figure 2-4 shows that the grid points closer to the source are boxed in by much smaller

Figure 2-4. Pairing of BG/ED with Concentration Within A 3.5 Km Radius



A, B, C - Locations of BG/ED Centroids

a, b, c - Polar grid points to be allocated a portion of population reported at centroids A, B, C, respectively.

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sectors than those further away. Hence, the b grid points closer to the center will receive a smaller apportionment of the people from population centroid B than those further away. Both concentration and population counts are thus available for each polar grid point.

Log-log linear interpolation is used to estimate the concentration at each ED/BG population centroid located between 3.5 km and 50 km from the source. Concentration estimates for 96 (6 x 16) grid points (receptors at 5.0, 10.0, 20.0, 30.0, 40.0 and 50.0 km from the source along each of the sixteen directions) resulting from dispersion modeling are used here as reference points for this interpolation. For each ED/BG centroid, four reference points are located at the four corners of the polar sector in which the centroid is located. These four reference points (labeled C_1, C_2, C_3, and C_4) would surround the centroid (C_x) as depicted in Figure 2-5. As shown in Figures 2-1, 2-2, and 2-3, there is a linear relationship between the logarithm of concentrations and the logarithm of distances for receptors more than 2.0 km away from the source. This relationship is used to estimate the concentrations at points CA_1 and CA_2 (see Figure 2-5). These estimates, are then linearly interpolated with the polar angle to determine the concentration at the centroid (C_x). Using the two-level approach, concentrations and populations are paired up for the 64 concentration grid points within 3.5 km of the source and for all BG/ED centroids located between 3.5 km and 50 km from the source.

The total dosage was then computed as follows:

$$\text{Total Annual Dosage } (\mu g/m^3\text{-person}) = \sum_{i=1}^{N} P_i C_i \quad ,$$

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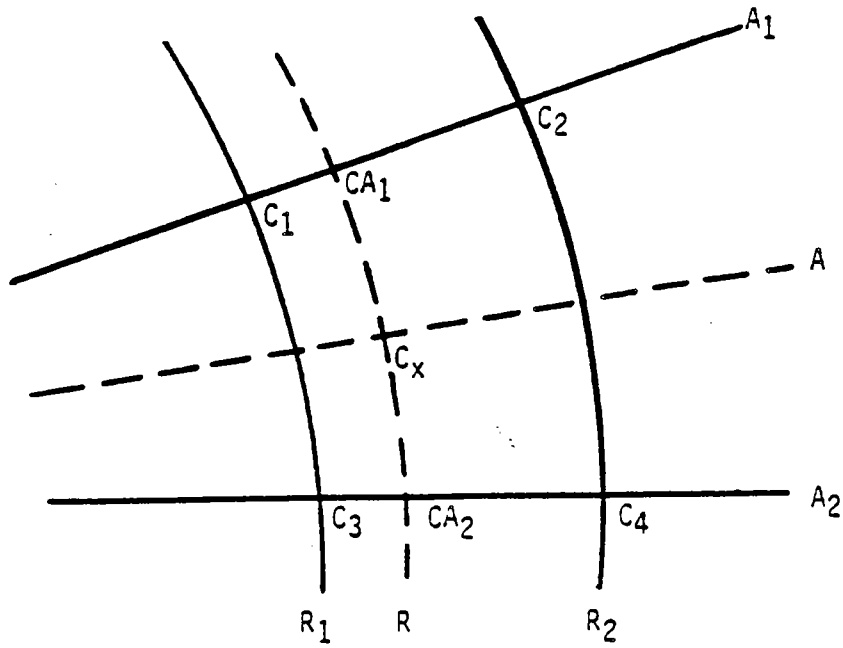
Figure 2-5 Log-linear Interpolation Scheme



Given:

A = The angle in degrees subtended clockwise about the source from due south to the BG/ED centroid;

A_1 = The angle from due south to the radial line immediately counterclockwise from A, or passing through A if there is an exact match;

A_2 = The angle from the south to the radial line immediately clockwise of A_1 (A_2 is 0 if it is due south);

R = The distance from the source to the BG/ED centroid;

R_1 = The distance from the source to the largest circular arc of radius on grid that is less than R;

R_2 = The distance from the source to the smallest circular arc of radius on grid that is greater than or equal to R;

C_1 = The concentration value at (A_1, R_1);

C_2 = The concentration value at (A_1, R_2);

C_3 = The concentration value at (A_2, R_1);

C_4 = The concentration value at (A_2, R_2); then

$$CA_1 = \exp\left(\ln C_1 + (\ln C_2 - \ln C_1)(\ln R - \ln R_1) / (\ln R_2 - \ln R_1)\right)$$

$$CA_2 = \exp\left(\ln C_3 + (\ln C_4 - \ln C_3)(\ln R - \ln R_1) / (\ln R_2 - \ln R_1)\right)$$

$$C_x = CA_1 + (CA_2 - CA_1)(A - A_1) / (A_2 - A_1)$$

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where P_i = the population at point i, C_i = the annual average concentration at point i, and N = the total number of grid points and ED/BG centroids with a specified combination of concentration and population (representing the entire area within 50 km of the source).

The population exposed to each of a number of concentration levels, L_j, was computed by:

$$\text{Exposure to } L_j \text{ (person)} = \sum_{i=1}^{N} P_i S_i(C_i, L_j) \quad ,$$

where

$$S_i = \begin{cases} 0 & , \quad \text{if } C_1 < L_j \\ 1 & , \quad \text{if } C_i \geq L_j \end{cases} \quad .$$

The dosage of the fraction of the population that is exposed to concentrations greater than or equal to each of a number of concentration levels, L_j, was computed by using the following summation:

$$\text{Annual Dosage at } L_j \text{ } (\mu g/m^3\text{-person}) = \sum_{i=1}^{N} P_i C_i S_i(C_i, L_j) \quad .$$

Note that the annual dosage at the minimum concentration within 50 km of the source will equal the total annual dosage.

The concentration levels at which exposure is to be estimated are selected by an exponential function coded in the program.

2-4. Assumptions

In order for SHED to be simple, run quickly and require as little input data as it does, certain assumptions must be made. This section outlines the necessary assumptions to provide the user with an understanding of the limitations of the model and the need to consider such limitations in the use of the output data.

Population Count Errors

The SHED model uses census data to the BG/ED level. Although this is the smallest defined population unit, it still places on average approximately 800 people at one point. In reality, some people will reside closer to the plant and may be more highly exposed. For others, the modeled exposure will be an overestimate of the actual exposure.

Another problem occurs when two plants are located within 50 km of one another. The people who are exposed to both plants will be counted twice in the summation of the exposed population. Although the number of people will be an overestimate, the dosage (people times concentrations) is not affected by the overlap of the study areas. Two people each exposed to a concentration X from one of two plants is regarded as the same amount of exposure as a single person exposed to a concentration of X from both. Populations may be partially doublecounted if sources are close to each other, but aggregate exposure is not.

The SHED model may also mislocate people if a plant is located near a large body of water. The manner in which SHED spreads the population to the concentrations within the 3.5 km radius allows the program to assign

people to areas which may be covered by bodies of water. One potential problem may arise if the program determines a maximum concentration to which people are exposed that is located over a lake or other body of water. In this case, it could be argued that no one is actually exposed to this concentration. For those sources that appear to produce maximum concentrations, identification of the receptor location and consultation of topographical maps to verify public exposure is recommended. If the maximum receptor is located in an area where people would not reside, the next highest receptor should be used or that plant should be modeled individually with a different more specific model.

Concentration Pattern Errors

The concentration patterns used in the exposure computations are obtained through atmospheric dispersion modeling based on known source characteristics and weather patterns at nearby stations. Naturally, any deviations in these estimates from the true pattern directly affect the exposure results. Thus, if the nearest STAR station is 50 - 100 miles away, the weather patterns may not be representative of the weather patterns in the area around the source.

The program also assumes flat terrain. This is especially crucial when dealing with sources in a valley/mountainous area because the STAR station will not give adequate information to model the wind patterns accurately.

In addition, the SHED model uses a Gaussian dispersion model to determine the concentrations around the source. This model is based on how gases will act when dispersed from a stack. Thus, if the pollutant is fibrous or particulate, such as asbestos, the assumption that the pollutant behaves as a gas may misrepresent the actual dispersion pattern.

The assumption is also made that the annual average weather conditions continually persist and that the source emits at the annual average amount. At times, these averages may not be representative over shorter terms. It also assumes that each recorded wind persists in a given direction long enough to yield dispersion out to 50 Km.

Commuting Pattern Errors

There are also time-dependent aspects of the exposure problem. The exposure program uses a time-averaged concentration pattern for each source, so that the time dimension is ignored in the computations. If the population distribution were essentially constant over the averaging time period, the resulting estimates would be true averages. However, population distributions are constantly changing as people commute to work, go shopping, and take longer trips. Particularly in urban industrial centers, the shifts in populations and concentrations throughout the day may be highly correlated; thus, the actual exposure may differ considerably from the value obtained by matching time-averaged concentrations with population distributions based on census addresses. Whether the exposure is over- or underestimated depends on whether populations in the vicinity of a source are drained (e.g., because people leave residences near the source for work in an urban center) or are augmented (e.g., because of employment near the source).

2-5. Using the SHED Model

To use the model you must first obtain (1) a user ID, (2) an account number and (3) a project ID. These may be obtained by following the instructions in Section 1-3. You, the user, may then access and use the HEM by the procedures described throughout this chapter.

Logging On

Generally, when you approach a hard-wired terminal, the screen will be blank but the terminal is on. To get the Sperry log on directions push the button labeled transmit (or XMIT). The screen should now look like this:

```
**************************************************
*                                                *
*       Welcome  to the Sperry 110/82 System!    *
*                                                *
*       "Tab" to the desired session and XMIT    *
*                                                *
*            DEMAND for a DEMAND session         *
*                                                *
*            MAPPER for a MAPPER session         *
*                                                *
**************************************************
```

The small rectangle in the upper left corner is the cursor. The cursor may be moved by pressing any of the directional keys, the space bar, the back space, tab forward or tab back. The easiest way to position the cursor in this instance is to press TAB FWD as indicated by the directions. This should place the cursor immediately following the first "DEMAND" on the screen. Now press XMIT. If you are accessing the model through a modem, you must establish communication with the UNIVAC computer. The commercial phone number for the NCC is (919) 541-4642. Long distance users can use TELENET to reduce phone charges. Please refer to Section 1-4 for the appropriate contact personnel who can help with more specific instructions. Once you are connected with the NCC, press XMIT. The screen will write the options for access. Type UNI and hit XMIT.

After requesting the UNIVAC demand mode with either the hardwired system or the modem connection, the screen should roll up and write the following:

```
xxxxxxxxxxxxxx  ENTER USER ID/PASSWORD:
```

If the soe (>) or prompt and cursor appear above the line, type

@@INS 11 and XMIT. This should move the cursor below the line. The very first time you log on to the terminal, you must type your user ID, a slash (/), your user ID again, a slash (/) and your password. The password is your own invention but after the first log on remains the same until changed (i.e., remember what you used). After the first log on, you simply type your user ID, a slash (/) and your password. At any time, you may change your password when you log on. UNIVAC requires that you change your password every 90 days. This is accomplished by typing your user ID, a slash (/), your old password, a slash (/), and your new password. Remember to hit XMIT, enter or return in order to enter any line. The system should respond with:

```
* Destroy user-ID/password entry
* UNIVAC 110 Operating System
  Enter Run ID or (CR) for default to USER ID
```

The Run ID consists of 2-6 characters which are chosen from A-Z and 0-9 only. As a National Computer Center (NCC) user, the first two characters of the Run ID should be your NCC bin number. The last four characters can be anything which will allow you to identify your run. The user's initials are often chosen for this reason.

Always press XMIT enter or return after typing any line to be entered.

The computer will then ask a series of questions which you, the user, answers. The example below shows the questions the computer will ask (underlined here to distinguish from user response) and the user's response to each question.

```
Enter Run ID or (CR) for Default to USER ID
08XY
Enter Account Number
69096FRZ
Enter Project-ID
ABCD
```

Enter UID

SASDPHEP

After typing each response, the user must hit XMIT for the transmission of the response. After entering the final response, the computer will type out several lines of information. For example:

Run Number 46

Last Run at: 072784 140637

Date: 073084 Time: 103448

*** News Current as of 11:19:47 on 07/23/84 ****

When the computer stops typing information and the cursor stops beside an soe (>) you are logged on to the computer and ready to begin.

* * *

NOTE: For all the instructions below, all information within commands which are specific to your file or run will be typed in small letters and contained in parentheses. For example, @@CONS RC (run id) means type @@CONS RC Ø8PT if Ø8PT is the run id of the run you needed to check. Do not type the paretheses.

* * *

Cataloging Files

The UNIVAC system works with two types of files; data files and program files. Contrary to its title, the program file is used only for storage and may be broken into elements to store several sets of data. The data file has only one set of data and is available for use by the program.

In order to use the HEM, a program file must be cataloged to store data and two data files must be cataloged in order to run the program

(one more data file must be cataloged in order to run Decay rates for the chemical). To catalog these files certain commands must be entered which basically name the files. Many catalog options are available but the catalog statements conventionally used to catalog the files for HEM are:

```
Program file:   @CAT,P (FileName).,F33,NCCØ4Ø
                 \_____1-12 Alphanumeric characters_____/

  Data files:   @CAT,P  (Qualifier)*Gauss-in.,F33, NCCØ4Ø
                 \_____1-12 Alphanumeric characters_____/

                @CAT,P  (Qualifier)*Gauss-out.,F33,NCCØ4Ø
                         \__SAME AS ABOVE__/

                @CAT,P  (Qualifier)*Decay.,F33,NCCØ4Ø
                         \__SAME AS ABOVE__/
```

Please type the above lines exactly as they appear except the "Filename" and "Qualifier" should be your own invention. The Filename in Line(1) may be any alphanumeric name with 1-12 characters. The Qualifier lines (2), (3) and (4) may also be any alphanumeric name of 1-12 characters. The Qualifier used in line (2) must, however, be exactly the same as the Qualifier in lines (3) and (4).

Once this is accomplished, you have cataloged all the files you will ever need to catalog to run HEM. As previously mentioned, the program file cataloged by line (1) can store a large number of files under various element names. To run the program you can empty the GAUSS-IN file and add the data from the element. This must be done because data files (GAUSS-IN is a data file) cannot be broken into elements. By emptying and reusing the GAUSS-IN. file, however you only need one.

At this time, a discussion of file names is pertinent. A program file name has three primary parts: the qualifier, file name, and element name.

It looks like this:

Qualifier*Filename.Element

The cataloging instructions given above do not give the program file a qualifier. Hence, the system assumes that the project ID (which was used to log on) is the qualifier. If a different project ID is used to log on, the old project ID must be included as the qualifier when calling the file. Otherwise the Filename.Element is sufficient to call the file.

Data files have only two primary parts because data files have no elements. Data files look like this:

Qualifier*Filename.

In the case of HEM data files the file name is always GAUSS-IN, GAUSS-OUT and DECAY. The qualifier is not the project ID but whatever was assigned when the files were cataloged.

Now that all necessary files have been cataloged, data can be entered using the instructions below.

Entering Data

To enter data into a file a text editor must be used. Several text editors are available but the most frequently used on the UNIVAC for HEM is the Maryland Editor. PC users familiar with the PC editor and KERMIT or XTALK can create a file in the proper format on the PC and send the file to the UNIVAC. A text editor has various commands which allow data to be input, changed, rearranged and/or deleted. A summary of often used commands for the Maryland Editor is shown in Appendix C. At this point it is important to read Appendix C and become somewhat familiar with the commands listed. A complete list of commands for the Maryland Editor may be found in the "Text Editor User's Guide" by Hagerty and Sibbald (1975).

To call the Maryland Editor, enter the command @EDM, a space, the file name which has been cataloged, a period and an element name.

For example:

```
@EDM Filename.Element (An element is any alphanumeric name
                       including "-" which has 1-12 characters)
```

The first time this file element is accessed, the element is created and the editor automatically places you in input mode. The UNIVAC will respond with:

```
EDM 29B1 MEM 02/28/86  16:34 I(0):F
INPUT
>
```

Please hit XMIT, enter or return as suggested in Appendix C to get to the edit mode and use the commands listed there to input the data. When you hit XMIT, or when you enter an element that has been created previously, the UNIVAC responds with:

```
EDIT
*>
```

Once in the edit mode, the file is ready for entering data. The format in which data must be entered for HEM is discussed in the following subsection.

Data Format

The HEM is designed such that the program reads numbers from certain columns and rows of data. If the numbers are not in the proper position, the computer will misread the data. This can cause unusual and incorrect results or prevent the program from completing the run. Thus, this section is very important to follow closely. To check to see if a line has been entered correctly type P and XMIT. This should print the line. Next type SC and XMIT. This will print a scale of numbers under the line to make column counting easier.

Each line of data, referred to as a card, has a specific function and format. The first card to be entered is entered once for each run and contains the following information [Remember to type I and a space in order to enter the data in the edit mode]:

Columns 1 - 5 = Greater than or equal to the number of plants; right justified (used as scratch space allocation)

Columns 6 - 10 = Blank spaces

Column 11 = Indicator as to whether maps are to be produced as part of the output, (Maps - Table of estimated BG/ED and Population at centroid by 16 wind directions and 10 distances), T = Yes, F = No

Column 12 = Indicator as to whether the exposure analysis should be performed out to each ring distance separately, T = Yes, F = No

Columns 13 - 23 = Unit risk number for lifetime risk

Next, one set of three cards is entered for each facility. They contain the following information:

Card 1, Columns 1-80 = The name of the chemical being modeled.

Card 2, Columns 1-80 = The location of the facility given as the facility name, city and state.

Card 3, Columns 1-6 = Latitude of the facility in degrees, minutes, seconds. (Two digits each with no spaces or symbols between, e.g., 414900).

Columns 7-13 = Longitude of the facility in degrees (must be three digits), minutes, seconds. (e.g., 0784900).

Columns 14-18 = Star site identification number. This is the location to be used as a source for meteorological data by the model. It is optional and if a number is not provided (the field is left blank) the

program will automatically find the closest source of meteorological data and use it (see note below).

Columns 19-38 = Meteorological data values which may be left blank if such meteorological data are not available. The program will automatically use standard values for these fields. (19-23 = ambient temperature in degrees Kelvin, 24-28 = temperature lapse rate to be used for D stability, 29-33 = temperature lapse rate to be used for E stability, 34-38 = temperature lapse rate to be used for F stability). (See note below)

* * *

NOTE: To make data entry easier, enter all columns of consecutive data using I, space, and the data. If several blank spaces are to be entered between the first group of data and the next group, enter the first group hit XMIT and use the R, column number command to enter the second group. For example, to enter card 3 with sample data type:

I 4249ØØØ7849ØØ (XMIT)

R,39 ØØØØØ1

This will enter 42°49'00" for the latitude, 78°49'ØØ" for the longitude, blanks for the star site and meteorological data, urban setting and one source at the facility.

* * *

Column 39 = Indicator as to whether the facility is located in an urban or rural setting. Ø = urban; 1 = rural

Columns 40-44 = Total number of sources to be modeled at this facility (right justified). These columns must be filled and must be accurate or the program will not run.

Finally a set of cards, one card for each source at the facility identified in columns 40 - 44 in card 3, is entered. These cards give the emission characteristics of each source as follows:

Column 1 = Indicator as to emission type, P = process vent,
S = storage vent, F = fugitive emissions,
H = stack.

Columns 2-13 = Emission rate in kg/year <u>including decimal point.</u>

Columns 14-17 = Release height (Stack, vent or height of fugitive release) in meters with decimal point.

Columns 18-21 = For P, S or H, this is the vertical building (off vent or stack) cross-sectional area (m^2) perpendicular to the mean wind flow, including decimal point. For F, this is the area of release. This should be right justified or contain a decimal point. (The area should never exceed 2000 m^2.)

Column 22 = Indicator as to vent type, Ø = vertical stack, 1 = non-vertical stack or vent.

Columns 23-26 = Inside stack or vent diameter in meters including decimal point. (For fugitive leave blank)

Columns 27-31 = Gas exit velocity from vent or stack in m/sec including decimal point. (If this is unknown, use at least 0.1 m/sec.)

Columns 32-35 = Gas exit temperature in degrees K including decimal point. (If unknown, use 293-298 K.)

Figure 2-6 gives a good summary of all the above data. A xeroxed copy of that figure and Appendix C (or this manual) should always be available while adding data to a file.

You should now look at your file. The commands

```
  T     XMIT
0 9     XMIT
```

will allow you to see the first 9 lines of your file. Please compare this to Figure 2-7, a typical program file. Using the delete, change and SC commands correct your file so that it will contain the information you want.

You should now exit the file. To do this type "Exit" while you are in the edit mode. If you are running a chemical with no chemical reactivity, you are finished entering data and may skip to "Running the Program." If your chemical has chemical decay, you must follow additional instructions below.

In order to run a program with chemical decay, a separate file must be opened. A good suggestion to remember which decay file coincides with which source file is to add -DK to the title of the source file to entitle the decay file. So, to open the file (again using the Maryland editor), type:

@EDM File Name. Element-DK

Only one card is entered into this file which contains the following information in the following format:

CONTROL CARDS FOR PROGRAM SHED

SUBMIT ONE CARD OF THIS FORM PER RUN

NUMBER OF PLANTS	MP	RG	Unit Risk No (13–23)	(23–80)

NUMBER OF PLANTS IS THE NUMBER OF DIFFERENT LOCATIONS FOR THIS RUN
MP - ARE MAPS DESIRED AS OUTPUT FROM THE EXPOSURE PROGRAM T = YES F = NO
RG - IS IT DESIRED TO DO THE EXPOSURE ANALYSIS OUT TO EACH RING DISTANCE T = YES F = NO

SUBMIT ONE SET OF THE FOLLOWING THREE (3) CARDS PER FACILITY

CHEMICAL NAME (1–80)

FACILITY IDENTIFICATION (1–80)

LATITUDE DEG MIN SEC (1–7)	LONGITUDE DEG MIN SEC (7–14)	STAR SITE (14–19)	AMBIENT TEMP (K) (19–24)	LAPSE RATE STAB D (24–29)	LAPSE RATE STAB E (29–34)	LAPSE RATE STAB F (34–39)	U (39)	NUMBER SOURCES (40–80)

MISSING STAR SITE CAUSES AUTOMATIC SELECTION OF THE NEAREST SITE
U (COLUMN 39) CODE ZERO (0) FOR URBAN OR ONE (1) FOR RURAL

SUBMIT ONE OF THE FOLLOWING FOR EACH SOURCE AT THE FACILITY

ET (1)	EMISSION RATE (KG / YEAR) (1–14)	STACK METERS (14–18)	AREA Mee2 (18–22)	VT (22)	DIA METERS (22–27)	VELOCITY M/SEC (27–32)	TEMP (K) (32–40)	(40–80)

ET (COLUMN 1) EMISSION TYPE
P = PROCESS VENT
S = STORAGE VENT
F = FUGITIVE EMISSIONS
H = STACK

VT (COLUMN 22) VENT TYPE
0 = VERTICAL STACK
1 = NON-VERTICAL STACK OR A VENT

Figure 2-6. Summary of SHED Data Entry Format

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Figure 2-7. Typical SHED Data File

```
00004      FF    .0076
ASBESTOS
PLANT NAME      NEW YORK CITY
4043000740100                                   0      1
F144.           10.0100.110.0.0009293.
PLANT NAME      RALEIGH, NC
3547000783900                                   0      1
F6.80           10.0100.110.0.0009293.
ASBESTOS
PLANT NAME      MONTPELIER, VT
4416000723500                                   0      1
F.150           10.0100.110.0.0009293.
ASBESTOS
PLANT NAME      PHEONIX, AZ
4244560734145                                   000003
H301.9          4.50613.0.21615.46297.
H8003.          7.50613.0.21611.85297.
H214.50         12.6613.0.79014.54297.
```


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Columns 1-10: Daytime Decay rate (/minute)

Columns 11- 20: Nighttime Decay rate (/minute)

To convert half-lives to decay rates, you may use the following formula:

Decay Rate = $0.693/T_{1/2}$

where $T_{1/2}$ is the half-life in minutes.

Running the Program

Entering data into the program file stores the data for future use. The contents of the program file must be entered into the data file in order to run the program.

Adding the program file to the data file consists of three simple steps: 1) open the file, 2) delete any previously stored data, and 3) copy the program file into the data file. These steps can be easily performed using any text editor. The Maryland Editor would use the following commands:

@EDM (Qualifier)*Gauss-In.	XMIT [Hit XMIT a second time if not in edit mode.]
D *	XMIT [This step deletes all previously stored data.]
Add (Filename).(Element)	XMIT

This places the data from the source parameter program file into the Gauss-In data file. If decay rates are to be included, this data must also be entered into a data file. To do this, using the Maryland editor, type:

@EDM (Qualifier)*Decay.	XMIT
D *	XMIT
Add (Filename).(Element-DK)	XMIT

Once the data is added to the file, the file should be exited and a start card entered. The start card for the HEM without chemical decay

should be entered as below:

@Start SASD*Start.Xposure/Point-50,/(Site ID),,,(Qualifier)

The start card for the HEM with chemical decay should be entered as follows:

@Start SASD*Start.Xposure/Decay-50,/(Site ID),,,(Qualifier)

The site ID is the code which indicates where the results will be printed. If the site ID is omitted the results will be printed at Research Triangle Park. A site ID of FDØ5CR will cause the results to be printed on the 6th floor of the Mutual Building. Most regional offices have a printer dedicated to the UNIVAC that will have a Site ID. If there is not a UNIVAC printer available to you, please see the information below. The Qualifier is the same as the Qualifier in Qualifier*Gauss-In and Qualifier*Decay. Once XMIT is hit, the computer will print out a line of information. This information states the run ID, the category and whether the project was accepted or rejected. If it is accepted, the program is queued for execution and it is a matter of time before the results will be printed.

The run ID is the value printed after *TM*. If you would like to know if the program has finished, you may use the run ID in one of two commands. The first is:

@@CONS RC (run id)

This will tell you how many pages have been finished or if the program has "finned." The second:

@SASD*WAIT.WAIT (run id)

will give you the same information but will continue to update the information every 60 seconds or when the XMIT key is pressed. Typing any other command cancels the @WAIT.WAIT command.

Users who are using a remote terminal and who do not wish the results of the SHED run to go to the National Computer Center (NCC) and do not have

access to another site ID should use a different run card. This is typed as as follows for the 50 Km run:

@ START SASD*START.XPOSURE/USER-50,,,(Filename)

The 50 may be replaced with 20 or 80 for 20 Km or 80 Km analyses. Once executed, the file will not print out but will be saved until you type in:

@@SEND, U

This down loads the files to your PC. Before typing this, however, check on the file to see if it has been completed and is in the queue for being printed. To do this type:

@@CONS SQ (user id) *U

or

@@CONS SQ (run id) *R

Once the file is in the queue, type @FIN. This will scroll up information on the screen. When it finishes scrolling, type the @@SEND, U. It is important that you do not hit XMIT until this is typed in. Immediately you will see the file on the screen. Once you have downloaded the file and have the printout you want, you need to delete the file from the queue.

To do this, simply type:

@@CONS SX (run id)

Additional Miscellaneous Information

If the program is accepted but does not complete running, the most common error is in the entering of the data. To check the data in the file, reopen the file with the @EDM Filename.Element command and type:

NSITE X Y RM95PR

The symbols "X" and "Y" here represent the the beginning line number and ending line number. The RM95PR indicates where the data will be printed. This specific code is for the Mutual Building 6th floor printer. Other codes should be printed if another location is desired.

When the printout is available make sure all the data was entered exactly as the cards indicate. The most common error is inconsistency between the number of point sources indicated in the third card and the number of emission point source data listed. This will prevent the program from running.

Another common problem occurs when large amounts of data are being run. If the run takes longer than 10 minutes to run, the system will "time out". This can be resolved by adding a comma and the number of minutes needed to run the program to the end of the start statement. For example, if 30 minutes were needed, the start card would appear as below:

```
@Start  SASD*Start.Xposure/Point-5Ø,/(site id),,,(Qualifier),30
```

Printouts of programs which exceed 200 pages are not allowed to be printed on the Mutual Building printer. A simple addition to the start card will cause only the summary pages to be printed at the Mutual Building or other Site ID while the bulk of the material is laser printed at Research Triangle Park. The simple addition is "-L" and is inserted after xposure as below:

```
@Start  SASD*Start.Xposure-L/Point-5Ø,/(site id),,,(Qualifier),3Ø
```

This manual cannot cover all possible errors and you will probably find newer and more exciting ways to make mistakes. Therefore, please use References 2 and 3 to help find your errors, correct them and maybe learn a few short cuts.

2-6. Using Output from other Dispersion Models

The exposure portion of SHED model can be run using concentration inputs from other dispersion models. To do this, the concentration file must be in a compatible format. The Model Application Section of the Monitoring and Data Analysis Division in the OAQPS ((919) 541-5690 or FTS 629-5690) has succeeded in causing the Industrial Source Complex Long-Term Dispersion Model (ISCLT) to yield compatible output. Once the ISCLT output is stored, you need only the filename and element (if there is one) to access the concentrations.

Entering Data

Similar to running SHED without concentration input data you must set up a file. The following information describes what data must be entered and the proper format.

The first card is entered once for each run and contains the following information:

Columns 2-3	= Number of radial rings you wish to analyze, right justified (generally 10).
Column 4	= Indicator as to whether maps are to be supplied as part of the output, (maps - table of estimated BG/ED and population at centroid by 16 wind directions and 10 distances), T = Yes, F = No.
Column 5	= Indicator as to whether the exposure analysis should be performed out to each ring distance separately, T = Yes, F = No.
Columns 6-10	= Number of sources to be analyzed.
Columns 11-20	= Conversion factor. (This number will be multiplied times the concentration points to yield a converted

concentration. Since the emission rate is proportional to the concentration points, this factor may be used to analyze various possible emission rates with only one ISCLT run. Enter 1.0 if you wish the concentration points to remain the same).

Columns 21-30 = Unit Risk Number for lifetime risk; right justified.

The second, third, and fourth cards are entered only once for each run and depend on the number entered above as the number of radial rings. If the number is ten or less, only card 2 needs to be completed. If the number is twenty or less, cards 2 and 3 must be filled. If the number is thirty or less, cards 2, 3 and 4 must be used. The program is prepared to handle only up to 30 radial distances. The format for each of the cards is identical. Eight digits are allowed for each distance, ten distances are allowed per card. For example, the first three distances would be entered as below on card 1:

Columns 1-8 = radial distance closest to the plant (Km)

Columns 9-16 = radial distance second closest to the plant (Km)

Columns 17-24 = radial distance third closes to the plant (Km)

The next group of cards is entered for each plant or each chemical analyzed and contain the following information:

Card 1, Columns 1-80 = The name of the chemical being modeled.

Card 2, Columns 1-80 = Title of the concentration chart that will be output. Generally, we enter, "Concentration in Micrograms per Cubic Meter."

Card 3, Columns 1-80 = Name of the facility.

Card 4, Columns 2-7	= Latitude of the facility in degrees, minutes, seconds (two digits each).
Columns 9-15	= Longitude of the facility in degrees (three digits), minutes (two digits) and seconds (two digits).

Now the concentration information must be added to the file. If you are analyzing only one plant and have only one concentration group, you may add the entire file with the following command:

ADD concentration filename.element

If you have concentration results for several plants, you may add blocks of data with the following command:

NUMADD concentration filename.element x y

where x is the starting line number and y is the ending line number of the section you want to copy.

The process of entering plant data and copying the concentration file for that chemical must be repeated until all plants have been entered.

Running the Program

Once the program file is complete, it must be entered into the data file in order to run the program. This process is identical to running SHED without concentration inputs except that the data file is called GAUSS-OUT. rather than GAUSS-IN.. Using the Maryland editor, you would type the following commands:

@EDM (Qualifier)*GAUSS-OUT.	XMIT
D *	XMIT
ADD Filename.Element	XMIT

Once the data has been entered into the data file, you may type the following start card to execute the program:

@START SASD*START.XPOSURE/XQT,/(Site id),,,(Qualifier)

Now you may follow the instructions in Section 2-5 to check on the status of the run and obtain the printout.

2-7. Output from SHED

SHED produces two sets of output. The first set included the input data and the concentration grid table for each plant and the cummlulative risk summary and the overall plant summary. This set also contains maps of population centroids if this option was selected. The second set contains only the cummulative risk summary and the individual plant summary.

This summary of the input data for one plant is shown in Figure 2-8. Some of the values are rounded off but can be used to proof the input data.

The concentration grid, as shown in Figure 2-9, presents the modeled concentration at each grid point. For example, the figure shows that the concentration 1.00 kilometers south of the plant is predicted to be 8.8588 x 10-6 g/m3. The column labeled wind direction is actual direction from the plant, not wind direction.

The optional maps show the population distribution about the source as a polar grid displayed rectangularly. The four plots differ in the orientation of their grids relative to the input concentration grid. Again, direction refers to actual direction from the plant, not wind direction.

The first plot, seen in Figure 2-10, shows both the number of BG/ED centroids and the number of people in each cell of the input concentration grid. The labels of the wind directions refer to the line directly above them and the radius label refers to the line directly to the right.

The second plot, seen in Figure 2-11, gives the same type of plot as the first except that the spaces shown are patches rather than grid cells.

Figure 2-8. Summary of the Input Data

```
SHED/GAUSS -- SUMMARY OF THE INPUT DATA

          BETHLEHEM STEEL  LACKAWANNA, NY
               LATITUDE: 424900, LONGITUDE:  784900
               STAR STATION:     0
               FOR AN    URBAN SOURCE
               AMBIENT TEMPERATURE: 293. DEGREES KELVIN
               CHEMICAL COMPOUND NAME: IRON AND STEEL
               NUMBER OF EMISSION TYPES:  2

               THE LAPSE RATES USED ARE
                        .00000 DEGREES K PER METER FOR STABILITY CLASS D
                        .00000 DEGREES K PER METER FOR STABILITY CLASS E
                        .00000 DEGREES K PER METER FOR STABILITY CLASS F

          THE NEAREST STAR SITE WAS CHOSEN
               STAR SITE USED
                    STATION NUMBER 14747  AT DUNKIRK          , NY
                    STARTED 49/01    ENDED 53/12 46
                    LATITUDE  423000 LONGITUDE   791659
                    DISTANCE   51.89 KM  BEARING 227


            EMISSION TYPE INDEX = (P) PROCESS VENT
               EMISSION RATE:        .003196 GRAMS/SECOND
                                   100.800000 KILOGRAMS/YEAR
               STACK HEIGHT:  68. METERS
               BUILDING CROSS SECTION:      1000. SQUARE METERS
               EMISSIONS ARE FROM A     VERTICAL STACK
               STACK DIAMETER:  6.10 METERS
               EXIT VELOCITY:  15.8 METERS/SECOND
               EXIT TEMPERATURE:  478. DEGREES KELVIN

            EMISSION TYPE INDEX = (F) FUGITIVE EMISSION
               EMISSION RATE:        .000105 GRAMS/SECOND
                                    3.300000 KILOGRAMS/YEAR
               STACK HEIGHT:  31. METERS
               BUILDING CROSS SECTION:      1000. SQUARE METERS
               EMISSIONS ARE FROM A     VERTICAL STACK
               STACK DIAMETER:  2.40 METERS
               EXIT VELOCITY:  20.9 METERS/SECOND
               EXIT TEMPERATURE:  339. DEGREES KELVIN
```

Figure 2-9. Individual Plant Concentration Grid

BETHLEHEM STEEL LACKAWANNA, NY

IRON AND STEEL

(CONCENTRATION (MICRO GRAMS/CUBIC METER))

WIND DIRECTION	DOWNWIND DISTANCE (KM) .200	.500	1.000	2.000	5.000	10.000	20.000	30.000	40.000	50.000
S	3.1248-007	4.8022-006	8.8588-006	7.7022-006	5.0673-006	2.6651-006	1.2593-006	8.1918-007	6.0946-007	4.8641-007
SSW	2.3631-006	2.8354-005	4.7424-005	3.6502-005	1.6587-005	7.8681-006	3.6893-006	2.3653-006	1.7217-006	1.3430-006
SW	9.2678-007	1.2581-005	2.1710-005	1.6840-005	7.7781-006	4.0595-006	2.1311-006	1.4487-006	1.0995-006	8.8675-007
WSW	1.3930-006	1.7671-005	3.0300-005	2.3339-005	1.0221-005	5.4812-006	3.0744-006	2.1707-006	1.6845-006	1.3773-006
W	1.6492-007	2.3099-006	4.2179-006	3.6072-006	2.1037-006	1.3779-006	8.8997-007	6.9326-007	5.8401-007	5.1045-007
WNW	4.5032-007	5.1345-006	8.8190-006	7.0336-006	3.5560-006	2.0301-006	1.1900-006	8.9060-007	7.3241-007	6.2978-007
NW	4.6912-007	4.4500-006	7.6494-006	6.1773-006	3.2511-006	1.9048-006	1.1445-006	8.7824-007	7.3842-007	6.4634-007
NNW	7.4701-006	5.0217-005	8.0205-005	5.8567-005	2.2946-005	1.0184-005	4.6058-006	2.9705-006	2.2163-006	1.7827-006
N	6.1570-006	4.8889-005	7.9423-005	5.8579-005	2.3518-005	1.0838-005	5.1378-006	3.3883-006	2.5606-006	2.0769-006
NNE	1.6300-005	1.5788-004	2.6054-004	1.9243-004	7.5911-005	3.4853-005	1.6567-005	1.0755-005	7.9056-006	6.2173-006
NE	3.4986-006	3.5345-005	5.8425-005	4.3456-005	1.7846-005	8.3118-006	3.9381-006	2.5548-006	1.8827-006	1.4862-006
ENE	1.9528-005	1.6507-004	2.6330-004	1.9224-004	7.5407-005	3.2475-005	1.3846-005	8.3712-006	5.8425-006	4.4137-006
E	2.4914-006	2.2872-005	3.7148-005	2.7945-005	1.2083-005	5.4017-006	2.3501-006	1.4417-006	1.0223-006	7.8501-007
ESE	1.2367-005	1.1828-004	1.9415-004	1.4480-004	5.9437-005	2.5948-005	1.1104-005	6.7265-006	4.7003-006	3.5531-006
SE	1.1515-006	1.4731-005	2.5381-005	1.9845-005	9.4195-006	4.5800-006	2.1831-006	1.4088-006	1.0299-006	8.0629-007
SSE	1.2144-006	1.8820-005	3.3463-005	2.7572-005	1.5341-005	7.6519-006	3.6334-006	2.3557-006	1.7323-006	1.3631-006

Figure 2-10. Map of Population Centroids and Population of Grid Cell

MAP OF POPULATION BY CONCENTRATION RADIUS

CONCENTRATIONS ARE IN UNITS OF MICRO-GRAMS PER CUBIC METER
ASARCO EL PASO, TX

DIR	RADIUS	.200	.500	1.000	2.000	5.000	10.000	20.000	30.000	40.000	50.000
S	# CNTRDS	0	0	0	0	0	0	0	0	0	0
	POP	0	0	0	0	0	0	0	0	0	0
SSW	# CNTRDS	0	0	0	0	0	0	0	0	0	0
	POP	0	0	0	0	0	0	0	0	0	0
SW	# CNTRDS	0	0	0	0	0	0	0	0	0	0
	POP	0	0	0	0	0	0	0	0	0	0
WSW	# CNTRDS	0	0	0	0	0	0	0	0	0	0
	POP	0	0	0	0	0	0	0	0	0	0
W	# CNTRDS	0	0	0	0	0	1	0	1	0	0
	POP	0	0	0	0	0	3377	0	405	0	0
WNW	# CNTRDS	0	0	0	0	1	5	2	1	0	0
	POP	0	0	0	0	932	6037	230	681	0	0
NW	# CNTRDS	0	0	0	0	0	6	13	1	3	2
	POP	0	0	0	0	0	13442	8218	774	1946	1201
NNW	# CNTRDS	0	0	2	0	1	4	2	7	3	3
	POP	0	0	818	0	375	11535	1071	4308	1998	3390
N	# CNTRDS	0	0	0	0	0	0	1	2	0	1
	POP	0	0	0	0	0	0	2	1417	0	0
NNE	# CNTRDS	0	0	0	0	4	3	33	4	1	1
	POP	0	0	0	0	10738	5691	55117	765	205	0
NE	# CNTRDS	0	0	0	1	1	18	20	1	0	0
	POP	0	0	0	577	1727	16771	37217	0	0	0
ENE	# CNTRDS	0	0	0	0	2	29	18	1	0	1
	POP	0	0	0	0	3175	28857	29072	1688	0	0
E	# CNTRDS	0	0	0	1	9	43	62	8	3	0
	POP	0	0	0	2347	8007	33481	103274	10228	1956	0
ESE	# CNTRDS	0	0	0	0	22	11	9	31	4	4
	POP	0	0	0	0	15861	5490	19038	31877	3709	2498
SE	# CNTRDS	0	0	0	0	2	1	0	0	0	0
	POP	0	0	0	0	1259	266	0	0	0	0
SSE	# CNTRDS	0	0	0	0	0	0	0	0	0	0
	POP	0	0	0	0	0	0	0	0	0	0

Figure 2-11. Map of Population Centroids and Population by Patch

MAP OF POPULATION BY PATCH RADIUS

CONCENTRATIONS ARE IN UNITS OF MICRO-GRAMS PER CUBIC METER
ASARCO EL PASO, TX

DIR	RADIUS	.200	.500	1.000	2.000	5.000	10.000	20.000	30.000	40.000	50.000
S	# CHTRDS	0	0	0	0	0	0	0	0	0	0
	POP	0	0	0	0	0	0	0	0	0	0
SSW	# CHTRDS	0	0	0	0	0	0	0	0	0	0
	POP	0	0	0	0	0	0	0	0	0	0
SW	# CHTRDS	0	0	0	0	0	0	0	0	0	0
	POP	0	0	0	0	0	0	0	0	0	0
WSW	# CHTRDS	0	0	0	0	0	0	0	0	0	0
	POP	0	0	0	0	0	0	0	0	0	0
W	# CHTRDS	0	0	0	0	0	0	0	0	0	0
	POP	0	0	0	0	0	0	0	0	0	0
WNW	# CHTRDS	0	0	0	0	1	0	0	1	0	0
	POP	0	0	0	0	3377	0	0	405	0	0
NW	# CHTRDS	0	0	0	0	5	9	2	1	0	0
	POP	0	0	0	0	5834	10160	808	1083	0	0
NNW	# CHTRDS	0	0	2	0	5	7	9	4	4	3
	POP	0	0	818	0	9815	3428	8369	2294	3673	2012
N	# CHTRDS	0	0	0	0	3	0	2	1	0	1
	POP	0	0	0	0	8593	0	2	69	0	0
NNE	# CHTRDS	0	0	0	2	0	1	13	4	0	1
	POP	0	0	0	5003	0	0	17278	1879	0	0
NE	# CHTRDS	0	0	1	0	5	32	14	1	0	0
	POP	0	0	577	0	5801	43857	26965	330	0	0
ENE	# CHTRDS	0	0	0	2	10	17	1	0	0	1
	POP	0	0	0	3028	12956	25862	0	0	0	0
E	# CHTRDS	0	0	0	2	30	41	30	0	0	0
	POP	0	0	0	1588	23547	42987	65461	0	0	0
ESE	# CHTRDS	0	0	0	6	22	18	45	15	1	0
	POP	0	0	0	5667	18926	23122	74422	8514	482	0
SE	# CHTRDS	0	0	0	5	16	0	0	9	3	2
	POP	0	0	0	5274	8745	0	0	7164	2511	362
SSE	# CHTRDS	0	0	0	0	0	0	0	0	0	0
	POP	0	0	0	0	0	0	0	0	0	0

Patches are defined by the midpoint between cell radii and the midpoint between wind directions. These patches form an area surrounding a receptor site rather than each corner being a receptor site as in the case of the grid cell.

The last two plots, not shown here, are versions of the first plot, with each input grid subdivided into quadrants. For each quadrant, the number of BG/ED centroids (third plot) or the population (fourth plot) is shown.

The cummulative summary is shown in Figure 2-12. This table starts at the highest concentration to which an individual is exposed. It then reports how many people are predicted to be exposed to that concentration and the resulting exposure. The exposure is the product of the population and concentration. The next level is a certain increment lower concentration (about 1/2 of the previous concentration) with the number of people exposed to that concentration or higher. The exposure in this instance is the cummulative exposure from the level 2 concentration and those higher. The following levels are similarly calculated until the concentration level reaches the miniumum predicted.

The overall plant summary is shown in Figure 2-13. Three such summaries are usually produced. The first is ordered according to the order of the data file. The second is ordered highest to lowest by the maximum lifetime risk number. The third is ordered highest to lowest by the annual incidence.

The first half of the overall plant summary deals with the risk to the maximum concentration. The first column reports the maximum concentration to which a person is predicted to be exposed. The second column reports the number of people predicted to be exposed to that concentration. The third column reports the exposure (people x concentration) due to that concentration. The fourth column reports the predicted lifetime incidence (exposure x unit

Figure 2-12. Cummulative Summary

SUMMARY FOR IRON AND STEEL
MAXIMUM RADIUS = 50.0 KM

LEVEL	CONCENTRATION	POPULATION	EXPOSURE
1	1.64E-03	7	1.19E-02
2	1.00E-03	32	4.24E-02
3	5.00E-04	422	3.17E-01
4	2.50E-04	7,230	2.72E+00
5	1.00E-04	66,700	1.10E+01
6	5.00E-05	240,000	2.27E+01
7	2.50E-05	733,000	3.95E+01
8	1.00E-05	2,810,000	7.00E+01
9	5.00E-06	8,000,000	1.04E+02
10	2.50E-06	22,500,000	1.57E+02
11	1.00E-06	28,000,000	1.67E+02
12	5.00E-07	31,500,000	1.69E+02
13	2.50E-07	33,500,000	1.70E+02
14	1.00E-07	33,600,000	1.70E+02
15	5.00E-08	33,600,000	1.70E+02
16	4.61E-08	33,600,000	1.70E+02

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Figure 2-13. Overall Summary Chart

SUMMARY FOR IRON AND STEEL
WITH A UNIT RISK OF 2.30E-03

-MAXIMUM-					--MINIMUM--					
CONC	PEOPLE	EXPOSURE	LIFETIME INCIDENCE	MAX RISK	CONC	PEOPLE	EXPOSURE	ANNUAL INCIDENCE	REPEAT INTERVAL	SOURCE
2.63E-04	605	1.59E-01	3.66E-04	6.06E-07	1.65E-07	1,270,000	1.53E+01	0.0005	2,000.	BETHLEHEM STEEL LACKAWANNA, N
7.41E-05	399	2.96E-02	6.80E-05	1.70E-07	4.61E-08	1,270,000	5.98E+00	0.0002	5,100.	REPUBLIC STEEL BUFFALO, NY
2.89E-04	1	1.69E-04	3.88E-07	6.65E-07	9.35E-07	1,140,000	5.71E+00	0.0002	5,300.	CRUCIBLE, INC. SYRACUSE, NY
4.37E-04	20	8.63E-03	1.99E-05	1.00E-06	2.99E-07	237,000	1.03E+00	<0.0001	30,000.	ROBLIN STEEL DUNKIRK, NY
1.19E-04	25	2.98E-03	6.84E-06	2.74E-07	4.99E-07	8,000,000	3.42E+01	0.0011	890.	NEW JERSEY STEEL & STRUCTURE
1.64E-03	7	1.19E-02	2.73E-05	3.78E-06	6.91E-07	904,000	1.94E+01	0.0006	1,600.	AL TECH SPECIALTY STEEL WATER
1.19E-04	50	5.96E-03	1.37E-05	2.74E-07	5.43E-07	10,800,000	4.95E+01	0.0016	620.	RARITAN RIVER STEEL PERTH AMB
2.01E-04	59	1.20E-02	2.75E-05	4.63E-07	1.89E-07	739,000	2.30E+00	0.0001	13,000.	AUBURN STEEL CO AUBURN, NY
2.37E-04	7	1.74E-03	4.00E-06	5.45E-07	1.92E-07	707,000	5.91E+00	0.0002	5,100.	COLT INDUSTRIES SYRACUSE, NY
2.10E-04	91	1.98E-02	4.54E-05	5.02E-07	1.49E-07	1,240,000	1.81E+00	0.0001	17,000.	GUTERL SPECIAL STEEL CORP. LOC
6.88E-05	4	2.82E-04	6.48E-07	1.58E-07	2.89E-07	4,530,000	4.76E+00	0.0002	6,400.	JARSCO ROEBLING, NY
1.15E-03	4	4.20E-03	9.67E-06	2.64E-06	9.91E-07	2,750,000	2.43E+01	0.0008	1,300.	CARPENTER TECHNOLOGY CORP. BR
						33,600,000	1.70E+02	0.0056	180.	OVERALL

risk) due to the maximum concentration. The fifth column is one of the values EPA uses to report risk. This is the maximum individual lifetime risk and is calculated by multiplying the maximum concentration by the unit risk number.

The next part of the summary deals with the minimum and overall concentrations and exposures. The first column of this half (the sixth column overall) reports the minimum predicted concentration within 50Km of the plant. The next column reports the total number of people exposed to any concentration of the chemical within 50Km of the plant. The next column reports the cummulative exposure. This is calculated by summing the exposure from each modeled receptor site. The next column reports annual incidence and is calculated by multiplying the cummulative exposure by the unit risk number which yields lifetime risk and dividing by seventy (the estimated life span) to yield an average annual incidence. This number is also frequently used to describe risk. The next column, labeled repeat interval, is simply the inverse of the annual incidence column. This is used to describe how many years elapse before one death is predicted to occur. The last column reports the source name.

Chapter 3

3-1. Introduction to SHEAR

The Systems Applications Human Expsoure and Risk (SHEAR) model is based on code and concepts developed in SHED. In contrast to SHED, which was developed for a national estimation of risk, SHEAR was developed for regional analysis. SHEAR is also more complicated to run as it has more options and input files than does SHED.

There are four basic instances where SHEAR should be used: 1) If there are two major point sources very close (within 5 km) to each other and the additive concentration needs to be determined, 2) multiple pollutants from one source need to be analyzed, 3) there are a large number of sources within an area which cannot feasibly be located individually, or 4) when the sources are so numerous and widespread that they act as an area source rather than several point sources. In the first instance, SHEAR holds the population constant within the study area and sums the risk. So, if a person were exposed to a concentration X from source A and a concentration Y from source B, SHEAR would report a single person exposed to a concentration (X+Y). In contrast, SHED would report 2 people, one exposed to concentration X and the other to concentration Y. Both models yield the same exposure results but SHED double counts some of the people. Unfortunately, the same mechanism which allows SHEAR to prevent double counting often causes the model to underpredict the maximum lifetime risk. Even though SHEAR sums the risk, it only sums these risks at population centroids. This eliminates the area closer to the plant where people actually may be residing and where the concentrations are much higher. For this reason, SHED, which spreads the population out, almost always predicts a higher maximum lifetime risk than SHEAR. Hence, SHEAR is generally not used to determine maximum lifetime risk.

In the second instance, SHEAR merely allows many chemicals to be run at once. The same results could be obtained manually with SHED by adding results of each run. SHEAR automates this procedure and, again, holds the population constant.

The last two instances in which SHEAR would be used provide a means of analyses not available through SHED. SHEAR allows modeling of sources too numerous to model individually through its prototype and area source models. Therefore, such sources as service stations, dry cleaners, etc. are more appropriately modeled with SHEAR rather than SHED.

In addition, SHEAR allows areas to be specified within the study region. For instance, you can define each neighborhood in a county in order to model residential emissions for that county, rather including downtown areas, farmland and lakes. These capabilities make SHEAR a very useful model for sources which cannot be modeled with SHED.

3-2. Input Data

SHEAR requires several pieces of information in order to run properly.

Although SHEAR requires somewhat different input data than SHED, the information still falls into the four major categories:

> Location Data

> Emissions Data

> Vent Parameter Data

> Atmospheric Reactivities

In addition, SHEAR requires input of the STAR station code number to identify which meteorological data should be used. The following section describes the input information needed for SHEAR and possible sources of this information. Much of this additional information can be derived from the same sources as those indicated in Section 2-2. In those instances,

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the appropriate earlier section will be referenced. Placement of the data into the various files for use by the SHEAR program is discussed in Section 3-5.

As in SHED, SHEAR requires input of the unit risk estimate to link the exposure to health risk. These estimates for cancer risk are generally generated by the Carcinogen Assessment Group in a Health Assessment Document for the chemical. A unit risk estimate is the estimated risk to an individual of contracting cancer if the individual is exposed to one $\mu g/m^3$ of the chemical for their entire lifetime. Hence it is expressed in units of $(\mu g/m^3)^{-1}$. If the unit risk is not included, the concentrations and exposure results are calculated with no calculations of health risk. Insertion of zero for the unit risk will prevent the program from running properly. So, insert one or leave blank if the unit risk is unknown.

Location Data

The location data for the major point source portion of SHEAR can be determined by the means discussed in Section 2-2. It is important with SHEAR, as with SHED, to locate the plants accurately, as the additive concentrations will not be representative of the actual situation.

The location of area and prototype sources is different from major point sources. These sources are not located specifically, but a box is defined around them. First, you must determine the general area you wish to study. (The area should be about the size of a county or a few counties.) Then you must determine the specific coordinates of the southwest corner of the box and the length and width of the box. This information can be determined from:

> United States Geological Survey maps (7 1/2 and 15 minute series).

> U.S. atlas which has county breakdowns in state maps.

The southwest corner must be in UTM coordinates. To translate geodetic coordinates to UTM use the program described in Appendix B.

Often you will wish to model only a specific county(s) or part of a county(s) within the box. The program has the areas of all the counties in the U.S. defined. You still must box in the county and define the grid cells but if you enter the Federal Information Processing System (FIPS) code of the county(s), only the area both inside the county and inside the box will be modeled. The FIPS codes for the counties can be obtained from the most recent copy of Worldwide Geographic Location Codes produced by the U.S. General Service Administration, Office of Finance or from the National Bureau of Standards FIPS Publication 55.

Emissions Data

Again, for major point sources, the emissions data can be obtained as discussed in Section 2-2.

The emissions data for prototype sources can also be obtained by using methods in Section 2-2. The emission rate used, however, should be an average or prototypical emission rate because all sources will be modeled to emit at the same rate.

The area emission rate may be obtained from a number of published sources which include:

> Statistical Abstracts of the United States.

> Chemical Engineering Progress and other journals.

> Government publications of emissions and/or material consumption.

From these, the emission rate may determine as emissions/area or emissions/person. Consumption rates can yield emission rates if an emission factor is applied as earlier discussed.

Vent Parameter Data

Vent parameter data are necessary for the major point and prototype dispersion modeling. These data can be obtained in the manner discussed in

section 2-2. The parameters include the number of vents, vent height, vent diameter, gas discharge temperature, gas velocity, fugitive discharge area and building cross-sectional area. The area source analysis does not require these data.

Atmospheric Reactivities

At present, chemical reactivity input is not available with the SHEAR model. Although the card is structured to accept the data input, a separate runstream initiating the program to use the data has not been implemented. The need has not yet risen to develop this portion of the program because very few chemicals are reactive enough to demonstrate changes within the 50 km radius.

Meteorological Data

Unlike SHED, SHEAR requires input of the desired STAR station code number. The station selected should normally be the station closest to the region currently being analyzed. A more remote station can be selected if it is judged that its climate is more representative of conditions in the analysis region. This might occur because of the relative proximity of the region and each weather station to coastlines or major topographical features. Selection of a station other than the closest should be made only upon expert advice. (See Section 1-2 for additional information.)

To obtain STAR station code numbers for the area of interest, a program available on UNIVAC may be used. This program is called STAR-PICK and is described in detail in Appendix A.

3-3. Dispersion Modeling

This section describes the algorithms used to process the input data into the resulting exposures to populations. Each of the three types of sources, major point, prototype and area, must be discussed individually as each uses its own method to reach the end result.

Major Point Source

The major point source for SHEAR is analyzed almost exactly the same as for SHED (see Section 2-3). Therefore, the complete discussion will not be repeated here. Two differences exist between the SHEAR point source and the SHED point source. First, the two-level scheme adopted by SHED for pairing concentrations to populations is not used in SHEAR. SHEAR uses the method of interpolating the concentration receptors to the BG/EDs from the source out to the maximum radius. This is the same method SHED uses outside the 3.5 km radius. Secondly, SHEAR is capable of storing all the concentrations and their locations. In the event that another plant emits the pollutant within the same area, the new concentrations at each location (BG/ED centroid) will be added to the stored concentrations at that same location. SHEAR handles exposure to several chemicals from the same plant in a similar manner. SHED does not have this capability.

Prototype Sources

Prototype sources are treated exactly as specific point sources except for an algorithm for selecting sites for the required samples of each prototype. PROTO code is the POINT code with the addition of the siting algorithm and the provision of a single source characterization (the prototype) to be used for every source that is sited.

The siting algorithm provides for a random selection of L centroids where L is the number of locations to be selected. If it is desired that some sites serve multiple samples--as, for example, a fraction of gasoline service stations are sited in pairs, triplets, etc.--then the number of locations is determined by $L = S + 2(D) + 3(T) + 4(Q)$:

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where

L = number of locations,

S = number of singles (single source),

D = number of doubles (two sources),

T = number of triplets (group of three sources),

Q = number of quadruplets (group of four sources)

The actual sites are placed at randomly perturbed locations within each selected district. That is, each site location is at the population centroid map coordinates + (-) a random fraction of the district mean radius to the east (west) + (-) a random fraction to the north (south).

This procedure approximately distributes sources by population density. However, there is a rural/urban bias to BG/ED population because some rural BG/EDs can be very small; urban BG/EDs almost never are. This bias would tend to over-represent rural districts since the small rural BG/EDs would have an equal probability of being selected; a counter-bias is provided whereby BG/EDs of less than 1,000 population are randomly rejected and replaced with another selection.

Area Source Analysis

The area source is used for those sources which cannot be specified in detail. Such emissions must be inferred by relating them to population, motor vehicles, etc. For these sources, it is necessary to use a simple dispersion algorithm to estimate concentration patterns. The Gifford urban area dispersion algorithm (Hanna and Gifford, 1973) has proved to be a simple but physically realistic model capable of estimating atmospheric

pollutant concentrations caused by area source emissions in cities. The basic Hanna-Gifford Equation is given as:

$$X = CQ_0/U \quad ,$$

where X is the air pollutant concentration, Q_0 is the effective emissions rate per unit area, and U is the wind speed. The parameter C, generally referred to as the Gifford coefficient, is a weak function of the city size; it may be taken to be approximately constant. Theoretically, the parameter C is given by:

$$C = (2)^{1/2} \cdot X^{1-b}/[a(1 - b)]^{-1} \quad ,$$

where X is the distance from a receptor point to the upwind edge of the area source. The constants a and b are defined by the vertical atmospheric diffusion length, $\sigma_z = ax^b$. Values of a and b for different atmospheric dispersion conditions have been discussed by Pasquill (1970, 1971). The parameter C can be estimated for various combinations of the stability factors a and b and by assuming that X equals half the city size (Hanna, 1978). For example, 213 would be an appropriate value of C for a city with a land area of 400 km^2 under Pasquill Class D stability (while a = 0.15 and b = 0.75). Specific values of the parameter C have been empirically estimated by Hanna and Gifford (1973) for a large number of U.S. cities based on a large quantity of air quality data, average annual emissions, and meteorological conditions. The mean value of C has been found to equal 225, with a standard deviation roughly half that magnitude. This value of the parameter C has been recommended for use in evaluating an area source by the EPA (1977a, b) if removal and decay processes may be neglected. Estimates of the parameter C were calculated by using Equation 11 and by

assuming Pasquill Class D stability as the average long-term meteorological condition.

The application of the Gifford approach within SHEAR has been modified to provide variation of atmospheric concentration across a modeling region in proportion to the local emission rate per unit area. This approach provides a higher degree of resolution of concentration patterns than does the single urban box approach, but does not address the details of pollutant advection and dispersion that are treated by grid dispersion models.

In the present approach, box model (Gifford model) dispersion results are simply scaled at each BG/ED by the ratio of the density of emissions per surface area at the BG/ED to the regional mean emission density.

Options in the AREA code provide for varying or non-varying (from district to district) emission rates. Emissions that vary with BG/ED are scaled by the population density of the BG/ED. This is to address pollutant emitting activities that uniform fractions of the population are expected to be engaged in at any given time. Examples of such activities are motor vehicle usage and operation of home furnaces.

Either uniform or nonuniform emission rates may be restricted to specified portion of the modeling region. This feature is provided so that the user may address such source types as crop spraying, tillage dust, area burning, or other activities for which specified areas may be identified.

Equation 11 shows that the concentration is inversely proportional to the wind speed. In SHEAR, each wind speed in the STAR set is used. The STAR matrix is summed over wind direction and stability class to give the frequency of occurrence of each speed. The concentration is computed as the sum of the frequency-weighted concentrations for each wind speed.

p3

3-4. Assumptions

Similar to SHED, SHEAR makes certain assumptions in order to run with limited data. This section describes the necessary assumptions to provide the user with an understanding of the limitations of SHEAR and the need to consider such limitations in the use of the output data. The assumptions for SHEAR include both those listed here and those covered in Section 2-4.

The SHEAR model uses census data to the BG/ED level. Although this is the smallest defined population unit, it still places approximately 800 people at one point. This is not a realistic depiction of their residence. Some of the people may actually be located closer to the plant and receive greater exposure than modeled or vice versa. Unlike SHED, this is especially true closer into the plant. Where SHED spreads the population out to all the concentration points within the 3.5 km range, SHEAR simply uses the interpolation method (which SHED uses from 3.5 - 50 km radius) for all distances from the source so that all exposure occurs only at the population centroid. This can result in concentration receptors close to the plant being ignored because no people are assigned to them, even though people counted in a nearby population centroid may actually be living in such areas. This would result in an under estimation of the maximum concentration to which people are exposed. Thus, even though the major point source portion of SHEAR can add concentrations from several plants and risks of different chemicals, the modeled maximum risk may not be as high as that modeled by SHED. One advantage of the SHEAR methodology for using the interpolation of concentration to people rather than people to concentration, is that this method never locates people over large bodies of water, provided population centroids are not so located (a circumstance the Census Bureau strives to avoid).

The prototype algorithm of SHEAR with the random location of sources obviously cannot be assumed to correctly represent the actual source locations. The results of the prototype model depend strongly on the population density of the county being modeled.

The area source model requires more fundamental assumptions concerning population and concentrations than do the other two types of sources. Unless the area is well known and defined, portions of the study area such as parks or lakes which contain no sources may be included into the area over which the emissions are spread. Since area is contained in the denominator of the Hanna Gifford Equation, the resulting concentration may be somewhat lower than the actual. In addition, unless rural areas are deleted from models of urban sources, people in the rural area who may not be exposed to the pollutant will be included with those exposed. This model should be used only to determine a rough estimate of what public exposure might be, unless the study is restricted to urban areas.

3-5. Using the SHEAR Model

The SHEAR model is more complex to run than the SHED model. It is designed to handle the various modeling techniques (area, prototype and point), as well as, multiple chemicals. This flexibility requires the use of several files and each file has its own format. Some of the data entered in each file may seem redundant but must be entered in order for the program to identify the appropriate files and to execute properly.

The number of files and means of accessing the appropriate files requires a brief explanation of how files are identified before you can effectively use SHEAR. In order for a file to be identified, the qualifier and the filename must be provided. If you type only the filename, the

project ID is assumed as the qualifier. If you type *filename, the program searches for the last @QUAL statement. That statement becomes the qualifier. If no @QUAL exists, the project ID again becomes the default. If these methods cannot define the appropriate file, you must type qualifier*filename to identify the file.

* * *

NOTE: For all the instructions below, all information within commands which are specific to your file or run will be typed in small letters and contained in parentheses. For example, @@CONS RC (run id) means type @@CONS RC Ø8PT if Ø8PT is the run id of the run you needed to check. <u>Do not type the parentheses</u>.

* * *

SHEAR groups its files into two categories; area specific and chemical specific. This allows several chemicals to be analyzed for the same study area, using the same study area file. Both groups of files must be cataloged before entering the data.

To name the area specific files, type:

@QUAL (Study Area)

The study area name may be any alpha numeric name with 1-12 characters. This name is now the qualifier for all the area specific files. To catalog the files type:

@ADD SASD*HEP-RUN.SHEAR-CAT/NON-QUALED

Several lines of symbols will be printed when you push XMIT. When the computer responds with "READY" the area specific files are cataloged. You may enter data now or catalog the second group of files.

To name the chemical specific files, type:

@QUAL (Chemical Name)

The chemical name may be any alpha numeric name with 1-12 characters. This chemical name is now the qualifier for all the chemical specific files. To catalog these files type:

@ADD SASD*HEP-RUN.SHEAR-CAT/QUALED

Again, the computer will print several lines of symbols until it responds with "READY." At this point the chemical specific files are cataloged and you are ready to enter data.

Entering the Data

You are now ready to enter data into each data file. To do this, some sort of text editor must be called. Several text editors are avilable but for this example, we will use the Maryland text editor. Specific editing commands for the Maryland editor are available in Hagerty and Sibbald's "Text Editor User's Guide." A few commands are also provided in Appendix C of this manual.

The first file to be entered is an area specific file which identifies to the program the name of the chemical-specific files. This is the only area-specific file which must be changed when running an additional chemical with the same study area.

To open the file type:

@EDM (Study-Area)*QUAL.

Enter the following information:

@QUAL (Chemical Name)

In order to have the output printout alligned correctly, the format should follow figure 3-1.

To open the first data file type:

@EDM (Studyarea)*SHR-XTRACT.

The data you enter into this file defines the area of the country which will be modeled. Each line of data, referred to as a card, has a specific

@QUAL CARD FOR SHEAR FILE QUAL

THE QUAL CARD ALLOWS THE USER TO SELECT DIFFERENT SETS OF DATA FOR THE SAME REGION

1	15 26
@QUAL	THE QUALIFIER

Figure 3-1

function and format. If data is not entered in the correct columns and rows, the data will be misinterpreted by the program. Therefore, you should enter the data exactly as described below (see also Figure 3-2):

Card 1, Columns 1-80 = An identifying name of the region, to be selected by user. This name is used in subsequent output headings generated by any module using this data. The name may be up to 80 alpha characters.

Card 2, Columns 1-10 = The UTM easting of the SW corner of a rectangle sufficiently large to include the desired modeling region. UTM coordinates are expressed in meters on all USG maps. The 7 1/2- and 15-minute series maps are likely to be most appropriate sources of this data. Because UTM coordinates are numerically large, trailing zeros may be suppressed on some map displays. Care should be taken to acquire and input coordinates in kilometers. Up to 10 digits are allowed.

Columns 10-20 = The UTM northing of the SW corner referred to above.

Columns 21-25 = The UTM zone number. Since UTM coordinates are plane approximations to a spherical surface, they are defined for zones, each of which is limited in size to limit the approximation error. UGS maps note zones used. Coordinates are entered as up to 5-digit integers.

Columns 26-34 = The size of cell to be used in Cartesian grid resolution of BG/ED areas. Small cells lead to fine resolution on the plotter, but, since actual BG/ED perimeters are

POPULATION EXTRACTION DATA FOR SHEAR FILE SHR-XTRACT.

CARD 1

1 ... 80
REGION NAME

CARD 2 - DEFINES BASIC RECTANGLE

1	11	21	26	36	41 ... 45
MINIMUM X (KILOMETERS)	MINIMUM Y (KILOMETERS)	UTM ZONE	GRID SIZE (KILOMETERS)	NUMBER X CELLS	NUMBER Y CELLS

CARD 3

1	5 ... 9
POP YEAR	NUMBER OF COUNTIES

CARD 4 FIPS CODES OF COUNTIES TO BE SELECTED - AS MANY CARDS AS REQUESTED ON CARD 3

1 ... 5
ST CNT

Figure 3-2

not known, finer resolution does not necessarily produce more accurate definition of BG/ED areas. Hence, larger grid cells produce the same risk results as small grid cells but the smaller cells produce better plotted output. Larger cells also require less computer time to run. The number of grid cells used may be limited by available space or computing time on the computer used. This XTRACT code limits the grid to 10,000 cells. This limitation may be changed at the user's discretion by recompiling the programs. The cells will be square, so this datum serves as both as X and a Y cell dimension.

Columns 35-40 = The number of grid cells desired in the X (E-W) direction.

Columns 41-45 = The number of grid cells desired in the Y (N-S) direction.

Card 3, Columns 1-4 = The year for which population is desired (used for extrapolation from 1980).

Columns 5-9 = The number of counties for which the populations is desired. (optional)

Card 4, Columns 15 = The FIPS codes of the counties to be selected. The number of codes listed must be the same number of counties stated in Card 3. (optional) If this option is exercised, the analysis will be restricted to the county(s) specified. The study area then consists of the portions of the specified counties that are within the box defined above.

Card 5 = The region within the defined analysis area to be excluded from the analysis (optional). The region is defined in the card by the minimum and maximum rows (y coordinates) of any cluster of cells to be deleted followed by the minimum and maximum columns (x coordinates) in each affected row, in sequence. Coordinates are expressed in units of cell number (five digits). Cell number (1, 1) is the lower left corner of the defined rectangle. (See Figure 3-3.)

This is all the data needed for the XTRACT file. The next data file requires information concerning the weather (STAR) data. To open the file type:

@EDM (chemical)*SHR-STAR.

The data should then be entered in the following format (see also Figure 3-4):

Card 1, Columns 1-80 = The name of the chemical addressed in the present run. This is to be used in subsequent headings.

Card 2, Columns 1-10 = The hazard factor (unit risk) for the chemical, if available. This is required if hazard or risk or other multi-species computations are desired. The factor has units of cases (of health effect) per person.$\mu g/m^3$.year. Hazard factors are based on extensive analysis of clinical and/or epidemic toxicology.

Card 3, Column 1 = A flag, zero or one, to indicate if rural (1) or urban (0) dispersion conditions prevail. This flag should be

EXCLUSION DATA FOR SHEAR FILE SHR-XTRACT.

CARD 5 (EXCLUSION CARDS USING CELL COUNTS) OPTIONAL

1	6	11	16	21	26	31	36	41	46	51	56	61	66	71	76 80
MIN ROW	MAX ROW	MIN 1 COLUMN	MAX 1 COLUMN	MIN 2 COLUMN	MAX 2 COLUMN	MIN 3 COLUMN	MAX 3 COLUMN	MIN 4 COLUMN	MAX 4 COLUMN	MIN 5 COLUMN	MAX 5 COLUMN	MIN 6 COLUMN	MAX 6 COLUMN	MIN 7 COLUMN	MAX 7 COLUMN

Figure 3-3

CHEMICAL & STAR DATA FOR SHEAR FILE *SHR-STAR.

CARD 1

1	80
CHEMICAL NAME	

CARD 2

1	10
UNIT RISK	

CARD 3

1	11	21	31	41	56
RU	STAR SITE	EXCLUDED STABILITIES	EXCLUDED WIND SPEEDS		EXCLUDED WIND DIRECTIONS

COLUMN ONE EQUAL 1 IMPLIES THE AREA IS RURAL. USE ALL STABILITY CLASSES
COLUMN ONE EQUAL 0 IMPLIES THE AREA IS URBAN. COMBINE STABILITY CLASSES D, E, & F TO GIVE REVISED CLASS D

!ITEMS CODED 1 ARE EXCLUDED

CARD 4

1	11	21	31	40
AMBIENT TEMP DEGREES K	LAPSE RATE FOR STABILITY CLASS D	LAPSE RATE FOR STABILITY CLASS E	LAPSE RATE FOR STABILITY CLASS F	

Figure 3-4

set by a person familiar with EPA dispersion modeling practices.

Columns 11-15 = The station number of the United States Weather Service reporting station from which STAR dispersion data is desired for the present run. The station selected will normally be the station closest to the region currrently being analyzed. A more remote station might be selected if it is judged that its climate is more representative of conditions in the analysis region. This might occur because of the relative proximity of the region and each weather station to coast lines or major topographic features. Selection of a station other than the closest should be only upon expert advice. (See Section 1-2)

Columns 21-27, Columns 31-36 and Columns 41-56 = Specification of portions of the selected STAR data matrix to be deleted. The STAR matrix consists of a three-dimensional array. The array variables are wind speed, direction, and atmospheric stability. The set of standard values of one or more of these variables may be diminished if it is assumed that correlations between source operation and occurrence of meteorological conditions are such that the emissions and the variable values are mutually exclusive. This data should only be entered upon expert advice. These data entries are in flag style (zeros and ones). Each parameter is addressed by a string of flags, one for each

standard value, in sequence. There are six wind speeds, so there is a string of six flags for this parameter; there are seven stabilities and 16 directions with corresponding flag strings. If these columns are left blank, all of the STAR data is used.

Card 4, Columns 1-40 = Ambient temperature (in °K) and lapse rate (in °K/m). Since the computation is an annual average computation, only representative values can be used. Depending on the application, mean or extreme values might be used. If these cards are left blank, default values are used. It is important, however, that a blank card actually be inserted here. One way to do this is to type:

```
I Y    (XMIT)
  C / Y /  /    (XMIT)
```

This will insert a blank card.

This completes the STAR data. The next set of commands demonstrates what to enter for point, prototype and area sources. For major point source model, enter the following (see also Figure 3-5):

@EDM (chemical)*SHR-POINT.

The data to be entered for this file is very similar to that entered for SHED with a few exceptions. In fact, a SHED file can be added and edited to create this file. The three cards should be entered for each plant and each chemical. The data is entered in the following format:

Card 1, Columns 1-80 = The facility identification in alpha numeric characters.

Card 2, Columns 1-6 = Latitude of the facility in degrees, minutes and seconds.

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POINT SOURCE & PROTOTYPE DATA FOR SHEAR

FILES *SHR-POINT. & *SHR-PROTO.

CARD 8

1	80
FACILITY IDENTIFICATION	

CARD 9

1	7		40	45	50	55	60	64
LATITUDE DEG MIN SEC	LONGITUDE DEG MIN SEC		NUMBER SOURCES	PROTOS SINGLE	PROTOS DOUBLE	PROTOS TRIPLE	PROTOS QUADRUPLE	

CARD 10

SUBMIT ONE OF THE FOLLOWING FOR EACH SOURCE AT THE FACILITY

1		14	18	22		27	32	35
E T	EMISSION RATE (KG / YEAR)	STACK METERS	AREA M**2	V T	DIA METERS	VELOCITY M/SEC	TEMP (K)	

ET (COLUMN 1) EMISSION TYPE
- P = PROCESS VENT
- S = STORAGE VENT
- F = FUGITIVE EMISSIONS
- H = STACK

VT (COLUMN 22) VENT TYPE
- 0 = VERTICAL STACK
- 1 = NON-VERTICAL STACK OR A VENT

Figure 3-5

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Columns 7-13 = Longitude of the facility in degrees, minutes and seconds.

(This is all that is entered in Card 2 for major point sources)

Card 3, Column 1 = Indicator as the emission type.

P = process vent; S = storage vent

F = fugitive emissions; H = stack

Columns 2-13 = Emission rate in Kg/year including decimal point.

Columns 14-17 = Stack or vent height in meters with decimal point.

Columns 18-21 = Building (of vent or stack) cross sectional area (M^2) perpendicular to the mean wind flow, including demical point.

Column 22 = Indicator as to vent type.

Ø = vertical stack, 1 = nonvertical stack or vent.

Columns 23-26 = Inside stack or vent diameter in meters, including decimal point.

Columns 27-31 = Gas exit velocity from vent or stack in m/sec including decimal point.

Columns 32-35 = Gas exit temperature in degrees K including decimal point.

In order to use the prototype portion of the SHEAR model you must open the following file:

@EDM (chemical)*SHR-PROTO.

The data entered for the prototype source is identical to the data entered for the major point source described above except for Card 2. This card should be filled out exactly as follows (see also Figure 3-5):

Card 2, Columns 1-39 = Blank

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Columns 40-44	= The number of prototype sources to be located within the specified area.
Columns 45-49	= The number of sources which will not be located in the same cell as another prototype (protosingle).
Columns 50-54	= The number of times that sources which will be colocated with only one other prototype.
Columns 55-59	= The number of times three prototype sources will be colocated.
Columns 60-64	= The number of times four prototype sources will be colocated.

(The sum of columns 45-49 plus 2X columns 50-54 plus 3X columns 55-59 plus 4X columns 60-64 must equal the number entered in columns 40-44.)

In order to use the area source portion of the SHEAR program type in the following:

@EDM (chemical)*SHR-AREA.

The data should be entered into this file as indicated below (see also Figure 3-6):

Card 1, Columns 1-80	= The area source identification name.
Card 2, Columns 1-10	= The emission rate per year per unit population or per square kilometer. The units are Kg/yr.
Columns 11-20	= The number of people which you use as the unit population above. If this number is zero, the model assumes the emission rate to be Kg/yr/Km^2.
Card 3, Columns 1-5	= Indicator as to whether the whole area is to be used or whether additional areas are to be added or subtracted. If the number of areas is positive, then the areas are included; if

AREA SOURCE DATA FOR SHEAR FILE *SHR-AREA

CARDS 1-4 COME FROM FILE *SHR-STAR CARD 4 IS IGNORED CARD TYPES 5-8 ARE REPEATED AS OFTEN AS NEEDED

CARD 5

1 ... 80
AREA SOURCE IDENTIFICATION

CARD 6

1	11 ... 20
EMISSION RATE (KG/YR/2)	UNIT POPULATION

IF UNIT POPULATION = 0, EMISSIONS ARE IN KG/YR/SQ KM
IF UNIT POPULATION > 0, EMISSIONS ARE IN KG/YR/UNIT POPULATION

CARD 7

1 ... 5
NUMBER OF AREAS

IF NUMBER OF AREAS > 0, THEN THE AREAS ARE INCLUDED
IF NUMBER OF AREAS < 0, THEN THE AREAS ARE EXCLUDED
IF NUMBER OF AREAS = 0, THEN THE WHOLE AREA IS USED

CARD 8 (THE AREAS)

1	11	21	31 ... 40
MIN X	MAX X	MIN Y	MAX Y

Figure 3-6

negative, the areas are excluded and if the number of areas is zero, the whole area is used.

Card 4, Columns 1-40 = These cards define the area to be included or excluded from the defined analysis region (optional). The area is defined by the minimum and maximum UTM x coordinates (10 digits each in kilometers) and the minimum and maximum y coordinates (10 digits each in kilometers). This could be used to look at only crop areas in a county (inclusion) or deleting a city park from the analysis area (exclusion).

The last data file, called the Summarization Data File, must be filled out for any SHEAR run. This file enters the unit risk number for the final calculation. To open this file type:

@EDM (studyarea)*SHR-REPORT.

Enter the data as follows (see also Figure 3-7):

Card 1, Columns 1-80 = Enter the chemical name as previously entered.

Card 2, Columns 1-10 = Unit risk number for lifetime risk.

Columns 11-42 = Filename. (chemical name*CONC-FILE.)

Cards 1 and 2 should be filled out for each chemical to be analyzed. This allows separate reports to be printed for each chemical when running multiple chemicals.

Figures 3-1 through 3-7 gives a summary of the data to be entered for each file described above. It is strongly recommended that these summary sheets be used when entering data into the data files.

SUMMARIZTION DATA FOR SHEAR FILE SHR-REPORT.

REPEAT THE SETS OF TWO CARDS

CARD 1

1	80
CHEMICAL NAME	

CARD 2

1	11	42
UNIT RISK	FILE NAME	

CARD 1

1	80
CHEMICAL NAME	

CARD 2

1	11	42
UNIT RISK	FILE NAME	

Figure 3-7

Running the Program

Once the files have been filled as described above, the program is ready to run. Unlike SHED, you have entered data into data files not program files. Therefore, the files are ready to use by the model and do not need to be copied.

Also unlike SHED, SHEAR has several options for being run. The following set of commands demonstrate a good way to run the prototype and area sources. To begin, type:

@START START.SHR-PROTO-A,/(Site id),,,(Filename)

Once the program has finished running for prototype sources, you must empty the XTRACT file of all concentrations. This is accomplished by entering:

@Copy (Filename)*BGED-FILE., (Filename)*CONC-FILE.

This allows the program to use the data derived from EXTRACT without rerunning that portion of the program. It also blanks out the prototype, data to prevent its addition to any subsequent runs.

To run area sources, type:

@START START.SHR-AREA,/(Site id),,,(Filename)

If you want to run area first, just substitute the word "area" for "proto" and vice versa. The same applies to point source.

Two points are important to remember:

1. The "-A" as typed in the first start command is only used in the start command for the first run of a chemical. (The "A" initiates the XTRACT portion of the program which is not necessary to run again.)

2. Before making the next run, you must always empty the CONC. file using the @copy command described above.

This method of running the program keeps the analyses separate. If you wish to know the cumulative risk from thee point prototype and area sources, simply omit the step in which you empty the conc. file.

Users who would like the results of the SHEAR run to go to their PC or user ID rather than be printed at the Mutual Building or other dedicated UNIVAC printer should replace the letters SHR in the start card with USR. Do not replace SHR with USR in the filenames. The file will then not print out until requested. Please see instructions in section 2-5 to obtain results at your PC. To receive a laser printout at the Research Triangle Park replace SHR with LAZ.

Plotting SHEAR Data

Each time SHEAR is run by the commands listed earlier, a plot of the study area is sent to the CALCOMP plotter. These plots include: 1) the BG/ED locations in the region analyzed, 2) the population density, 3) the locations of the sources, and 4) the concentrations around each source. These plots are large and use various colors to depict the variable plotted.

The TEKTRONICS plotter could also be used for the SHEAR output. This produces 8 1/2 x 11 plots that are not color. To send the SHEAR output to the TEKTRONICS plotter rather the calcomp plotter, type /TEK after the point, proto or area portion of the start command. To run a stripped down version (no legends) of the output, type/TEK-B in the same place. These commands are shown in Appendix D to demonstrate all the variations (e.g., different radial distances).

The specifications for the plots described above are initiated by the run stream and can only be changed by a programmer who is familiar with the Executive Control Language (ECL). The format for the information is shown in the top portion of Figure 3-8. Additional legends, however, can be added to the plot by the general user. This format is shown in the bottom portion of Figure 3-8 and is described below:

Columns 1-13 = location of legend in UTM coordinates (e.g., source locations that you need to label.

PLOT DATA FOR SHEAR

SPECIFICATIONS (VARIOUS DEFAULT DATA SUPPLIED FOR EACH MAP)

1	4	9	12
MAP SIZE	P	PEOPLE SYMBOL	C	SYM SIZE
. .	.	. . . .	.	. .

MAP SIZE OF 1.0 YIELDS A MAX SIZE MAP OF 31.0 BY 23.6 INCHES OTHER VALUES YIELD FRACTIONS OF 31.0 BY 23.6 INCHES

COLUMN 4 EQUAL TO 1 IMPLIES PLOT THE POPULATION CENTROIDS

COLUMN 9 IS THE COLOR FOR THE SYMBOL 1=BLACK 2=RED 3.BLUE 4=GREEN

LEGENDS FOR SHEAR FILE LEG-FILE.

FILE *PLOT-FILE. CONTAINS THE LOCATION OF POINT SOURCES AND PROTOTYPES AND HAS THE SAME FORMAT

1	7	14	18	22	26	29	80
UTMX (KMS)	UTMY (KMS)	SYMBOL NUMBER	C S	SYMB SIZE	C T	TEXT SIZE	TEXT ANG	LEGEND TEXT
. . . . .	. . . . .	. . .		. .		. .	. .	. . . . .
. . . . .	. . . . .	. . .		. .		. .	. .	. . . . .
. . . . .	. . . . .	. . .		. .		. .	. .	. . . . .
. . . . .	. . . . .	. . .		. .		. .	. .	. . . . .
. . . . .	. . . . .	. . .		. .		. .	. .	. . . . .
. . . . .	. . . . .	. . .		. .		. .	. .	. . . . .
. . . . .	. . . . .	. . .		. .		. .	. .	. . . . .
. . . . .	. . . . .	. . .		. .		. .	. .	. . . . .
. . . . .	. . . . .	. . .		. .		. .	. .	. . . . .
. . . . .	. . . . .	. . .		. .		. .	. .	. . . . .

COLUMN 18 IS THE COLOR FOR THE SYMBOL
COLUMN 22 IS THE COLOR FOR THE TEXT

Figure 3-8

Columns 14-17	= symbol number (see Appendix E).
Column 18	= color of symbol. 1 = black, 2 = red, 3 = blue, 4 = green.
Column 19-21	= Height of symbol in inches.
Column 22	= Color of the text.
Columns 23-25	= Height of letters of text in inches.
Columns 26-28	= Angle at which the text should be printed in degrees.
Columns 29-80	= The text of the label (will be printed in Simplex Roman type).

Miscellaneous

As mentioned previously, SHEAR is much more complicated to run than SHED. You must complete a larger number of files and select the appropriate start card for the analysis. The available SHEAR start cards are listed in Appendix D.

Some of the start cards cause the SHEAR program to generate a concentration ranking from the center of the box. These start cards are noted in Appendix D. If these cards are used, it is also possible for the user to choose a location other than the center of the box. See Figure 3-9 for the appropriate format.

Figure 3-10 is provided for the programmer who has a good knowledge of ECL. The radial distances for SHEAR can be altered by changing the runstream. Figure 3-10 provides the appropriate format. The current defaults for 50 Km run are ten radii at .20, .50, 1.00, 2.00, 5.00, 10.00, 20.00, 30.00, 40.00 and 50.00 Km. The decay rate is assumed to be zero.

SELECTION OF CENTER FOR LISTING OF CONCENTRATIONS

FILE *SHR-CONCS.

LATITUDE DEG MIN SEC	LONGITUDE DEG MIN SEC	

Figure 3-9

POINT SOURCE & PROTOTYPE DATA FOR SHEAR NO FILE (DEFAULTS)

CARD 1

1 – 3
NUM RADII

CARDS 2A, 2B, 2C (RADII IN KM AS NEEDED)

1 – 8	9 – 16	17 – 24	25 – 32	33 – 40	41 – 48	49 – 56	57 – 64	65 – 72	73 – 80
RADIUS 1, 11, 21	RADIUS 2, 12, 22	RADIUS 3, 13, 23	RADIUS 4, 14, 24	RADIUS 5, 15, 25	RADIUS 6, 16, 26	RADIUS 7, 17, 27	RADIUS 8, 18, 28	RADIUS 9, 19, 29	RADIUS 10, 20, 30

CARD 3

1 – 10	11 – 20
DECAY RATE - DAY (PER HOUR)	DECAY RATE - NIGHT (PER HOUR)

CARDS 4-7 COME FROM FILE *SHR-STAR.

Figure 3-10

3-6. Using Output from other Dispersion Models

Similar to SHED, SHEAR can be executed using concentration inputs from other models for the point source portion of the model. It is currently capable of using ISCLT results. The ISCLT output must be created as tape file output on disk using options when the ISCLT model is run. You need then know only the filename(s) to access the concentrations.

Entering Data

To execute SHEAR using output concentrations, you must enter data into all the files as usual with one additional file. To open this file, type:

@EDM (chemical)*SHR-ISCLT.

Enter the data as follows (see also Figure 3-11):

Card 1,	Columns 1-6	= Latitude of the plant in degrees, minutes, and seconds (two digits each).
	Columns 7-13	= Longitude of the plant in degrees (three digits), minutes (two digits), and seconds (two digits).
	Columns 14-23	= Conversion factor. (This number will be multiplied by the concentration points to yield a converted concentration. Since the emission rate is proportional to the concentration points, this factor may be used to analyze various possible emission rates with only one ISCLT run. Enter 1.0 if you wish the concentration points to remain the same.)

SELECTION OF ISC OUTPUT FILES FILE *SHR-ISCLT.

1	7	14	24	56	80
LATITUDE DEG MIN SEC	LONGITUDE DEG MIN SEC	CONVERSION FACTOR	FILE NAME	ISCLT POINT SOURCES TO BE INCLUDED	

Figure 3-11

Columns 24-25	= filename in which the ISCLT concentration values are listed.
Columns 56-80	= Point sources (individual stacks) at the plant to be included. Each digit represents each stack. If the stack is to be included, type 1; if excluded, type Ø. Leaving this part blank includes all the stacks.

This card should be completed for each plant and chemical analyzed.

Running the Program

There are several options for running the program depending upon your needs. If you have not yet executed a SHEAR run for these sources, the XTRACT program must be run. Hence the start card would be as follows:

@ START START*SHR-ISCLT-A,/(Site ID),,,(filename)

If XTRACT has been run previously for these sources, simply empty the conc. file as described in section 3-5 and type the start card as shown above deleting the "-A".

3-7. Output from SHEAR

The major output from SHEAR is very similar to SHED. It includes a listing of the input data and concentration grid for each point source. The output also includes the cummulative exposure summary similar to that discussed under SHED. The overall summary constitutes the major difference between SHEAR and SHED output. SHEAR output presents a chart similar to the cummulative exposure summary in lieu of the overall summary. This chart presents levels of hazard (concentration plus unit risk divided by seventy), the number of people exposed to that hazard or greater and the annual incidence (people x hazard).

///

In addition to these output, SHEAR also reports the location of each prototype source and each BG/ED used in the analysis. The area and prototype data output are cummulative for the area analyzed rather than presented for each individual source.

References

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Appendix A

STAR-PICK

To access STAR-PICK you must have access to the UNIVAC computer system (as described in Section 1-3) and be logged on (as described in Section 2-4). Once logged on type the following:

@ADD,PL HEP-RUN.STAR-PICK

and hit XMIT. The program will then respond with several strange lines of information. At the end of the information the computer types:

Enter the location's latitude (DEG, MIN, SEC) and longitude (DEG, MIN, SEC) and the number of sites to list (default of 20) Format (3I2, I4, 2I2, I4) or @ EOF if finished.

You should now type the following in exactly the format shown below:

DDMMSS DDDMMSSNNNN

where: D = degrees (latitude in first group of number, longitude in the second

M = minutes

S = seconds

N = Digits of the number of star stations you wish to be displayed (default is 20)

When you hit XMIT, the computer will respond with the STAR station code number, the city in which it is located, its distance from the source longitude and latitude, and other information. The listing will be in order of closest distance from the given longitude and latitude.

After you have obtained all the STAR station code numbers you need, type:

@EOF

and hit XMIT. This will exit you from the program.

Appendix B

Conversion of UTM Coordinates to Latitude/Longitude Coordinates

To use the program available on the UNIVAC system you must have access to the UNIVAC system (as described in Section 1-3) and be logged on (as described in Section 2-4). To access the program type the following:

@XQT EDS*RUN.UTM-CALC

and hit XMIT. You then must enter the UTM coordinates in the following format:

UEEE.EØNNNN.NØZZ

where: U = signals program that these are UTM coordinates

E = digits of the UTM easting

N = digits of the UTM northing

Z = zone of the UTM coordinates

Be careful to place exactly the indicated number of digits and to place the zeros or spaces in. Once you hit XMIT, the computer will respond with the latitude and longitude with both decimal units and degrees, minutes, seconds units. You are interested in the degrees, minutes, seconds reading for SHED.

You may also translate geoditic coordinates to UTM by using the following format:

LDDMMSSØDDDMMSS

where: L = signals program that these are geodetic coordinates

D = degrees (latitude in the first number; longitude in the second)

M = minutes

S = seconds

Be careful to enter all the digits indicated and the zero (or space). Once you hit XMIT, the computer will respond with the same format as with the conversion of UTM to latitude and longitude.

It is also possible to translate longitude and latitude represented by a decimal figure into UTM coordinates or units of degrees, minutes and seconds. To do this, use the following format:

DXX.XXXXØYYY.YYYY

where: D = signals program that these are decimal coordinates

X = latitude digits

Y = longitude digits

Be careful to enter the digits and zero (or blank) as shown with the decimal points in the indicated positions. The computer will respond with the same format as with the previous conversions.

Appendix C

Helpful Hints With the Maryland Editor

The Maryland Editor operates in two modes, the input mode and the edit mode. In the input mode, every typed character is entered into the data file. In the edit mode, the user directs the Editor to change or scan the text in various ways. Data can also be input in the edit mode by typing I, a space, and the information to be inserted.

The Editor toggles between edit and input modes by pressing XMIT after an SOE (>). We suggest remaining in the edit mode at all times in order to make use of the editing commands.

The most used commands are listed below in brief summary form. Please refer to reference 2 to obtain a complete explanation of the Editor, a more extensive list of commands and a more complete definition. The numbers 9 and Ø used below are examples, any number may be used.

Maryland Editor Commands:

To move around in a file (Remember that moving the cursor may move you around on the screen but it does not move you around in the file.)

D - deletes the line you are on

D 9 - deletes the line you are on and the next eight lines

O 9 - prints the next 9 lines on the screen

P 9 - prints the line you are on & the next 8 lines

N - prints the next line on the screen

T - takes you to the top of the file (this also stores any changes that have been made in a backup data file)

LA - takes you to the last line of a file

9 - takes you to line number 9

-9 - moves you up 9 lines

+9 - moves you down 9 lines

To Change a file

C /old/new/ - changes the old (type whatever you want changed) to the new (type what you want it changed to) the first time it appears in the line

C /old/new/ G - changes the old to the new everytime it occurs in the line

C /old/new/ 9 - changes the old to the new the first time it occurs in the line for the line you are on and the next 8 lines

R (a space) new - replace the line you are on with new

R,9(a space) new - replace part of line starting in column 9 with new

To Copy a Part of a file

Ditto Ø 9 - copies lines Ø to 9 below the line you are on

BE - begins to copy (move to first line you want copied before typing)

CO - ends part to copy (move to the line below the last line you want copied before typing)

ADD - copies the data defined by BE and CO below the line you are on

CO Filename - used in place of CO and ADD to copy data to a separate file

For Help

HELPS[Procedure Name] - displays information on a particular procedure; use @EOF to exit

SC - prints column scale

120

Appendix D

Summary of SHEAR Run Cards

This Appendix lists parts of the SHEAR run card which can be inserted for slight variations of the SHEAR run. The general format for all the cards will be:

@START SASD*START. [part from below],/site ID ,,, filename

The following rules apply to the variations and may help in selecting the correct card:

1. If TEK is included as part of the card, the output will be plotted on the tektronics plotter. Otherwise the output goes to the calcomp plotter. The "-B" omits the legends on the plots.
2. If the point or proto run cards have no numbers, the analysis will be performed out to 20 Km. A number with the card indicates the distance to which the analysis will be performed. (e.g., 50 Km)
3. The "-A" commands the XTRACT portion of SHR to be executed.
4. The "All" commands all (point, proto and area) to be run.
5. The "-P" commands the concentration values to be added to those values already in the CONC. FILE (i.e., XTRACT must have been run previously). This is similar to running without "-A" except that -P also commands the output to be plotted.

The following inserts include as output the concentration levels surrounding the center of the city or other designated location:

SHR-ALL
SHR-ALL/TEK
SHR-ALL/TEK-B
SHR-AREA-A
SHR-AREA-A/TEK
SHR-AREA-A/TEK-B
SHR-ISCLT
SHR-ISCLT-A
SHR-ISCLT-A/TEK
SHR-ISCLT-A/TEK-B
SHR-ISCLT-P
SHR-ISCLT-P/TEK
SHR-ISCLT-P/TEK-B
SHR-POINT
SHR-POINT-A
SHR-POINT-A/TEK
SHR-POINT-A/TEK-B
SHR-POINT-P
SHR-POINT-P/TEK
SHR-POINT-P/TEK-B
SHR-PROTO
SHR-PROTO-A
SHR-PROTO-A/TEK
SHR-PROTO-A/TEK-B
SHR-POINT/50-KM
SHR-POINT-A/50-KM
SHR-POINT-A/TEK-50-KM
SHR-POINT-A/TEK-B-50-KM
SHR-POINT-P/50-KM
SHR-POINT-P/TEK-50-KM
SHR-POINT-P/TEK-B-50-KM
SHR-POINT/80-KM
SHR-POINT-A/80-KM
SHR-POINT-A/TEK-80-KM
SHR-POINT-A/TEK-B-80-KM
SHR-POINT-P/80-KM
SHR-POINT-P/TEK-80-KM
SHR-POINT-P/TEK-B-80-KM
SHR-POINT/100-KM
SHR-POINT-A/100-KM
SHR-POINT-A/TEK-100-KM
SHR-POINT-A/TEK-B-100-KM

The following inserts do not include the concentration ranking as output:

SHR-AREA
SHR-AREA-P
SHR-AREA-P/TEK
SHR-AREA-P/TEK-B
SHR-PROTO-P
SHR-PROTO-P/TEK
SHR-PROTO-P/TEK-B

To send the results of the SHEAR run to your specific location to be printed out from your PC substitute USR for SHR in any of the above start cards. The actual printout of the material requires that you type @@SEND, U after the program has finished running (see section 2 - 5). To print out on the laser printer substitute LAZ for SHR.

Appendix E

BG/ED	Block Group/Enumeration District
CDM	Climatological Dispersion Model
ECL	Executive Control Language
EIQ	Emission Inventory Questionnaires
FIPS	Federal Information Processing System
HAD	Health Assessment Document
HEM	Human Exposure Model
ISCLT	Industrial Source Complex Long-Term
MARF2	Master Area Reference File 2
NCC	National Climatic Center, National Computer Center
NEDS	National Emissions Data System
NTIS	National Technical Information Service
SAI	Systems Applications Incorporated
SHEAR	Systems Applications Human Exposure and Risk
SHED	Systems Applications Human Exposure and Dosage
STAR	Stability Array
U.S.G.S.	United States Geological Survey
UTM	Universal Transverse Mercator

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QUALITY ASSURANCE OF HEM SOURCE INFORMATION FOR ETHYLENE OXIDE

FINAL REPORT

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4

1.0 INTRODUCTION

The U. S. Environmental Protection Agency (EPA) is evaluating the potential for adverse effects from exposure to ethylene oxide in the ambient air. One of the source categories under investigation is ethylene oxide production. The EPA has identified 14 ethylene oxide producers and has developed some preliminary exposure and risk estimates for populations near them. The purpose of this work assignment is to validate data used in making the preliminary assessment. Data to be validated includes location of the production facility and location of the most appropriate meteorological station. Other information to be generated in this work assignment relates to descriptions of terrain and population density and an assessment of habitability surrounding the source of ethylene oxide emissions.

The results of the evaluation of input data and other information are documented in summary sheets, one for each ethylene oxide production facility. These summary sheets are included in Appendix A. The summary sheets contain:

- the verified latitude and longitude of the facility,
- a description of terrain features in the area surrounding the source,
- a description of population density in the area surrounding the source,
- an identification of the most appropriate STAR (STability ARray) meteorological station,
- a geographical description of the predicted area of maximum modeled concentration, and
- an indication of habitability of the predicted area of maximum modeled concentration.

A summary of the results of the validation work is presented in Section 2.0. Section 3.0 is a description of the methodology used to perform the work. A list of references for information resources used in this project is presented in Section 4.0. As mentioned previously, the summary sheets containing validation information for each ethylene oxide production facility are included in Appendix A. Appendix B includes copies of U.S. Geological Survey maps with each source and the location of the maximum predicted concentration of ethylene oxide identified.

5

2.0 RESULTS

A summary of results from this validation study is contained in Table 2-1. The complete results of this validation study are presented in Appendix A in the form of 14 summary sheets,one for each production location. The information presented in the summary sheet for each source includes:

I. Plant Information

II. Current Modeling Information

III. Validated Modeling Information

IV. Terrain and Population Density

V. Description of the Area of Maximum Modeled Concentration

VI. Discussion of Validation Results

Table 2-1 presents a summary of the results for each of the 14 sources reviewed in this study. For each source the table indicates whether the latitude/longitude and/or the STAR site should be changed from that used in the preliminary assessment. The last column of the table indicates whether another HEM run is warranted based on the results of this study.

A rerun of the HEM analysis is suggested for three sources. These sources are:

- Dow/Plaquemine, LA,
- Norchem/Morris, IL, and
- Shell/Geismar, LA

In each of these cases the reason a rerun is suggested is the change in the location of the source as indicated by the validated latitude/longitude data.

Essentially, a rerun is suggested if the changes indicated would substantially change the HEM results. The criteria used to suggest a rerun of the HEM analysis are as follows. If the latitude or longitude changes from the data used in the preliminary analysis by more than 1.5 minutes, a re-run of the HEM analysis is indicated. Sensitivity analyses of the HEM indicate that ambient air concentration estimated by the dispersion algorithm used by the HEM are not sufficiently accurate if the latitude or longitude data is in

TABLE 2-1. SUMMARY OF SUGGESTED CHANGES IN THE ETHYLENE OXIDE HEM SOURCE INPUTS

Facility/Location	Change Source Latitude & Longitude[1]?	Change STAR Site Selection?	Rerun?
1. BASF Wyandotte/Geismar, LA	No	No	No
2. Celanese Chemical/ Clear Lake, TX	No	No	No
3. Dow/Freeport, TX	No	No	No
4. Dow/Plaquemine, LA	Yes	No	Yes
5. ICI Americas/Bayport, TX	No	No	No
6. Norchem/Morris, IL	Yes	No[2]	Yes
7. Olin/Bradenburg, KY	No	No	No
8. PPG/Beaumont, TX	No	No	No
9. Shell/Geismar, LA	Yes	No	Yes
10. Sunolin/Claymont, DE	No	No	No
11. Texaco/Port Neches, TX	No	No	No
12. Texas Eastman/Longview, TX	No	No	No
13. Union Carbide/Seadrift, TX	No	No[2]	No
14. Union Carbide/Taft, LA	No	No	No

[1]Corrected latitude and/or longitude is >1.5 minutes different from that used in the Ethylene Oxide producers HEM run dated January 16, 1986.

[2]STAR site used in preliminary analysis does not need to be changed, however, the distinction between the STAR site used and other STAR sites considered is not straightforward. These differences between STAR sites are discussed in the data sheets for those sources contained in the Appendix.

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error by more than 1.5 minutes. [NOTE: 1 minute ≅ 1.5 km] Any change in the STAR data used by the dispersion algorithm could produce results that differ substantially from the preliminary results. Thus, any change in the STAR site used indicates an HEM rerun.

While none of the STAR sites used in the preliminary analyses need to be changed based on this study, it should be noted that in two (2) cases there is some question as to the appropriateness of the STAR site used. These are Norchem/Morris, IL and Union Carbide/Seadrift, TX. The reason for the question is that the selection of the STAR site is complicated by site-specific factors and the choice of one of the two most representative sites is not straightforward. The sources for which this situation exists are indicated in Table 2-1 by a footnote.

The appropriateness of the STAR site selection is discussed in more detail for these two sources in the summary sheets for those two plants.

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3.0 VALIDATION PROCEDURE FOR STAR SITE SELECTION

The methodology of validating source information and gathering information for interpreting the results of the Human Exposure Model (HEM) are explained in this section. The procedures used to validate source information are similar to those used in a previous work assignment titled "Validation of Source Information for Chromium Risk Assessments," EPA Contract No. 68-02-3818, Work Assignment No. 27. One additional piece of information is provided to aid in the interpretation of the HEM runs. This is the documentation of any bodies of water or other uninhabitable regions within one half kilometer of a facility. The rest of this section details each step of the validation procedure and the information gathering procedure.

Validation Procedure For Latitude and Longitude

Radian used several references to validate current latitude and longitude information in this work assignment. First, state agencies were contacted and asked if they could provide the latitude and longitude coordinates supplied by the facility listed in state air permit applications. Second, summaries of the National Emission Data System (NEDS), provided by the Project Officer, were examined for their latitude and longitude information. Third, plant addresses were reviewed in trade publications to aid in locating the sources on U. S. Geological Survey maps. If after these procedures were carried out there were still a question as to the exact location of a facility, Radian contacted personnel at the facility in question and asked them for latitude and longitude information. Finally, the sources were pinpointed on U.S. Geological Survey maps.

If the validated latitude and longitude of a facility differed by more than one and one half minutes (approximately 2 kilometers), Radian suggested that the facility be re-modeled with the validated location data.

Validation Procedure For STAR Site Selection

The Human Exposure Model (HEM) uses meteorological data for air dispersion modeling near a source. The HEM chooses meteorological data from the STAR (STability ARray) site closest to the facility being modeled.

However, meteorological information from the STAR site nearest to the facility may not provide the best basis for dispersion modeling for that source. Wind patterns at the source location may differ significantly from those at the nearest STAR site if the source is located in complex terrain or near a coastal region. For sources located in these topographically complex regions, further analysis of the STAR site selected by the HEM is necessary to ensure that the meteorological conditions at the STAR site selected are truly representative of those at the facility.

The following discussion is a description of the procedure followed by Radian's staff meteorologist to evaluate the appropriateness of the STAR site chosen by the HEM for each facility. The STAR sites selected for each facility were obtained from previous ethylene oxide HEM runs provided by the Project Officer.

For each facility, Radian identified the current STAR site location on a U.S. Geological Survey topographical map. The coordinates of other nearby STAR site locations were identified from the STAR site selection maps found in the SAI "Human Exposure to Atmospheric Concentrations of Selected Chemicals, Volume 1." Only STAR sites within two hundred kilometers of the point source were considered as alternative choices for modeling.

The topography around the site of the source location was examined to identify any significant surface features, such as river valleys, mountains, or coastal areas, in the vicinity of the source that would affect the wind flow near the source. The same description was also compiled for the STAR site location selected by the HEM.

Next, Radian examined the annual surface wind roses in the area near the source. Climatological wind rose patterns at many locations across the U.S. are presented in the Climatic Atlas of the United States, prepared by the U. S. Department of Commerce. If any significant differences in wind rose patterns between the STAR site selected and the source location were identified, then the wind rose patterns at other nearby STAR sites were examined to determine if a more appropriate STAR site could be selected. The possible influence of topography on wind flow at the STAR site was also considered.

Procedure For Gathering Population and Geographical Data

Population density information was gathered from U. S. Bureau of the Census data collected in 1980. Once a facility had been located on a U.S. Geological Survey map, Radian gathered the populations of all census tracts within a 50 kilometer radius of the facility.

Radian prepared geographical and terrain descriptions using both U.S. Geological Survey maps and an atlas of the United States.

Procedure For Determining The Habitability Of The Area Of Predicted Maximum Concentration of Ethylene Oxide

The HEM generates a single point estimate of maximum concentration. In order to assess the reasonableness of the maximum individual risk estimate, Radian examined the point of predicted maximum concentration to determine if that point were likely to be habitable.

Although the HEM provides a single point estimate as the point of maximum concentration, there are several reasons that the point of maximum concentration should be examined as an area of maximum concentration when interpreting HEM results. First, there is uncertainty associated with input parameters used in the HEM (e.g., emission rates, stack gas velocity). Second, even when a particular model input may be well defined such as in cases where years of meteorological data are available, the input parameters may better be characterized statistically (e.g., a mean with some variance) than by a single point estimate. Third, the information on population distributions near facilities and the assumptions employed in the HEM are only intended to provide reasonable estimates of the relationship between population distribution and modeled concentrations. All of these considerations taken together suggest that while the model predicts a point of maximum concentration, the maximum concentration could be characterized in terms of an area that is a reflection of a distribution of points of maximum concentration. Therefore, Radian also examined the area that surrounds the point of maximum concentration. Following discussions with individuals familiar with HEM, meteorology and dispersion modeling in general, it has been decided, with EPA agreement, to examine the area within a 0.5 km radius of the point of each production facility.

There is one additional reason for providing descriptive information about the area surrounding the point of maximum modeled concentration. If better or different information characterizing the source to be modeled becomes available, the area predicted to experience the maximum concentration may shift to a nearby point. In this case it would be useful to know whether the new predicted point of concentration were habitable.

Radian examined U.S. Geological Survey maps to determine whether or not there were any uninhabitable areas within a 0.5 kilometer radius of a facility. These topographical maps indicate if there are any mountains or bodies of water near the facility. If so, this fact is noted on the summary validation sheets which are presented in the Appendix. A summary of the facilities which had a body of water within a 0.5 kilometer radius is provided in Table 3-1.

Summaries Of The Validation And Information Gathering Procedures

Information gathered for all fourteen ethylene oxide production facilities analyzed in this work assignment are presented in the Appendix. A summary of results of is discussed in Section 2 of this report.

TABLE 3-1. SUMMARY OF FACILITIES WITH BODIES OF WATER WITHIN A ONE-HALF KILOMETER RADIUS OF THEIR BOUNDARIES

Facility	Location	Body of Water
Northern Petrochem	Morris, IL	Illinois River
Sunolin	Claymont, DE	Delaware River
Texas Eastman	Longview, TX	A nearby lake (2.5 km wide)
PPG	Beaumont, TX	Neches River
Union Carbide	Taft, LA	Mississippi River

4.0 REFERENCES

Thirty-three U.S. Geological Survey Maps were used in this study. These are listed in Table 4-1. Other references are cited below.

1. WBAN Station Numbers Master List, National Climatic Data Center, Asheville, NC. August, 1978.

2. STAR Tabulations Master List, National Climatic Data Center, Asheville, NC. May, 1983.

3. U. S. Department of Commerce, Bureau of the Census. Number of Inhabitants, 1980 Census of Population.

4. "Human Exposure to Atmospheric Concentrations of Selected Chemicals," EPA Contract No. 68-02-3066, Office of Air Quality Planning and Standards, Environmental Protection Agency, Research Triangle Park, NC 27711, February 10, 1982.

5. Delaware Department of Natural Resources and Environmental Control Air Resources Division, Robert Taggert, 715 Grantham Lane, New Castle, DE 19720. (302) 323-4542.

6. Illinois Environmental Protection Agency, Wayne Montney, 2200 Churchill Road, Springfield, IL 62706. (217) 782-7326.

7. Kentucky Department of Environmental Protection, Division of Air Pollution Control, Diana Parker, 18 Reilly Road, Frankfurt, KY 40601. (502) 564-3382.

8. Louisiana Department of Environmental Quality, Douglas Walters, P. O. Box 44066, Baton Rouge, LA 70804. (504) 342-1265.

9. Texas Air Control Board, Roger LaPrelle, 6330 Highway 290 East, Austin, TX 78723. (512) 451-5711.

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Table 4-1 U.S. Geological Survey Maps Used in the Longitude and Latitude Validation Process

Facility/Location	1:24,000	1:250,000
BASF Wyandotte/Geismar, LA	Gonzales	Baton Rouge New Orleans
Celanese Chemical/Clear Lake, TX	League City	Houston Beaumont
Dow Chemical/Freeport, TX	Jones Creek	Bay City Houston
Dow Chemical/Plaquemine, LA	Plaquemine	Baton Rouge New Orleans
ICI Americas/Bayport, TX	La Porte League City	Houston Beaumont
Norchem/Morris, IL	Minooka	Aurora Chicago
Olin/Bradenburg, KY	Laconia Rock Haven	Louisville Vincennes Evansville Winchester
PPG/Beaumont, TX	Beaumont East	Lake Charles Beaumont Houston Port Arthur
Shell/Geismar, LA	Carville Gonzales	Baton Rouge New Orleans
Sunolin/Claymont, DE	Marcus Hook	Wilmington Newark
Texaco/Port Neches, TX	Port Arthur North	Lake Charles Beaumont Houston Port Arthur
Texas Eastman/Longview, TX	Tatum (1:62,500)	Tyler
Union Carbide/Seadrift, TX	Green Lake	Beeville
Union Carbide/Taft, LA	Hahnville	Baton Rouge Mobile Breton Sound New Orleans

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APPENDIX A

SUMMARY VALIDATION SHEETS

I. PLANT INFORMATION

Name: BASF Wyandotte
Location: Geismar, Louisiana
Source Category: Ethylene Oxide Production

II. CURRENT MODELING INFORMATION

Latitude: 30 11 22
Longitude: 90 59 43
STAR Site: #13970 Baton Rouge

III. VALIDATED MODELING INFORMATION

Latitude: 30 11 45
Longitude: 90 59 42
STAR Site: #13970 Baton Rouge

IV. TERRAIN AND POPULATION DENSITY

Terrain: Geismar is located on the north shore of the Mississippi River, 25 km south of Baton Rouge. The terrain is relatively flat with no mountains.
Population Density: 73 persons/km^2
Population of Geismar: 100 persons

V. DESCRIPTION OF THE AREA OF MAXIMUM MODELED CONCENTRATION

Predicted maximum individual lifetime risk: 1.05 E-2
Predicted maximum concentration of ethylene oxide: 1.0515 EO2 ug/m^3
Location: 0.2 km W of source
Likely to be habitable: Yes
Terrain description: Same as above

VI. DISCUSSION OF VALIDATION RESULTS

The STAR site selected by the HEM to provide meteorological data for modeling this facility was found to be acceptable. The latitude and longitude information provided by the Louisiana Department of Environmental Quality and NEDS was verified on USGS topographical maps and was found to agree closely with the existing information.

I. PLANT INFORMATION

Name: Celanese Chemical
Location: Clear Lake, Texas
Source Category: Ethylene Oxide Production

II. CURRENT MODELING INFORMATION

Latitude: 29 37 24
Longitude: 95 03 34
STAR Site: #12906 Houston, TX

III. VALIDATED MODELING INFORMATION

Latitude: 29 37 48
Longitude: 95 03 53
STAR Site: #12906 Houston, TX

IV. TERRAIN AND POPULATION DENSITY

Terrain: Clear Lake is 8 km northeast of the Lyndon B. Johnson Space Center. It is 24 km northwest of Galveston Bay. Houston (population 1,595,138) is within a 50 km radius to the northwest. Clear Lake is in the Houston metropolitan area.
Population Density: 192 persons/km^2
Population of Clear Lake: 2,300 persons

V. DESCRIPTION OF THE AREA OF MAXIMUM MODELED CONCENTRATION

Predicted maximum individual lifetime risk: 8.65 E-4
Predicted maximum concentration of ethylene oxide: 6.7116 E01 ug/m^3
Location: 0.2 km N of source
Likely to be habitable: Yes
Terrain description: Same as above

VI. DISCUSSION OF VALIDATION RESULTS

The STAR site selected by the HEM to provide meteorological data for modeling this facility was found to be acceptable. The latitude and longitude information gathered from the NEDS database and verified using USGS topographical maps was found to agree closely with the existing information.

I. PLANT INFORMATION

Name: Dow
Location: Freeport, Texas
Source Category: Ethylene Oxide Production

II. CURRENT MODELING INFORMATION

Latitude: 28 59 34
Longitude: 95 24 22
STAR Site: #12923 Galveston, TX

III. VALIDATED MODELING INFORMATION

Latitude: 28 59 46
Longitude: 95 24 14
STAR Site: #12923 Galveston, TX

IV. TERRAIN AND POPULATION DENSITY

Terrain: Freeport is located near the Gulf of Mexico, southwest of Galveston. Large oil fields are in the surrounding area which is a marshy coastal plain.
Population Density: 32 persons/km^2
Population of Freeport: 13,444 persons

V. DESCRIPTION OF THE AREA OF MAXIMUM MODELED CONCENTRATION

Predicted maximum individual lifetime risk: 2.57 E-3
Predicted maximum concentration of ethylene oxide: 2.5681 E01 ug/m^3
Location: 0.2 km N of source
Likely to be habitable: Yes
Terrain description: Same as above

VI. DISCUSSION OF VALIDATION RESULTS

The STAR site selected by the HEM to provide meteorological data for modeling this facility was found to be acceptable. Latitude and longitude information was provided by the Texas Air Control Board for three Dow plants in Freeport. The plant closest to the current modeling location was chosen as the validated location. The location was also verified for reasonableness on USGS topographical maps and with NEDS information. The validated latitude and longitude information agreed closely with the existing information.

I. PLANT INFORMATION

Name: Dow
Location: Plaquemine, Louisiana
Source Category: Ethylene Oxide Production

II. CURRENT MODELING INFORMATION

Latitude: 30 19 00
Longitude: 91 16 20
STAR Site: #13970 Baton Rouge, LA

III. VALIDATED MODELING INFORMATION

Latitude: 30 17 00
Longitude: 91 14 16
STAR Site: #13970 Baton Rouge, LA

IV. TERRAIN AND POPULATION DENSITY

Terrain: Plaquemine is located near the Mississippi River, 15 km south of Baton Rouge. The terrain is relatively flat with no mountains.
Population Density: 73 persons/km^2
Population of Plaquemine: 7,521 persons

V. DESCRIPTION OF THE AREA OF MAXIMUM MODELED CONCENTRATION

Predicted maximum individual lifetime risk: 1.57 E-3
Predicted maximum concentration of ethylene oxide: 1.5661 E01 ug/m^3
Location: 0.2 km W of source
Likely to be habitable: Yes
Terrain description: Same as above

VI. DISCUSSION OF VALIDATION RESULTS

The STAR site selected by the HEM to provide meteorological data for modeling this facility was found to be acceptable. The latitude and longitude information provided by the Louisiana Department of Environmental Quality, taken from USGS topographical maps, and gathered from NEDS differed significantly from the existing information. A re-run of the model for this facility with the validated latitude and longitude information is recommended.

I. PLANT INFORMATION

Name: ICI Americas
Location: Bayport, Texas
Source Category: Ethylene Oxide Production

II. CURRENT MODELING INFORMATION

Latitude: 29 37 44
Longitude: 95 03 04
STAR Site: #12906 Houston, TX

III. VALIDATED MODELING INFORMATION

Latitude: 29 37 44
Longitude: 95 03 04
STAR Site: #12906 Houston, TX

IV. TERRAIN AND POPULATION DENSITY

Terrain: Bayport is located near the west shore of Galveston Bay. There are no mountains within a 50 km radius of Bayport. Houston (population 1,595,138) is within a 50 km radius to the northwest.
Population Density: 202 persons/km^2
Population of Bayport: <1,000 persons

V. DESCRIPTION OF THE AREA OF MAXIMUM MODELED CONCENTRATION

Predicted maximum individual lifetime risk: 3.14 E-2
Predicted maximum concentration of ethylene oxide: 3.1386 E02 ug/m^3
Location: 0.2 km N of source
Likely to be habitable: Yes
Terrain description: Same as above

VI. DISCUSSION OF VALIDATION RESULTS

The STAR site selected by the HEM to provide meteorological data for modeling this facility was found to be acceptable. The latitude and longitude information provided by the Texas Air Control Board and the NEDS database was verified on USGS topographical maps and was found to agree with the existing information.

I. PLANT INFORMATION

Name: Norchem (formerly Northern Petrochem)
Location: Morris, Illinois
Source Category: Ethylene Oxide Production

II. CURRENT MODELING INFORMATION

Latitude: 41 24 30
Longitude: 88 25 00
STAR Site: #94846 Chicago, IL

III. VALIDATED MODELING INFORMATION

Latitude: 41 24 07
Longitude: 88 17 18
STAR Site: #94846 Chicago, IL

IV. TERRAIN AND POPULATION DENSITY

Terrain: Morris is located near the north shore of the Illinois River. There are state parks on the southern shore of the river. The area is relatively flat with no mountains or large bodies of water (other than the river). There are pit mines southwest of Morris and strip mines northeast of Morris. Joliet (population 77,956) is 39 km to the east and Ottowa (population 18,166) is 35 km to the west.
Population Density: 138 persons/km^2
Population of Morris: 8,833 persons

V. DESCRIPTION OF THE AREA OF MAXIMUM MODELED CONCENTRATION

Predicted maximum individual lifetime risk: 4.46 E-3
Predicted maximum concentration of ethylene oxide: 4.2198 E01 ug/m^3
Location: 0.2 km E of source
Likely to be habitable: Yes. The Illinois River is within 0.5 km of the facility.

Terrain description: Same as above

VI. DISCUSSION OF VALIDATION RESULTS

The STAR site selected by the HEM to provide meteorological data for modeling this facility was found to be acceptable. The latitude and longitude information provided by the Illinois EPA, Permit Section, and the NEDS database was verified on USGS topographical maps and found to differ significantly from the existing information. A re-run of the model for this facility with the validated latitude and longitude information is recommended.

The nearest representative STAR site to the facility is site No. 94846 located at the Chicago-O'Hare airport in the northwest section of Chicago. Although the Chicago site is located near Lake Michigan, which produces some localized wind flow that is not typical of the Morris location, the STAR site data is considered sufficiently representative for the HEM analysis.

The Chicago site is located approximately 20 kilometers west of Lake Michigan and 85 kilometers northeast of the source located at Morris. The presence of the lake affects the wind flow patterns in a broad region around the lake. The region of lake influence can extend through the area around Morris at certain times. More localized effects, called lake breezes, also have some impact on the wind flow recorded at the Chicago site. These effects do not, however, affect the Morris site. The next closest STAR site to Morris is located in Rantoul, Illinois, which is approximately 200 kilometers south of Morris. The Rantoul site is beyond the region of influence for the localized weather patterns that develop around the lake. The Rantoul site is 200 kilometers and is at the limits of the distance criterion established for STAR site validation. Thus, the Chicago site is considered more representative than the Rantoul site for the HEM analysis.

I. PLANT INFORMATION

Name: Olin
Location: Bradenburg, Kentucky
Source Category: Ethylene Oxide Production

II. CURRENT MODELING INFORMATION

Latitude: 38 00 10
Longitude: 86 07 16
STAR Site: #13807 Ft. Knox, KY

III. VALIDATED MODELING INFORMATION

Latitude: 38 00 00
Longitude: 86 07 18
STAR Site: #13807 Ft. Knox, KY

IV. TERRAIN AND POPULATION DENSITY

Terrain: Bradenburg is located near the Ohio River, 50 km southeast of Louisville. Fort Knox Military Reservation is 15 km to the east. The terrain is fairly level with no mountains or large bodies of water (other than the river).
Population Density: 70 persons/km^2
Population of Bradenburg: 1,831 persons

V. DESCRIPTION OF THE AREA OF MAXIMUM MODELED CONCENTRATION

Predicted maximum individual lifetime risk: 4.45 E-5
Predicted maximum concentration of ethylene oxide: 9.5153 E01 ug/m^3
Location: 0.2 km N of source
Likely to be habitable: Yes
Terrain description: Same as above

VI. DISCUSSION OF VALIDATION RESULTS

The STAR site selected by the HEM to provide meteorological data for modeling this facility was found to be acceptable. The latitude and longitude information provided by the Kentucky Department of Environment Protection Division of Air Pollution Control and the NEDS database was verified on USGS topographical maps and found to agree closely with the existing information.

I. PLANT INFORMATION

Name: PPG
Location: Beaumont, Texas
Source Category: Ethylene Oxide Production

II. CURRENT MODELING INFORMATION

Latitude: 30 03 45
Longitude: 94 02 53
STAR Site: #12917 Port Arthur, TX

III. VALIDATED MODELING INFORMATION

Latitude: 30 03 26
Longitude: 94 02 33
STAR Site: #12917 Port Arthur, TX

IV. TERRAIN AND POPULATION DENSITY

Terrain: Beaumont is located on the Neches River. There are no mountains within a 50 km radius. Orange (population 23,628) is 35 km to the east. The Gulf of Mexico is 50 km to the south. Marsh land is nearby.
Population Density: 52 persons/km^2
Population of Beaumont: 118,102 persons

V. DESCRIPTION OF THE AREA OF MAXIMUM MODELED CONCENTRATION

Predicted maximum individual lifetime risk: 2.74 E-3
Predicted maximum concentration of ethylene oxide: 2.7425 E01 ug/m^3
Location: 0.2 km N of source
Likely to be habitable: Yes. The Neches River is 0.2 km to the east and north.
Terrain description: Same as above

VI. DISCUSSION OF VALIDATION RESULTS

The STAR site selected by the HEM to provide meteorological data for modeling this facility was found to be acceptable. Longitude and latitude information gathered from the NEDS database was verified on USGS topographical maps and found to agree closely with the existing information.

I. PLANT INFORMATION

Name: Shell
Location: Geismar, Louisiana
Source Category: Ethylene Oxide Production

II. CURRENT MODELING INFORMATION

Latitude: 30 11 12
Longitude: 90 59 28
STAR Site: #13970 Baton Rouge, LA

III. VALIDATED MODELING INFORMATION

Latitude: 30 13 02
Longitude: 91 01 59
STAR Site: #13970 Baton Rouge, LA

IV. TERRAIN AND POPULATION DENSITY

Terrain: Geismar is located near the north shore of the Mississippi River ~25 km south of Baton Rouge. The terrain is relatively flat with no mountains.
Population Density: 73 persons/km^2
Population of Geismar: 100 persons

V. DESCRIPTION OF THE AREA OF MAXIMUM MODELED CONCENTRATION

Predicted maximum individual lifetime risk: 1.76 E-2
Predicted maximum concentration of ethylene oxide: 1.7582 E02 ug/m^3
Location: 0.2 km W of source
Likely to be habitable: Yes
Terrain description: Same as above

VI. DISCUSSION OF VALIDATION RESULTS

The STAR site selected by the HEM to provide meteorological data for modeling this facility was found to be acceptable. The latitude and longitude information provided by the Louisiana Department of Environmental Quality and gathered from the NEDS database was verified on USGS topographical maps and found to differ significantly from the existing information. A re-run of the model for this facility with the validated latitude and longitude information is recommended.

I. PLANT INFORMATION

Name: Sunolin
Location: Claymont, Delaware
Source Category: Ethylene Oxide Production

II. CURRENT MODELING INFORMATION

Latitude: 39 48 20
Longitude: 75 25 40
STAR Site: #13739 Philadelphia, PA

III. VALIDATED MODELING INFORMATION

Latitude: 39 48 28
Longitude: 75 26 04
STAR Site: #13739 Philadelphia, PA

IV. TERRAIN AND POPULATION DENSITY

Terrain: Claymont is located on the west shore of the Delaware River and is a northern suburb of Wilmington (population 70,195). Parts of the states of Delaware, New Jersey, Pennsylvania and Maryland are located within a 50 km radius. There are no mountains within a 50 km radius.

Population Density: 440 persons/km^2
Population of Claymont: 10,022 persons

V. DESCRIPTION OF THE AREA OF MAXIMUM MODELED CONCENTRATION

Predicted maximum individual lifetime risk: 1.59 E-3
Predicted maximum concentration of ethylene oxide: 5.5657 E01 ug/m^3
Location: 0.2 km NE of source
Likely to be habitable: Yes. The Delaware River is within 0.5 km of the facility.
Terrain description: Same as above

VI. DISCUSSION OF VALIDATION RESULTS

The STAR site selected by the HEM to provide meteorological data for modeling this facility was found to be acceptable. The latitude and longitude information gathered from the Delaware Department of Natural Resources and from the NEDS database was verified on USGS topographical maps and was found to agree with existing information.

I. PLANT INFORMATION

Name: Texaco
Location: Port Neches, Texas
Source Category: Ethylene Oxide Production

II. CURRENT MODELING INFORMATION

Latitude: 29 58 19
Longitude: 93 55 51
STAR Site: #12917 Port Arthur

III. VALIDATED MODELING INFORMATION

Latitude: 29 58 14
Longitude: 93 55 55
STAR Site: #12917 Port Arthur

IV. TERRAIN AND POPULATION DENSITY

Terrain: Port Neches is located near the Neches River, 12 km north of Port Arthur and 16 km southeast of Beaumont. The Gulf of Mexico is within a 50 km radius to the south. The Texas/Louisiana border is 25 km to the east.
Population Density: 49 persons/km^2
Population of Port Neches: 13,944 persons

V. DESCRIPTION OF THE AREA OF MAXIMUM MODELED CONCENTRATION

Predicted maximum individual lifetime risk: 1.91 E-2
Predicted maximum concentration of ethylene oxide: 8.8366 E01 ug/m^3
Location: 0.2 km N of source
Likely to be habitable: Yes
Terrain description: Same as above

VI. DISCUSSION OF VALIDATION RESULTS

The STAR site selected by the HEM to provide meteorological data for modeling this facility was found to be acceptable. Latitude and longitude information was provided by the Texas Air Control Board for two Texaco plants in Port Neches. The plant closest to the current modeling location was chosen as the validated location. The location was also verified for reasonableness on USGS topographical maps and with the NEDS database. The validated latitude and longitude information agreed closely with the existing information.

I. PLANT INFORMATION

Name: Texas Eastman
Location: Longview, Texas
Source Category: Ethylene Oxide Production

II. CURRENT MODELING INFORMATION

Latitude: 32 26 44
Longitude: 94 41 17
STAR Site: #13972 Tyler, TX

III. VALIDATED MODELING INFORMATION

Latitude: 32 26 29
Longitude: 94 41 21
STAR Site: #13972 Tyler, TX

IV. TERRAIN AND POPULATION DENSITY

Terrain: Longview is located in northeast Texas, 80 km from the Louisiana border. There are large gas and oil fields in the area, especially to the north. The terrain is gently rolling with no mountains. Lake O' the Pines is within a 50 km radius to the north.
Population Density: 32 persons/km^2
Population of Longview: 62,762 persons

V. DESCRIPTION OF THE AREA OF MAXIMUM MODELED CONCENTRATION

Predicted maximum individual lifetime risk: 8.84 E-3
Predicted maximum concentration of ethylene oxide: 8.8366 E01 ug/m^3
Location: 0.2 km N of source
Likely to be habitable: Yes. A small lake is within 0.5 km of the facility.
Terrain description: Same as above

VI. DISCUSSION OF VALIDATION RESULTS

The STAR site selected by the HEM to provide meteorological data for modeling this facility was found to be acceptable. The latitude and longitude information provided by the Texas Air Control Board and verified on USGS topographical maps agreed closely with the existing information.

I. PLANT INFORMATION

Name: Union Carbide
Location: Seadrift, TX
Source Category: Ethylene Oxide Production

II. CURRENT MODELING INFORMATION

Latitude: 28 30 30
Longitude: 96 46 15
STAR Site: #12925 Beeville, TX

III. VALIDATED MODELING INFORMATION

Latitude: 28 30 30
Longitude: 96 46 15
STAR Site: #12925 Beeville, TX

IV. TERRAIN AND POPULATION DENSITY

Terrain: Seadrift is located 90 km north of Corpus Christi (population 231,999) near the northeast shore of San Antonio Bay. The Gulf of Mexico is to the south within a 50 km radius. The nearby terrain is marshy.
Population Density: 7 persons/km^2
Population of Seadrift: 1,277 persons

V. DESCRIPTION OF THE AREA OF MAXIMUM MODELED CONCENTRATION

Predicted maximum individual lifetime risk: 1.32 E-5
Predicted maximum concentration of ethylene oxide: 8.3590 E01 ug/m^3
Location: 0.2 km NW of source
Likely to be habitable: Yes
Terrain description: Same as above

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VI. DISCUSSION OF VALIDATION RESULTS

The STAR site selected by the HEM to provide meteorological data for modeling this facility was found to be acceptable. The latitude and longitude information provided by the Texas Air Control Board and gathered from the NEDS database was verified on USGS topographical maps and found to agree with the existing modeling information.

The closest STAR site to the facility is located at Beeville, Texas. Beeville is located 96 kilometers to the west of Seadrift. Seadrift is located along the eastern shore of Texas which borders the Gulf of Mexico. STAR data from the Beeville site does not include a sea breeze component typical of coastal sites such as Seadrift. However, the Beeville site more accurately represents the prevailing winds in Seadrift, and is therefore more representative of Seadrift wind flow patterns than the nearest coastal STAR site located in Galveston, 190 kilometers to the northeast.

The effect on wind flow resulting from the position of the high pressure cell which predominates the synoptic weather patterns during the summer months can also play an important role in shaping the wind flow patterns along the east coast of Texas. The Seadrift site has a stronger westerly wind flow component from the high pressure cell than Galveston which is located further to the north and east. Also, frontal passages during the winter months are less frequent in Beeville which is farther south than Galveston. The fontal passages effect the northerly wind component of the STAR data set.

I. PLANT INFORMATION

Name: Union Carbide
Location: Taft, Louisiana
Source Category: Ethylene Oxide Production

II. CURRENT MODELING INFORMATION

Latitude: 29 59 27
Longitude: 90 26 50
STAR Site: #12958 New Orleans, LA

III. VALIDATED MODELING INFORMATION

Latitude: 29 59 17
Longitude: 90 27 15
STAR Site: #12958 New Orleans, LA

IV. TERRAIN AND POPULATION DENSITY

Terrain: Taft is located west of New Orleans within a 50 km radius of the Mississippi River. Lake Pontchartrain is 12 km to the north. The nearby terrain is marshy.
Population Density: 87 persons/km^2
Population of Taft: <1,000 persons

V. DESCRIPTION OF THE AREA OF MAXIMUM MODELED CONCENTRATION

Predicted maximum individual lifetime risk: 8.44 E-3
Predicted maximum concentration of ethylene oxide: 8.44413 E01 ug/m^3
Location: 0.2 km N of source
Likely to be habitable: Yes. The Mississippi River is 0.2 km to the north of the facility.
Terrain description: Same as above

VI. DISCUSSION OF VALIDATION RESULTS

The STAR site selected by the HEM to provide meteorological data for modeling this facility was found to be acceptable. The latitude and longitude information provided by the Louisiana Department of Environmental Quality and gathered from the NEDS database was verified on USGS topographical maps and was found to agree closely with the existing information.

APPENDIX B

U.S. GEOLOGICAL SURVEY MAPS

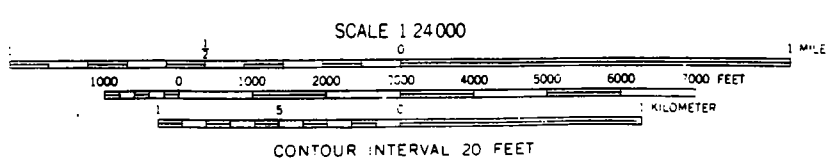
KEY TO MAPS

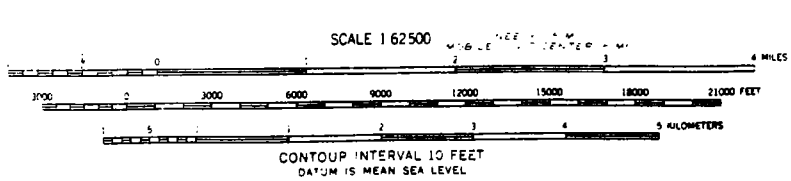
The maps in this appendix are labelled in the following way:

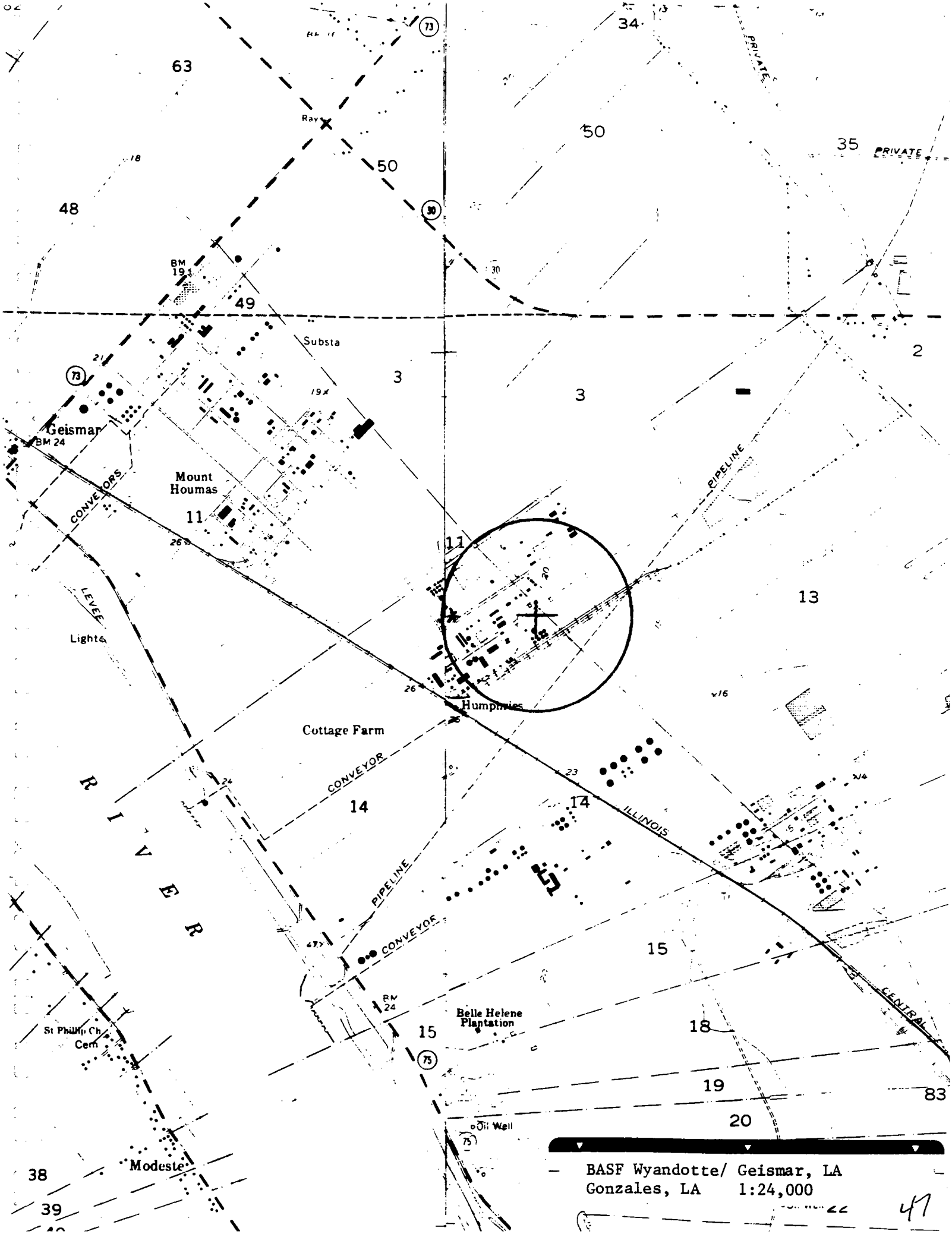
Facility name/ Location
Map name Scale

Circles with a diameter of 1.0 km have been drawn around each source. The point of predicted maximum concentration of ethylene oxide are noted on the maps by an 'x'.

Below are copies of the scales for the 1:24,000 and 1:62,500 maps.






63
Ray
50
34
PRIVATE
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PRIVATE
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BM
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49
Substa
3
3
2
Geismar
BM 24
Mount
Houmas
11
CONVEYORS
PIPELINE
11
13
LEVEE
Lights
Humphries
Cottage Farm
CONVEYOR
14
14
ILLINOIS
RIVER
PIPELINE
CONVEYOR
15
CENTRAL
BM
24
Belle Helene
Plantation
St Philip Ch
Cem
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Oil Well
Modeste
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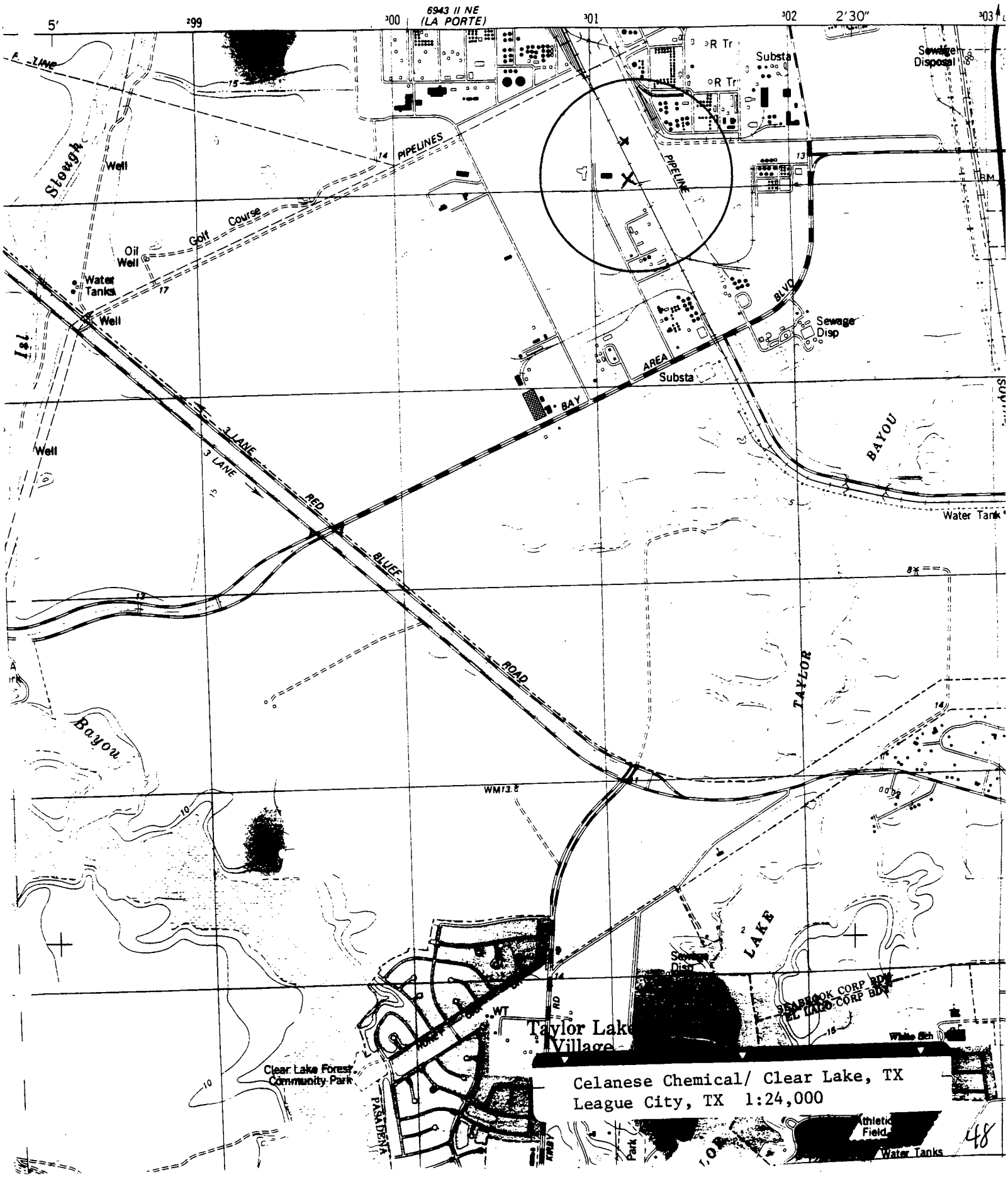
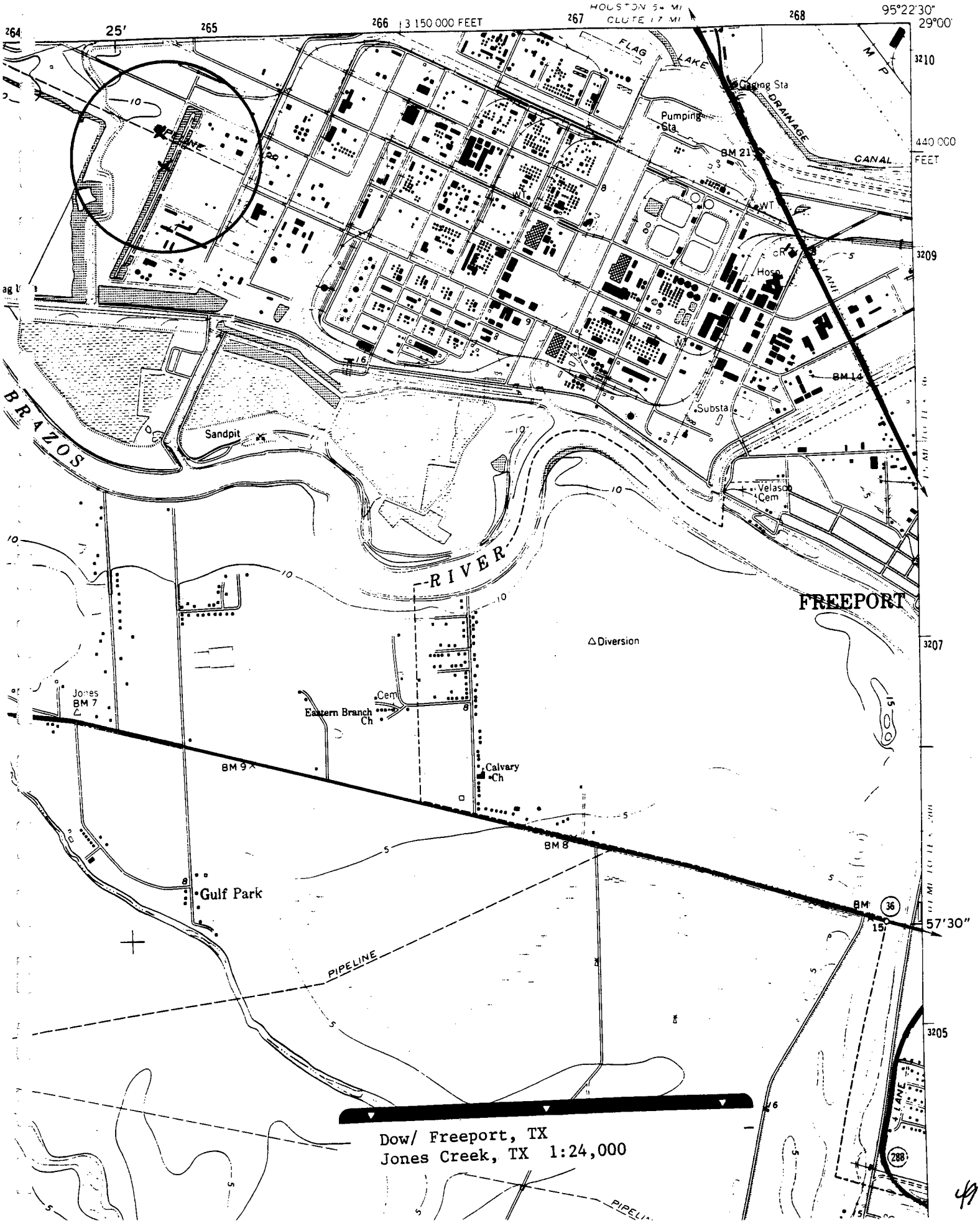
BASF Wyandotte/ Geismar, LA
Gonzales, LA 1:24,000



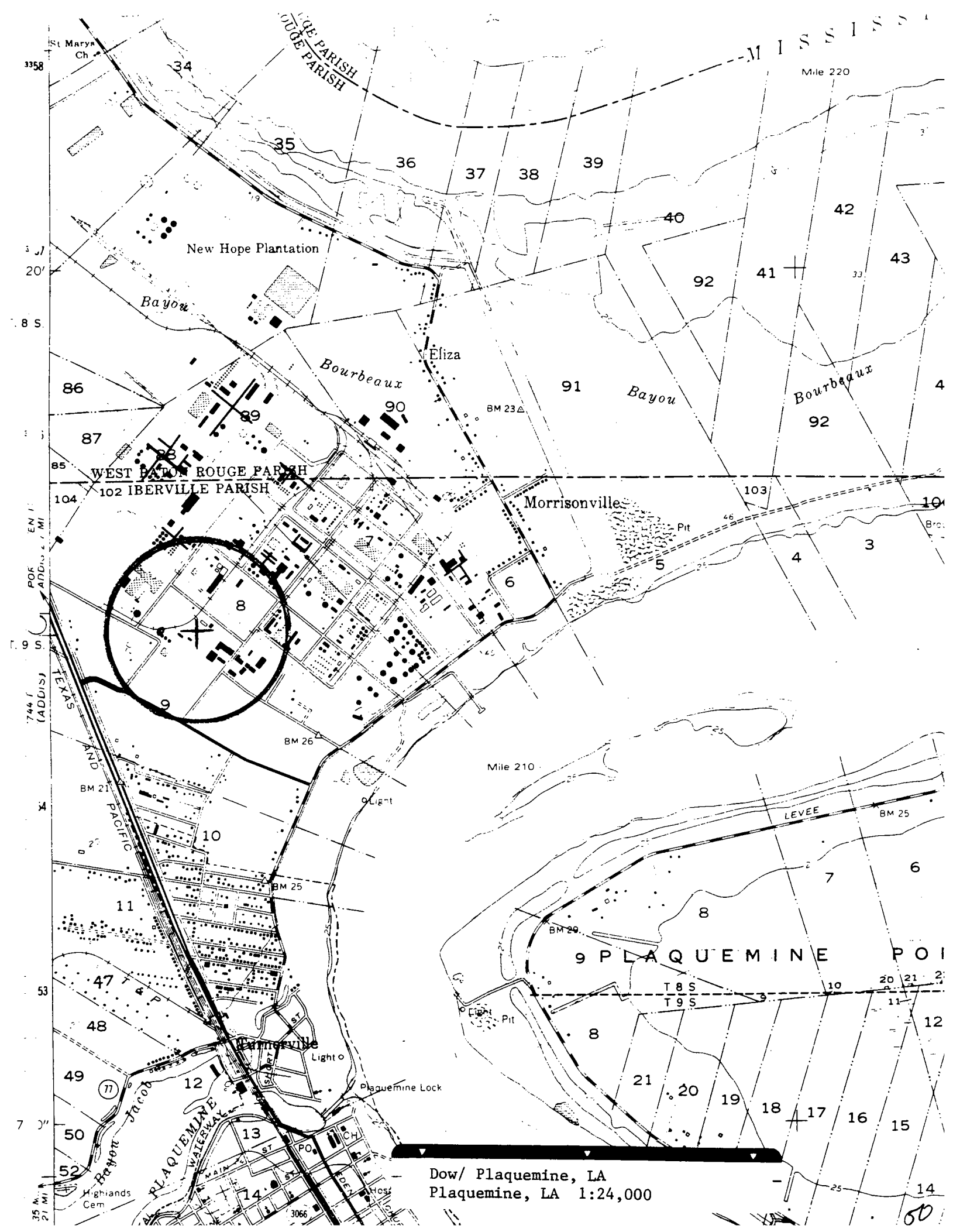
Celanese Chemical/ Clear Lake, TX
League City, TX 1:24,000

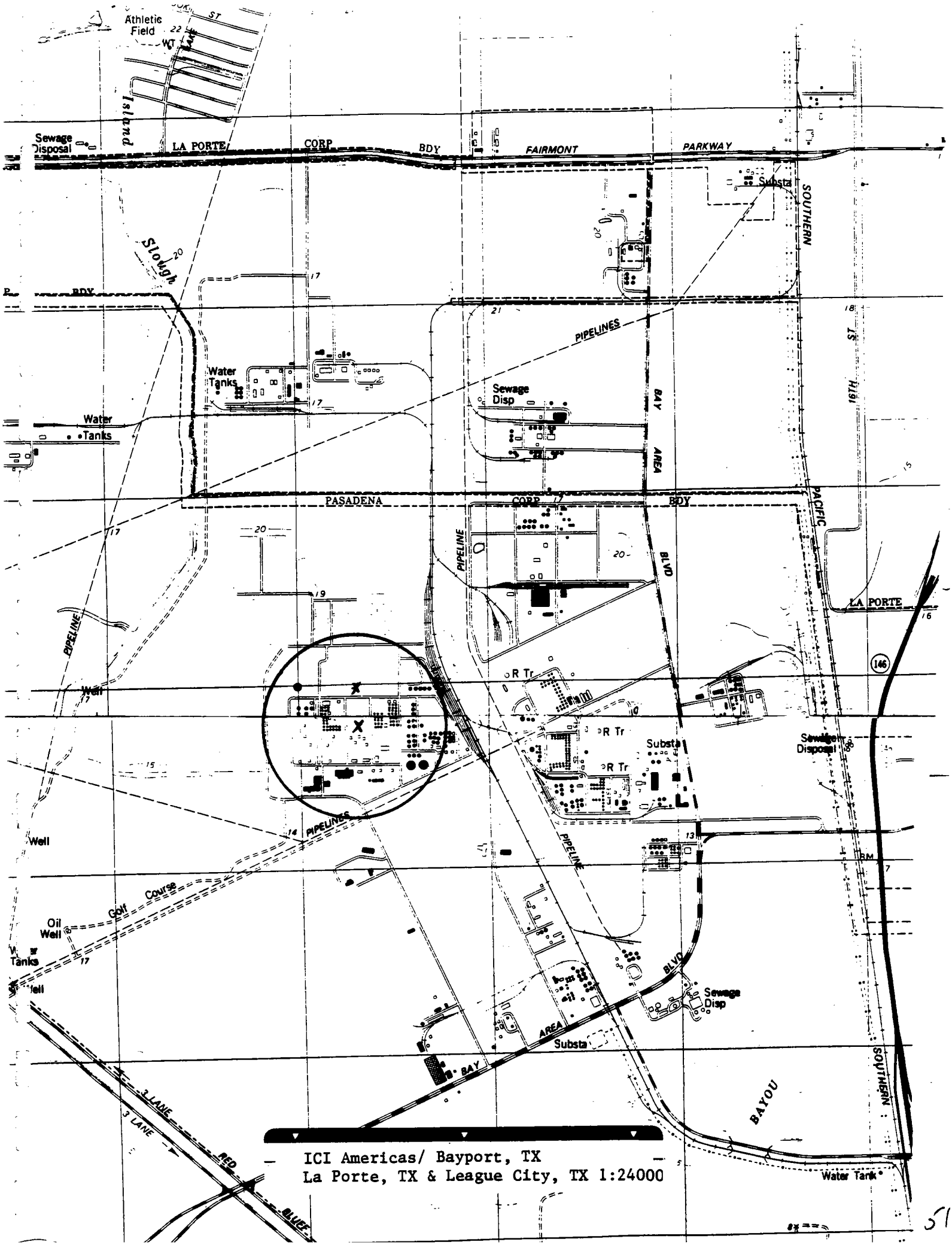
JONES CREEK QUADRANGLE
TEXAS-BRAZORIA CO.
7.5 MINUTE SERIES (TOPOGRAPHIC)



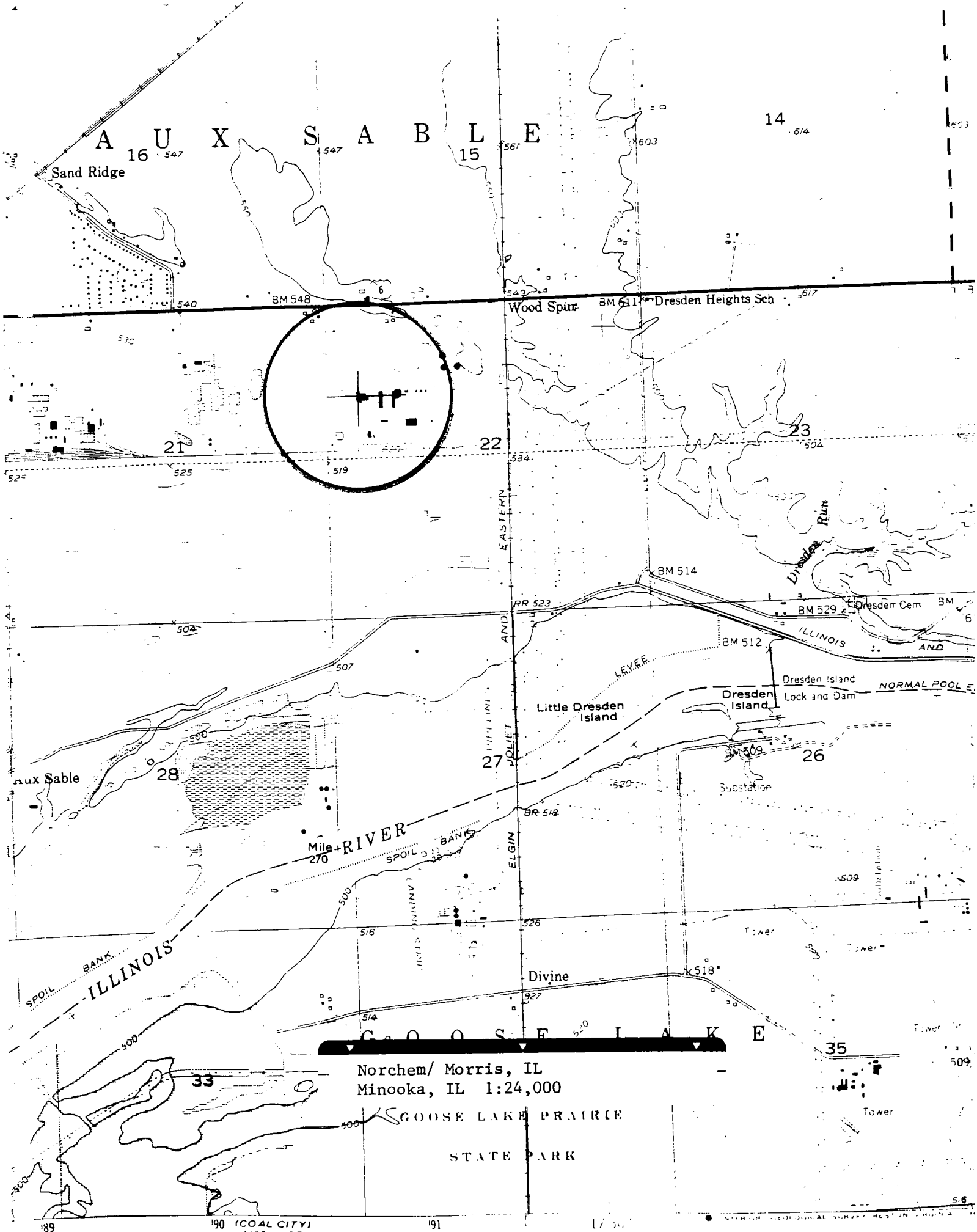
Dow/ Freeport, TX
Jones Creek, TX 1:24,000

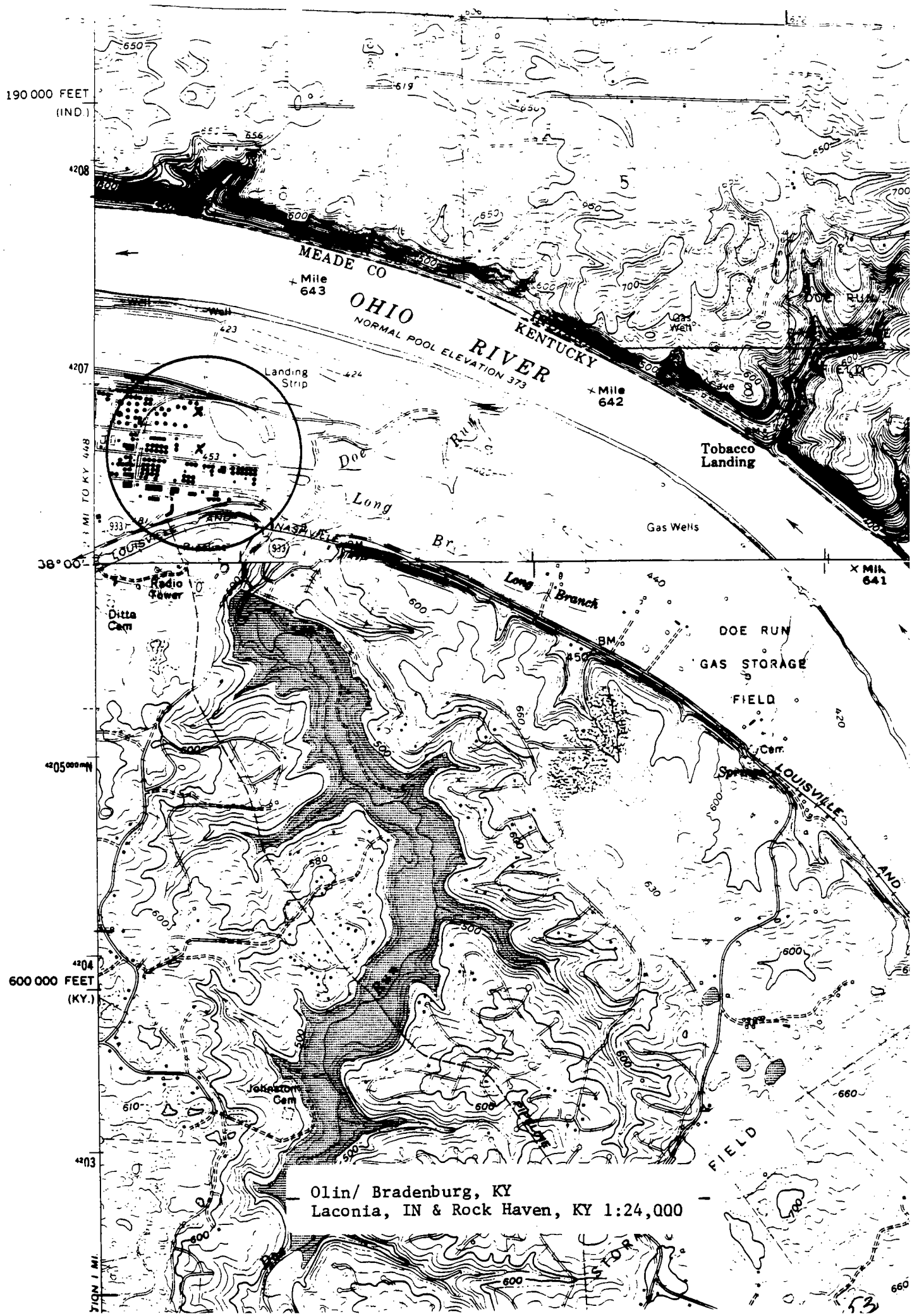
49


St Marys Ch
MISSISSI
Mile 220
New Hope Plantation
Bayou
Bourbeaux
Eliza
Bayou
Bourbeaux
BM 23
WEST BATON ROUGE PARISH
IBERVILLE PARISH
Morrisonville
Pit
TEXAS AND PACIFIC
BM 26
Mile 210
Light
BM 21
BM 25
LEVEE
BM 25
BM 29
PLAQUEMINE POI
T 8 S
T 9 S
Light
Pit
Plaquemine
Light
Plaquemine Lock
Bayou Jacob
PLAQUEMINE WATERWAY
Highlands Cem
Dow/ Plaquemine, LA
Plaquemine, LA 1:24,000



ICI Americas/ Bayport, TX
La Porte, TX & League City, TX 1:24000


A U X S A B L E
Sand Ridge
Wood Spur
Dresden Heights Sch
BM 548
BM 511
Dresden Run
BM 514
RR 523
BM 529
Dresden Cem
BM 512
ILLINOIS AND
EASTERN
JOLIET
ELGIN
LEVEE
Little Dresden Island
Dresden Island
Dresden Island Lock and Dam
NORMAL POOL E
BM 509
Substation
Aux Sable
Mile 270
RIVER
SPOIL BANK
ILLINOIS
Divine
G O O S E L A K E
Norchem/ Morris, IL
Minooka, IL 1:24,000
GOOSE LAKE PRAIRIE
STATE PARK
Tower
(COAL CITY)
SCALE 1:24000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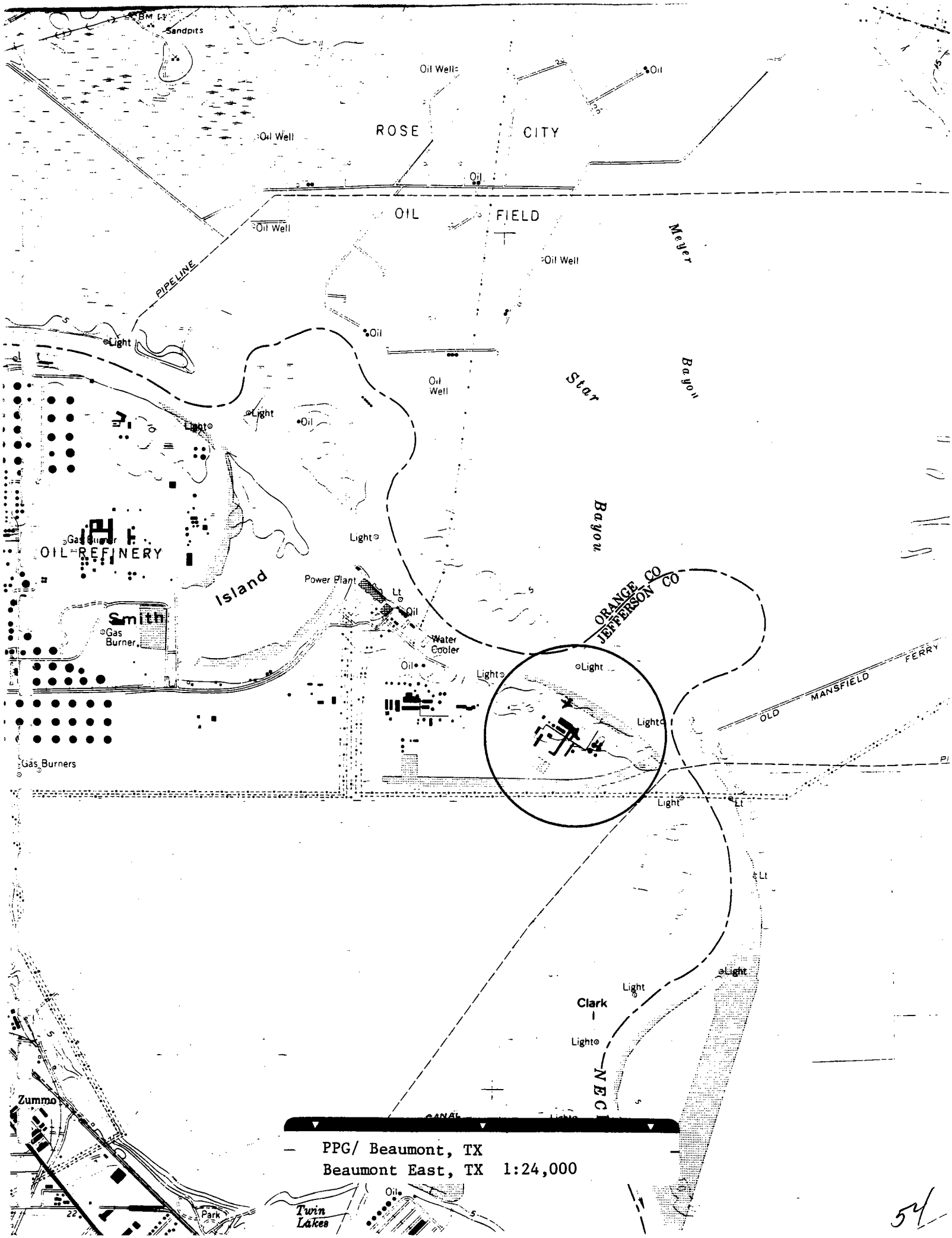
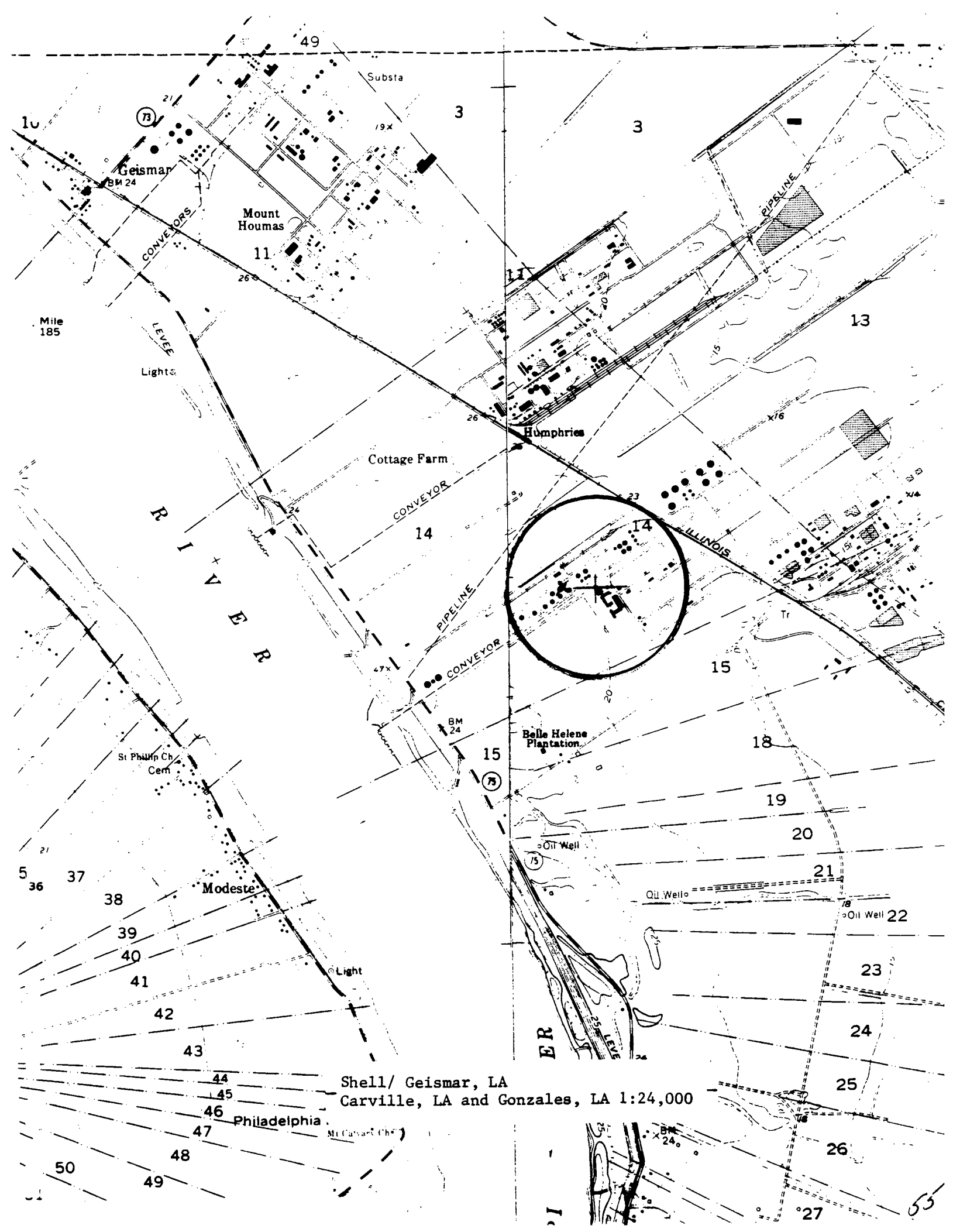
(KY.)
4203
MEADE CO
KENTUCKY
OHIO
RIVER
NORMAL POOL ELEVATION 373
Mile 643
Mile 642
Mile 641
Landing Strip
Doe Run
Long Br.
Long Branch
Tobacco Landing
Gas Wells
Radio Tower
Ditta Cem
DOE RUN
GAS STORAGE
FIELD
Cem.
LOUISVILLE
AND
NASHVILLE
Jolleston Cem
FIELD
Olin/ Bradenburg, KY
Laconia, IN & Rock Haven, KY 1:24,000



PPG/ Beaumont, TX
Beaumont East, TX 1:24,000

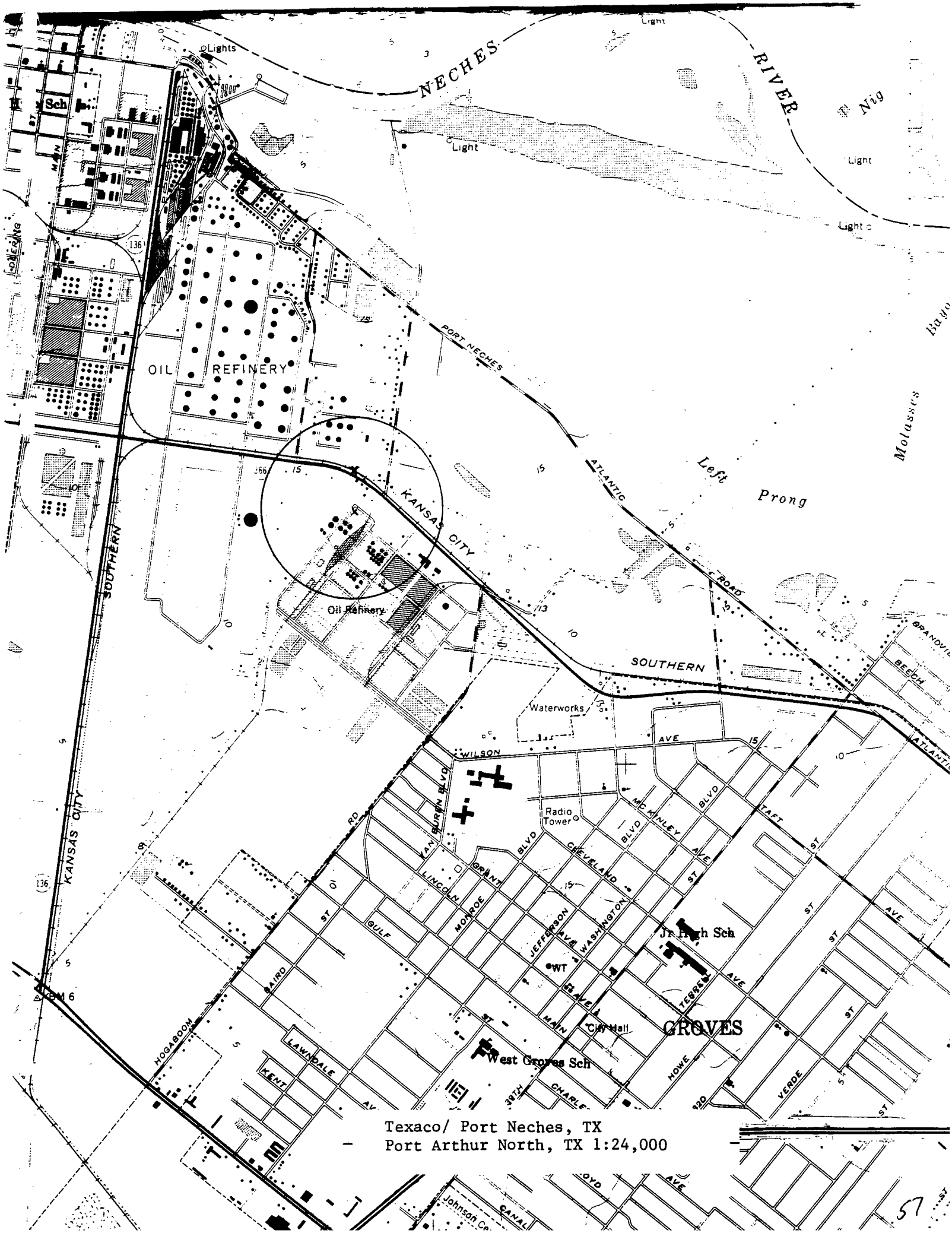
54



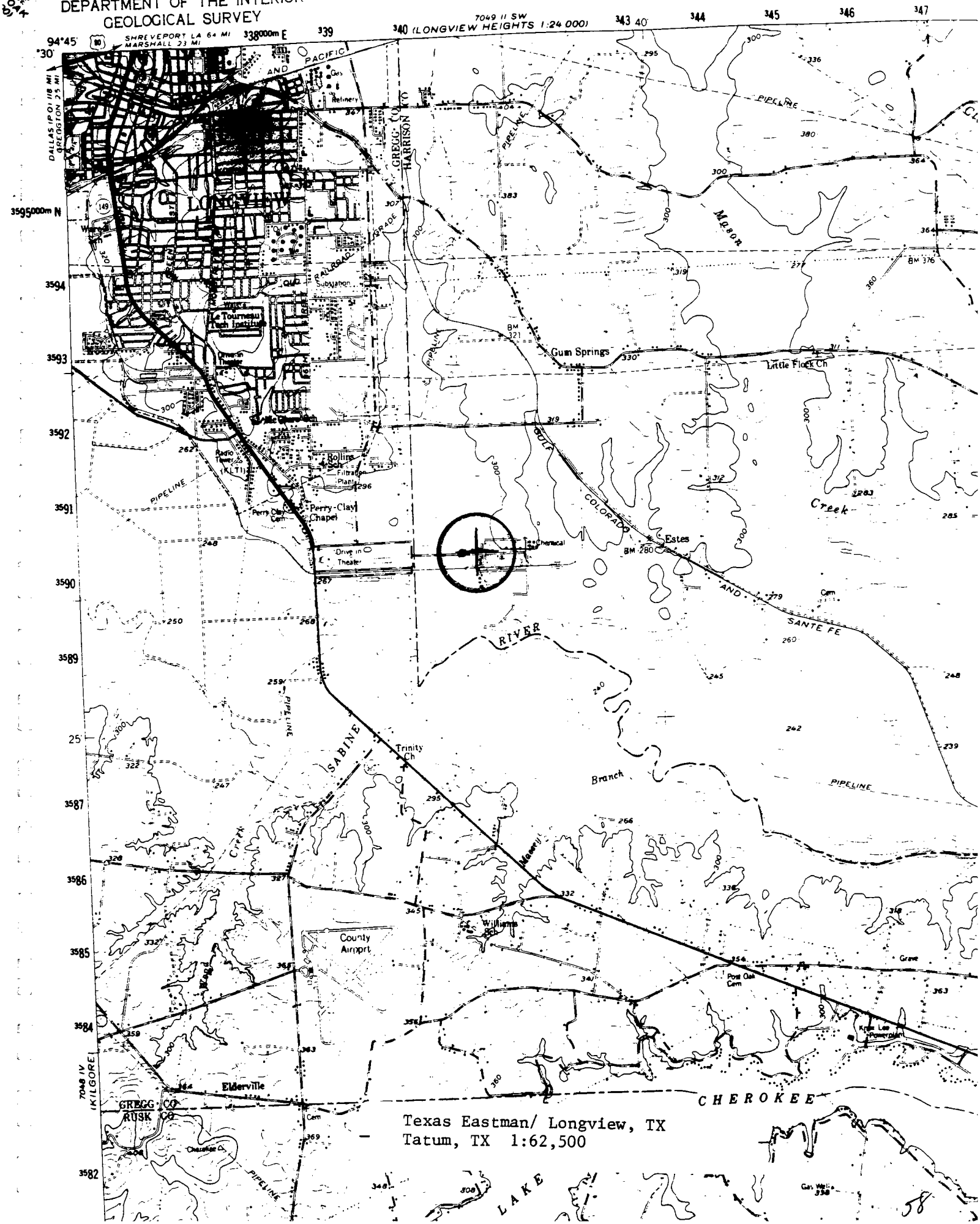
Shell/ Geismar, LA
Carville, LA and Gonzales, LA 1:24,000

55

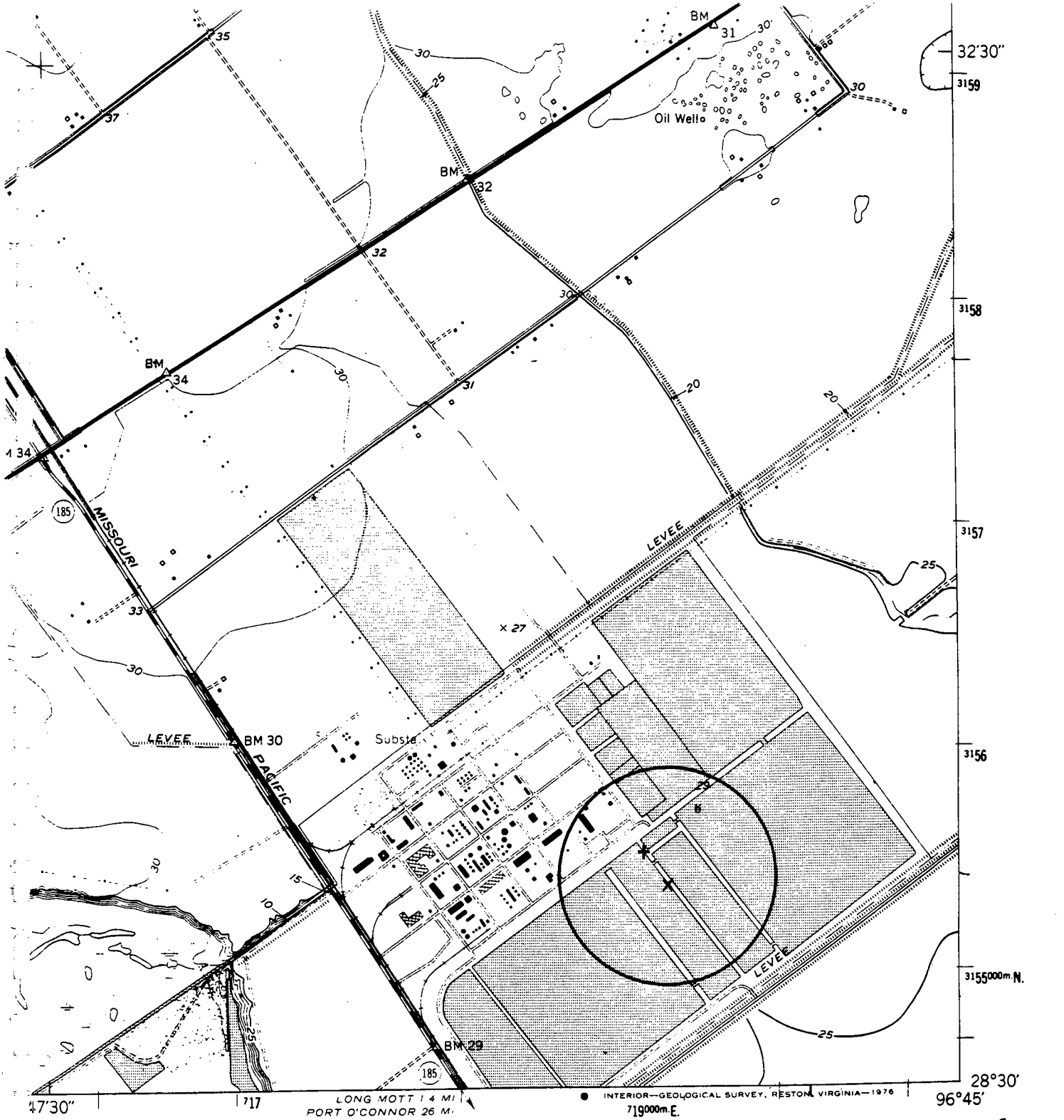
Sunolin/ Claymont, DE
Marcus Hook, PA 1:24,000


NECHES RIVER
Lights
Light
Nig
OIL REFINERY
Oil Refinery
PORT NECHES
ATLANTIC
KANSAS CITY
SOUTHERN
Left Prong
Molasses
Waterworks
WILSON
AVE
Radio Tower
LAN BURN BLVD
LINCOLN
GRANT
BLVD
MONROE
CLEVELAND
JEFFERSON
WASHINGTON
MC KINLEY
TAFT
GULF
BAIRD
HOGABOOM
LAWNDALE
KENT
MAIN
City Hall
West Groves Sch
Jr High Sch
GROVES
TEGRE
HOWE
VERDE
CHARLES
BEECH
GRANDVIEW
CANAL
Johnson Ce
136
Texaco/ Port Neches, TX
Port Arthur North, TX 1:24,000

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY



Texas Eastman/ Longview, TX
Tatum, TX 1:62,500



ROAD CLASSIFICATION

Heavy-duty — 4 LANE 6 LANE

Light-duty

Medium-duty — 4 LANE 6 LANE

Unimproved dirt

U. S. Route

State Route

QUADRANGLE LOCATION

GREEN LAKE, TEX.

N2830—W9645/7.5

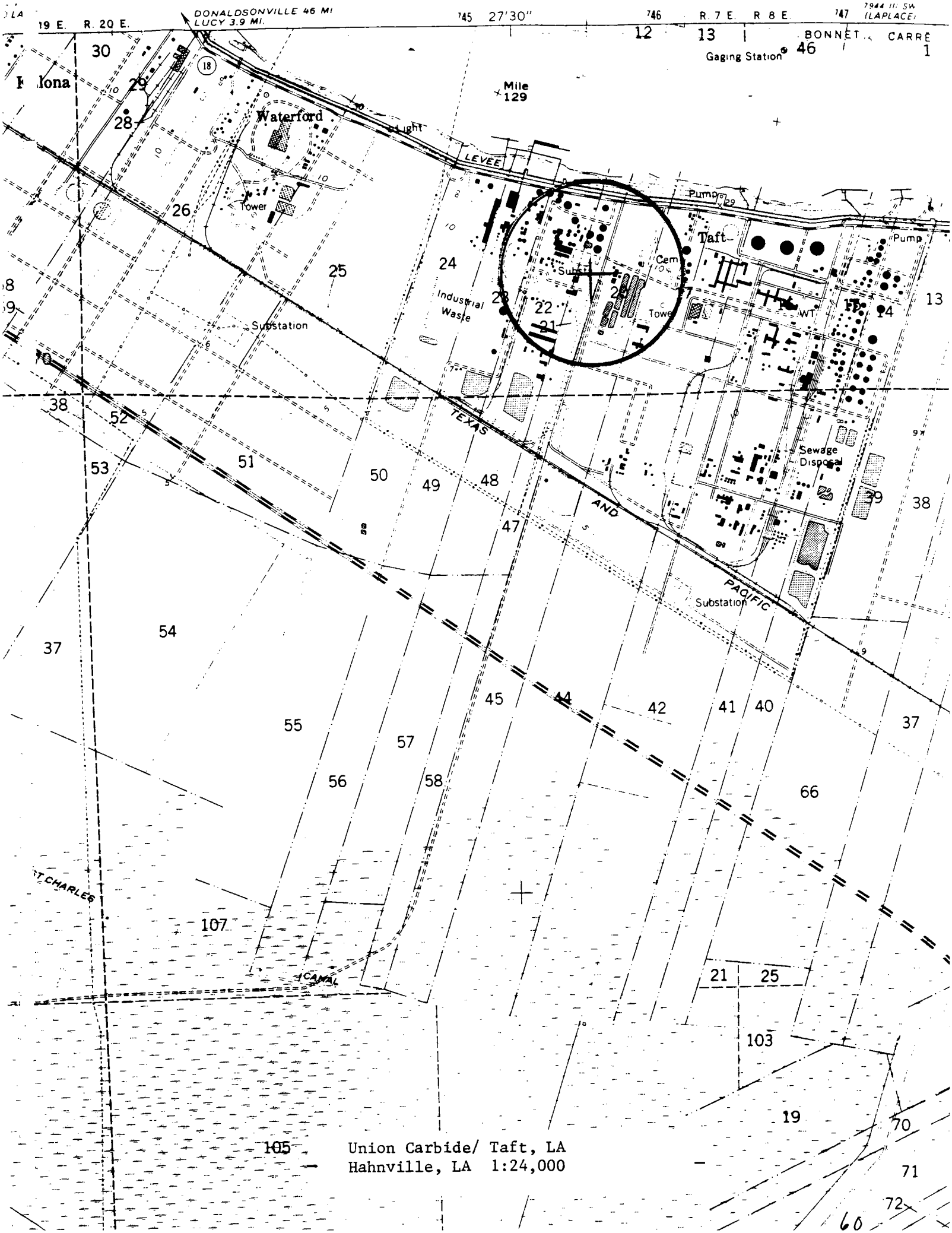
1952

PHOTOREVISED 1973

AMS 6641 III SE—SERIES V882

Union Carbide/ Seadrift, TX
Green Lake, TX 1:24,000

59



Union Carbide/ Taft, LA
Hahnville, LA 1:24,000

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OAQPS AIR
DOCKET CONTROL ROOM

RESEARCH TRIANGLE INSTITUTE

January 1988

Economic Analysis of the Candidate Ethylene Oxide NESHAP Controls on Commercial Sterilization

Draft Report

Prepared for

Thomas G. Walton III
Office of Air Quality Planning and Standards
U.S. Environmental Protection Agency
Research Triangle Park, NC 27711

Prepared by

Richard W. Dunford
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Lisa D. McNeilly

EPA Contract Number 68-02-4321
RTI Project Number 233U-4048-30

POST OFFICE BOX 12194 RESEARCH TRIANGLE PARK, NORTH CAROLINA 27709

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3

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CHAPTER 9

ECONOMIC IMPACT ANALYSIS FOR THE COMMERCIAL STERILIZATION NESHAP

9.1 PROFILE OF THE COMMERCIAL STERILIZATION PROCESS

This economic profile focuses on the commercial process of ethylene oxide (EO) sterilization/fumigation of medical equipment and other miscellaneous products, excluding sterilization activities in hospitals. For simplicity, we hereafter refer to this process simply as sterilization. For a variety of reasons discussed later in this section, sterilization does not form a cohesive industry, but is instead a part of the production process in several industries. Therefore, this profile will be limited in the scope of its analysis. The most important limiting factor is the lack of data on sterilization as a separate step in the production process. Consequently, we use an approach in which commercial sterilizers are grouped by industry; sterilization is then analyzed within the context of that industry. In addition, an industry profile would ideally follow a model of industrial organization that analyzes an industry in the context of its basic conditions, market structure, market conduct, and market performance.[1] However, isolation of the necessary economic factors for this kind of analysis is not possible since sterilization is just one step in production processes.

The profile is divided into three major sections. Section 9.1.1 provides a general background on sterilization. Section 9.1.2 briefly describes the actual sterilization process. These sections, which are not meant to repeat information stated in previous chapters, provide an economic perspective on various aspects of the sterilization process. Finally, Section 9.1.3 presents relevant data on the industries that use this process.

9.1.1 Background on Sterilization

Ethylene oxide was developed as a sterilizer during World War II when the U.S. Army investigated ways to sterilize germ-warfare materials.

Widespread acceptance of EO as a sterilizer began in 1949 when the Army released the results of its study. Since that time, EO has had a profound impact on health care because of its ability to sterilize plastics. This has allowed the health care industry to use plastic products that are versatile, convenient, and economical.[2] However, the use of EO as a sterilizer is not limited to the health care industry. Ethylene oxide is used as a sterilant/fumigant by pharmaceutical manufacturers, spice manufacturers, and museums, as well as medical equipment suppliers.

Products may be sterilized for several reasons. The main reason concerns the ultimate safety and effectiveness of the object that is sterilized. Specifically, many products cannot be marketed unless they meet U.S. Food and Drug Administration sterilization standards. For example, inadequate sterilization, especially by medical equipment suppliers, can lead to harmful health effects for users of the supplies. Sterilization is, therefore, a necessary process for these products. Other miscellaneous sterilization and fumigation procedures, such as those used by museums, greatly enhance an object's value or useful life.

There are several ways that products can be sterilized or fumigated. The most popular methods use either a sterilant gas, gamma radiation, heat, or steam. Sterilization facilities use EO as a sterilant gas either alone or mixed with an inert gas. The most widely used sterilant gas is referred to as 12/88, which is 12 percent EO and 88 percent dichlorodifluoromethane (CFC-12) by weight.[3] Another common sterilant gas is a mixture of carbon dioxide (CO_2) and EO. The percentage of EO in the EO/CO_2 mixture can range from less than 10 percent by weight up to 80 percent (or more) by weight.

The economic analysis presented in this chapter covers 191 sterilization facilities for which data are available from two recent surveys. About half of the 191 facilities are suppliers of medical equipment or other health-related items; the other facilities engage in several miscellaneous sterilization and fumigation operations (discussed later). As shown in Figure 9-1, the facilities are located throughout the United States and Puerto Rico, but are concentrated in the East and upper Midwest.

8

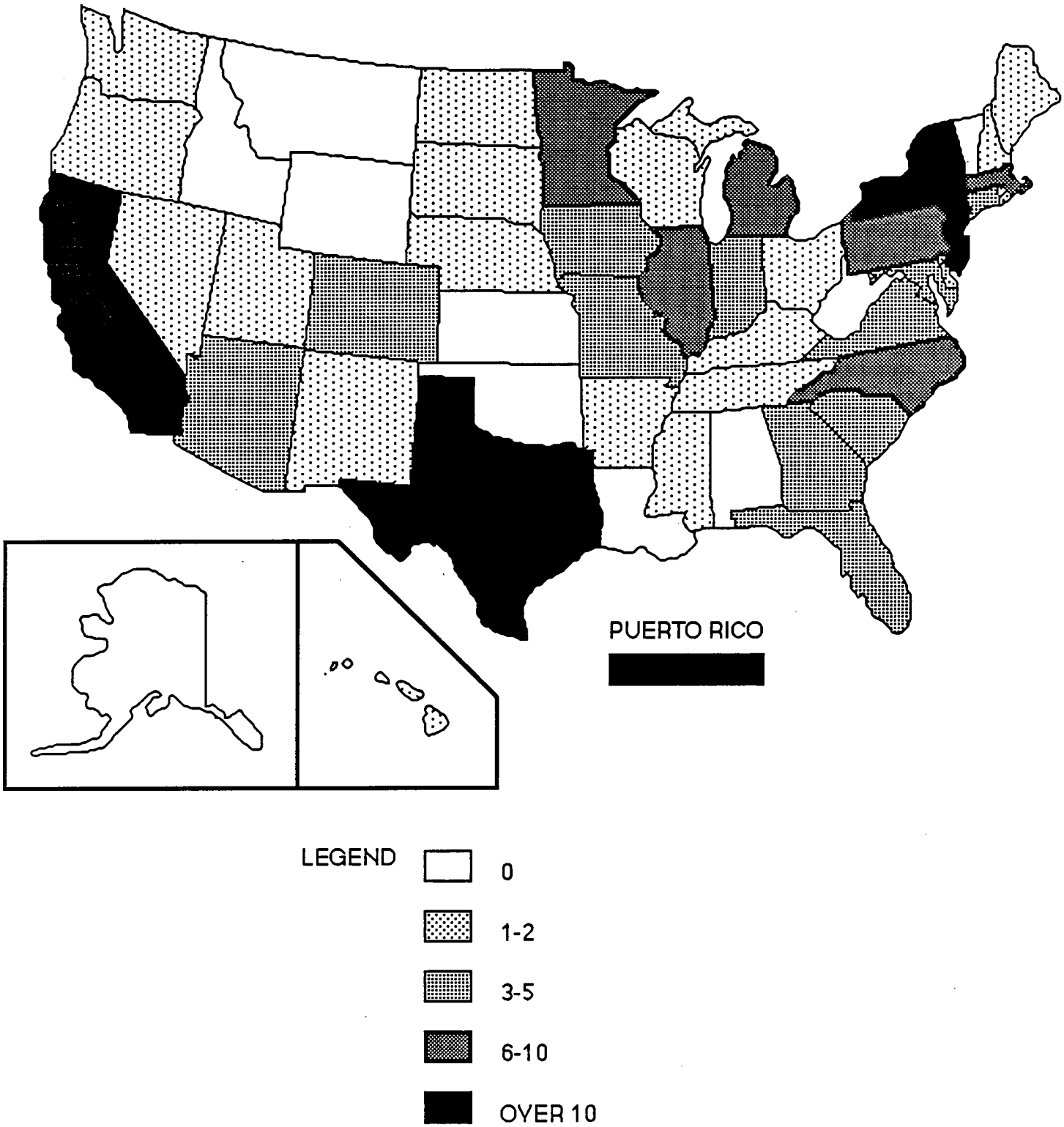

Figure 9-1. Distribution of 191 commercial sterilization facilities by state, 1986.[5]

9

As discussed above, several characteristics of the sterilization process make it difficult to profile the process as a distinct industry. The most important characteristic stems from the role of sterilization in the overall production process. Except for contract sterilizers, the sterilization process is an intermediate step in the production process. Therefore, it is difficult to separate sterilization from the production of the sterilized products. Another difficulty is the absence of a SIC code listing for sterilization either separately or within the classifications for the industries that employ this process. Furthermore, EO sterilization accounts for only 50 to 60 percent of all sterilization activities.[6] Finally, the diversity and specialization of the industries that sterilize products limit the amount of data available for this profile.

In 1986, approximately 2,250 megagrams (2,490 tons) of EO were used for sterilization purposes by the 191 facilities covered in this analysis.*[7] Table 9-1 presents some summary statistics on the use of the sterilant gases at the 191 facilities, separated into two categories--EO use and total gas use. The tremendously wide range in the use of sterilant gas per facility is noteworthy.

9.1.2 Sterilization Process

This section describes the sterilization process, inputs into the sterilization process, and substitution possibilities among types of sterilization.

9.1.2.1 Description of Process Technology. The sterilization process involves four main phases: presterilization conditioning, sterilization phase, evacuation phase, and aeration. The different types of sterilant gases have similar sterilization cycles; the main differences between the processes are the operating pressures of the sterilization chamber.

After the products have been loaded into the sterilization chamber, the chamber pressure is lowered with a vacuum pump in what is called the initial drawdown. The temperature and relative humidity in the chamber are then adjusted. Next, the sterilant gas is pumped into the chamber to

*Approximately half of the data in the EPA commercial sterilization database are 1985 values; the remainder are 1986 values.

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TABLE 9-1. SUMMARY STATISTICS ON THE USE OF STERILANT GAS AT 191 COMMERCIAL STERILIZATION FACILITIES, 1986[8]

		Ethylene oxide	Total gas[a]
Total use	(Mg/yr)	2,250	7,890
Use per facility			
Average	(kg/yr)	11,800	41,500
Range	(kg/yr)	1 - 109,000	6 - 443,000
Use per chamber			
Average	(kg/yr)	5,380	18,600
Range	(kg/yr)	<0.5 - 79,800	2.3 - 199,000
Use per chamber volume[b]			
Average	($kg/m^3/yr$)	253	1,300
Range	($kg/m^3/yr$)	1 - 1,620	8 - 7,970

[a]One facility did not report its total gas use and has been omitted.

[b]The sum over all facilities of the gas used at each facility divided by each facility's chamber volume, divided by the number of facilities.

achieve the desired concentration of EO. Many facilities sterilize with a concentration of approximately 600 milligrams of EO per liter (8.49 grains per quart) inside the chamber; however, some facilities use concentrations as high as 1,000 milligrams per liter (14.5 grains per quart).

During the sterilization phase, the chamber pressure is set according to the requirements of the sterilant gas and is maintained at that level for 2 to 16 hours. At the conclusion of the sterilization phase, the chamber is evacuated, and the pressure is returned to the level achieved during the initial drawdown. Following evacuation, filtered air is introduced into the chamber. The evacuation/air wash is then repeated two to four times. Finally, the products are aerated either in the sterilization chamber or in a separate aeration room. The aeration phase can last from 12 hours to several days, depending on the aeration procedure and the type of product sterilized.

9.1.2.2 Process Inputs. The gases used for sterilization are a primary input into the sterilization process. As noted earlier, several different sterilant gases fall under the broad category of ethylene oxide sterilization--pure EO, 12/88, and EO/CO_2 mixtures.

The importance of EO to the sterilization process lies mainly with the chemical's ability to sterilize a wide variety of products. Ethylene oxide can sterilize almost any product that is contained in a permeable package and can withstand temperatures up to 57 °C (135 °F) and pressures of between -15 psig and +15 psig. However, liquids and products in vapor-tight packages cannot be sterilized effectively with EO.[9]

The major capital equipment requirement for sterilization is the sterilization chamber. The 191 facilities covered in this profile operate 422 chambers, an average of 2.2 chambers per facility. The number of chambers per facility ranges from one to nine. Chamber sizes range from 0.01 m^3 (.35 ft^3) to 177 m^3 (6250 ft^3) and average about 16 m^3 (565 ft^3).[10] A typical chamber has a useful life of approximately 10 years; at the end of that time, the salvage value of the chamber is less than 1 percent of the initial capital investment.[11]

Certain design characteristics of the sterilization chamber are determined by the gas to be used for sterilization. These design charac-

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teristics limit the possibility of switching gases in the short run. When pure EO is used, the chamber instrumentation and room must be explosion-proof.[12] Pure EO chambers must also operate with a deep vacuum to rid the chamber of oxygen.[13] Chambers that use an EO/CO_2 mixture, which requires a substantially higher operating pressure than other gases, have to meet higher standards of construction in order to withstand the pressure.[14]

The various chamber specifications are not mutually exclusive. For example, a chamber designed to withstand the high operating pressure associated with the EO/CO_2 mixture can also accommodate the lower pressures required by other sterilant gases. Therefore, some facilities have chambers with the characteristics necessary for use with more than one type of sterilant gas. Consequently, these facilities have the ability to alternate between gases to achieve optimal combinations of product and sterilant gas for each sterilization cycle. Facilities involved in testing and research and those that sterilize a wide variety of products are more likely to operate chambers in this manner.

Other equipment required for the sterilization process includes:

- A pump to create a vacuum in the chamber
- A pump to force sterilant gas or air into the chamber
- Chamber vents and pump drains for use in the evacuation and aeration process.

Some facilities also have a separate room for the aeration step of the process, although aeration can be accomplished in the sterilization chamber so that products do not have to be moved.

Labor requirements for EO sterilization are usually higher than for other types of sterilization (e.g., thermal or radiation). Each sterilization cycle must be closely monitored because there are several critical process variables that require careful attention.[15] In addition, sterilization with pure EO requires strict safety precautions and extensive monitoring by facility personnel, since that gas is flammable.

9.1.2.3 Substitution Possibilities. The extent of substitution between the EO-based gases is limited by the characteristics of the sterilization chamber and the compatibility of the sterilizing medium with the products

being sterilized. As noted earlier, both pure EO and the EO/CO_2 mixtures may require specially designed sterilization chambers. Chambers may be modified to use pure EO, but industry standards prohibit modification of chambers for use with the EO/CO_2 mixture. However, the different pressures under which sterilization is performed for each sterilant gas can damage some products or packaging. Consequently, substitution to sterilant gases that require extremely high or low operating pressures is limited by the characteristics of the products being sterilized.

Gamma radiation sterilization can substitute for EO sterilization for many products. Unlike EO, radiation can sterilize liquids and products in vapor-tight packages; however, it discolors plastics and damages Teflon and acetyl delrin.[16,17] Gamma radiation is expected to make inroads into the EO market for sterilization, perhaps gaining an additional 10 percent of the sterilization market.[18] While gamma radiation is a likely substitute for EO sterilization, safety concerns regarding transportation and disposal of the radiation source will probably limit any increase in the percentage of the products sterilized by radiation.*[19]

The importance of the sterilization procedure in the overall production process of many products presumably has a profound effect on its demand elasticity, i.e., the responsiveness of quantity demanded to a change in the price of sterilization services. There are four main influences on the elasticity of demand for a factor within an industry.[20] Specifically, the elasticity of demand should vary directly with the elasticity of demand for the final product, the factor's share of the costs of production, the elasticity of supply of other factors, and the elasticity of substitution between the factors.

These influences suggest that the demand for sterilization within the relevant industries is relatively inelastic. This conclusion is based in part on the low ratio between the cost of sterilization and the total cost

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*Several other chemical substitutes for EO exist, but their use is more limited than gamma radiation. The substitution possibilities for these chemicals are discussed in later sections in conjunction with the appropriate end products.

of production.[21] Additionally, the elasticity of substitution between factors of production within the industries is relatively low; precautions taken to minimize contamination during production do not necessarily lessen the need for sterilization, but enhance the effectiveness of the process. Generalizations regarding the elasticity of demand for the final product and the elasticity of supply of other factors are not possible due to variations from industry to industry.

9.1.3 Profile of Industries Using Sterilization

There are several main categories of facilities that sterilize some portion of their output: medical equipment suppliers; other health-related suppliers; pharmaceutical manufacturers (and other drug-related manufacturers); spice manufacturers (and other food-related manufacturers); museums and libraries; laboratories (research, testing, and animal breeding); and contract sterilizers. Table 9-2 summarizes the specific Standard Industrial Classification (SIC) codes associated with these industry categories, and the number of facilities in each. As might be expected from the large number of SIC codes, the 191 sterilization facilities sterilize a wide variety of products. These products range from surgical gloves and hypodermic needles sterilized by medical equipment suppliers to books fumigated by libraries and museums to the spices fumigated by spice manufacturers.

As discussed earlier, the sterilization processes used by the above industries have several similarities. However, a distinction can be made between in-house sterilization and contract sterilization. A majority of the facilities covered in this profile operate a sterilization chamber at the same location as the remainder of the production process. The exception to this rule is the subset of commercial sterilizers that sterilize products for other companies on a contract basis. Not only do contract sterilizers accept a variety of products for sterilization, but they may also supervise the final distribution of the products. It should be noted that the distinction between these two types of sterilization is not always well-defined. There are facilities, especially within the medical equipment supplies and pharmaceutical industries, that sterilize their own products in-house and also accept products on a contract basis from other firms.

TABLE 9-2. STANDARD INDUSTRIAL CLASSIFICATION CODES FOR 191 COMMERCIAL STERILIZATION FACILITIES, 1986[22]

SIC Code	No. of facilities	Description of category
Medical equipment suppliers = 62		
3841	44	Surgical and medical instruments and apparatus
3842	18	Orthopedic, prosthetic, and surgical appliances and supplies
Other health-related suppliers = 25		
3079	7	Miscellaneous plastic products
3693	5	Radiographic x-ray, fluoroscopic x-ray, therapeutic x-ray, and other x-ray apparatus and tubes; electrochemical and electrotherapeutic apparatus
5086	4	Professional equipment and supplies
2211	2	Broad woven fabric mills, cotton
2821	2	Plastics materials, synthetic resins, and nonvulcanizable elastomers
2879	1	Pesticides and agricultural chemicals, NEC
3069	1	Fabricated rubber products, NEC
3569	1	General industrial machinery and equipment, NEC
3677	1	Electronic coils, transformers, and other inductors
3999	1	Manufacturing industries, NEC
Pharmaceutical manufacturers = 40		
2834	34	Pharmaceutical preparations
5122	3	Drugs, drug proprietaries, and druggist's sundries
2831	2	Biological products
2833	1	Medicinal chemicals and botanical products

(continued)

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TABLE 9-2 (continued)

SIC Code	No. of facilities	Description of category
Spice manufacturers = 24		
2099	17	Food preparations, NEC
5149	3	Groceries and related products, NEC
2034	2	Dried and dehydrated fruits, vegetables, and soup mixes
2035	1	Pickled fruits and vegetables, vegetable sauces and seasonings, and salad dressings
2046	1	Wet corn milling
Museums and libraries = 13		
8411	11	Museums & art galleries
8231	2	Libraries & information centers
Laboratories = 11		
0279	4	Animal specialties, NEC
7391	2	Research and development labs
8071	2	Medical labs
8922	2	Noncommercial educational, scientific, and research organizations
7397	1	Commercial testing labs
Contract sterilizers = 16		
7399	14	Business services, NEC
7218	1	Industrial launderers
8091	1	Health and allied services, NEC

NEC = Not elsewhere classified.

9.1.3.1 Medical Equipment Suppliers. Sterilizers of medical equipment (SIC 3841 and 3842) represent the largest single segment of commercial sterilizers covered in this analysis, having 62 of the 191 facilities. The total annual output of medical equipment sterilized in the United States is estimated as 15 to 20 billion products, with at least 50 percent of these products sterilized with EO.[23]

As indicated earlier, some medical equipment must be sterilized in order to be marketed. Ethylene oxide, especially the 12/88 mixture, is used for medical equipment sterilization because of its wide range of effectiveness. The U.S. Food and Drug Administration (FDA) has set strict guidelines for medical equipment sterilizers to ensure achievement of necessary levels of sterility. These guidelines, called Good Manufacturing Practices (GMP), include requirements for such things as preliminary testing, procedural supervision, quality assurance, and final labeling.[24]

In the last few years, the medical equipment industry has been under pressure to reduce health-care costs. The cost containment measures have resulted in decreased hospitalization time and fewer surgical procedures. Consequently, medical equipment suppliers face declining demand from traditional health-care providers, which has heightened price competition among the suppliers. Emerging alternatives to hospitals, such as health maintenance organizations, have countered this trend somewhat by opening new markets for medical equipment suppliers. However, the medical equipment industry must continue to adjust to the increasingly cost-conscious environment of health care. The medical equipment industry is expected to grow at a rate of 6 to 7 percent through the year 1991.[25]

Although a wide range of products are included under the broad category of medical equipment, it is still possible to generalize about the importance of the products. Medical equipment is a basic part of the health-care service, which is a necessary service. Therefore, the elasticity of demand for medical equipment should be highly inelastic. However, the trends mentioned above, i.e., increased price competition among health care facilities and increased use of alternatives to hospitals, may be indications that the demand for medical equipment is becoming more elastic.

According to the Census of Manufactures, there were over 2,200 medical equipment suppliers in 1982.[26] Table 9-3 summarizes various statistics for this industry. Product data were collected for all products classified in either SIC 3481 or 3842 that are produced by all industries; industry data represent all facilities classified in either SIC 3841 or 3842, including their output of non-medical products.

The data presented in Table 9-3 reveal several trends within the industry. The total value of shipments for medical equipment suppliers is given in current dollars and in 1982 dollars. In both instances, the value of shipments has continually increased, although the rate of increase has diminished in recent years. Additionally, total employment has increased steadily from 1972, while production workers have consistently represented 65 to 70 percent of the total workforce. Another interesting trend is the dramatic increase in foreign trade within the medical equipment industry. Not only have imports and exports risen in absolute terms, but imports have increased as a percentage of value of shipments. Shipments between the United States and the European Economic Community account for 37 percent of exports and 50 percent of imports. The United States maintains a trade surplus in medical equipment with all its major trading partners except West Germany and Japan. This trade surplus, which decreased every year from 1981 to 1986, is expected to rise in 1987.[29]

Table 9-4 shows some summary statistics on the sterilization chambers and sterilant gases used by the 62 medical equipment suppliers included in this study. These 62 facilities operated a total of 158 EO sterilization chambers in 1986, an average of 2.5 per facility. The number of chambers per facility varied from one to eight. Average chamber volume per facility was 41.8 m^3 (1,476 ft^3); but covered a wide range from 0.2 m^3 (8 ft^3) to 272 m^3 (9,590 ft^3). In 1986, these 62 facilities used 877 Mg (969 tons) of EO, slightly over 14 Mg (15 tons) per facility. Like chamber volume per facility, EO use varied widely from 0.01 Mg (.01 tons) to 109 Mg (120 tons). Total gas use, which averaged 49.9 Mg (55 tons) per facility, also covered a wide range--the smallest user reporting 0.05 Mg (.06 tons) and the largest reporting 418 Mg (462 tons).

TABLE 9-3. RECENT PERFORMANCE AND FORECAST DATA FOR MEDICAL EQUIPMENT SUPPLIERS (SIC 3841 AND 3842)[a,27]

		1972	1975	1980	1981	1982	1983	1984	1987[b]
Product data[c]									
Value of shipments	(10^6 $)	2,126	3,302	6,185	7,483	9,291	9,994	10,615	13,580
Value of shipments	(10^6 1982$)	4,435	5,243	6,892	7,744	9,291	9,696	9,819	11,900
Industry data[d]									
Total employment	(10^3 people)	78.4	94.4	113.1	119.5	125.7	129.5	135.1	151.5
Production workers	(10^3 people)	54.1	64.1	75.8	79.4	84.6	85.7	89.2	100.5
Capital expenditures	(10^6 $)	89.5	157.6	281.0	374.0	418.0	371.0	480.0	NA
Value added[e]	(10^6 $)	1,559.0	2,240.9	4,077.3	5,013.0	6,335.6	NA	NA	NA
Trade Data									
Value of imports[f]	(10^6 $)	44.2	106.4	268.4	289.6	330.0	367.0	478.0	799.0
Value of exports[f]	(10^6 $)	217.6	432.0	698.0	922.0	980.0	981.0	1,060.0	1,314.0

NA = not available.

[a]Numbers represent the sum of the values of the two industry groups.
[b]Forecast.
[c]Represents products classified in SIC codes 3841 and 3842 produced by all industries.
[d]Represents all facilities classified as SIC 3841 and 3842.
[e]Source: Reference 28.
[f]Developed by International Trade Administration

TABLE 9-4. SUMMARY STATISTICS ON STERILIZATION CHAMBERS AND GASES USED BY 62 MEDICAL EQUIPMENT SUPPLIERS, 1986[30]

	Average	Standard deviation	Range
Sterilization chambers = 158			
Number per facility	2.5	1.8	1 - 8
Chamber volume per facility (m^3)	41.8	58.0	0.2 - 272
Ethylene oxide use = 876.5 Mg/yr			
Use per facility (Mg/yr)	14.1	23.6	<0.05 - 109
Use per chamber volume ($kg/m^3/yr$)	287	256	10.3 - 1,260
Total gas use = 3,096.0 Mg/yr			
Use per facility (Mg/yr)	49.9	77.2	<0.05 - 418
Use per chamber volume ($kg/m^3/yr$)	1,468	1,351	45.8 - 6,927

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By subtracting EO use from the total gas use, and then dividing by EO use, an inert-gas ratio is obtained. This ratio indicates the extent of reliance on pure EO versus mixed sterilant gases. In particular, a ratio near zero would suggest extensive reliance on pure EO (because EO use and total gas use would be almost identical), while a much higher ratio would indicate greater use of sterilant mixtures, such as 12/88. During 1986, the inert-gas ratio for the 62 medical equipment suppliers was 2.5.

9.1.3.2 Other Health-Related Suppliers. There are 25 facilities included in this study that produce some type of health-related supplies but are classifed under a more general SIC code (see Table 9-2). For example, there are five facilities whose primary SIC code involves the manufacturing of x-ray equipment and nine facilities who manufacture various plastic products. The large number of SIC codes illustrates the diversity of industries that sterilize health-related equipment with EO. For this reason the value of shipments in Table 9-3 was presented on a product basis rather than on an industry basis. No other data specific to the relevant SIC codes will be presented.

Table 9-5 provides some summary statistics on the sterilization chambers and sterilant gas used by the 25 other health-related suppliers included in this study. These 25 facilities operated a total of 57 sterilization chambers in 1986, an average of 2.3 per facility. This is slightly lower than the medical equipment suppliers group, which averaged 2.5 chambers per facility.

The other health-related suppliers used 233.2 Mg (258 tons) of EO in 1986. They averaged 9.3 Mg (10 tons) per facility covering a range of 0.002 Mg (.0022 tons) to 42.0 Mg (46 tons). These facilities used less EO than the medical equipment suppliers, both in total and per facility. However, their total gas use per facility was higher than the medical equipment suppliers. This suggests that the other health-related suppliers rely less on pure EO and more on mixed sterilant gas than the medical equipment suppliers. Comparing the inert-gas ratios confirms this conclusion. Medical equipment suppliers have an inert-gas ratio of 2.5, while the other health-related suppliers have an inert-gas ratio of 5.3.

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TABLE 9-5. SUMMARY STATISTICS ON STERILIZATION CHAMBERS AND GASES USED BY 25 OTHER HEALTH-RELATED SUPPLIERS, 1986[31]

	Average	Standard deviation	Range
Sterilization chambers = 57			
Number per facility	2.3	1.5	1 - 6
Chamber volume per facility (m^3)	43.7	49.0	0.4 - 207
Ethylene oxide use = 233.2 Mg/yr			
Use per facility (Mg/yr)	9.3	11.7	<0.05 - 42.0
Use per chamber volume ($kg/m^3/yr$)	212	123	5.5 - 467
Total gas use[a] = 1,461.2 Mg/yr			
Use per facility (Mg/yr)	60.9	75.8	<0.05 - 342
Use per chamber volume ($kg/m^3/yr$)	1,660	1,020	45.8 - 3,890

[a]One facility did not report its total gas use and has been omitted.

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9.1.3.3 Pharmaceutical Manufacturers. The broad category of pharmaceutical manufacturers includes those facilities whose SIC code was either 2834, 5122, 2831, or 2832. These facilities are all connected with pharmaceutical preparations or other medicinal or biological products as a manufacturer or, in some cases, as a wholesaler. However, a vast majority of the facilities operate in SIC 2834. Therefore, the profile of pharmaceutical manufacturers is focused on that industry group. Sterilization has a variety of uses in this industry, but it is as closely tied to the ultimate safety and effectiveness of the products as in the medical equipment industry.

The pharmaceuticals industry has been facing eroding profit margins as a result of two trends. One is the dramatic increase in generic drugs in all sectors of the industry; the other is the increasing cost of research and development for new pharmaceuticals.[32] Another factor in the economic status of the pharmaceuticals industry is the proliferation of patent piracy. The industry classified under SIC 2834 is especially susceptible to this problem because of its reliance on new products and heavy expenditures on research and development.[33]

The U.S. Department of Commerce projects moderate long-term growth for pharmaceutical manufacturers. Industry and product shipments are expected to increase at an annual rate of 3 percent through 1991.[34] The costs of research and development will continue to increase, but at a lower rate than in recent years. The market for over-the-counter drugs has been expanding at a rate of 4 percent per year and this growth is expected to continue, mainly due to the change in status of drugs from prescription to over-the-counter.[35] Generic drugs, which currently represent one-third of the adult market, are predicted to show dramatic growth. The most significant increases will occur from 1987 to 1989, as a large number of patents expire.[36]

According to the Census Bureau, there were a total of 683 facilities classified under SIC code 2834 in 1982. Of these 683 facilities, only 34 have been identified as commercial sterilizers. The pharmaceuticals group, as defined in this chapter, includes six additional facilities from SIC codes 5122, 2831, and 2833. Table 9-6 reports recent performance and

TABLE 9-6. RECENT PERFORMANCE AND FORECAST DATA FOR PHARMACEUTICAL MANUFACTURERS (SIC 2834)[37]

		1972	1975	1980	1981	1982	1983
Product data							
Value of shipments	(10^6 \$)	6,295	8,247	13,012	14,623	16,691	18,980
Value of shipments	(10^6 1982\$)	12,427	14,202	15,974	16,082	16,691	17,392
Industry data							
Total employment	(10^3 people)	112.0	123.0	135.0	131.0	124.0	124.0
Production workers	(10^3 people)	57.0	60.2	68.4	64.8	62.2	61.9
Capital expenditures	(10^6 \$)	167.0	321.0	675.0	729.0	861.0	834.0
Value added[a]	(10^6 \$)	5,640	6,923	11,048	12,059	13,484	NA
Trade Data							
Value of imports[b]	(10^6 \$)	14.5	33.9	61.6	52.6	40.7	141.0
Value of exports[b]	(10^6 \$)	182.0	270.0	421.0	532.0	563.0	670.0

NA = not available.

[a]Source: Reference 38.

[b]Developed by International Trade Administration.

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forecast data for all pharmaceutical manufacturers classified under SIC code 2834. The data are presented in much the same manner as in Table 9-3, with a distinction between industry and product data.

As shown in Table 9-6, the value of pharmaceutical shipments increased steadily in the early 1980s in nominal and real terms. In contrast, industry employment during this same period exhibited a downward trend. Capital expenditures increased rapidly through 1982, but dropped slightly in 1983. While exports were steadily rising, imports fell in 1981 and again in 1982, but increased dramatically in 1983.

Table 9-7 contains some summary statistics on the sterilization chambers and sterilant gas used by the 40 pharmaceutical manufacturers included in this study. These 40 facilities operated a total of 84 sterilization chambers in 1986, averaging 2.1 per facility. The average chamber volume per facility for pharmaceutical manufacturers is 28.3 m^3 (999 ft^3), ranging from 0.1 m^3 (4.9 ft^3) to 147 m^3 (5,200 ft^3). Although the number of chambers per facility in the pharmaceuticals group roughly equals the number for the medical equipment suppliers group, the average chamber volume per facility for pharmaceutical manufacturers is about 70 percent of the average for medical equipment suppliers.

The pharmaceutical manufacturers used 532 Mg (588 tons) of EO in 1986, averaging 13.3 Mg (15 tons) per facility and varying from 0.01 Mg (.011 tons) per facility to 79.8 Mg (88 tons) per facility. They also used 949 Mg (1,049 tons) of total gas, with an average of 23.7 Mg (26 tons) per facility and a range of 0.1 (.07 tons) to 92.0 Mg (102 tons) per facility. The ranges of both EO use and total gas use are much narrower for pharmaceutical manufacturers than they are for medical equipment suppliers. Finally, the inert-gas ratio for pharmaceuticals is 0.8, compared to a 2.5 ratio for the medical equipment suppliers.

9.1.3.4 Spice Manufacturers. Twenty-four of the 191 facilities in this study have been categorized as spice manufacturers. These firms fall into five SIC codes: 2099, 5149, 2034, 2035, and 2046. However, as shown in Table 9-2, about two-thirds of these firms are in SIC code 2099. Consequently, we focus on this industry group in the discussion below.

TABLE 9-7. SUMMARY STATISTICS ON STERILIZATION CHAMBERS AND GASES USED BY 40 PHARMACEUTICAL MANUFACTURERS, 1986[39]

	Average	Standard deviation	Range
Sterilization chambers = 84			
Number per facility	2.1	1.3	1 - 6
Chamber volume per facility (m^3)	28.3	35.1	0.1 - 147
Ethylene oxide use = 532 Mg/yr			
Use per facility (Mg/yr)	13.3	22.8	<0.05 - 79.8
Use per chamber volume ($kg/m^3/yr$)	301	299	11.2 - 1,300
Total gas use = 949 Mg/yr			
Use per facility (Mg/yr)	23.7	28.7	0.1 - 92.0
Use per chamber volume ($kg/m^3/yr$)	1,310	1,440	82.2 - 7,970

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About one-quarter of all spices manufactured in the United States are treated with EO to control fungi, molds, bacteria and insect eggs.[40] Ethylene oxide pasteurization increases shelf life and decreases health risks.[41] An industry magazine reports that "since the spice processor cannot preclude or remove microorganisms from spices, the only means to control microorganisms are: (1) to maintain low moisture content to hinder growth and activity and (2) to treat spices with EO."[42]

Several substitutes within the spice industry are available for EO, each of which has disadvantages. Heat sterilization is useful on only a small number of spices, because it lightens or darkens spice color and can cause a 15 percent loss in spice strength by volatizing spice oils. Neither ionizing radiation nor ethylene imine are approved by the FDA, and their effectiveness is not known. The use of propylene oxide is restricted by the FDA to starches, gums, processed spices, cocoa, and processed nut meats.[43] However, propylene oxide must be heated in order to be as effective as EO. The use of heat restricts its use to a small number of spices because heat volatizes oils in spices, affecting their quality. Without heat, propylene oxide has one-tenth the microbial killing activity of EO. Finally, propylene oxide requires 16 to 48 hours of exposure time, compared with 6 to 8 hours for EO.

According to an industry source, radiation treatment is a promising alternative to EO fumigation, having several advantages over EO.[44] First, whereas EO kills a high percentage of bacteria, radiation kills all bacteria. Second, EO requires high humidity and a vacuum, while radiation treatment can be done under ambient conditions. Third, EO leaves a residue in all foods that have been treated, but radiation leaves no residues of any kind.

According to the Census Bureau, SIC 2099 had 1,976 firms in 1982.[45] As shown in Table 9-8, the value of shipments for SIC 2099 increased steadily from $3.6 billion in 1972 to $11.0 billion in 1982, a nominal growth of 201 percent over the 10-year period. Value added also increased steadily over the same period rising from $1.8 billion in 1972 to $5.7 billion in 1982. Employment experienced two low periods, one in the mid-1970s and another in the early 1980s. The number of production workers declined in

TABLE 9-8. RECENT PERFORMANCE DATA FOR SPICE MANUFACTURERS (SIC 2099)[46]

		1972	1975	1977	1978	1979	1980	1981	1982
Product data									
Value of shipments	(10^6 $)	3,647.9	5,583.8	6,531.0	7,360.6	7,568.9	8,536.5	9,598.9	10,979.3
Industry data									
Total employment	(10^3 people)	66.2	64.3	71.5	76.8	71.8	73.4	72.8	81.4
Production workers	(10^3 people)	44.7	44.2	50.9	55.8	52.3	51.7	52.3	57.9
Capital expenditures	(10^6 $)	91.8	171.3	166.2	199.6	236.0	285.0	208.3	295.4
Value added	(10^6 $)	1,805.2	2,431.3	3,028.1	3,487.8	3,493.8	4,038.0	4,569.6	5,663.3

1975 and again in 1979 and 1980, while total employment declined in 1979 and 1981. Both employment measures increased from 1981 to 1982. Capital expenditures increased from $91.8 million in 1972 to $295.4 in 1982 with declining years in 1977 and 1981.

The spice and seasoning industry relies heavily on foreign trade. According to one estimate, two-thirds of the spices consumed in the United States are imported.[47] This estimate includes some dehydrated vegetables that are used as seasonings but are not included in the FDA definition of spices.

The 24 firms in the spice manufacturers group that use EO sterilization are distributed evenly across the country, except for a large concentration of seven firms in California. Table 9-9 shows some summary statistics on the sterilization chambers and sterilant gas used by these manufacturers. The 24 facilities operated a total of 29 sterilization chambers in 1986, an average of only 1.2 per facility. The number of chambers per facility ranged from one to four. Average chamber volume per facility was 27.0 m^3 (954 ft^3), which is much lower than the average for medical equipment suppliers, i.e., 41.8 m^3 (1,476 ft^3). In addition, the range of chamber volumes per facility, 0.1 m^3 to 112 m^3 (2.5 ft^3 to 4,000 ft^3), was much narrower for the spice manufacturers. Both average chamber volume per facility and the range of chamber volumes per facility for the spices group were roughly equal to the average and range for the pharmaceuticals group.

The spice manufacturers used 167 Mg (184 tons) of EO and 545 Mg (603 tons) of total gas during 1986. Annual EO use per facility averaged 6.9 Mg (8 tons) while total gas use per facility averaged 22.7 Mg (25 tons). Average total gas use per facility is roughly equal to average total gas use for the pharmaceuticals group, but average EO use per facility is about half the average for pharmaceutical manufacturers. The inert-gas ratio for the spice manufacturers is 2.3, which is comparable to the 2.5 ratio for the medical equipment suppliers. This indicates that both industries rely on pure EO processes to about the same extent.

9.1.3.5 Museums and Libraries. According to the 1982 Census of Services, there are 1,909 non-commercial museums and art galleries (SIC 8411) in the United States.[49] Additionally, there are 29,843 public and

TABLE 9-9. SUMMARY STATISTICS ON STERILIZATION CHAMBERS AND GASES USED BY 24 SPICE MANUFACTURERS, 1986[48]

	Average	Standard deviation	Range
Sterilization chambers = 29			
Number per facility	1.2	0.6	1 - 4
Chamber volume per facility (m^3)	27.0	23.8	0.1 - 112
Ethylene oxide use = 167 Mg/yr			
Use per facility (Mg/yr)	6.9	12.3	<0.05 - 59.0
Use per chamber volume ($kg/m^3/yr$)	257	373	4.5 - 1,610
Total gas use = 545 Mg/yr			
Use per facility (Mg/yr)	22.7	42.1	<0.05 - 200
Use per chamber volume ($kg/m^3/yr$)	1,090	1,690	37.1 - 7,050

private libraries in the country.[50] The sterilization database contains eleven museums and two libraries. Interestingly, four of the thirteen are in Massachusetts and there are none in the Southeast or Northwest.

Museums and libraries fumigate books, documents, and other artifacts with EO chiefly to control insect pests and mold. Museum experts report that EO is "especially valuable for treatment of books and archival documents, furs, textiles, and furniture."[51] However, EO has one significant drawback as an artifact fumigant. It settles in rubber, leather, wood, and other organic materials, making it necessary for EO-fumigated artifacts to be aerated for up to a month before they are safe to handle.[52,53]

It is recommended that all organic materials be fumigated before they are introduced into a museum or library collection.[54] Telephone conversations with museum and library conservators who use EO, however, revealed a range of fumigation criteria. Some conservators fumigate all new articles, while others fumigate only those articles that fail a visual inspection or that have suspect backgrounds--e.g., books that were kept in a damp basement.[55,56]

Ethylene oxide has several substitutes as a fumigant in museum and library use. The most promising of these is sulfuryl fluoride, marketed under the trademark VIKANE. Sulfuryl fluoride is not absorbed by organic materials and dissipates more quickly than EO.[57] Therefore, it eliminates the need to aerate artifacts for long periods before handling. Furthermore, the cost of sulfuryl fluoride is comparable to the cost of 12/88, based upon current retail prices and the recommended doses of each sterilant.[58] Sulfuryl fluoride, however, is corrosive to metals, making it an unacceptable alternative for artifacts that contain metal. In particular, it could damage books with staple bindings.[59]

Some EO fumigation chambers would require modifications to use sulfuryl fluoride. Because sulfuryl fluoride is corrosive to metals, the vent pipes from the chamber must be stainless steel; installation of these new vent pipes would represent a startup capital cost for museums/libraries converting to sulfuryl fluoride use.[60]

Sulfuryl fluoride is registered with the U.S. Department of Agriculture as a "restricted" pesticide and, therefore, can only be applied by a

certified applicator. Certified applicators must pass a test administered by the U.S. Department of Agriculture. Ethylene oxide is not registered as a "restricted" pesticide and can, therefore, be applied by anyone.[61] The time and effort involved in passing the certified applicator test would represent another startup cost for museums/libraries converting to sulfuryl fluoride. Finally, sulfuryl fluoride is registered for use in fumigation chambers and there are no controls on its emissions.[62]

Other alternatives to EO fumigation include deep freezing, carbon dioxide fumigation, and vacuum treatment. Several European institutions have tested the freezing method and reported that maintaining -18 °C (-0.4 °F) for 48 hours kills 100% of insect life in all stages of the life cycle. Freezers ranging from 0.9 to 1.1 m^3 (30 to 40 ft^3) in size have been most commonly used.[63] The necessary freezing apparatus costs approximately $3,000-4,000.[64] Placing artifacts in a vacuum or fumigating them with carbon dioxide also kills insect life.[65,66] These three methods, however, do not kill mold and fungi; therefore, they are only partial substitutes for EO.

Table 9-10 provides some summary statistics on the sterilization chambers and sterilant gas used by the 11 museums and two libraries included in this study. Each of these 13 facilities operated one sterilization chamber in 1986. These chambers averaged 2.60 m^3 (91 ft^3) in volume and ranged from 0.5 to 13.8 m^3 (18 to 486 ft^3). The average chamber volume per facility for this group is roughly one-twentieth the average chamber volume per facility for the medical equipment suppliers. Additionally, all of the gas use figures are much lower than the figures for medical equipment suppliers.

During 1986, the museums and libraries group used a total of 0.20 Mg (.22 tons) of EO and 1.67 Mg (1.85 tons) of total gas. Medical equipment suppliers used over 4,000 times as much EO and over 1,800 times as much total gas as the museums and libraries group. In addition, gas use per cubic meter of chamber volume was much lower for this group than for any other group. Medical equipment suppliers used fourteen times as much total gas and twenty-two times as much EO per cubic meter of chamber volume as the museums and libraries group. Furthermore, this group used substan-

TABLE 9-10. SUMMARY STATISTICS ON STERILIZATION CHAMBERS AND GASES USED BY 13 MUSEUMS AND LIBRARIES, 1986[67]

	Average	Standard deviation	Range
Sterilization chambers = 13			
Number per facility	1.0	0.0	1 - 1
Chamber volume per facility (m^3)	2.6	3.7	0.5 - 13.8
Ethylene oxide use = 0.20 Mg/yr			
Use per facility (Mg/yr)	0.0	0.0	0.0 - 1.0
Use per chamber volume ($kg/m^3/yr$)	12.6	17.9	0.9 - 57.0
Total gas use = 1.67 Mg/yr			
Use per facility (Mg/yr)	0.1	0.1	0.0 - 0.4
Use per chamber volume ($kg/m^3/yr$)	105	149	7.6 - 472

tially less EO per cubic meter of chamber volume than any other industry group in this study, i.e., 12.6 $kg/m^3/yr$ (.78 $lb/ft^3/yr$) while all other industry groups used over 200 $kg/m^3/yr$ (12.5 $lb/ft^3/yr$). The inert-gas ratio for the museums and libraries group was 7.35, which suggests that facilities in this group used 12/88 exclusively.

9.1.3.6 Laboratories. Four of the firms being considered for regulation are commercial laboratory rat and mice breeders, which are classified in SIC code 0279. Animal breeders use EO to sterilize heat-sensitive plastics, heat/water-sensitive electronic lab equipment, and pre-packaged articles required for breeding. These articles include books, phones, optical equipment, meters, microscopes, and face masks.[68]

There are some alternatives to EO sterilization for laboratory animal breeding, although each has disadvantages. Pressurized steam damages plastics, electronic equipment and other heat/water-sensitive materials. In addition, steam does not permeate pre-packaged materials as effectively as EO. Dry heat degrades those heat-sensitive materials that cannot withstand temperatures of 160-165 °C (320-329 °F). Another alternative, peracetic acid, is not registered as a pesticide, and is considered to be carcinogenic. It is also corrosive to most metals and plastics, and has poor penetrating properties. Glutaraldehyde requires at least 10 hours immersion, and cannot be used with prepackaged materials. It poses a recontamination danger from hand manipulations and air and cannot be used for materials that would be damaged by water.[69]

Two noncommercial research organizations, SIC code 8922, have also been identified as operators of sterilization chambers. These firms use EO in the same manner as the lab animal breeders mentioned above, but on a somewhat more limited scale. EO alternatives and disadvantages mentioned for animal breeders also apply here.[70]

The remaining facilities classified as laboratories are two research and development labs (SIC code 7391), two medical labs (SIC code 8071), and one commercial testing lab (SIC code 7397). These five firms are considered together because their sterilization practices are similar. In particular, these facilities investigate whether medical devices can be effectively sterilized and yet still function within the human body. There are

limited alternatives to EO for these facilities; EO must be used for heat- and moisture-sensitive medical devices and drugs.[71]

Table 9-11 reports some summary statistics on the sterilization chambers and sterilant gas used by the 11 laboratories included in this study. These facilities operated 30 EO sterilization chambers during 1986, an average of 2.7 per facility. The number of chambers per facility ranged from one to eight. Average chamber volume per facility was 14.7 m^3 (520 ft^3), but varied from 0.02 to 120 m^3 (.7 to 4,230 ft^3) per facility. The laboratories group averaged about the same number of chambers per facility as the medical equipment suppliers group; however, the laboratories group had a lower average chamber volume per facility than all other groups (except the museums and libraries group). This suggests that the laboratory group operated smaller chambers than the other groups (except the museums and libraries group).

The laboratory group used 70.6 Mg (77.4 tons) of EO and 139 Mg (154 tons) of total gas during 1986. The group average of 6.4 Mg (7.1 tons) of EO per facility is roughly equal to the spice manufacturer's use per facility, while less than all other groups (excluding museums and libraries). The laboratories also used less total gas per facility, 12.6 Mg/yr (14.0 tons), than all other groups excluding museums and libraries. The standard deviations for chamber size per facility, EO use per facility, and total gas use per facility were relatively high compared to their respective averages. This is not surprising since the laboratories group is more heterogeneous than the other groups in the study. The inert-gas ratio for the laboratory group was 1.0, implying that the laboratories rely heavily on pure EO.

9.1.3.7 Contract Sterilizers. As mentioned earlier, there is a subset of sterilization facilities that sterilize products on a contract basis. These contract facilities are normally classified under SIC 7399 (Business services, not elsewhere classified). However, depending on the main type of product sterilized, the facility may fall under another related category. For example, one contract sterilizer works with surgical garments and is classified under SIC 7218 (Industrial launderers). In addition to the facilities whose primary function is contract steriliza-

TABLE 9-11. SUMMARY STATISTICS ON STERILIZATION CHAMBERS AND GASES USED BY 11 LABORATORIES, 1986[72]

	Average	Standard deviation	Range
Sterilization chambers = 30			
Number per facility	2.7	2.3	1 - 8
Chamber volume per facility (m^3)	14.7	33.6	<0.05 - 119.9
Ethylene oxide use = 70.6 Mg/yr			
Use per facility (Mg/yr)	6.4	17.5	<0.05 - 61.1
Use per chamber volume ($kg/m^3/yr$)	143	184	6.3 - 539
Total gas use = 139 Mg/yr			
Use per facility (Mg/yr)	12.6	25.8	<0.05 - 72.2
Use per chamber volume ($kg/m^3/yr$)	800.0	1,220	51.5 - 4,490

tion, there are several facilities classified under a different category who sometimes accept contract work. These are especially prevalent within the medical equipment industry.

There are varying reports as to the number of contract sterilizers in the United States. One official at the FDA estimated that there are 100 to 125 contract sterilizers of all types, i.e., EO, steam, radiation, etc. Of these, approximately 60 are EO sterilizers.[73] Another source at the FDA estimated that there are 65 contract sterilizers of medical equipment, 18 of which do contract work only.[74] Only 16 of the 191 facilities in this study have been identified as contract sterilizers exclusively; however, an undetermined number of the other facilities also accept contract work.

The price for contract sterilization varies with the type of sterilization performed. An industry spokesman at a contract sterilization facility estimated that the average price for pure EO sterilization is currently $\$32/m^3$ ($\$0.90/ft^3$) of product.[75] Sterilization with 12/88 at a similar facility is estimated to average about $\$48/m^3$ ($\$1.35/ft^3$) of product. The difference in price between sterilization with pure EO and 12/88 is due to the increased amount of gas necessary to sterilize with 12/88.[76] In spite of the higher cost, facilities use the 12/88 formulation because some products or packaging cannot withstand sterilization with pure EO, as noted previously. In addition, pure EO is explosive, making worker safety a concern.

One expert on sterilization has predicted 30 percent growth in the next 5 years for contract sterilizers.[77] Growth would then continue at a rate of 4 to 5 percent annually. Implicit in this projection is the assumption of no additional Federal regulations in the future. Any new regulations would probably augment the positive growth of contract sterilization, because it is possible that smaller facilities would cease in-house sterilization operations and begin sending products off-site.* However, this trend may not be as great on the western coast of the United States. Currently, there are an inadequate number of contract sterilizers

*See Section 9.2.1 for further discussion of the possible substitution of contract sterilization for in-house sterilization due to the candidate NESHAP controls on EO emissions.

in that region to meet the needs of all the medical equipment suppliers and food distributors.[79] Presumably, larger facilities or facilities that sterilize a large volume of products will be able to install the control devices with less economic impact.

Table 9-12 contains some summary statistics on the sterilization chambers and sterilant gas used by the 16 contract sterilizers included in this study. These 16 facilities operated 48 EO sterilization chambers in 1986--an average of exactly 3 per facility, which is more than any other group in the study. The contract sterilizers also had more chamber volume than any other group, averaging 70.8 m^3 (2,500 ft^3) per facility. During 1986, the contract sterilizers used 375 Mg (414 tons) of EO and 1,700 Mg (1,880 tons) of total gas--approximately half the amounts used by the medical equipment suppliers. However, the contract sterilizers used much more EO and total gas than any other group on a per-facility and per-cubic-meter-of-chamber-volume basis. The inert-gas ratio for contract sterilizers was 4.4, indicating that contract sterilizers fall in the middle of the industry groups regarding their reliance on pure EO. This is not surprising since contract sterilizers service diverse industries with varying sterilization requirements.

9.2 ECONOMIC EFFECTS OF CANDIDATE NESHAP CONTROLS

In this section we analyze the economic effects that the candidate NESHAP controls will have on sterilization facilities. Section 9.2.1 briefly reviews the ideal conceptual framework for such an analysis. Section 9.2.2 describes the analytical procedure we used as a proxy for the ideal conceptual framework. Section 9.2.3 presents the empirical results of the economic analysis. Finally, Section 9.2.4 contains our conclusions based upon these empirical results.

9.2.1 Ideal Conceptual Framework

The ideal procedures for estimating the economic effects of the proposed NESHAP controls are based upon a demand-supply conceptual framework.* A market demand curve describes the maximum quantity (per time

*For a detailed description of this conceptual framework, see Chapter 2 in Reference 81.

TABLE 9-12. SUMMARY STATISTICS ON STERILIZATION CHAMBERS AND GASES USED BY 16 CONTRACT STERILIZERS, 1986[80]

	Average	Standard deviation	Range
Sterilization chambers = 48			
Number per facility	3.0	2.5	1 - 9
Chamber volume per facility (m^3)	70.8	67.9	13.8 - 278
Ethylene oxide use = 375 Mg/yr			
Use per facility (Mg/yr)	23.4	27.3	1.5 - 108
Use per chamber volume ($kg/m^3/yr$)	325	256	80.4 - 951
Total gas use = 1,701.2 Mg/yr			
Use per facility (Mg/yr)	106.3	117.6	12.3 - 442.9
Use per chamber volume ($kg/m^3/yr$)	1,720	1,310	146.9 - 4,800

period) of a commodity, Q, that individuals or firms are willing to purchase at various prices, ceterus paribus (all else equal). As shown in Figure 9-2, demand curves are downward sloping, indicating that consumers are willing to buy more of Q at lower prices than at higher prices. This assumes that all other factors that might influence demand--for example, income, prices of related goods, and tastes or preferences--do not change.

If the market process establishes a price of P_1, consumers will purchase Q1 of the commodity for a total expenditure equal to OP_1BQ_1. Since a demand curve measures maximum willingness to pay for each unit of a commodity, the total willingness to pay for Q_1 is the entire area $OABQ_1$--total expenditures plus the triangle P_1AB. This triangle, which is the difference between what consumers actually pay and the amount they are willing to pay, is known as consumer surplus. It is a good empirical approximation of the dollar value of the well-being consumers receive from consuming a commodity, over and above what they pay for the commodity.

The other principal construct in our conceptual framework is a market supply curve. A supply curve shows the maximum output (per time period) of a commodity that firms are willing to supply at various prices, ceterus paribus. The upward slope of supply curves (as shown in Figure 9-3) indicates that firms are willing to produce more at higher prices than at lower prices, assuming that other factors influencing the supply curve-- prices of inputs (such as labor, energy, and machinery) and production technology--do not change.

If the market process establishes a price of P_1, then suppliers will produce Q_1 units of the commodity, receiving OP_1BQ_1 in total revenues. However, the cost of producing these Q_1 units is represented by the area $OCBQ_1$. The triangle CP_1B, which is known as producer surplus, is the difference between the minimum amount firms would accept for the Q_1 units and the actual amount they receive for these units. Producer surplus is a good empirical approximation of the dollar value of the returns that firms experience from producing a commodity, over and above the costs of production.

Installing and operating controls on EO emissions from sterilization chambers will increase the cost of producing sterilized products. In a demand-supply framework, this additional cost is represented by an upward

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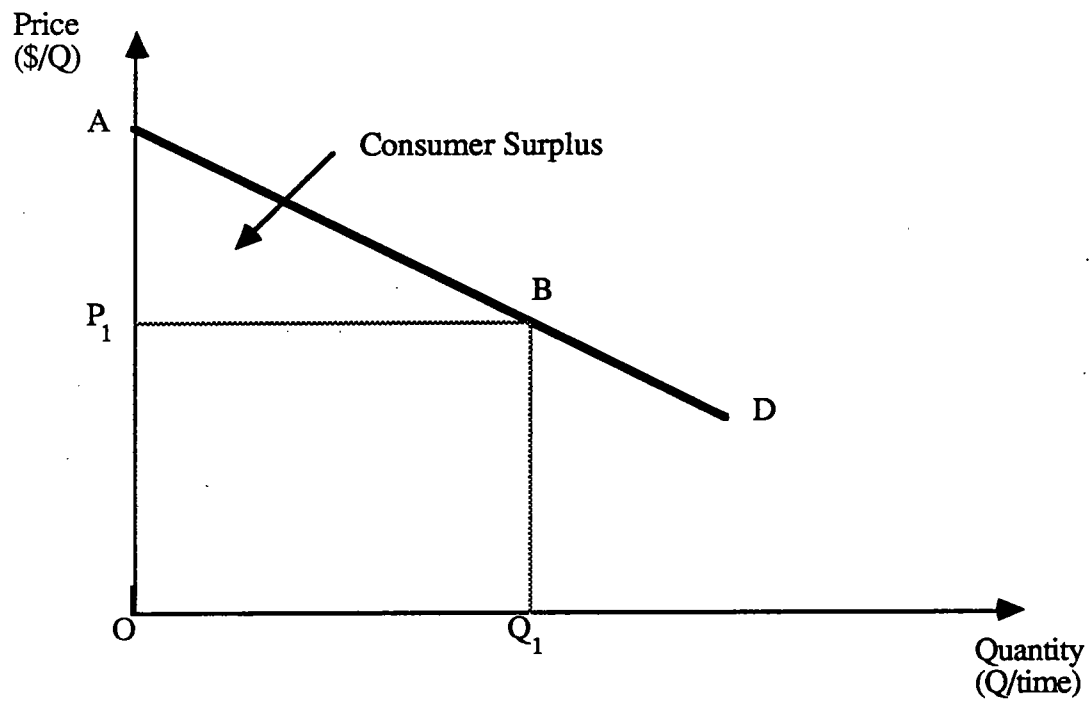

Figure 9-2. Demand curve for commodity Q.

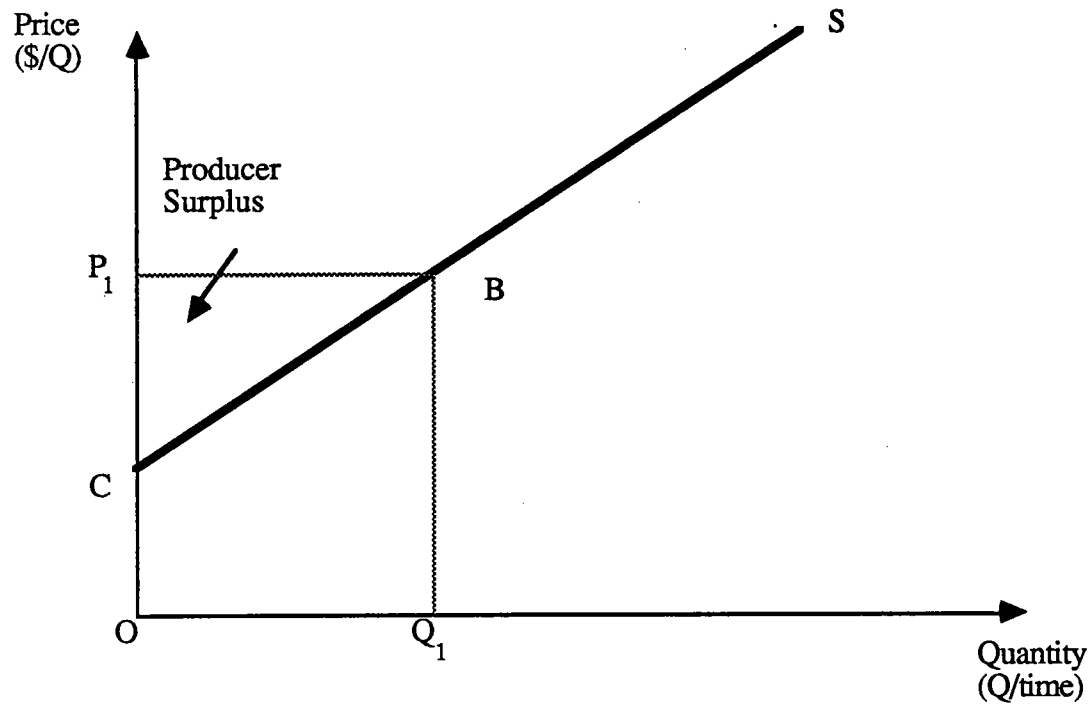

Figure 9-3. Supply curve for commodity Q.

shift in the supply curve (from S to S' in Figure 9-4). This upward shift in the supply curve leads to a higher market price (P_1') and smaller quantity demanded (Q_1'). The changes in price (from P_1 to P_1') and quantity (from Q_1 to Q_1') are the market adjustments attributable to the emissions controls.

The cost of this change in market-clearing price and quantity due to the emissions controls is represented by the area CDEB--the area between the two supply curves S and S' and under the demand curve. This area, which constitutes the cost that society experiences due to the emissions controls, equals the sum of the additional cost of producing Q_1' units of the commodity (area CDEF) plus the foregone consumer and producer surplus on the (Q_1 - Q_1') units of the commodity that are no longer produced or consumed (area EFB). Equivalently, the social cost of emissions controls can be determined by aggregating the impact of the controls on the well-being of consumers and producers of affected commodities. In other words, social cost equals the sum of the change in consumer and producer surplus as a result of the price-quantity adjustments.

The simple model in Figure 9-4 ignores two potentially important aspects of the economic impact of the candidate NESHAP controls. First, the controls will apply to both existing and new plants (when they are constructed) that produce sterilized products. Thus, there are two relevant supply curves--a supply curve from existing plants and a supply curve from new plants. The candidate NESHAP controls will shift both of these supply curves upward, although the magnitude of these shifts will probably differ. The potential effects of the candidate NESHAP controls on new facilities are addressed in Section 9.2.4.2.

Second, the candidate NESHAP controls will probably cause some firms to substitute "contract" sterilization for "in-house" sterilization. In-house sterilization refers to sterilization performed onsite by a firm as part of the production process, while contract sterilization refers to sterilization performed offsite under contract. If the candidate NESHAP controls are promulgated, facilities using the EO sterilization process will face four possible alternatives:

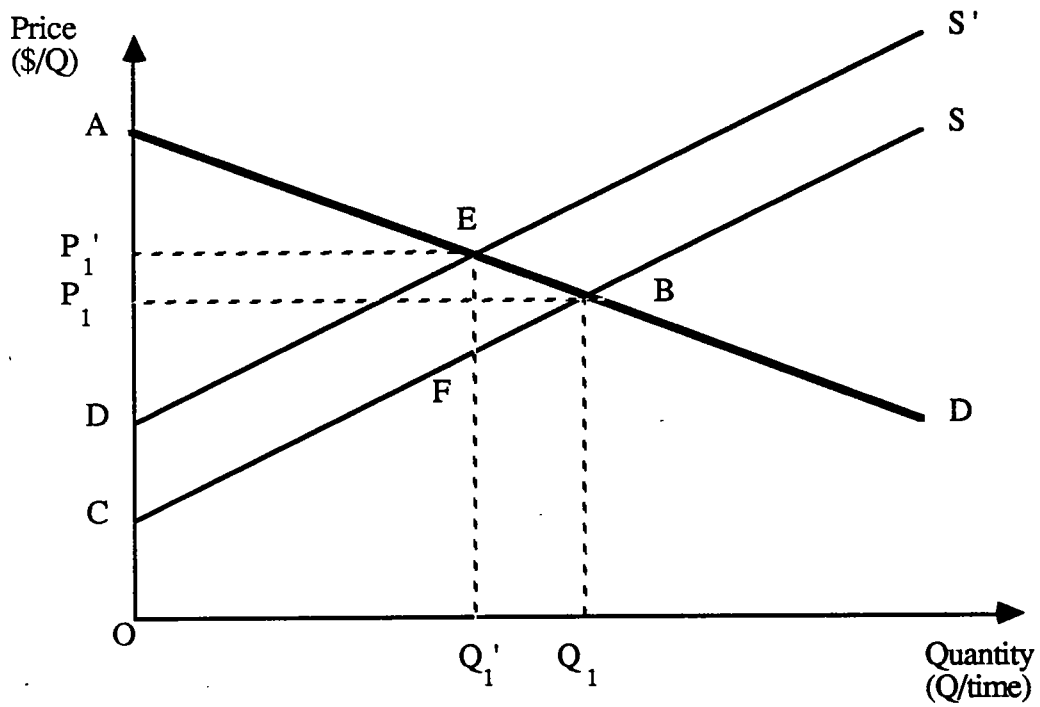

Figure 9-4. Market equilibrium with and without an upward shift in the supply curve due to ethylene oxide emissions controls.

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1. adopt the candidate controls,
2. switch to another sterilization process,
3. discontinue in-house sterilization, switching to contract sterilization, or
4. discontinue production of the sterilized product.

Undoubtedly, the substitution of contract sterilization for in-house sterilization (alternative 3) will be the least-cost alternative for some facilities. Due to a lack of needed data, no quantitative estimates of the extent of this substitution are made.*

9.2.2 Analytical Procedure

The ideal conceptual framework involves the market price and quantity sold of a single product. In this study, however, we are not modeling a single product; the candidate NESHAP covers a broad range of products produced by a number of different industries. Therefore, we cannot draw a single supply or demand curve for sterilized products. Consequently, we cannot use the ideal conceptual framework to analyze the economic effects of the candidate commercial sterilization NESHAP. As an alternative, we use a more qualitative approach that approximates the ideal approach.

Our approach has four parts. First, we impose some homogeneity by dividing commercial sterilizers into seven industry groups. Second, we use each facility's chamber volume and annual EO use as proxies for the quantity of goods produced. By dividing these proxies into the annual compliance cost, we obtain rough estimates of the per-unit production cost increase caused by the candidate NESHAP. Third, we divide each facility's annual compliance cost by its total cost of sterilization to obtain an upper bound for the percentage increase in production cost caused by the NESHAP. Finally, we divide each facility's annual compliance cost by its total sales to obtain a lower bound estimate of the percentage production cost increase. Each facility's actual percentage production cost increase attributable to the candidate NESHAP will lie somewhere between its upper and lower bound.

9.2.2.1 Industry Grouping. As discussed above, we have divided the 191 affected facilities into seven industry groups based on their SIC code

*For a detailed explanation of the substitution effect, see Appendix 9-A.

classifications: medical equipment suppliers, other health-related suppliers, pharmaceuticals manufacturers, spice manufacturers, museums and libraries, laboratories, and contract sterilizers. The firms within each of these sub-groups produce a more homogeneous mix of goods than the aggregate group. Nevertheless, the product mix is still quite diverse within the industry groups, as demonstrated in Section 9.1.

9.2.2.2 Chamber Volume as an Output Measure. The sum of the volumes of all sterilization chambers at a facility can be viewed as a measure of the facility's sterilization capacity. If we assume that sterilization cycles for all sizes and types of chambers are of equal duration, then a facility with twice the chamber volume of another facility will also have twice the sterilization capacity. If this assumption is not true, then the direct relationship will not hold. For example, if larger chambers undergo longer cycles, then chamber volume will overstate sterilization capacity for large chambers and understate capacity for small chambers. If small chambers undergo longer cycles, then the reverse will hold.

With two additional assumptions, chamber volume can be used not only as a measure of capacity, but also as a measure of output. First, we assume that all facilities within an industry group perform about the same number of sterilization cycles per year. Second, we assume that the sterilization chambers are always filled with products to approximately the same level. Under these assumptions, chamber volume would be highly correlated with the volume of goods sterilized.

How valid are these two assumptions? Data from the EPA commercial sterilization database indicate that facilities do not perform equal numbers of sterilization cycles per chamber, even within industry groups.[82] For example, in the medical equipment suppliers group, the number of sterilization cycles per chamber per year varies from 15 to over 1,000. The remaining six industry groups exhibit a similar variation. This indicates that our first assumption is not true. Therefore, chamber volume may be a poor output measure.

9.2.2.3 EO Use as a Measure of Output. EO use is our second surrogate output measure. The EPA commercial sterilization database provides data on the amount of EO used per facility during 1986 (1985 for some

facilities).[83] EO use is a better output measure than chamber volume because EO use will vary directly with the volume of goods sterilized, even if firms do not run a consistent number of sterilization cycles per chamber. We make two assumptions, however, when using EO as a measure of the volume of products sterilized. First, we assume that the concentration of EO per unit of chamber volume will be roughly the same for all chambers. Second, we assume that sterilization chambers will be filled with products to roughly the same level for each cycle.

Although we have no supporting data, we can speculate that sterilization chambers may not always be filled with products to the same level. It seems probable that facilities running frequent sterilization cycles would always fill their chambers to capacity in order to minimize costs. However, facilities that sterilize infrequently may run some cycles at less than capacity, as they face sporadic orders for sterilized goods and shipment deadlines. To the extent that this occurs, EO use may overstate the volume of goods sterilized by small-volume sterilizers. If the small-volume sterilizers are also high per-unit-cost producers (i.e., marginal facilities), then the overstatement of their output would make the industry supply curve appear flatter (i.e., more elastic) than it actually is.

To this point, we have ignored a potentially important problem with our output measures. As mentioned above, a broad range of products are sterilized with EO. Chamber volume and EO use are measures of the physical volume of products sterilized, but with such a diverse group of products, volume is not a wholly appropriate measure of output. For example, one facility may sterilize pacemakers while another sterilizes scalpels. It seems likely that output (in physical or monetary units) per cubic meter of chamber volume would differ substantially between pacemakers and scalpels. A similar conclusion seems reasonable regarding EO use as an output measure. In summary, the large number of products sterilized in the seven industry groups undermines the usefulness of chamber volume and EO use as proxies for facility output.

9.2.2.4 Cost of Sterilization. In light of the pacemaker-scalpel problem described above, we report TAC not only on a per-unit-of-output basis as described above, but also on a percentage-of-cost basis. Ideally,

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we would report TAC as a percentage of the total cost of producing sterilized products. However, no data on such costs at the affected facilities are available. Therefore, we report TAC as a percentage of the total annualized cost of sterilization at a facility (TAC/CS) and TAC as a percentage of total facility sales (TAC/S). Because the total cost of producing sterilized products (hereafter referred to as total production cost) will equal or exceed sterilization cost for any facility, TAC/CS is an upper bound for TAC/total production cost. Conversely, total production cost will generally be less than or equal to facility sales, particularly since most affected facilities produce a mix of sterilized and unsterilized products. Therefore, TAC/S will be a lower bound for TAC/total production cost.

We calculated the total annual cost of sterilization for each facility using a model chamber approach. Specifically, we calculated the capital cost and operating cost per cycle for representative sized chambers in the following chamber categories: 12/88, Pure EO, Non-Flammable EO/CO_2, and Flammable EO/CO_2. We picked four representative chamber sizes for the 12/88 gas-type, four for pure EO, three for flammable EO/CO_2 and two for non-flammable EO/CO_2. We selected representative chamber sizes by first minimizing the total variance between the representative chamber sizes and the sizes of chambers currently in use, as reported in the EPA Commercial Sterilization Database. Then we finalized our selection of representative chamber sizes by reviewing scatter plots of actual chamber sizes and talking with a vendor of sterilization chambers.

A sterilization chamber vendor provided estimates of capital and operating costs for each model chamber. Capital costs include the cost of the sterilization chamber, the cost of chamber installation, and the cost of explosion protection equipment for use with flammable sterilant gases. Chamber operating costs include labor, electricity, and sterilant gas costs.

Once we determined the capital and operating costs for the model chambers, we divided the chambers at the affected facilities into the four gas types outlined above. We then determined the operating cost per cycle and capital cost for each chamber by interpolating between the model chambers based on chamber size. We multiplied the operating cost per cycle

by the annual number of cycles for the chamber, as reported in the EPA Commercial Sterilization Database, obtaining the annual operating cost of the chamber. We annualized the capital cost using a useful life of 10 years and an interest rate of 10 percent and added the annualized capital cost and the annual operating cost to obtain the annual sterilization cost for the chamber. As a final step, we aggregated annual sterilization costs for individual chambers at each facility to determine the total annual cost of sterilization at the facility.

9.2.2.5 Facility Sales. Total facility sales provide an upper-bound estimate of the total costs of producing sterilized goods for several reasons. First, total sales for a facility include sales of sterilized and unsterilized products. For facilities that sterilize only a small portion of output, total sales may substantially exceed sales of sterilized products. Second, sales reflect the price of final products multiplied by the output of these products. They do not directly measure production costs. In general, sales equal production costs plus producer surplus. Producer surplus is only zero when the supply curve is horizontal or the firm is the marginal firm in its industry; therefore, using sales to measure production costs implies one of these two conditions. If producer surplus is not zero, then total sales will overstate total production costs.

As noted, we report sales on a facility-specific basis. When a facility did not report its own sales and the parent company sales were available, the amount of sales per employee for the parent company was multiplied by the number of employees at the facility to estimate sales at the facility. This assumes that the amount of sales per employee at the parent and the facility are the same, which would not be true, for example, if the facility were more capital-intensive than the parent company. We have no information regarding the validity of this assumption.

Where no sales or employment information was available, we used an ordinary-least-squares regression of facility sales on facility EO use to estimate facility sales. Dummy variables were included to represent the seven industry groups, and a log-log functional form was used.

9.2.3 Results

As explained in the previous section, we base our economic analysis on the annual cost of compliance with the candidate NESHAP controls relative to chamber volume, EO use, total sterilization costs, and total sales. We present the summary statistics on these values in this section.

9.2.3.1 Total Annualized Cost. Total annualized cost measures the annual engineering cost of compliance with the candidate NESHAP controls, as determined by Midwest Research Institute (an engineering subcontractor). Total annualized cost equals the capital cost of an acid-water scrubber and other necessary hardware annualized over a 10-year period at an interest rate of 10 percent, plus annual operating costs for the scrubber, including labor, materials, and ethylene glycol disposal costs. Electric and water costs for scrubber operation are assumed to be insignificant and are not included.

Table 9-13 reports the median and range of total annualized cost (TAC) per facility for each of the seven industry groups. Contract sterilizers have the highest median TAC at $46,900 per facility. The lowest median TAC is $21,100 per facility for the museums and libraries group. TAC per facility ranges from a low of $1,000 for one of the pharmaceutical manufacturers to a high of $117,000 for a medical equipment supplier. The medical equipment suppliers group exhibits the largest range in TAC values, while the museums and libraries group has the smallest TAC range.

9.2.3.2 TAC Relative to Chamber Volume. Table 9-14 reports the median and range of TAC per cubic meter of chamber volume per facility (TAC/CV). Applying the descriptions and assumptions discussed previously, TAC/CV reflects the cost increase per unit of sterilization capacity that the candidate NESHAP will cause. Museums/libraries have the highest median TAC/CV ($20,700) while laboratories have the second highest ($12,100). All other median TAC/CV are below $2,500, with contract sterilizers the lowest at $1,260.

The laboratory group has the highest upper range value of TAC/CV ($1,230,000). Facilities with the highest TAC/CV values are most likely to close or cease in-house-sterilization in response to the candidate NESHAP. The lowest TAC/CV value for most of the industry groups is under $100. However, the lowest TAC/CV value for the museums and libraries group is

TABLE 9-13. SELECTED SUMMARY STATISTICS ON THE TOTAL ANNUALIZED COST OF THE CANDIDATE NESHAP CONTROLS PER FACILITY, 1986[84]

Industry group	Median ($)	Range ($)
Medical equipment suppliers	26,600	1,300 - 117,000
Other health-related suppliers	29,300	2,500 - 70,400
Pharmaceutical manufacturers	23,400	1,000 - 98,600
Spice manufacturers	34,300	7,700 - 65,200
Museums and libraries	21,100	21,100 - 27,800
Laboratories	24,000	21,100 - 81,900
Contract sterilizers	46,900	8,000 - 105,000

TABLE 9-14. SELECTED SUMMARY STATISTICS ON THE TOTAL ANNUALIZED COST OF THE CANDIDATE NESHAP CONTROLS PER CUBIC METER OF CHAMBER VOLUME PER FACILITY, 1986[85]

Industry group	Median ($/m^3)	Range ($/m^3)
Medical equipment suppliers	1,830	17 - 93,200
Other health-related suppliers	1,280	46 - 53,200
Pharmaceutical manufacturers	2,430	13 - 149,000
Spice manufacturers	1,900	69 - 281,000
Museums and libraries	20,700	2,000 - 41,400
Laboratories	12,100	683 - 1,230,000
Contract sterilizers	1,260	29 - 2,430

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$2,000, which almost equals the highest TAC/CV in the contract sterilizers group. This suggests that control costs will be relatively high for all museums and libraries having sterilization chambers. This conclusion is supported by the large median value of TAC/CV for this group.

9.2.3.3 TAC Relative to EO Use. Table 9-15 reports median and range values of the total annualized cost per kilogram of EO used per facility (TAC/EO). TAC/EO reflects the per-unit production cost increase caused by the candidate NESHAP. Museums and libraries have the highest median TAC/EO ($2,620), which is over ten times the second highest median (i.e., $237 for laboratories). As noted above, museums/libraries and laboratories also have the highest medians of TAC/CV. The median values of TAC/EO for the remaining five industry groups are below $20, with contract sterilizers having the lowest median value at $4.

The lowest facility TAC/EO value for six of the industry groups is $1 or less. In contrast, the lowest TAC/EO value for museums and libraries is $462. This group also has the highest TAC/EO value at $31,000. In contrast, the highest TAC/EO for contract sterilizers is $20.

9.2.3.4 TAC Relative to Annual Sterilization Cost. Table 9-16 reports the median and range values of total annualized cost per dollar of annual sterilization cost per facility (TAC/CS). As previously indicated, TAC/CS provides an upper bound for TAC as a percentage of total production cost, which is the desired measure. Table 9-16 shows that the museums/libraries group has the largest median TAC/CS at 109 percent. So the candidate NESHAP controls will more than double the cost of sterilization at the median facilities in this group. The laboratories and spices groups have the second and third highest median values with 56.7 percent and 37.0 percent, respectively. The contract sterilizers group has the lowest TAC/CS at 9.3 percent. The low median value for this group supports the hypothesis that contract sterilizers may experience economies of scale in controlling ethylene oxide emissions. In other words, the candidate NESHAP controls may cause lower per-unit increases in production costs for contract sterilizers than for the other groups.

To further investigate the distribution of TAC/CS among the facilities in the seven industry groups, we developed scatter plots of TAC/CS versus

TABLE 9-15. SELECTED SUMMARY STATISTICS ON THE TOTAL ANNUALIZED COST OF THE CANDIDATE NESHAP CONTROLS PER KILOGRAM OF EO USED PER FACILITY, 1986[86]

Industry group	Median ($/kg)	Range ($/kg)
Medical equipment suppliers	7	<0.5 - 3,880
Other health-related suppliers	8	<0.5 - 9,770
Pharmaceutical manufacturers	13	<0.5 - 2,770
Spice manufacturers	20	<0.5 - 5,210
Museums and libraries	2,620	462 - 31,000
Laboratories	237	1 - 7,750
Contract sterilizers	4	<0.5 - 20

TABLE 9-16. SELECTED SUMMARY STATISTICS ON THE TOTAL ANNUALIZED COST OF THE CANDIDATE NESHAP CONTROLS AS A PERCENTAGE OF THE ANNUAL COST OF STERILIZATION PER FACILITY, 1986

Industry group	Median (%)	Range (%)
Medical equipment suppliers	14.5	<0.5 - 118
Other health-related suppliers	12.4	<0.5 - 114
Pharmaceutical manufacturers	23.9	<0.5 - 218
Spice manufacturers	37.0	0.6 - 113
Museums and libraries	109	28.9 - 127
Laboratories	56.7	3.0 - 122
Contract sterilizers	9.3	<0.5 - 45.4

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annual sterilization costs for each industry group (see Figures 9-5 through 9-11). In general, these plots depict a hyperbolic shape. In other words, TAC/CS decreases asymptotically as sterilization cost increases. These plots also display the magnitude of TAC/CS for individual facilities within the range of values shown in Table 9-16.

9.2.3.5 TAC Relative to Total Sales. Table 9-17 contains the median and range values of total annualized cost per dollar of facility sales (TAC/S). This measure is a lower bound for TAC as a percentage of total production cost. Therefore, a low TAC/S does not necessarily imply that the candidate NESHAP controls will cause a small rise in total production costs, or that firms in an industry group will adopt the controls and continue in-house sterilization operations. The latter point is discussed further in Section 9.2.4.1.

Contract sterilizers have the highest median TAC/S at 4.24 percent, with the museums and libraries group nearly equal at 4.22 percent. For the other five industry groups, the median TAC/S does not exceed 0.33 percent. High upper range values of TAC/S include 17.1 percent for a contract sterilization facility, 12.9 percent for a museum/library, and 10.1 percent for a pharmaceuticals manufacturing facility. Figures 9-12 through 9-18 show the distribution of TAC/S among the facilities in each industry group. These scatter plots depict the same hyperbolic shape found in the TAC/CS scatter plots - TAC/S decreases asymptotically as total sales increase.

9.2.4 Conclusions

In this section we summarize our conclusions regarding the economic effects of the candidate NESHAP controls on existing and new facilities.

9.2.4.1 Effects on Existing Facilities. Based on the median values reported in Section 9.2.3, we expect the candidate NESHAP to significantly affect only two industry groups: museums/libraries and contract sterilizers. The candidate NESHAP will have a substantial effect on all facilities in the museums/libraries group. These facilities have very small chambers and use a very small quantity of EO. Consequently, the TAC/CV and TAC/EO values for museums and libraries are relatively high. The TAC/CS values indicate that the candidate NESHAP controls will more than double sterilization costs for many museums and libraries.

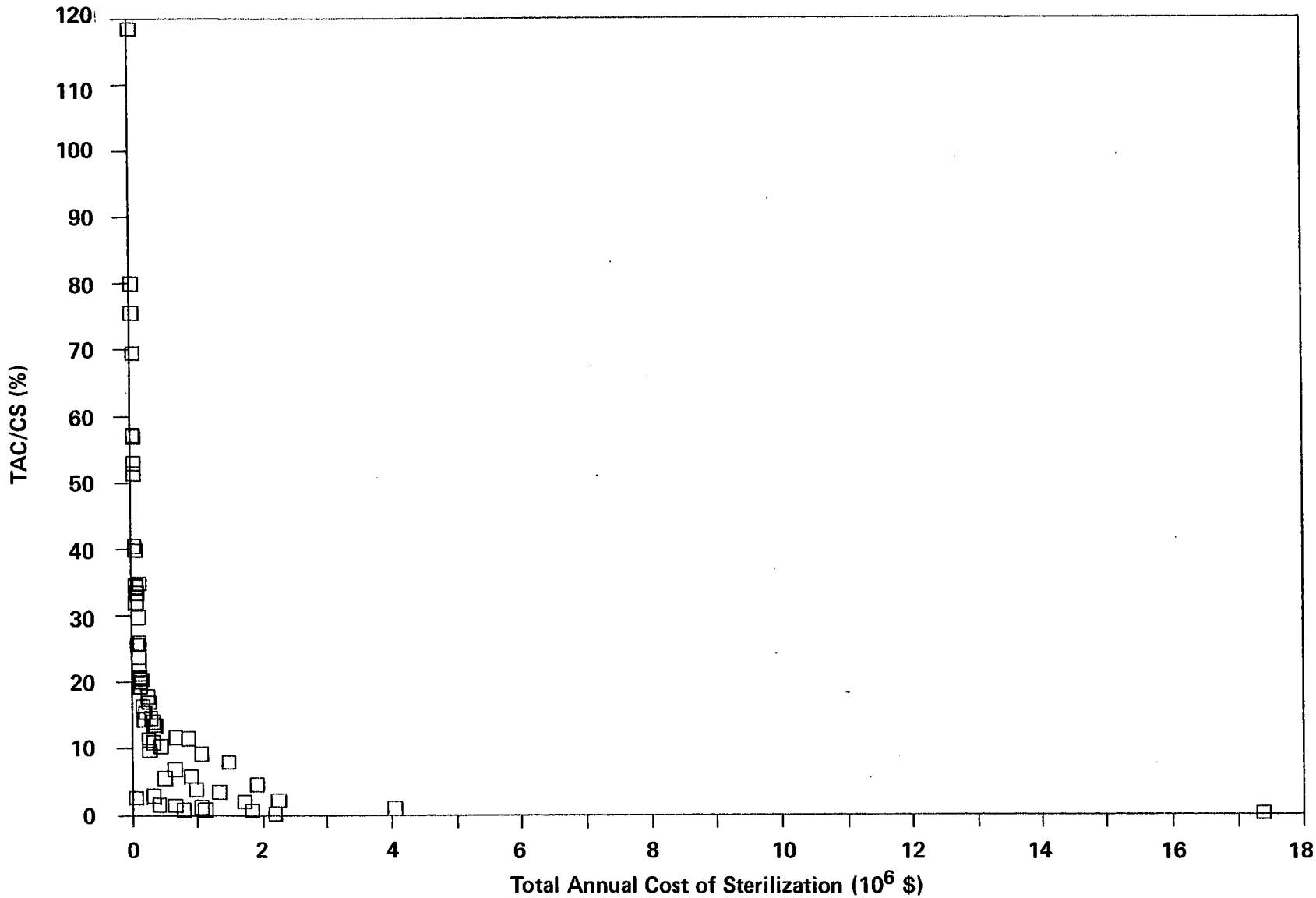

Figure 9-5. Scatter plot of TAC/CS and total annual cost of sterilization for medical equipment suppliers.

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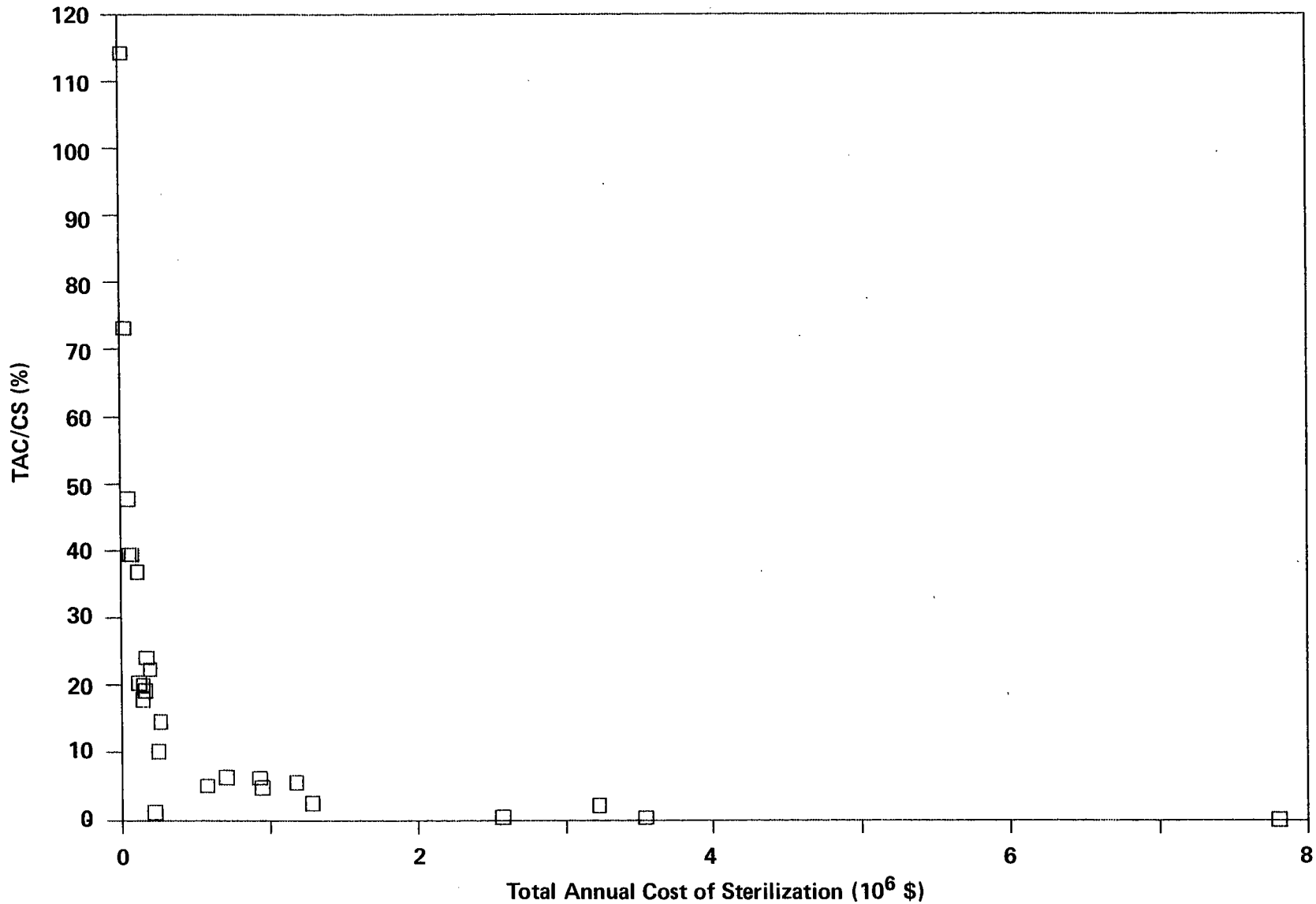

Figure 9-6. Scatter plot of TAC/CS and total annual cost of sterilization for other health-related suppliers.

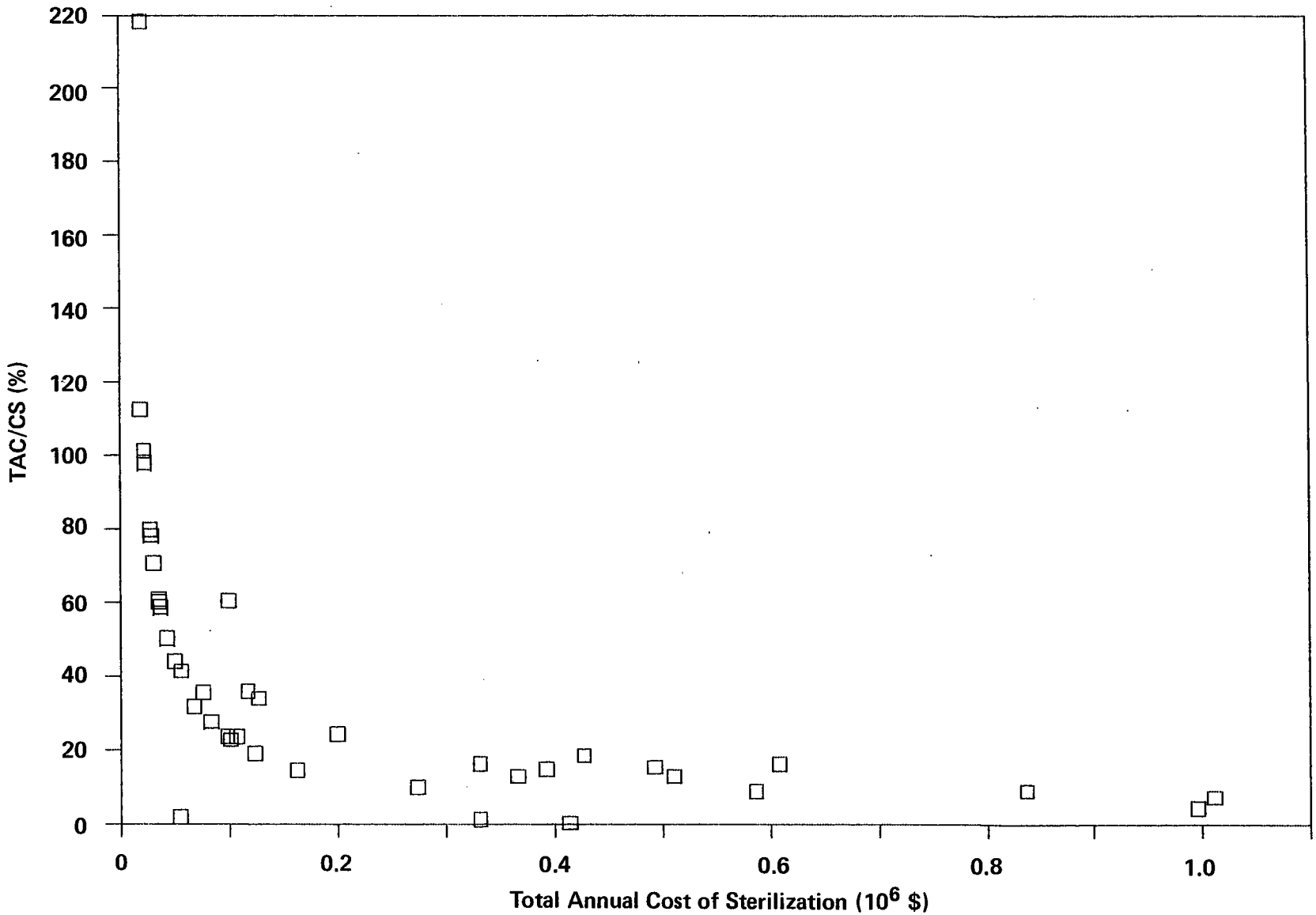

Figure 9-7. Scatter plot of TAC/CS and total annual cost of sterilization for pharmaceutical manufacturers.

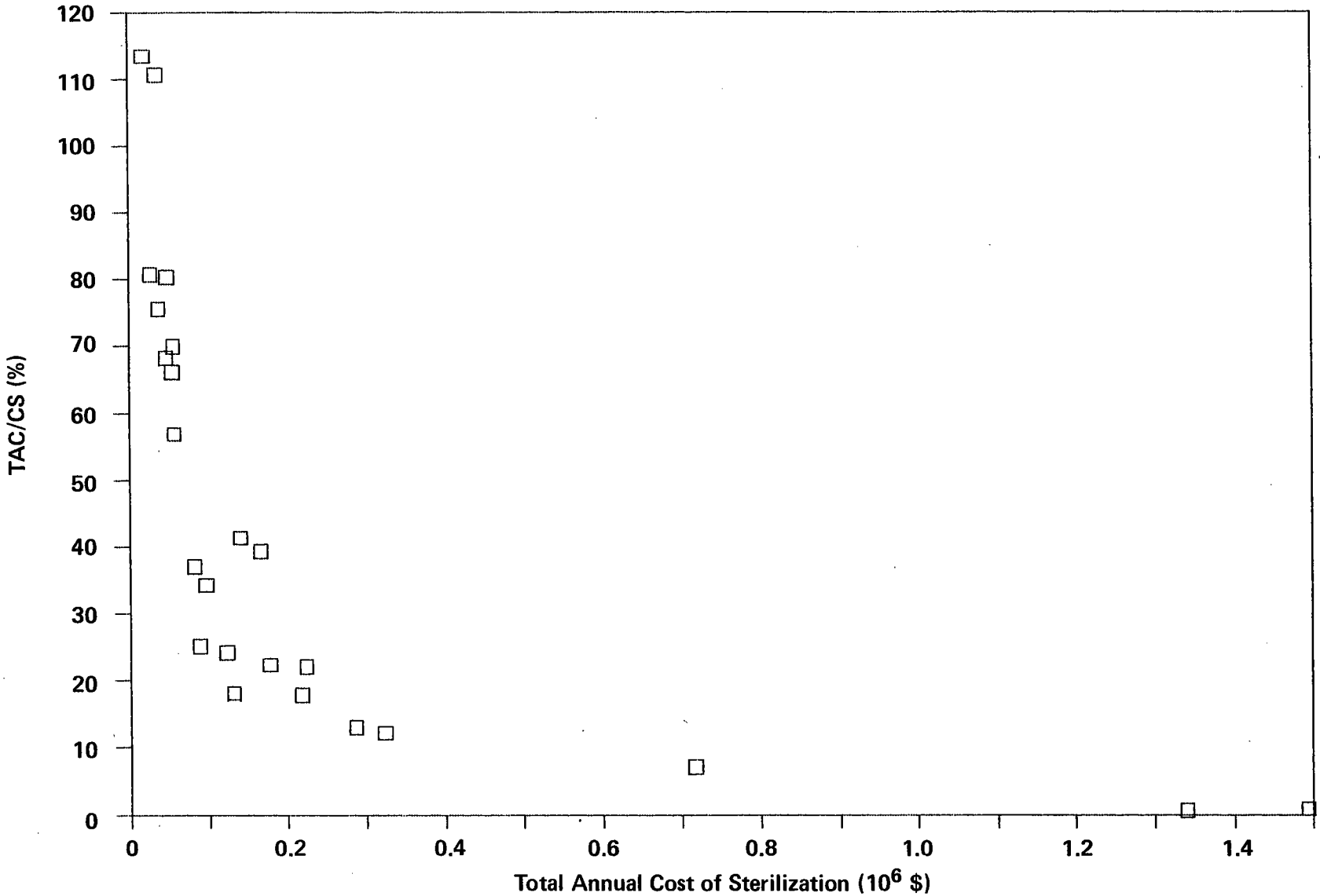

Figure 9-8. Scatter plot of TAC/CS and total annual cost of sterilization for spice manufacturers.

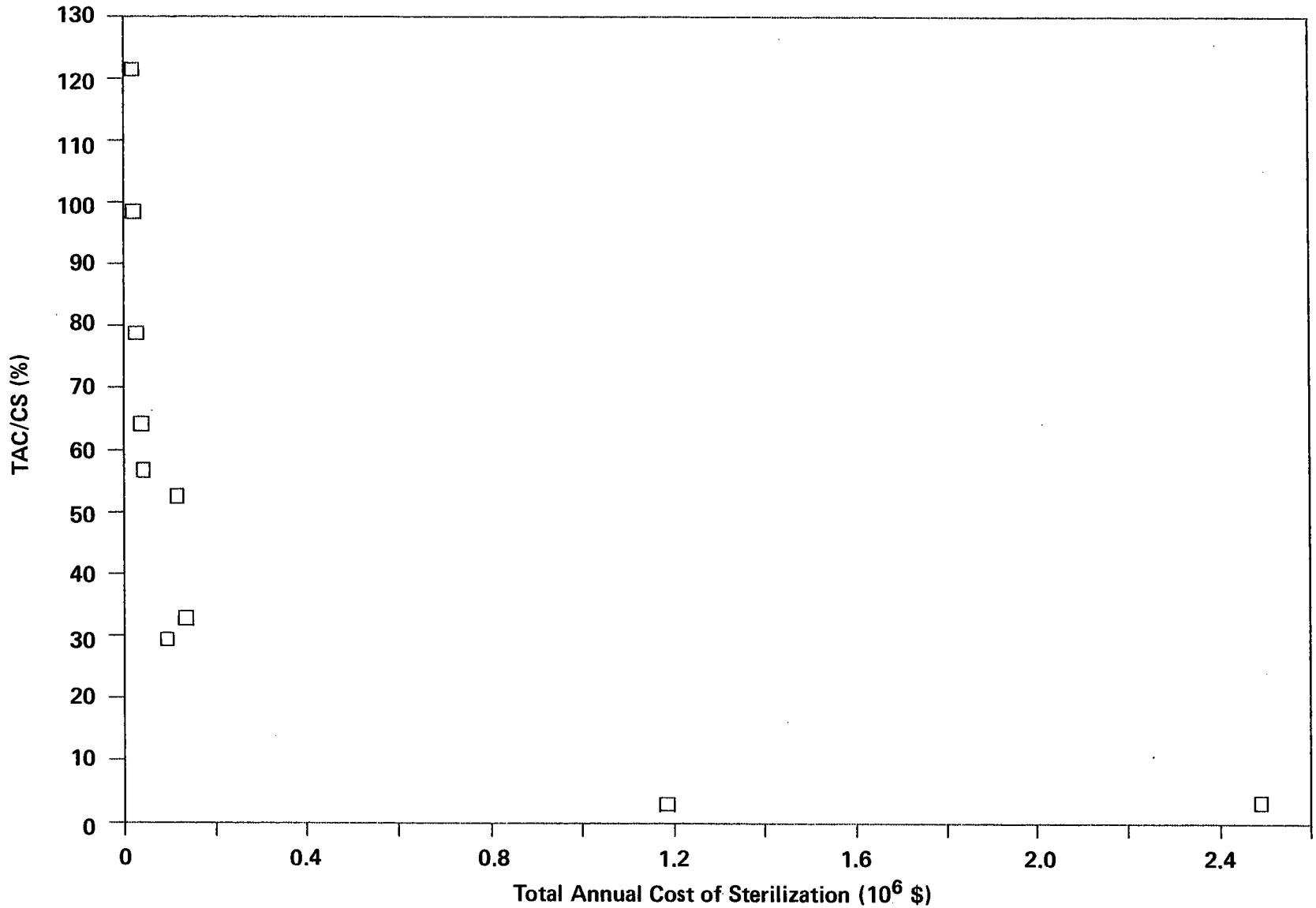

Figure 9-9. Scatter plot of TAC/CS and total annual cost of sterilization for laboratories.

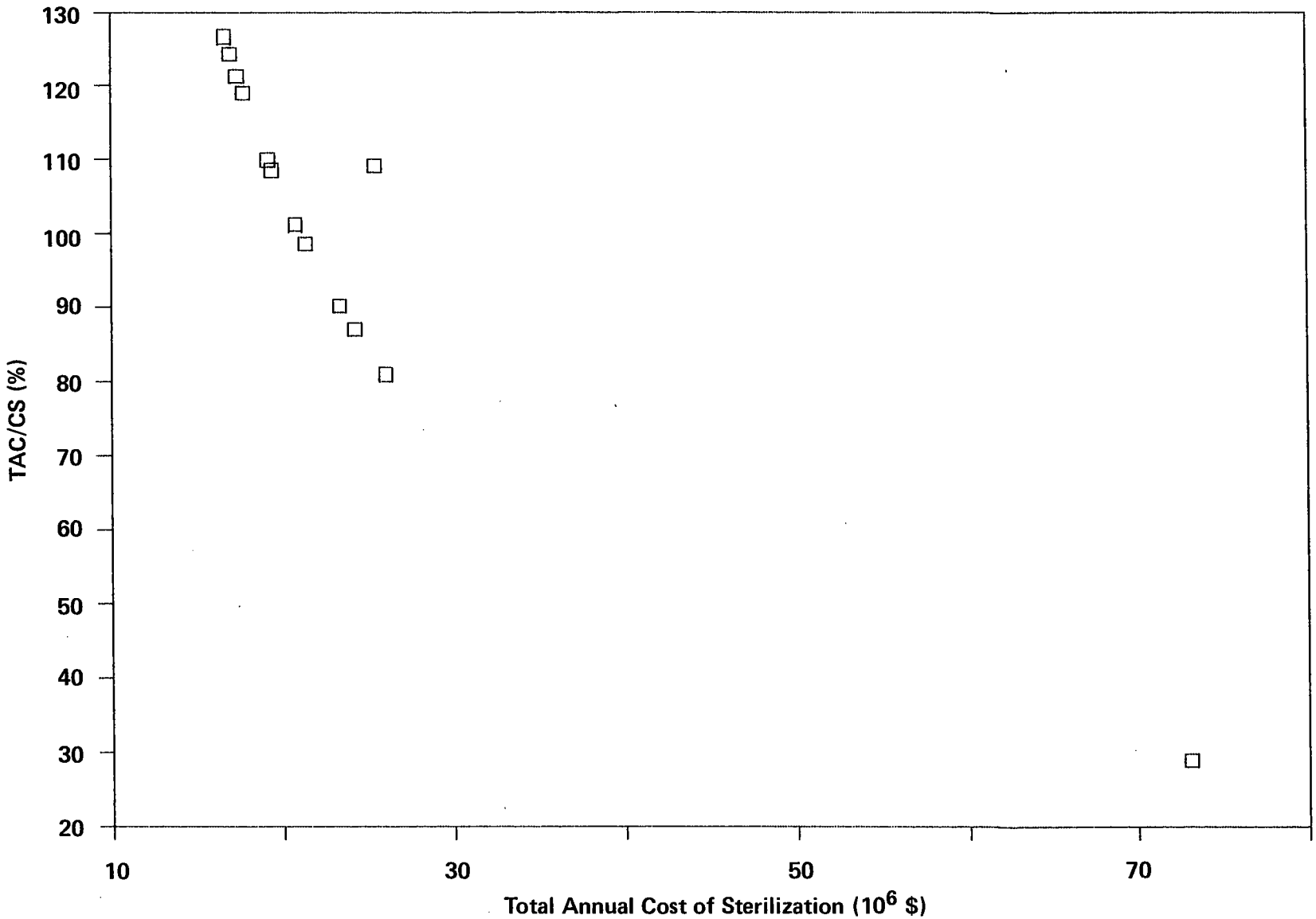

Figure 9-10. Scatter plot of TAC/CS and total annual cost of sterilization for museums and libraries.

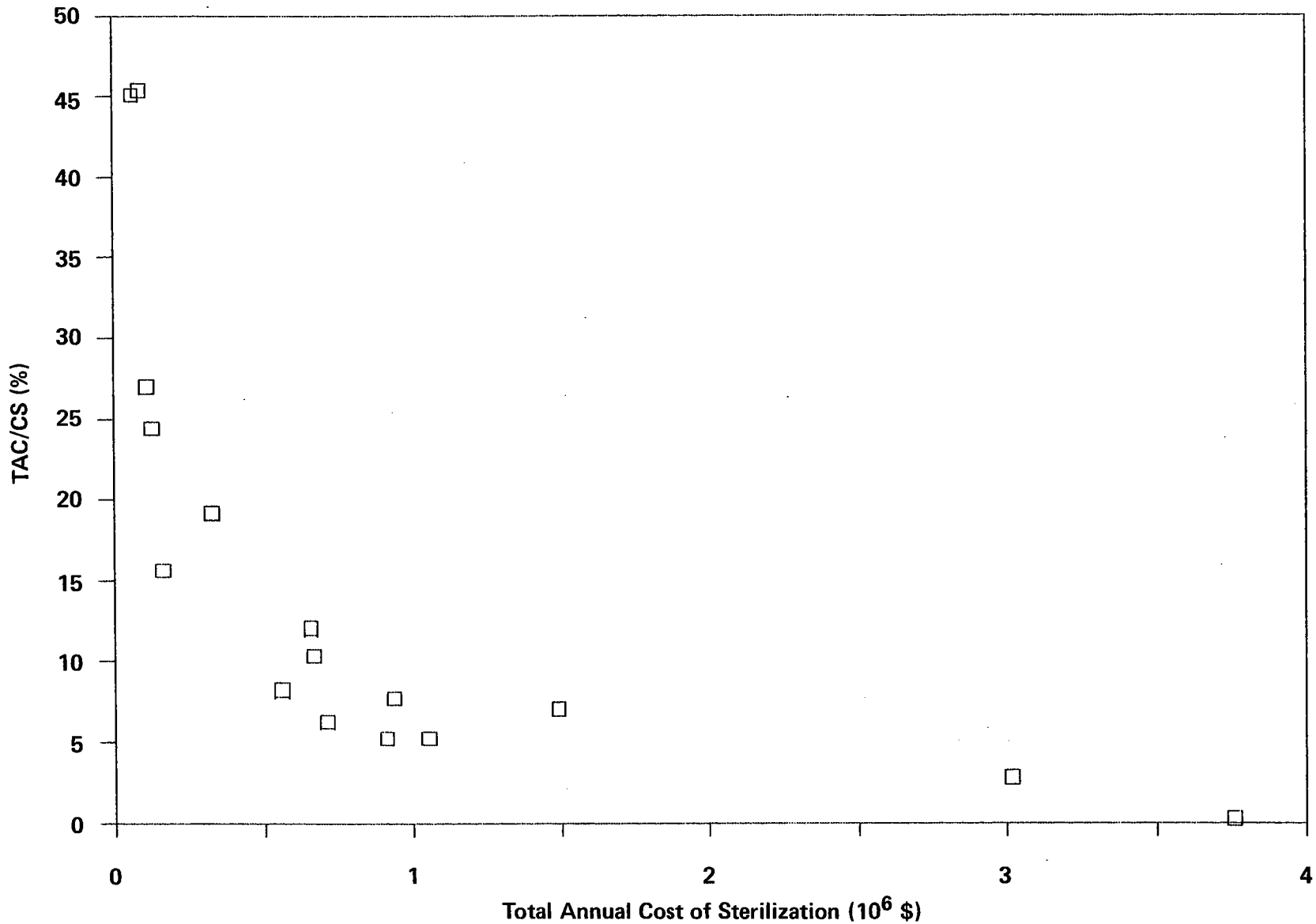

Figure 9-11. Scatter plot of TAC/CS and total annual cost of sterilization for contract sterilizers.

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TABLE 9-17. SELECTED SUMMARY STATISTICS ON THE TOTAL ANNUALIZED COST OF THE CANDIDATE NESHAP CONTROLS AS A PERFORMANCE OF FACILITY SALES, 1986[a,87]

Industry group	Median (%)	Range (%)
Medical equipment suppliers	0.11	<0.005 - 5.19
Other health-related suppliers	0.17	0.01 - 1.50
Pharmaceutical manufacturers	0.05	<0.005 - 10.1
Spice manufacturers	0.33	0.01 - 2.48
Museums and libraries[b]	4.22	0.23 - 12.9
Laboratories	0.27	0.01 - 4.94
Contract sterilizers	4.24	0.30 - 17.1

[a]Some facility sales figures were unavailable and were estimated using parent company sales or a regression of facility sales on EO use.

[b]Rather than facility sales, operating budgets were estimated for each facility in this group.

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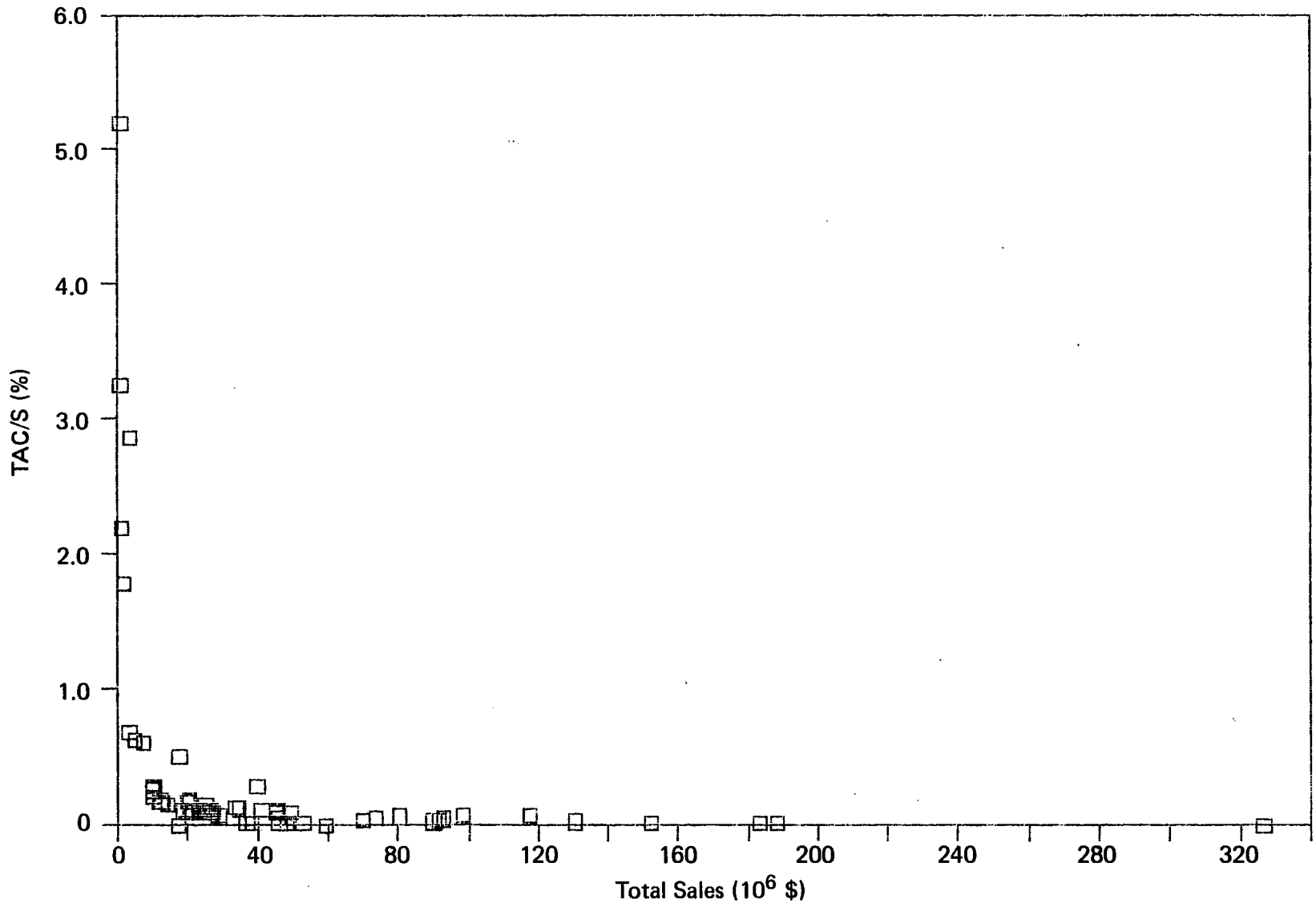

Figure 9-12. Scatter plot of TAC/S and total sales for medical equipment suppliers.

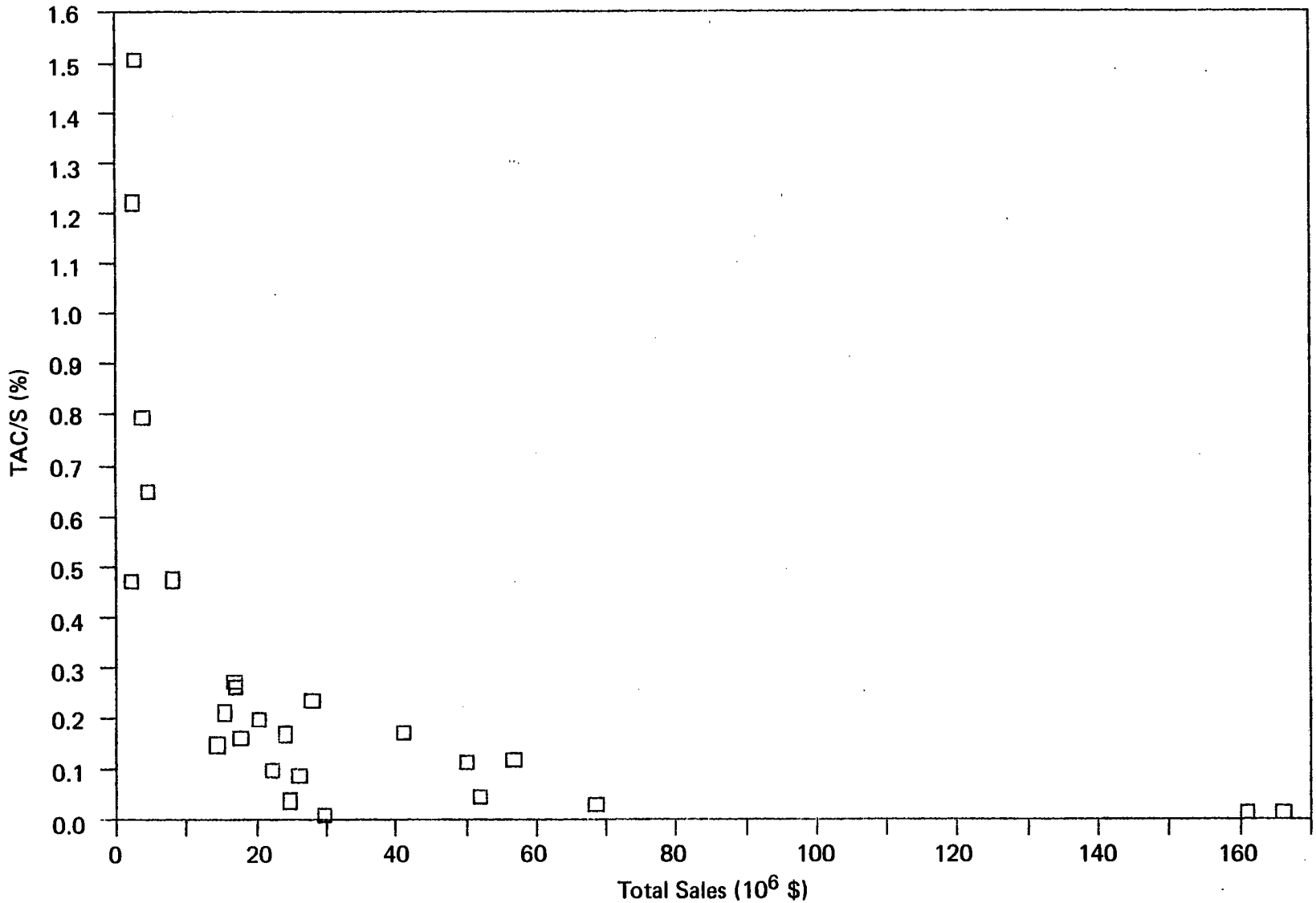

Figure 9-13. Scatter plot of TAC/S and total sales for other health-related suppliers.

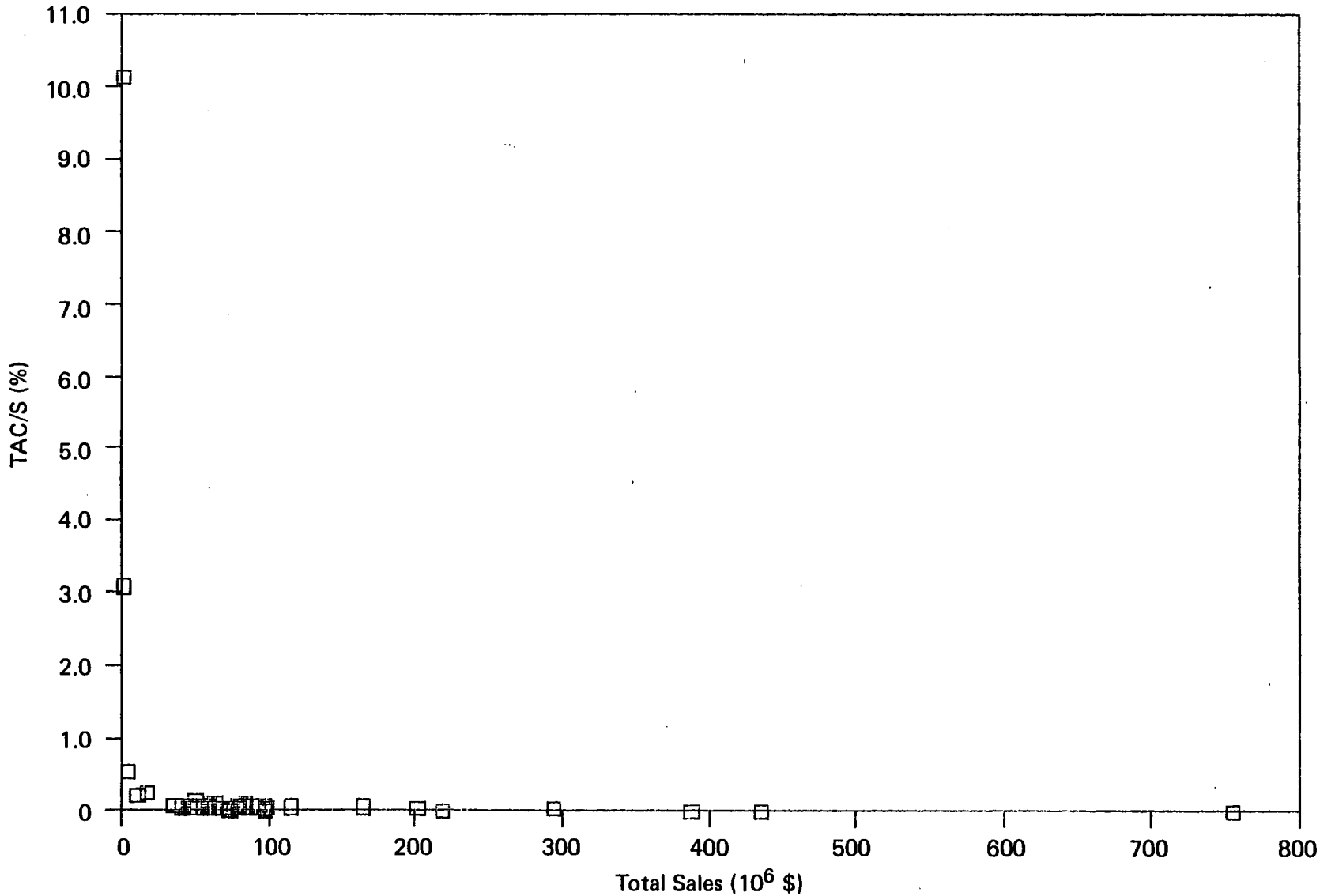

Figure 9-14. Scatter plot of TAC/S and total sales for pharmaceutical manufacturers.

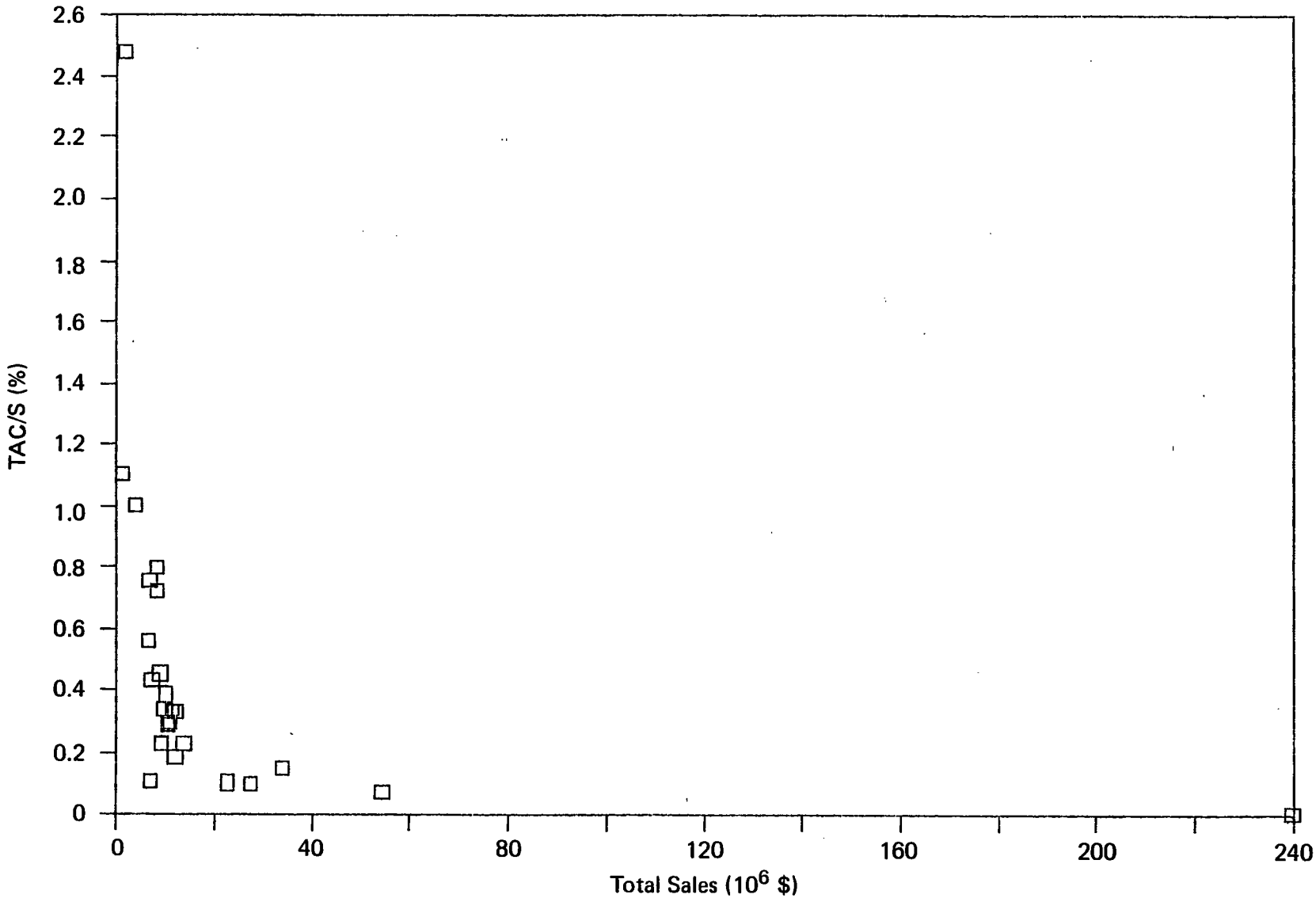

Figure 9-15. Scatter plot of TAC/S and total sales for spice manufacturers.

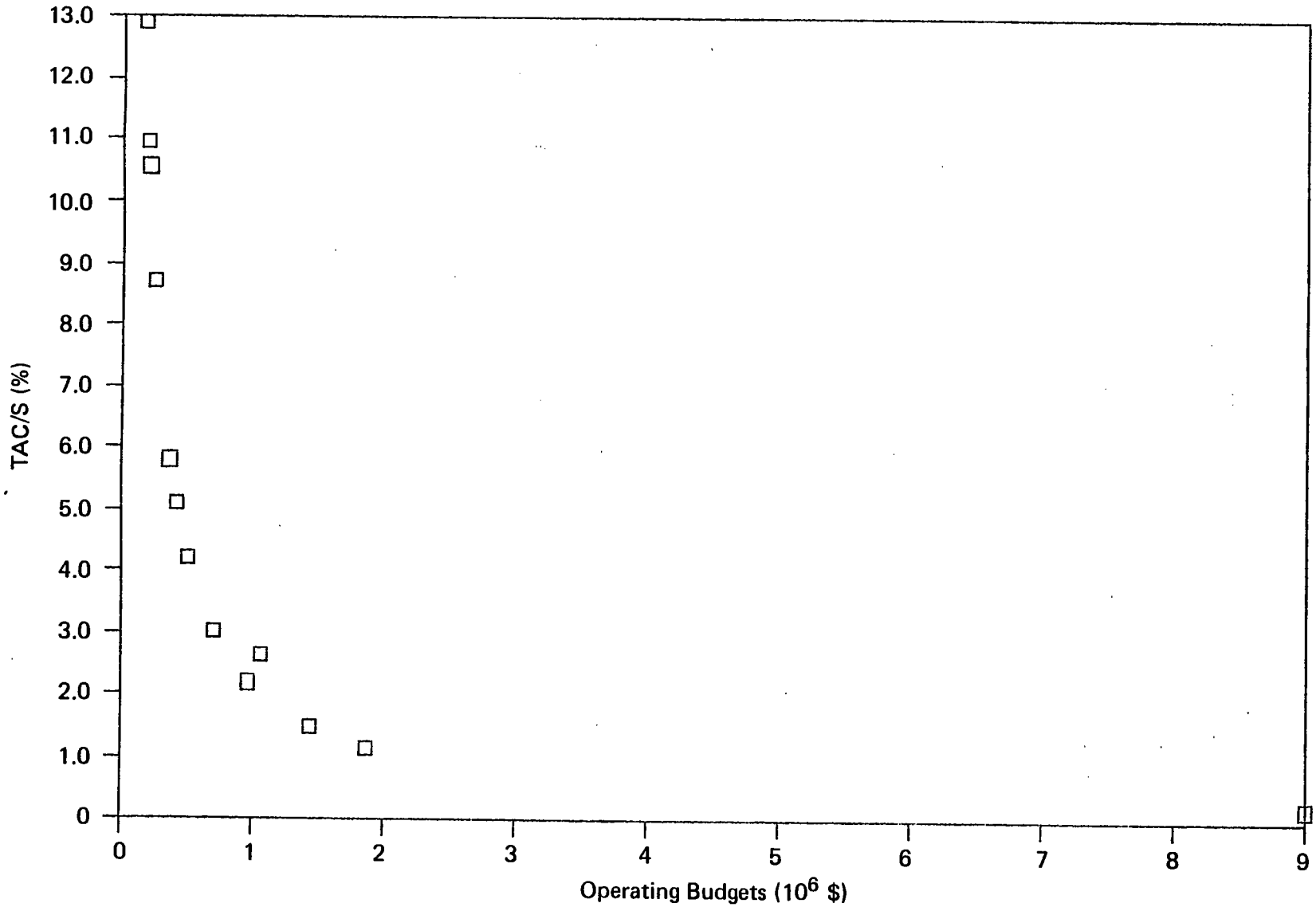

Figure 9-16. Scatter plot of TAC/S and operating budgets for museums and libraries.

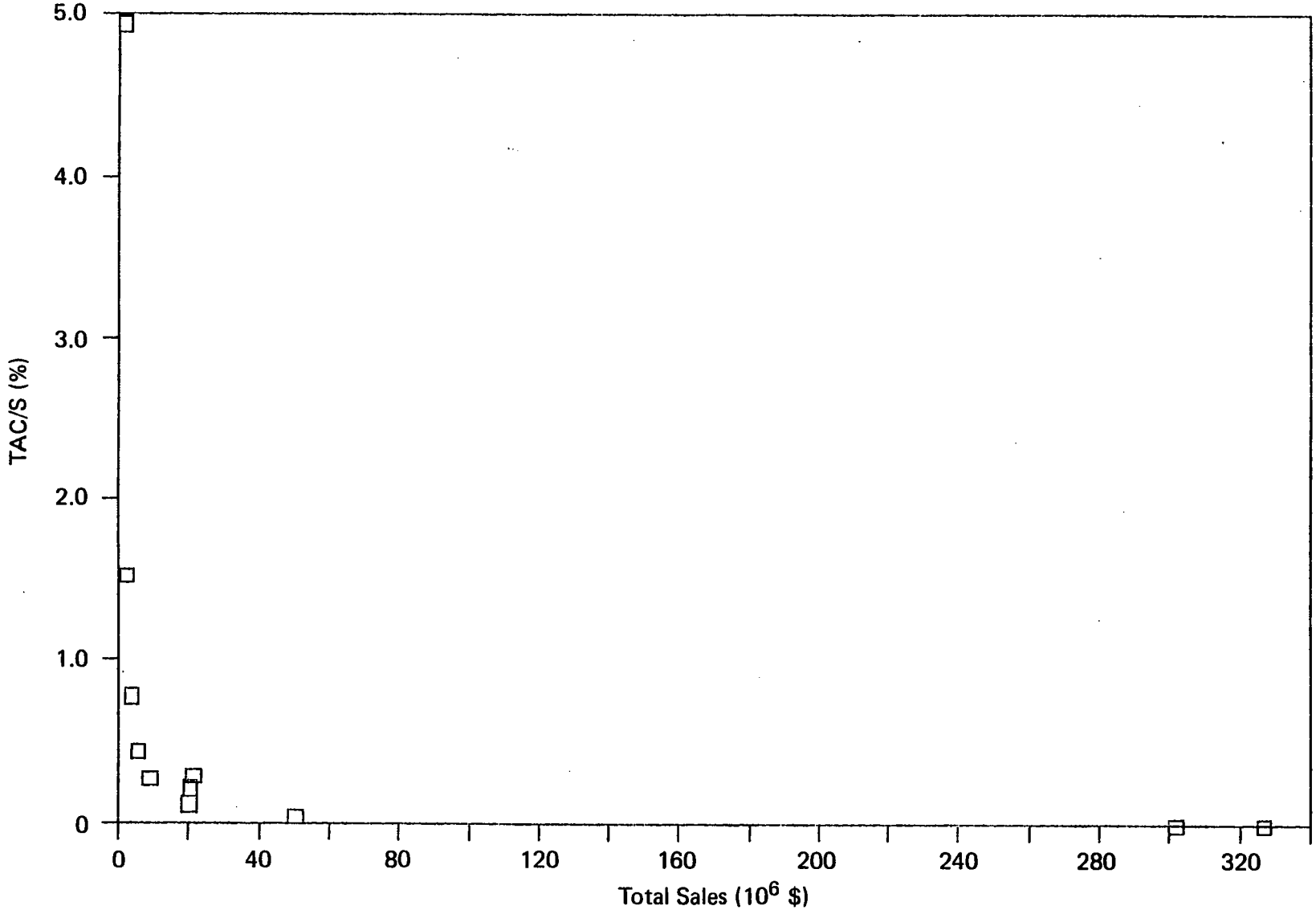

Figure 9-17. Scatter plot of TAC/S and total sales for laboratories.

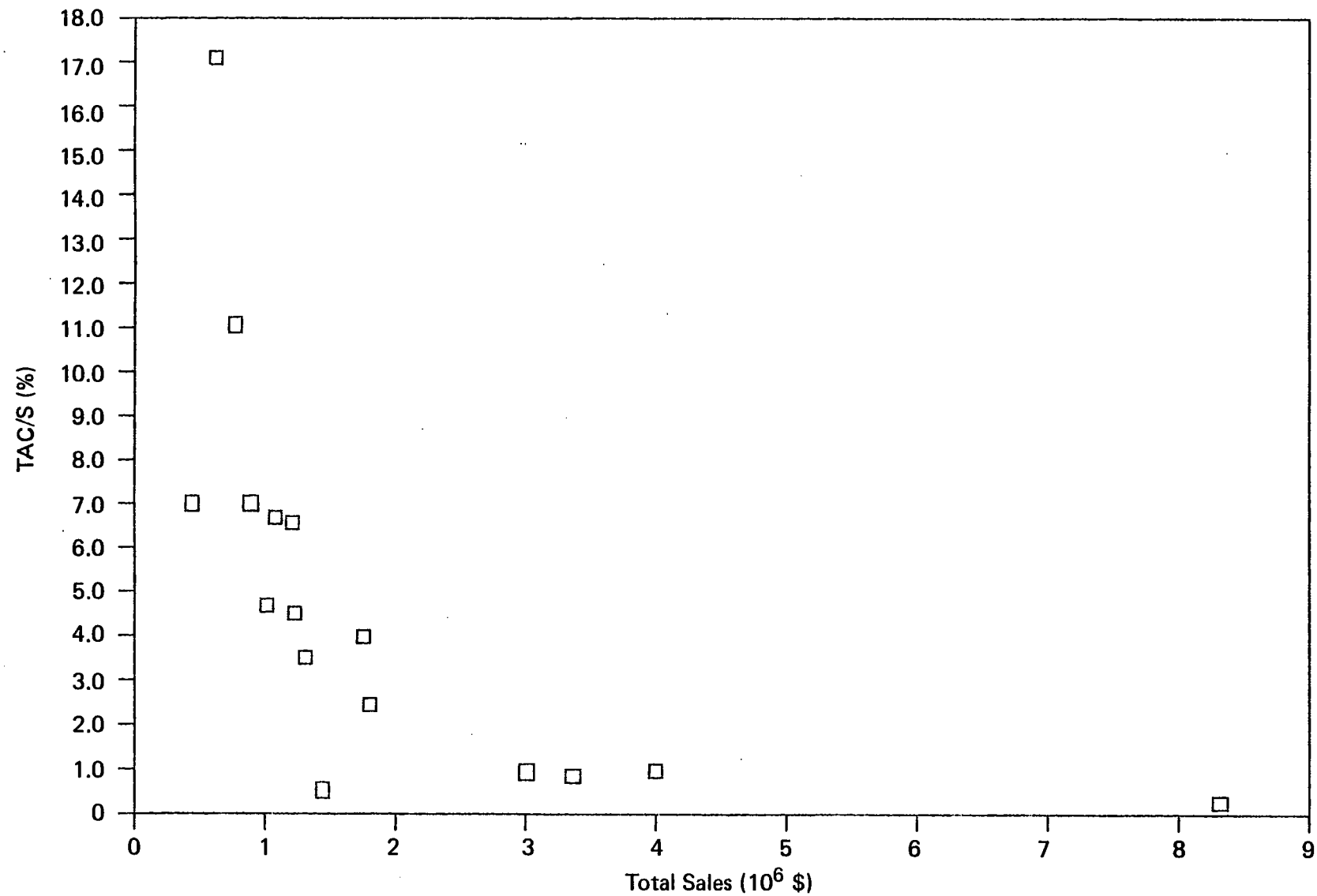

Figure 9-18. Scatter plot of TAC/S and total sales for contract sterilizers.

Furthermore, the TAC/S values indicate that the costs of the candidate NESHAP controls represent a significant percentage of the operating budget for many of the museums and libraries. To the extent that museums and libraries do not have ready access to capital markets, they may also have difficulty in getting the capital needed to acquire the relevant control devices.

Unlike the other industry groups, however, museums and libraries have a good substitute for EO. As discussed in Section 9.1, VIKANE performs all of the museum/library fumigation functions for which EO has been used and is comparable in price. Sterilization chambers may require some modification in order to use VIKANE, but the cost of this modification would probably be less than the cost of the candidate NEHSAP controls. It appears, therefore, that most museums and libraries would respond to the candidate NESHAP controls by substituting VIKANE for EO. Alternatively, some facilities in this group may discontinue fumigation altogether due to a lack of the capital necessary to switch to VIKANE or a perception that the value they receive from fumigation does not justify the additional cost of conversion to VIKANE.

The TAC/CV, TAC/EO, and TAC/CS values for the facilities in the laboratories group are relatively high, due to the below-average size of their sterilization chambers and relatively small quantity of EO they use. Nevertheless, the TAC/S values for the laboratories are low, which suggests that sterilization costs are a very small part of total production costs at these facilities. Although not knowing the precise figure, an animal-breeding laboratory indicated that sterilization costs are "surely less than 1 percent of total production cost."[88] Consequently, laboratories should absorb the costs of the candidate NESHAP controls without too much difficulty.

The median TAC/CS values for the medical equipment suppliers, other health-related suppliers, pharmaceutical manufacturers, and spice manufacturers range from 12.4 percent to 37.0 percent. Thus, the candidate NESHAP contorls will substantially increase sterilization costs in the industry groups. However, sterilization costs are generally very small relative to the total cost of producing sterilized products in these

industries. For example, a pharmaceutical manufacturer estimated that sterilization costs represent only about 3 percent of total production costs.[89] Consequently, we do not expect the candidate NESHAP controls to significantly increase production costs for medical equipment suppliers, other health-related suppliers, pharmaceutical manufacturers, and spice manufacturers. The very low TAC/S values for these industry groups support this expectation.

We expect that the candidate NESHAP will significantly affect many contract sterilizers. For the other industry groups in this study, sterilization is one of many steps in the production process. In contrast, sterilization is nearly the entire "product" for contract sterilizers.* Therefore, we expect the candidate NESHAP to cause a more pronounced increase in contract sterilizers' production costs. This is reflected in the relatively high median TAC/S (4.24%) for contract sterilizers.**

Despite the relatively large values for TAC/S among contract sterilizers, the candidate NESHAP will not necessarily have an adverse effect on contract sterilizers' business. Since contract sterilizers on average have larger chambers than the other industry groups and run more EO through them, the per-unit cost of the candidate NESHAP is less for contract sterilizers than for the other groups. This conclusion is supported by the data in Tables 9-14, 9-15, and 9-16, which indicate that contract sterilizers have the lowest median TAC/CV, TAC/EO, and TAC/CS of the seven industry groups. As explained in Appendix 9-A, the contract sterilizers' lower per-unit control costs may actually cause them to gain additional business as firms switch from in-house sterilization to contract sterilization.

Aside from the effects of the candidate NESHAP controls on the museums and libraries group and the contract sterilizers group, significant effects

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*As discussed in Section 9.1, many contract sterilizers perform some packaging, testing, and distribution services that are linked to their sterilization operations.

**As noted previously, one of the shortcomings of total sales is that it includes sales of sterilized and non-sterilized products. Since virtually all sales from contract sterilizers involve sterilized products, this shortcoming would tend to result in a higher TAC/S for these facilities than facilities in the other industry groups.

may occur at some individual facilities in the other five industry groups. In general, these are the facilities with the highest TAC/S values in Figures 9-12 through 9-18. Rather than incur the relatively high control costs, these facilities may switch to another sterilization process, switch from in-house to contract sterilization, or they may discontinue their production of sterilized products. Without further information on these facilities, we cannot predict which response might be chosen in each case.

9.2.4.2 Effects on New Facilities. Up to this point our analysis has been focused on the economic effects of the candidate NESHAP controls on existing facilities. Without data on possible control costs for new (as-yet-constructed) facilities in each industry group, we cannot make any quantitative estimates of the potential effects of the candidate NESHAP on these facilities. Nevertheless, we can reach some general conclusions on this matter based upon the information presented earlier in this chapter.

The apparent insignificance of control costs relative to total production costs for five of the seven industry groups suggest that the candidate NESHAP controls will have very little effect on investment decisions for new facilities in these five industry groups. Generally, emissions control costs for existing facilities are higher than the control costs for new facilities, because control equipment is usually more expensive to install once a facility is already built than it is as a part of the construction of new plants. Consequently, if the candidate NESHAP will have only minimal effects on existing facilities, it should not have much effect on new facilities.

As noted in the previous subsection, the candidate NESHAP controls may have a significant effect on the museums/libraries group and the contract sterilizers group. Thus, new facilities in these groups may be affected more than new facilities in the other five industry groups. In the case of museums and libraries, the candidate controls will probably cause new museums and libraries to use VIKANE as a sterilant, rather than EO. Since these two substances are comparable in price, it is unlikely that this substitution will have a significant adverse effect on decisions to invest in these new facilities.

As explained in Appendix 9-A, the likely substitution of contract sterilization for in-house sterilization attibutable to the candidate

NESHAP controls will increase the market share of the contract sterilizers group, and may even increase the quantity of goods sterilized by firms in this group. These substitution effects, in conjunction with the likelihood that new facilities will experience smaller costs from the candidate controls than existing facilities (as argued above), suggest that the NESHAP controls will not have important deleterious effects on new contract sterilization facilities.

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APPENDIX 9-A

SUBSTITUTION EFFECTS OF COMMERCIAL STERILIZATION NESHAP CONTROLS

This appendix utilizes a comparative statics approach to examine the potential substitution effects of the candidate NESHAP controls. Specifically, the analysis shows that a partial substitution of contract sterilization for in-house sterilization will likely occur if the candidate NESHAP controls are adopted.

In this analysis, "in-house" sterilization is the portion of total sterilization output that is performed onsite by firms as a part of the production process. All sterilization performed by medical equipment suppliers, other health-related suppliers, pharmaceutical manufacturers, spice manufacturers, museums and libraries, and laboratories is considered "in-house" sterilization. Contract sterilization is the portion of total sterilization output provided by facilities in the contract sterilizers group.

Figure A-1 shows sterilization supply curves for contract sterilization (S-C) and in-house sterilization (S-IH). These supply curves relate the marginal cost of sterilization to the quantity of goods sterilized per unit of time for contract sterilizers and in-house sterilizers, respectively. The upward slope indicates that the marginal cost of sterilization rises as facilities try to sterilize more goods.

The supply curve for contract sterilization (S-C) intersects the vertical axis at a higher value than the supply curve for in-house sterilization (S-IH). The distance between the two curves, AP*, represents the additional per-unit costs of contract sterilization over the cost of in-house sterilization. These additional costs include: the cost of transporting products to and from the contract sterilizer, the inventory cost of products while in-transit, the reliability and negotiation costs of dealing with an outside supplier, and the cost of products damaged or not properly

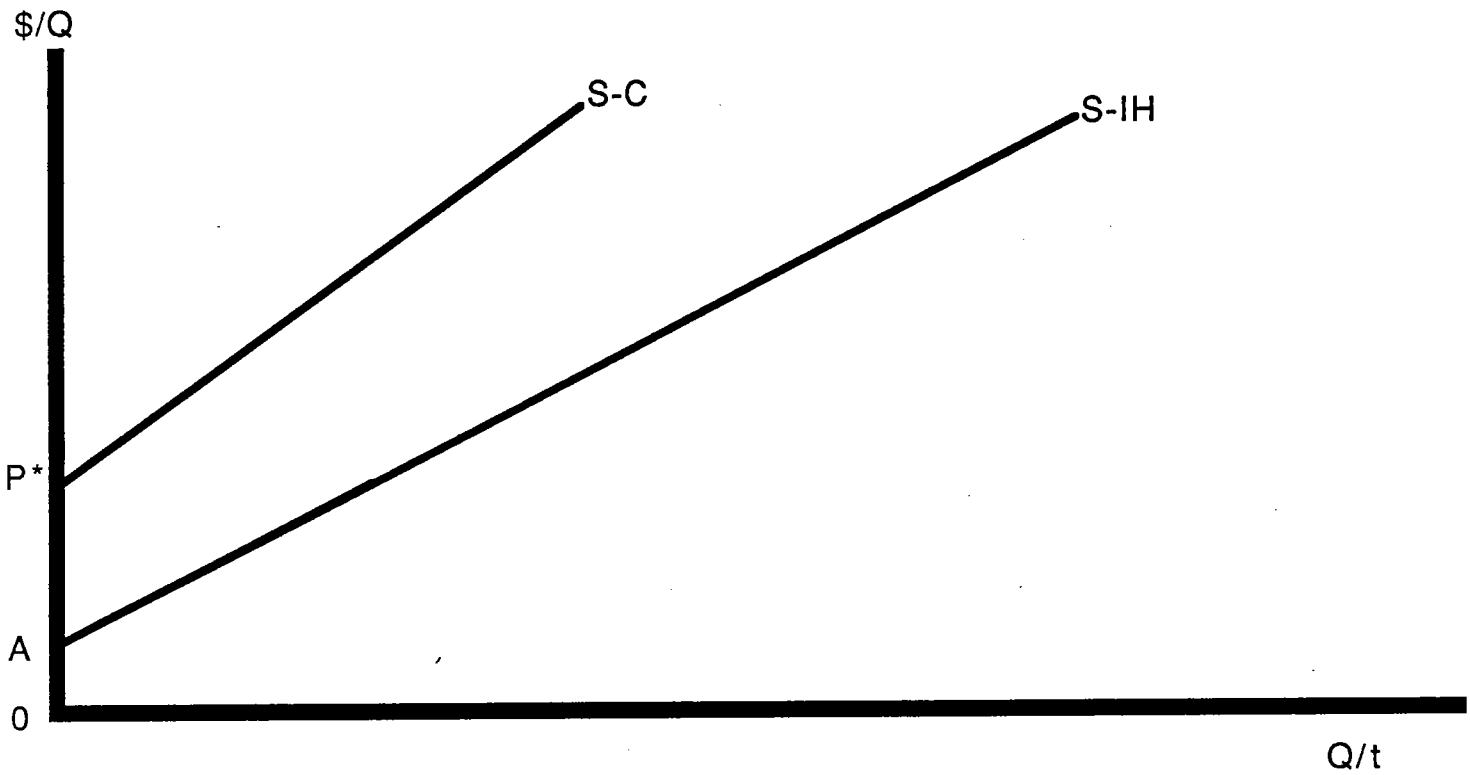

Figure A-1. Supply curves for contract sterilization (S-C) and in-house sterilization (S-IH).

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sterilized by the contract sterilizer. For simplicity, we refer to these additional costs as transportation costs.

As shown in Figure A-2, the market supply curve for sterilization (S-M) is the horizontal summation of the supply curves for contract and in-house sterilization (S-C and S-IH, respectively).* At all price levels below P*, the market supply curve equals the in-house supply curve. Below P*, no products are sterilized by contract sterilizers due to the transportation costs discussed above. At some arbitrary price, Po, contract sterilizers will sterilize quantity PoD, while in-house sterilizers will sterilize quantity PoE. Since contract sterilizers and in-house sterilizers constitute the entire sterilization market, the market quantity at price Po will be the sum of the quantities produced by the two groups, i.e., PoF.

In Figure A-3 we superimpose the derived demand for sterilization, DD-M, on the supply curves from Figure A-2. Market equilibrium occurs at price Po and quantity Q-M, the intersection of the market supply curve, S-M, and the market demand curve, DD-M. Contract and in-house sterilizers act as price takers, being unable to affect the market price, Po. The quantity of goods sterilized by contract or in-house sterilization (OQ-C or OQ-IH, respectively) is determined by the intersection of Po and the appropriate supply curve (Q-C for contract sterilization and Q-IH for in-house sterilization). In equilibrium, the marginal cost of contract sterilization, including transportation costs, will equal the marginal cost of in-house sterilization.

Figure A-4 illustrates the production cost increases that would be caused by the candidate NESHAP controls. Each supply curve would shift upward by the amount of the average total annualized cost (TAC) per unit of product sterilized. So S-C would shift upward to S-C', S-IH would shift upward to S-IH', and S-M would shift upward to S-M'. As shown in this figure, it is likely that the supply curve for contract sterilization would shift upward by a smaller amount than the shift in the supply curve for in-house sterilization. This may be attributed to a lower average TAC per unit of product sterilized for contract sterilizers due to economies of

*The S-C and S-IH curves are also horizontal summations of the supply curves of individual contract and in-house sterilizers, respectively.

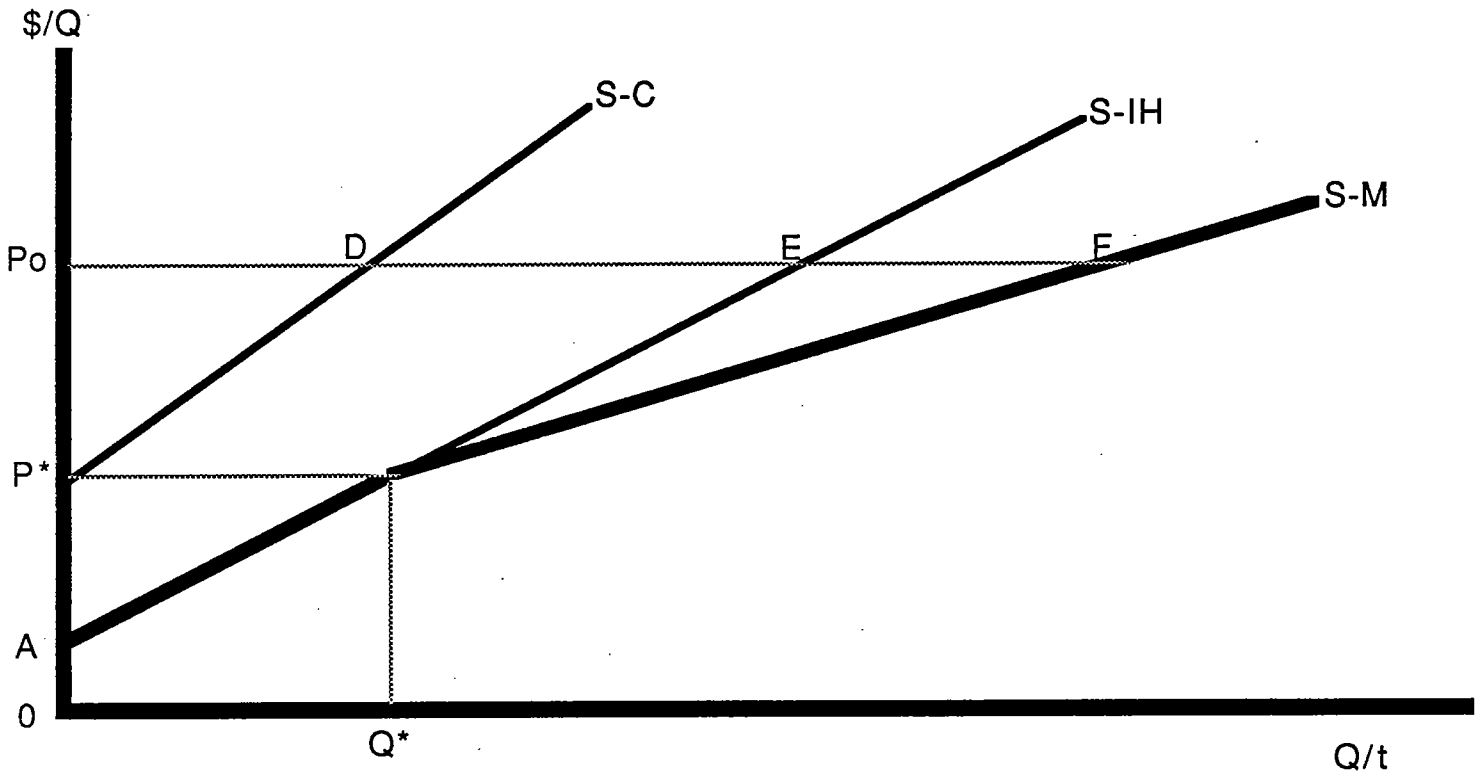

Figure A-2. The market supply curve for sterilization (S-M) as the aggregate of the supply curves for contract sterilization (S-C) and in-house sterilization (S-IH).

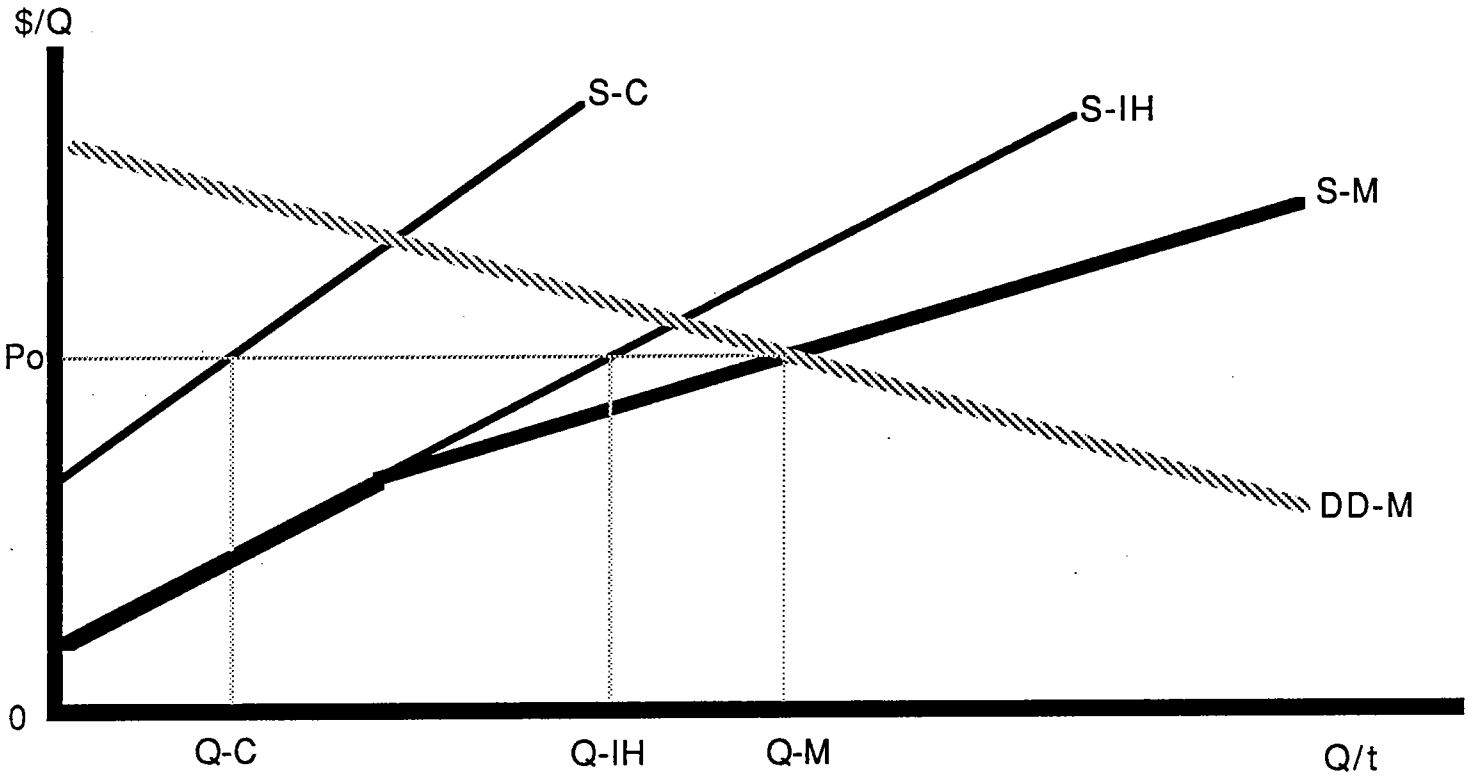

Figure A-3. Supply and demand curves for sterilization services, and the allocation of the equilibrium quantity of sterilization (Q-M) among contract sterilization (Q-C) and in-house sterilization (Q-IH).

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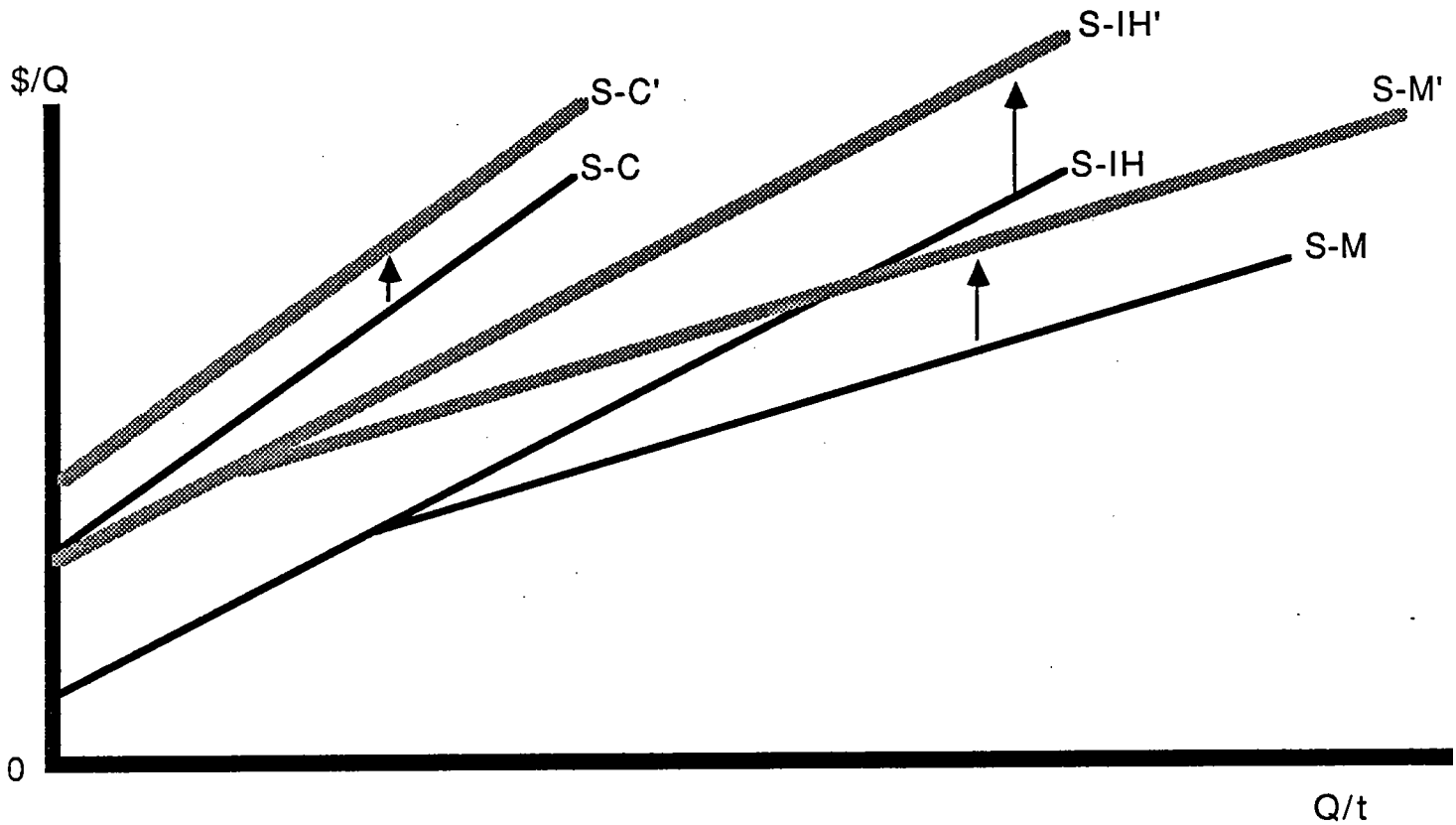

Figure A-4. Supply curves for sterilization services with and without ethylene oxide emissions controls.

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scale in compliance. A smaller shift in S-C than S-IH is supported by the data in Tables 9-15 and 9-16, which show that contract sterilizers have the lowest mean TAC per kilogram of EO used, and lowest TAC per dollar of annual sterlization cost.

In Figure A-5 we superimpose the derived demand curve, DD-M, on the supply curves from Figure A-4. As before, the market equilibrium without the NESHAP controls occurs at price Po and quantity Q-M; in-house sterilizers sterilize quantity Q-IH and contract sterilizers sterilize quantity Q-C. The adoption of the NESHAP controls causes the supply curves to shift upward to S-C', S-IH' and S-M'. The new market equilibrium occurs at a higher price, P', and a lower quantity, Q-M'. At the new price, in-house sterilizers sterilize a lower quantity, Q-IH', and contract sterilizers sterilize a higher quantity, Q-C'.

The absolute increase in contract sterilizers' quantity may or may not occur, depending on the actual positions and shapes of the supply and demand curves in Figure A-5. However, the contract sterilizers' share of total market quantity will definitely increase, due to their lower average TAC per unit of goods sterilized. The market price of sterilization will rise, unless DD-M is horizontal (i.e., perfectly elastic). The market quantity of sterilization will decrease unless the DD-M curve is vertical (i.e., perfectly inelastic). And finally, the quantity of in-house sterilization will decrease.

In summary, the adoption of the candidate NESHAP controls should cause some substitution of contract sterilization for in-house sterilization. So even though the candidate controls will increase the cost of sterilization for contract sterilizers, their market share of total sterilization will increase. Additionally, their total quantity may actually increase, rather than decrease, under certain circumstances regarding the demand and supply relationships in the sterilization market.

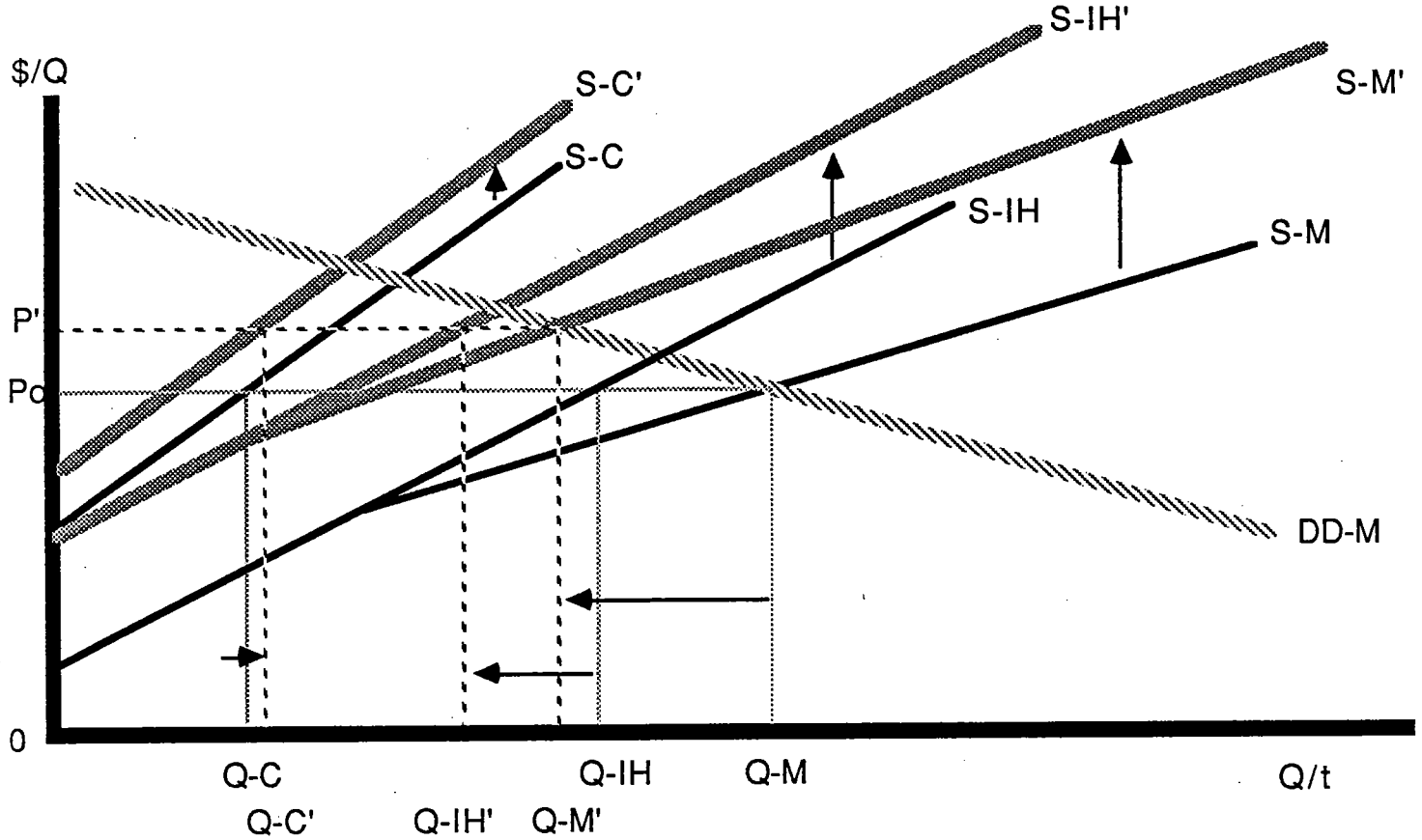

Figure A-5. Market equilibrium and allocation of sterilization services with and without ethylene exide emission controls.

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ETHYLENE OXIDE CONTROL TECHNOLOGY DEVELOPMENT FOR HOSPITAL STERILIZERS

FINAL REPORT

EPA Contract No. 68-02-3999
Work Assignments 2/005 and 2/010

MRI Project Nos. 8691-L and 8692-K

March 2, 1988

For

Air and Energy Engineering Research Laboratory
U.S. Environmental Protection Agency
Research Triangle Park, North Carolina 27711

Attn: Mr. Charles H. Darvin

PREFACE

Midwest Research Institute (MRI) is pleased to submit this draft final report to the U.S. Environmental Protection Agency, Air and Energy Engineering Research Laboratory. It was prepared under Contract No. 68-02-3999, Work Assignments 2/005 and 2/010.

The work reported consisted of two phases, Phase I was a review of potential control technologies for hospital sterilizers and Phase II involved actual testing of selected technologies identified in Phase I. Dr. Alfred F. Meiners was project leader for Phases I and II and coordinated the preparation of this report. Mr. Bill Moody and Mr. Bruce Nicholson were major contributors to Phase I. Dr. George Scheil directed the analytical studies of Phase II, assisted by Ms. Laurie Cone and Ms. Dannette Shaw. Mr. Bruce Nicholson was also a major contributor to Phase II, and had primary responsibility for the process cost estimates. Mr. Fred Bergman and Mr. Paul Gorman were major contributors to the design of the Phase II studies. Mr. Dennis Hooton and Ms. Carol Green were responsible for the quality assurance aspects of Phase II.

Approved for:

MIDWEST RESEARCH INSTITUTE

for

Clayten Cowherd, Director
Environmental Systems Department

March 2, 1988

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SECTION 1.0

INTRODUCTION

Ethylene oxide (EO) has been identified as a major toxic air pollutant. The Office of Air Quality Planning and Standards (OAQPS) designated EO as an Intent to List Compound in the Federal Register in early 1986. One of the major uncontrolled sources of EO emissions is hospital and clinic sterilizers. Over 400 Mg/year are estimated to be released to the atmosphere each year from these sources.

AEERL was requested by OAQPS to assist in the identification, development, and evaluation of viable control options for EO emissions from medical facility equipment. Phase I of this project (Work Assignment 5) identified three potential devices for the control of EO emissions from hospital and clinical sources. Phase II of this program (Work Assignment 10) involved tests of selected technologies identified in Phase I.

SECTION 2.0

SUMMARY

Phase I of this study involved a review of control requirements and potential control technologies for hospital sterilizers. Phase II involved actual testing of selected technologies identified in Phase I. This report describes the work accomplished during both Phase I and Phase II.

2.1 PHASE I - POTENTIAL SYSTEMS FOR THE CONTROL OF ETHYLENE OXIDE EMISSIONS FROM HOSPITAL AND CLINICAL SOURCES

2.1.1 Review of Hospital Sterilizers

Almost all hospitals sterilize heat-sensitive items in gas sterilizers which use a mixture of ethylene oxide (EO) and a chlorofluorocarbon (CFC), dichlorodifluoromethane. The active sterilizing agent is EO. The CFC is a flame-proofing diluent. This mixture, which is 12% by weight EO and 88% by weight CFC, is referred to as 12/88.

Hospital sterilizers are essentially enclosed chambers which can be pressurized with 12/88 to sterilize medical equipment. At the conclusion of the sterilization phase, the chamber is evacuated using a vacuum pump and brought to atmospheric pressure by introducing clean, filtered air. The combination of evacuation and air flushes is repeated. After the last air wash, the chamber door is opened, and the sterile products are removed and placed in an aeration cabinet. The purpose of aeration is to allow any residual EO to diffuse out of the sterilized articles.

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2.1.2 Ethylene Oxide Emissions

In the absence of control systems, EO emissions come primarily from four sources, the chamber vacuum pump (75-95% of the total emission), the aeration cabinet (5-25%), the sterilizer door area (varies widely), and the EO storage tanks (from accidental leaks). If the vacuum pump is a once-through, water-sealed pump, substantial quantities of EO (60-80% of the total emission) can be discharged to the sewer in the vacuum pump water.

2.1.3 Potential Control Technologies

The chemical reactions of EO and dichlorodifluoromethane were reviewed to evaluate sterilizer emission control options. Catalytic oxidation and acid hydrolysis were shown to be especially suitable. The following selection criteria were developed for EO control technology options (in order of priority): (1) cost, (2) effectiveness and environmental safety, (3) state of development, (4) complexity, (5) space requirements, and (6) safety.

Nine potential control options were examined. Six options were eliminated for the following reasons: carbon adsorption (high operating cost), thermal incineration (toxic by-product), condensation (explosion hazard), ozonation (high cost), corona discharge (toxic by-product), and ultraviolet photolysis (toxic by-product).

2.1.3.1 Catalytic Oxidation--

A control system has been developed in which relatively dilute mixtures of air and EO (12/88) are passed through a catalyst bed at 300°-350°F. The EO is oxidized to carbon dioxide and water; the CFC passes through unchanged. The system is characterized by relatively high flow rates (500-1,000 cfm) and relatively dilute concentrations of EO (5-500 ppm). The system is designed to treat EO emissions in the sterilizer exhaust and those in the ventilation air from the aeration cabinets and other areas. The system has had 2 years of apparently trouble-free operation at a hospital in Philadelphia. The unit is claimed to be 99.9% efficient in controlling EO.

2.1.3.2 Acid Hydrolysis--

Another control system has been developed which consists of a countercurrent packed column in which EO (in 12/88) is hydrolyzed to ethylene glycol using sulfuric acid at pH 1 (the CFC is unaffected). The system is characterized by relatively high concentrations of EO (250,000 ppm) and very low and highly variable flow rates (0.1-5 cfm). Many industrial-sized units have been installed, and test data on these units show that they are 99+% efficient.[1,2] A hospital system was installed in March 1987. Another type of acid hydrolysis system has been developed in which EO is bubbled through diffusers into aqueous sulfuric acid. A unit of this kind has been designed for hospitals and is claimed to be 99.2% efficient.

2.1.3.3 Adsorption/Reaction--

Some exploratory work has been done on a proprietary process which uses a combination of adsorption and reaction. The process is in the developmental stage and is not ready for full-scale application.

2.2 PHASE II - EVALUATION OF ETHYLENE OXIDE CONTROL TECHNOLOGY FOR HOSPITAL STERILIZERS

Two potential control technologies, catalytic oxidation and acid hydrolysis were selected for testing. Both systems demonstrated very high efficiencies (99+%) in destroying EO emissions discharged from hospital sterilizers. However, only the catalytic oxidation system can treat EO emissions from hospital aerators, which typically account for 5-10% of all EO emitted.

2.2.1 Field Tests of Catalytic Oxidation System

Field tests were performed to measure the EO destruction efficiency of a catalytic oxidation system which had been installed in a hospital. This system handled emissions from the sterilizer vacuum pump, an aeration cabinet, the sterilizer door area, and the EO storage tank area. Two types of experiments were performed; one type involved the treatment of the sterilizer discharge, and in another type, sterilizer gas was added directly to the system.

In the sterilizer discharge experiments, the observed EO destruction efficiency was high, greater than 99%. As expected for this type of system, the concentration of EO entering the catalyst system varied widely, reaching a maximum of 400-450 ppm. Flow rates were about 500 cfm.

In the sterilizer discharge experiments, only about 10-13% of the EO in the sterilizer actually reached the catalyst system. A major fraction of the EO was absorbed by the water which was used in the once-through, water-sealed vacuum pump. Analysis of the aqueous discharge indicated that an unexpectedly large proportion of the EO in the sterilizer (61-78%) was discharged to the sewer in the water from the vacuum pump.

Additional experiments were performed in order to supplement the analytical data obtained during sterilizer discharge. EO was added (at a controlled rate) to the system at a point located upstream from the catalyst. Sufficient EO was added to bring the concentration of the stream to selected levels of EO. Three levels, 125-250 ppm, 400-600 ppm, and 750-1,500 ppm were tested. The results of these experiments indicated high catalyst efficiencies, 99.8% or better.

An important significance of the EO addition experiments is that they demonstrated that the catalytic oxidation system was capable of operating very efficiently at concentrations of sterilizer gases comparable to those developed if the total discharge from the sterilizer were directed into the system.

All of the tests were performed using the common sterilizing gas mixture (12/88) which is 12% ethylene oxide and 88% chlorofluorocarbon (dichlorodifluoromethane). Separate tests demonstrated that there was no detectable decomposition of the chlorofluorocarbon under the conditions of the catalytic oxidation.

2.2.2 Laboratory Tests of Acid-Hydrolysis System

A full-scale acid-hydrolysis system was tested under laboratory conditions which closely simulated a system that could be used for hospital sterilizers. This system handled only the discharge from the vacuum pump, and was not designed to handle aeration discharges or other airflows containing low concentrations of EO. The tests demonstrated that the system was very efficient, destroying 99.99-99.999% of the EO.

Four tests involved actual discharges from a hospital-type sterilizer and three tests involved the direct addition of EO (12/88). In the sterilizer discharge studies, only about 25-26% of the EO in the sterilizer was observed to reach the system. Evidence indicated that a major fraction of the EO was absorbed by the ethylene glycol used in the closed-circuit, liquid-ring vacuum pump, thus reducing the amount of EO reaching the system. The concentrations of EO reaching the system were 20,000-140,000 ppm (2-14%) and the flow rates were 0.1-1.5 scfm.

Of the EO reaching the system, more than 99.99% was removed from the gaseous stream.

Ethylene oxide (12/88) was also added directly to the system in order to determine efficiencies at levels of flow rate near the maximum for which the system was designed (2.5 cfm). These studies also demonstrated the high efficiency of the hydrolysis system, greater than 99.999%.

2.2.3 Cost Effectiveness

Estimated costs for the two potential control technologies, catalytic oxidation and acid hydrolysis are as follows:

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	Catalytic Oxidation	Acid Hydrolysis
Capital costs		
Equipment	$25,000-$40,000	$15,000-$20,000
Installation	$ 5,000-$10,000	$ 4,000-$ 6,000
Total equipment cost	$30,000-$50,000	$19,000-$26,000
Annual operating cost	$ 5,700-$16,000	$ 600-$ 6,000

In considering the relative costs of these systems, the advantages and limitations of each should be considered. The catalytic oxidation system is capable of treating all of the gaseous EO emissions from the sterilizer vacuum pump, the aeration cabinets, the sterilizer door area, the EO storage tanks, and any other areas that can be ventilated. However, there are other EO emission problems related to the relatively large amounts of EO (60-80% of sterilizer charge) which can be lost to the environment through the aqueous discharge from once-through, water-sealed vacuum pumps. Recirculating vacuum pumps may prevent this emission, but most hospital sterilizers are apparently not currently equipped with recirculating vacuum pumps. (Installation of recirculating vacuum pumps will result in costs nearer the high side of the above capital cost estimates.) Furthermore, even with recirculating vacuum pumps, the substantial absorption of EO into the recirculating fluid produces a potential emissions problem.

The present acid-hydrolysis system can only treat the direct discharge from the sterilizer (through the vacuum pump). EO emissions from the aeration cabinets, sterilizer door area, and other dilute emissions could probably not be handled efficiently by the acid-hydrolysis systems. Recirculating vacuum pumps would ordinarily be used with acid hydrolysis systems; this would eliminate an immediate discharge of EO-contaminated sealant liquid, but methods of disposing of the contaminated sealant liquid would need to be devised.

As Table 2-1 shows, the catalytic oxidation system has a greater overall EO destruction efficiency than the acid-hydrolysis system. This is primarily because the acid-hydrolysis system cannot treat discharges from the aeration chamber or other dilute sources.

TABLE 2-1. COMPARISON OF SYSTEM EFFICIENCIES

EO source	Approximate percentage of total EO emissions[a]	Emission reduction potential[b]	
		Catalytic oxidation (%)	Acid hydrolysis (%)
Sterilizer[c]	75-95	99.5+	99.9+
Aerator	5-25	99.5+	0.0
Sterilizer room ventilation air	< 1	99.5+	0.0
Total reduction potential		99.5+	75-95

a The estimated percentages of total EO emissions were developed in Phase I of this program.

b The catalytic oxidation system has a greater overall EO emission reduction potential primarily because the acid hydrolysis system cannot treat the discharge from the aerator or other dilute sources.

c In the sterilizer discharge experiments described in this report, approximately 75 percent of the EO from the sterilizer was absorbed by the vacuum pump fluids and did not reach the control systems. However, other experiments demonstrated that the control systems were capable of handling the full discharge of the sterilizer. The efficiencies indicated for both types of control devices are based on the assumption that the vacuum pump fluids are not discharged.

2.3 REFERENCES FOR SECTION 2

References which discuss the efficiency of industrial-sized acid-hydrolysis units are as follows:

1. Buonicore-Cashman Associates (BCA), Inc. Certification Testing Report. BCA Project No. 85-260, January 1985.

2. Desai, P. R. Performance Test Report, DEOXX™ Ethylene Oxide Detoxification System. Chemrox Project No. 85-260, October 1985.

SECTION 3.0

CHARACTERIZATION OF HOSPITAL STERILIZERS

This section of the report provides a brief description of the sterilizing agent used in hospital sterilizers and a description of sterilizer operations. The sources of ethylene oxide emissions are also identified.

3.1 THE STERILIZING AGENT

Almost all hospitals sterilize heat-sensitive items in gas sterilizers which use a mixture of EO and a chlorofluorocarbon (CFC), dichlorodifluoromethane. The active sterilizing agent is EO. The CFC is a flameproofing diluent. The mixture, which is 12% by weight EO and 88% by weight CFC, is referred to as 12/88. The composition of 12/88 on a volume basis is 277,000 parts per million by volume (ppmv) EO and 723,000 ppmv CFC. Although 12/88 is a more costly sterilant gas than pure EO, it has the advantage of being nonexplosive and nonflammable. Pure EO is explosive in concentrations from 3-100%.

Pure EO is used only rarely by hospitals and only for very small sterilizers. In other, nonhospital applications where pure EO is used, the sterilizing chambers must be installed in explosion-proof rooms.

3.2 STERILIZER OPERATIONS

Hospital sterilizers are essentially enclosed chambers constructed of stainless steel which can be pressurized to about 10 psig and evacuated to

about 26 in. of mercury. A photograph of a typical sterilizer is shown in Figure 3-1. Also shown is a cart and tray system in which the articles to be sterilized are placed. A schematic of a hospital sterilizer is shown in Figure 3-2.

The articles to be sterilized are loaded into the chamber, and the doors are closed. A diagram of the sterilization pressure cycle is shown in Figure 3-3. The gauge pressure in the chamber is reduced to 22-26 in. of mercury vacuum using a vacuum pump. This portion of the cycle is called presterilization conditioning (Figure 3-3). The chamber temperature is then adjusted to 28°-49°C, and the relative humidity is raised to about 40-60% by injecting steam. After equilibrium is achieved, 12/88 is pumped into the chamber to achieve the desired concentration of EO, typically about 200,000 ppm. A typical chamber pressure is about 10 psig (Figure 3-3). The chamber is held at this pressure for 2-16 hr (typically 2-3 hr). This is the sterilization phase of the cycle. At the conclusion of the sterilization phase, the chamber is evacuated using a vacuum pump until the gauge pressure within the chamber reaches 22-26 in. of mercury vacuum. This evacuation phase typically lasts about 10 min. The pressure in the chamber is brought to atmospheric pressure by introducing clean, filtered air. This portion of the cycle lasts about 2 min. The combination of evacuation and air flushes is then repeated from 2-4 times to remove as much of the EO from the articles as possible.

After the last air wash, the chamber door is opened, and the sterile articles are removed and placed in an aeration chamber. The purpose of aeration is to allow any residual EO to diffuse out of the sterilized articles.

Figure 3-1. Typical hospital sterilizer showing cart and tray system.

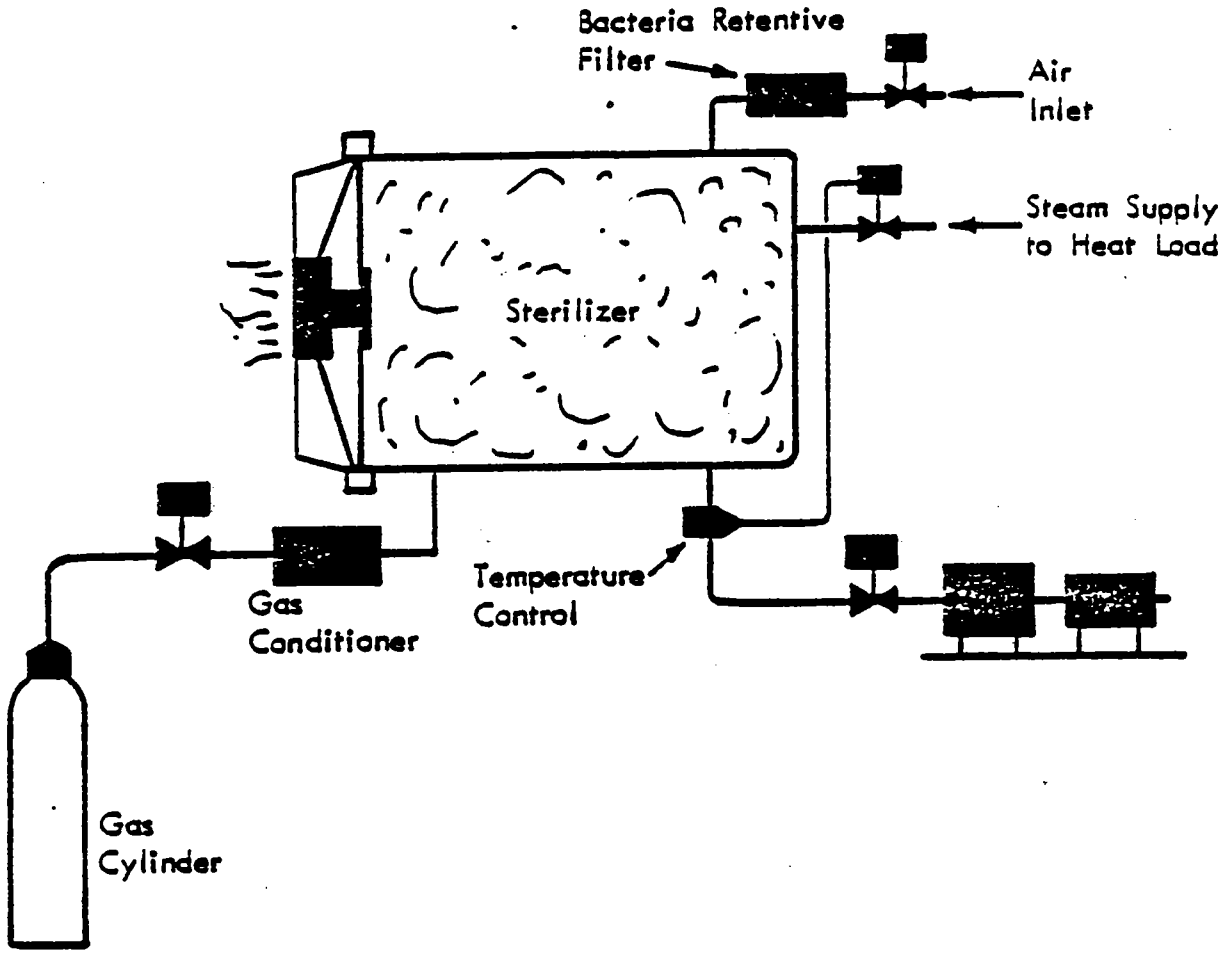
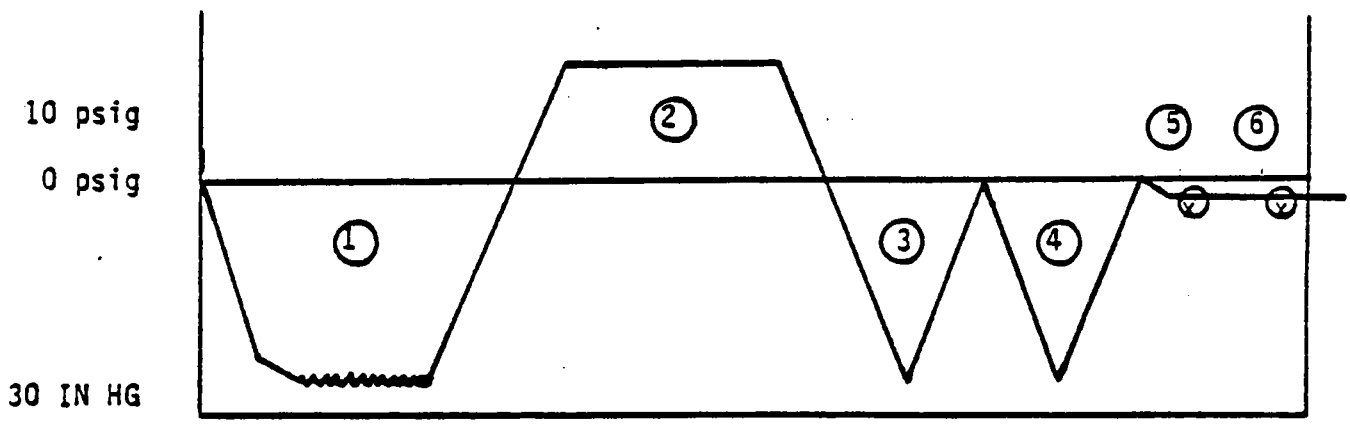


Figure 3-2. Schematic of hospital sterilizer.



1. PRESTERILIZATION CONDITIONING
2. STERILIZATION/EO EXPOSURE
3. FIRST EXHAUST VACUUM
4. SECOND EXHAUST VACUUM
5. AND 6. AIR FLUSH/VENTILATION

x BUZZER ALARM

Figure 3-3. Ethylene oxide process sterilization cycle.

The length of time necessary to remove residual EO from the sterilized items depends on the composition of the sterilized materials, their physical dimensions or surface area, the packaging material, the sterilization parameters used, and the temperature and air exchange rate of the aerator. The higher the residue level, the longer the required aeration time. The amount of absorbed EO in rubber and plastic components can range as high as 35,000 ppm (3.5%), as indicated in Table 3-1. An EO-sterilized item made from natural rubber requires a longer aeration time than the same item made from polyethylene because rubber absorbs more EO. Items that are large, have thick tubing, or have extensive surface area absorb greater quantities of EO and require longer times for aeration than small, thin-tubed, low-surface-area items. Typical aeration times range from 1-32 hr.

TABLE 3-1. THE EXTENT OF ETHYLENE OXIDE ABSORPTION AS A RESULT OF STERILIZATION

Material	Residue level (ppm)
Polyvinyl chloride	10,0000,000
Polystyrene	15,0005,000
Polyethylene	5,0000,000
Polypropylene	13,0008,000
Natural rubber	20,0005,000
Synthetic rubber	18,0002,000
Silicone rubber	15,0000,000

Source: Central Supply Department, Menorah Medical Center, Kansas City, Missouri.

3.3 ETHYLENE OXIDE EMISSIONS

Figure 3-4 shows the typical layout of a central EO sterilization room at a hospital. The sterilizers and aerators are generally flush-mounted through a wall enclosing a "core room" behind the sterilizers and aerators. The figure shows one sterilizer and one aerator, but there can be several of each

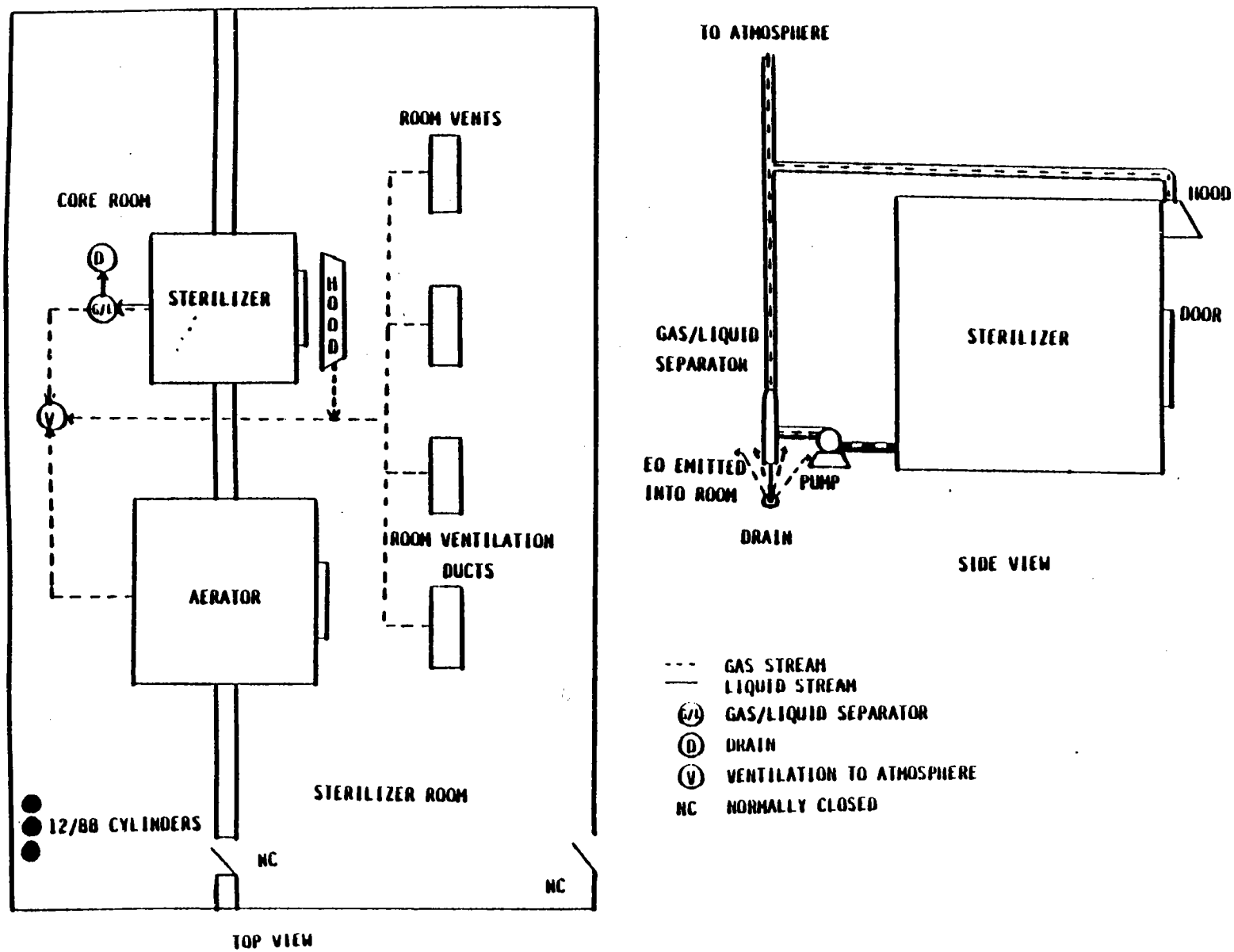


Figure 3-4. Typical hospital sterilizer room showing ethylene oxide emission sources.

along the wall depending on the size of the hospital. The core rooms contain the vacuum pumps, drain lines, ventilation ducting, and often the 12/88 tanks. The core room is accessible by a door from the main sterilizer room. This door remains closed except during cylinder changes, pump maintenance, etc. Core rooms tend to be small with little unused floor space. Because the sterilizer is maintained at 130°F throughout the sterilization cycle, the core room is usually much hotter than typical room temperature. Figure 3-4 also shows the major EO emission points: the sterilizer vent, the drain area, the sterilizer door, and EO cylinder leaks. The sterilizer and aerator are directly connected to ventilation ducts, while emissions from around the sterilizer door and sterilizer room ambient air are hooded and vented to the duct. Drain emissions can be hooded, but more often, the EO is allowed to enter the core room where it may be removed by ventilating the core room airspace.

A more detailed discussion of each EO emission source follows.

3.3.1 The Sterilizer Vent and Drain

The major source of EO emissions (70-95% of the total) is the chamber vacuum pump during the evacuation phase. These vacuum pumps are typically once-through liquid-ring pumps that use water as the working fluid. A mixture of water and chamber gas is expelled from the pump. The EO and CFC are released and emitted to the atmosphere. The water is sent to a sewer drain. Building codes require a 1-in. air break between the pump and the sewer drains. Some EO will desorb and be emitted to the atmosphere as the solution falls through the air break.

The fate of EO remaining in solution after the air break is uncertain. The EO could desorb from the liquid into the headspace of the sewer pipes and be emitted at leaks in sewer lines, pipe connections, and at other points in the sewer system. Another possible fate is chemical conversion within the sewer system. A wide variety of reactions is possible depending upon the exact chemical composition of the sewage and on physical conditions within the sewer. It is expected that any EO reaching the publicly owned treatment works (POTW) would be emitted during the aeration phases of treatment.

2

3.3.2 The Aeration Chamber

A second emission source is the aeration cabinet. As EO diffuses out of the sterile articles, it is emitted to the atmosphere via the cabinet vent. The amount of EO emitted from this source is directly related to absorbancy of the sterilized materials. Typically, plastic and rubber items absorb large quantities of EO. Table 3-1 shows the residual EO levels in different types of plastic and rubber after sterilization. If a sterilizer load contained a high proportion of these materials, the EO emissions from the aerator would be significant.

3.3.3 The Sterilizer Door

Small amounts of EO are emitted during the sterilization phase from leaks in the door seals. Also, after the evacuation cycles there is still some EO remaining in the sterilizer. This quantity is emitted when the door is opened to remove the sterilized articles. These two sources are relatively small in comparison to the sterilizer vent and aerator emissions.

3.3.4 The EO Storage Tanks

The storage tanks are pressure vessels, and no emissions should occur during routine operation. However, emissions may occur during cylinder changes and from gas cylinders, transfer lines, and valves during emergency or upset conditions.

3.4 MODEL STERILIZER PARAMETERS

Based on information obtained in a survey of hospitals and sterilizer manufacturers, parameters characteristic of three sizes of hospital sterilizers were developed. These model sterilizer parameters are presented in Table 3-2.

TABLE 3-2. MODEL STERILIZER PARAMETERS

	Sterilizer size		
	Small	Medium	Large
1. Sterilizer parameters			
Chamber volume, ft^3	8.8	30	71
Cycles per year	365	400	250
Cycle duration, min	180	240	240
Cycle processes (duration, min):			
Preconditioning/prevacuum	35-40	35-40	35-40
Sterilizer gas charge	5	5	5
Sterilizer/exposure	120	180	180
Postvacuum/exhaust	20	20	20
2. Chamber environmental conditions			
Temperature, °F			
Chamber	130	130	130
Exhaust stream	80-85	80-85	80-85
Relative humidity, %	50	50	50
Pressure, psig	8-10	8-10	8-10
Preconditioning vacuum, in. Hg	22-26	22-26	22-26
Postexhaust vacuum, in. Hg	22-26	22-26	22-26
Chamber EO concentration, ppm	200,000	200,000	200,000
3. Sterilizer gas characteristics			
Maximum EO concentration at exhaust, ppm	200,000	200,000	200,000
EO consumption per cycle, lb	0.31	1	2.4
EO consumption per year, lb	113	400	900

3.5 FLOW RATES AND EO EMISSIONS FROM MODEL STERILIZERS

Based on the model sterilizer parameters, the sterilizer flow characteristics were calculated. The results of these calculations are shown in Figures 3-5 through 3-10.

The data can perhaps best be explained by means of an example: in Figure 3-9, at time zero a large hospital sterilizer (71-ft^3 chamber) has been pressurized to about 10 psig. The sterilization cycle is complete, and the vacuum pump is turned on. The flow rate at the beginning of the cycle is about 0.0145 m^3/sec or about 31 ft^3/min. This flow rate decreases exponentially with time until, at the end of the first vacuum exhaust cycle, the rate is about 0.0015 m^3/sec or about 3.2 ft^3/min.

After ventilation air has entered the sterilizer, the pressure returns to atmospheric pressure, and the pump begins again. The flow rate is about 0.009 m^3/sec (19 ft^3/min) at this point and decreases exponentially in about 8 min to about 0.0015 m^3/sec (3.2 ft^3/min).

Corresponding EO concentrations in the exhaust of this sterilizer are shown in Figure 3-10.

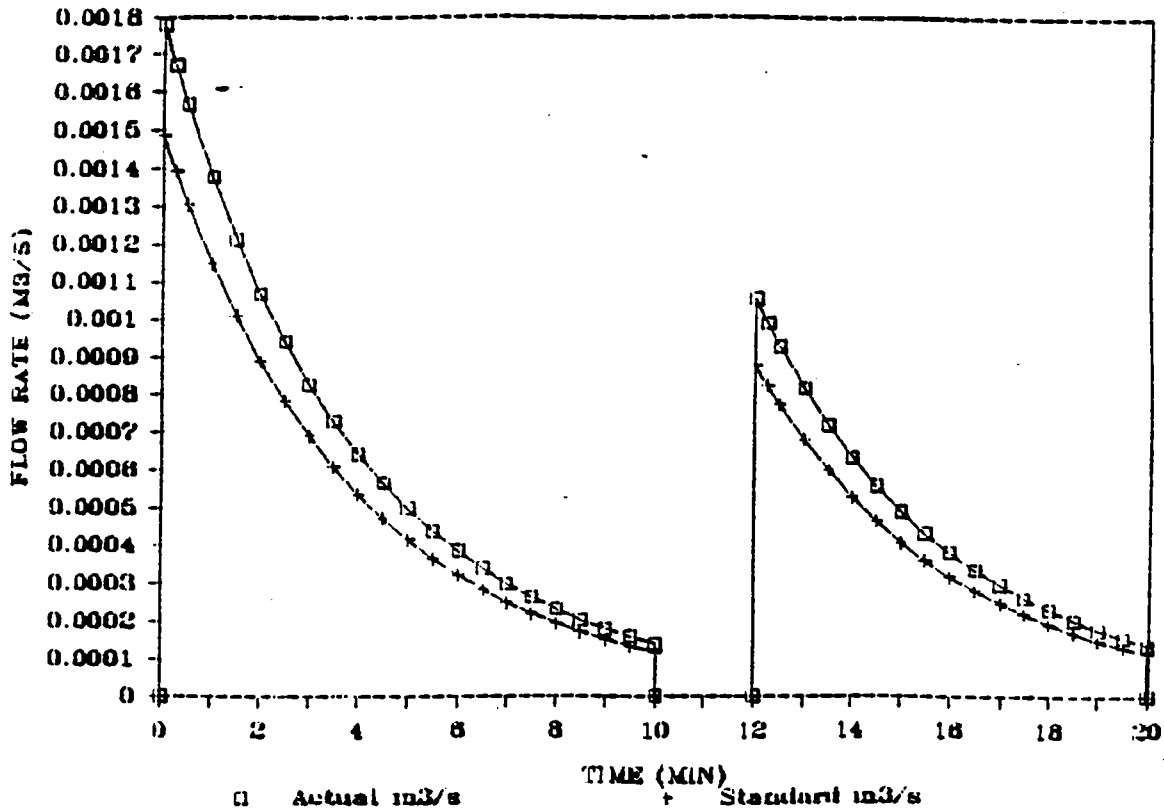


Figure 3-5. Gas flow rate versus time (8.8-ft^3 chamber).

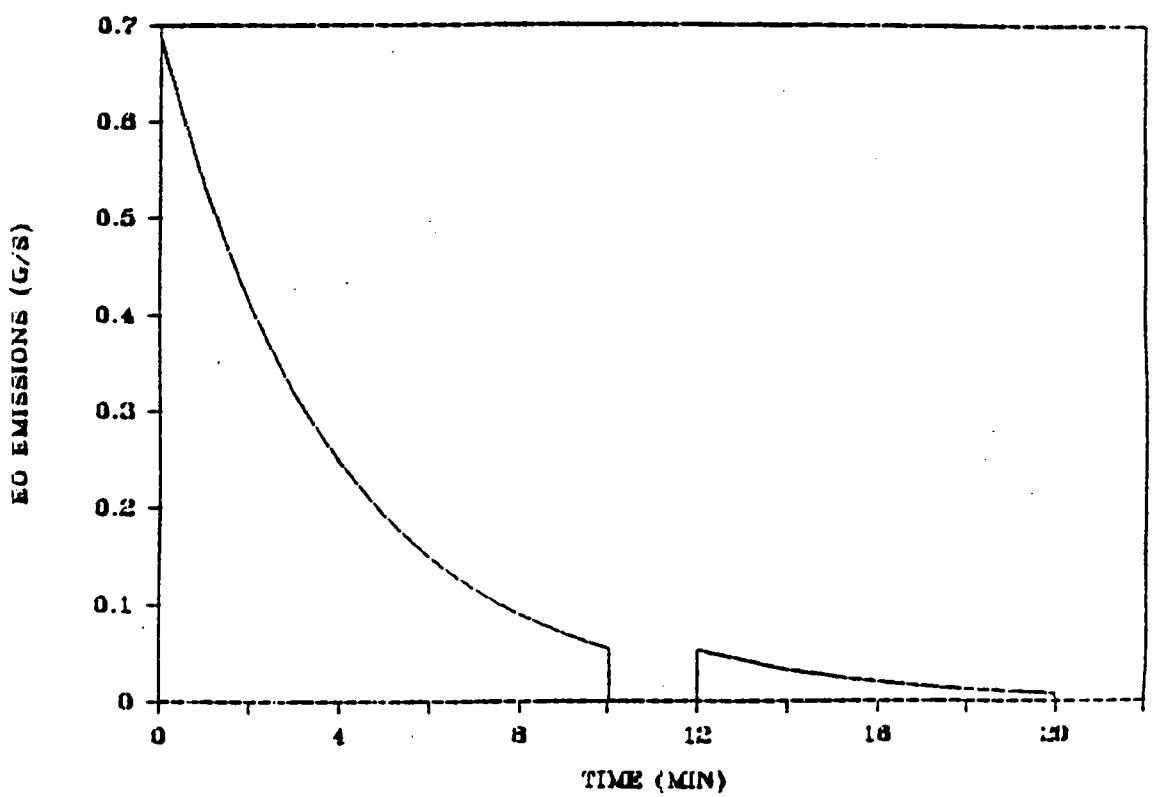


Figure 3-6. Ethylene oxide emissions versus time (8.8-ft^3 chamber).

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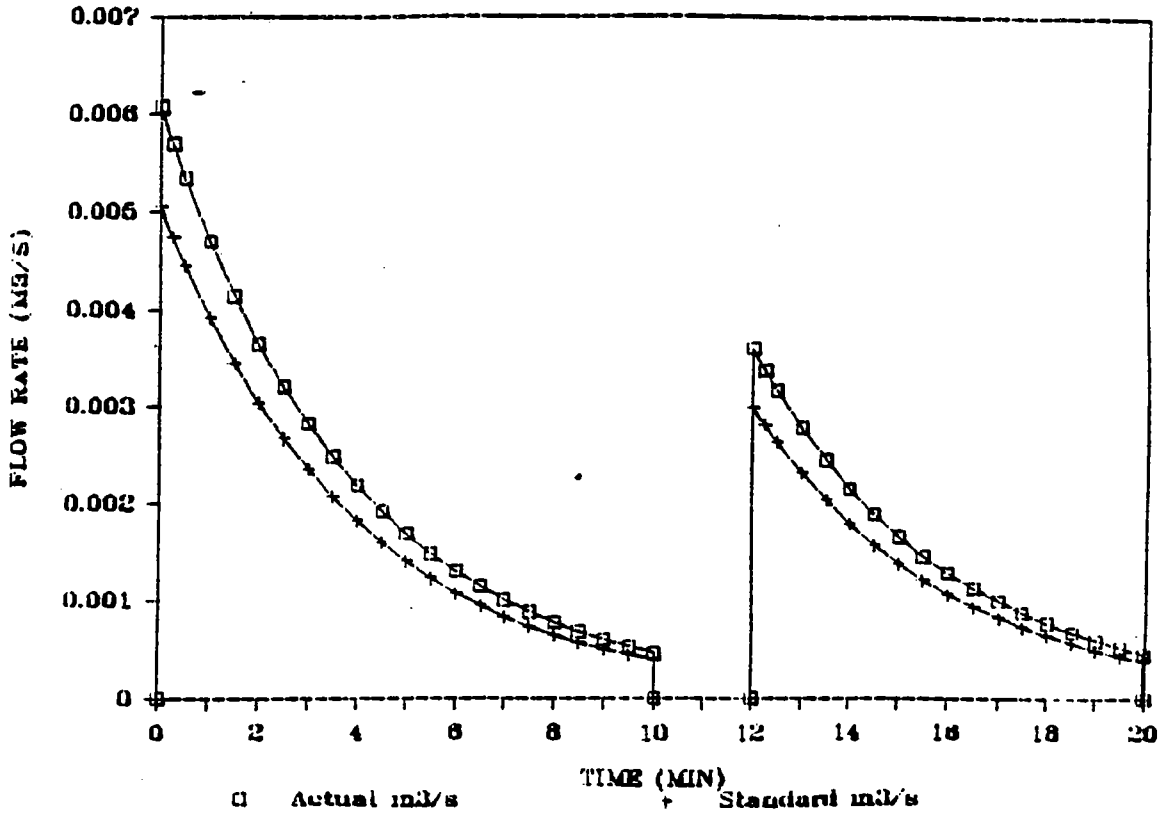

Figure 3-7. Gas flow rate versus time (30-ft^3 chamber).

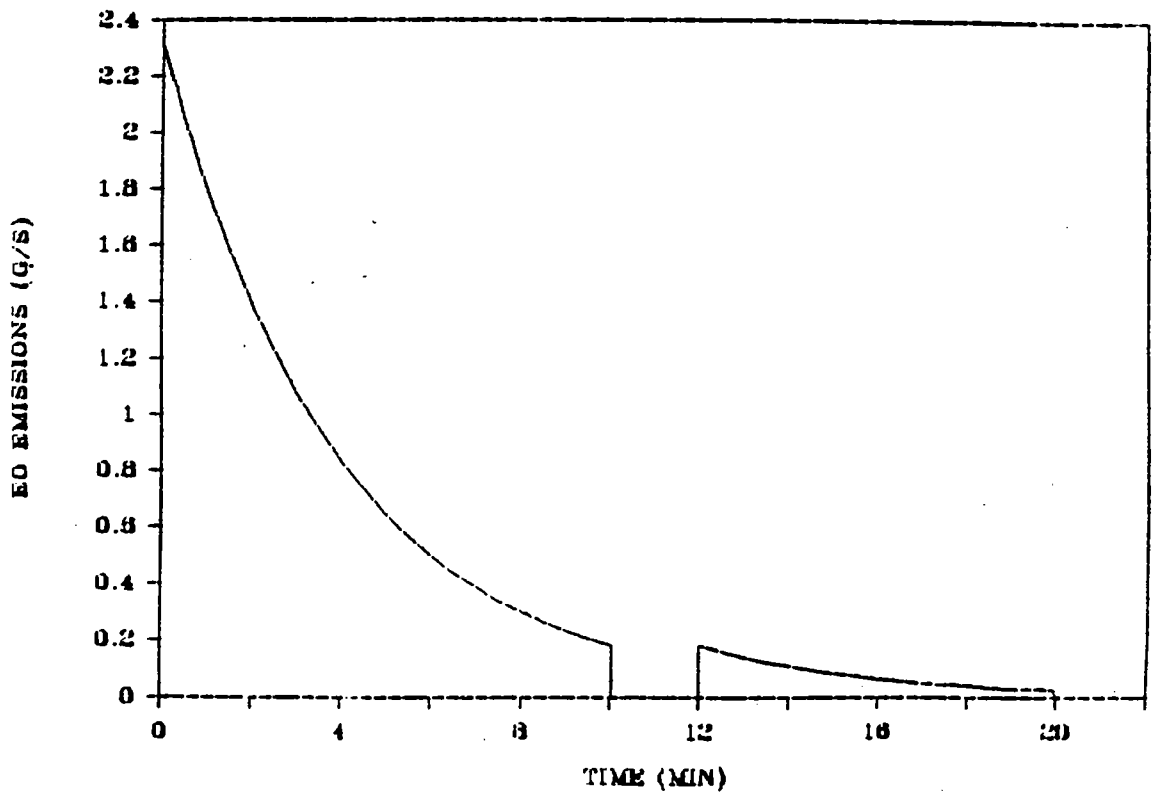

Figure 3-8. Ethylene oxide emissions versus time (30-ft^3 chamber).

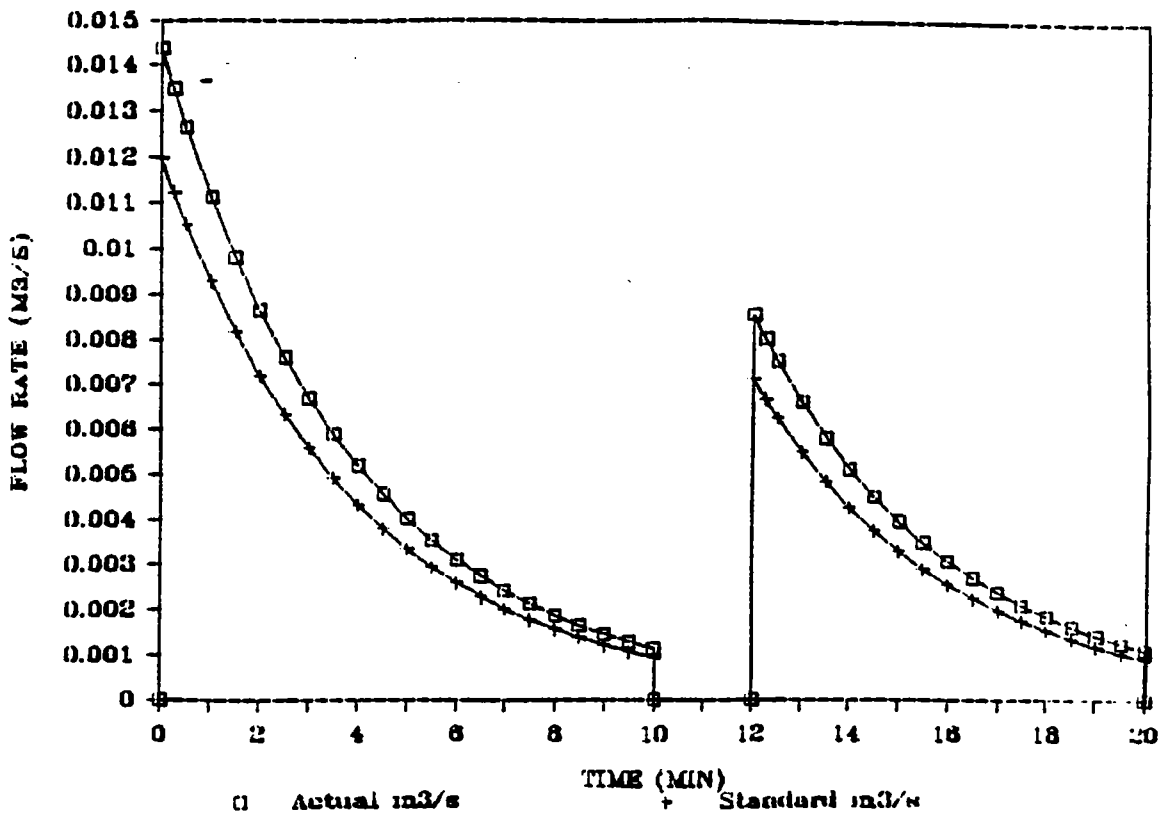

Figure 3-9. Gas flow rate versus time (71-ft^3 chamber).

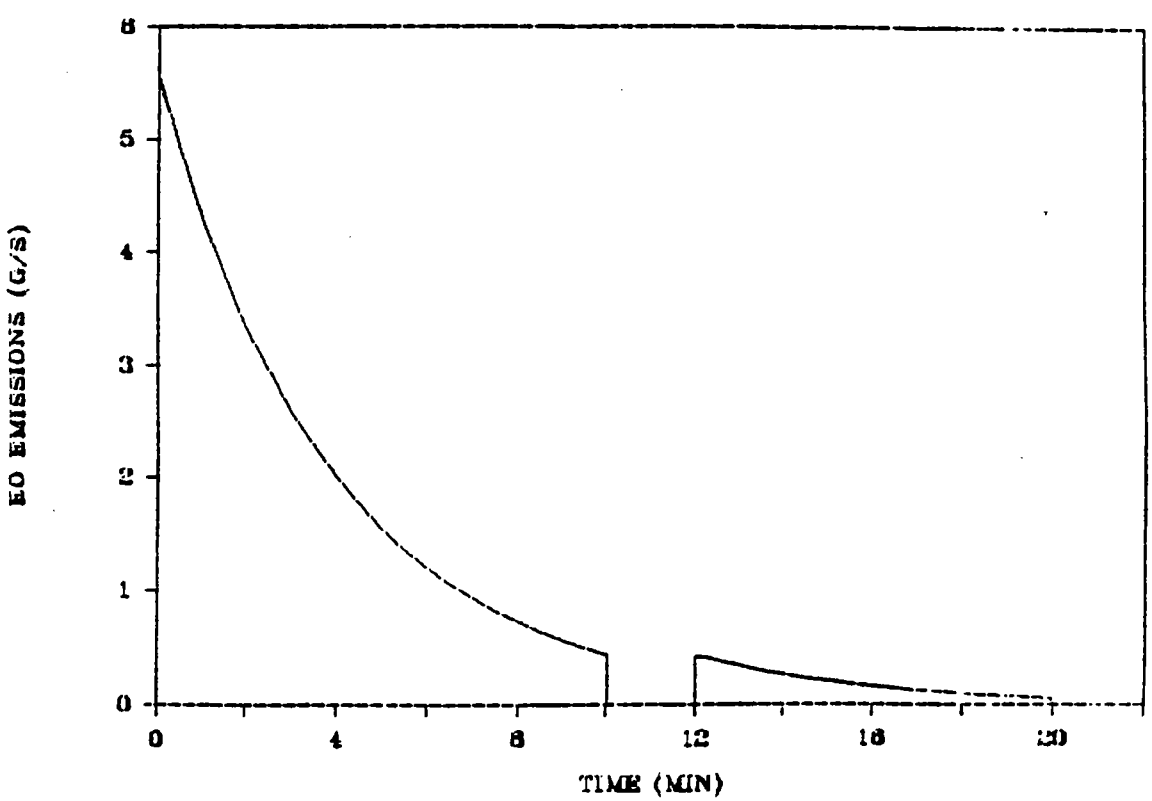

Figure 3-10. Ethylene oxide emissions versus time (71-ft^3 chamber).

SECTION 4.0

SELECTION OF ETHYLENE OXIDE CONTROL OPTIONS

The selection criteria that were developed for EO control options are listed in Table 4-1. The cost and effectiveness of the system (environmental safety) were given the highest priority with lesser but equal emphasis placed on the stage of development, complexity, space requirements, and safety.

4.1 SELECTION CRITERIA FOR EO EMISSION CONTROL OPTIONS

4.1.1 Costs

Costs to be considered are the capital cost, installation costs, and operating costs. Installation costs include the substantial costs that could be encountered as a result of retrofit installation into existing hospital sterilizer operations. Walls and ceilings may require removal or adaptation. Substantial piping and ductwork may be required if the control system is located remote from the sterilizers. If the system is at the research stage, the R&D costs of developing the system must be considered. Other important costs are the costs of disposing of any products or by-products of the control process.

4.1.2 Effectiveness/Environmental Safety

The effectiveness of the system is related to environmental safety. The extent to which EO and, to a lesser extent, the CFC are removed is a very critical parameter. Also to be considered are the possibilities of discharging toxic products to the air. A distinct possibility with some Table 4-1

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TABLE 4-1. SELECTION CRITERIA FOR STERILIZER CONTROL TECHNOLOGY

Costs		
	Capital equipment costs	
	Installation costs	
	Operating costs	
	Costs for disposal of products and by-products	
	Required R&D costs	
Effectiveness/environmental safety		
	Air	• Percent EO removal
		• Percent CFC removal
		• Absence of toxic by-products
		• Adaptivity to various flow rates and concentrations
	Water	• Magnitude of wastewater disposal problem
	Solid waste	• Magnitude of hazardous solid waste disposal
State of development		
	Developed	
	Developing	
	Research stage	
Complexity		
	Ability to run unattended	
	Required maintenance	
	Level of technical support	
	No startup, shutdown problems	
Space requirements		
	Location reference to sterilizer	
	Size	
Safety		
	Overall safety of operation	

control options is the decomposition of the CFC to toxic gases such as phosgene, hydrogen chloride, and hydrogen fluoride. Similarly, the necessity of disposing of toxic aqueous or solid products must be considered. For acid scrubbing systems, an important aqueous waste is the acidic ethylene glycol solution generated.

4.1.3 Stage of Development

The stage of development of the control option is also important. A system ready for installation in a hospital is obviously of more significance than a concept that has only been demonstrated at the laboratory level.

4.1.4 Complexity

Another important consideration, especially for hospitals, involves the complexity of the system. In most cases, very little chemical engineering expertise is available at hospitals. Therefore, the process should run unattended and require little maintenance. Since the system will operate intermittently, there should be no problems with regard to startup or shutdown.

4.1.5 Space Requirements

Since most control systems will be installed to service existing hospital sterilizers, the space requirements of the control system are critical. Little space is usually available in the sterilizer area, and walls and ceilings may need to be modified, and steam lines and electrical conduits may need to be installed. Alternatively, it may be necessary to install the system at considerable expense at a location remote from the sterilizer.

4.1.6 Safety

Finally, the system must be capable of functioning safely in regard to all of those personnel who will be involved: sterilizer operators, maintenance workers for the sterilizer and the control process, and all other personnel in the vicinity of the sterilizer and the control process.

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4.2 CHEMICAL REACTIONS OF ETHYLENE OXIDE AND DICHLORODIFLUOROMETHANE RELEVANT TO STERILIZER EMISSION CONTROL OPTIONS

The sterilizing gas used in hospital sterilizers contains EO (12% by volume) and dichlorodifluoromethane (88% by volume). In order to assess potential emission control options, the chemical properties and reactions of these gases must be considered. Some pertinent properties are presented in Table 4-2. The two most important reactions with regard to evaluating EO emission control technologies are oxidation and hydrolysis, which are discussed below.

4.2.1 Oxidation

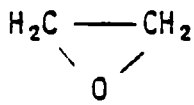
Ethylene oxide can be very easily and completely destroyed by thermal incineration to produce the harmless products carbon dioxide and water (Equation 1).

$$EO + O_2 \xrightarrow[\text{oxidation}]{\text{thermal}} CO_2 + H_2O \qquad (1)$$

However, under most conditions of thermal oxidation, CFC produces harmful and toxic by-products[1,2] (Equation 2).

$$CF_2Cl_2 + O_2 \xrightarrow{\text{thermal oxidation}} \begin{array}{ll} COCl_2 & \text{Phosgene} \\ COF_2 & \text{Carbonyl fluoride} \\ HCl & \text{Hydrogen chloride} \\ HF & \text{Hydrogen fluoride} \\ CF_4 & \text{Carbon tetrafluoride} \\ Cl_2 & \text{Chlorine} \\ CO & \text{Carbon monoxide} \end{array} \qquad (2)$$

TABLE 4-2. SOME PERTINENT PROPERTIES OF EO AND DICHLORODIFLUOROMETHANE

Ethylene oxide (EO)	Dichlorodifluoromethane (Freon-12)
	CF_2Cl_2
M.W. 44.04	M.W. 120.92
Flammable gas	Nonflammable gas
b.p. 10.4°C	b.p. -29.8°C
Miscible with water and most organic solvents	Water solubility: 280 mg/L; soluble in organic solvents
Highly reactive	Very inert
Explosive in air (3 to 100 vol %)	Nonexplosive

Catalytic incineration, which proceeds in the presence of a solid-phase catalyst, can be performed at lower temperatures and does not produce harmful CFC by-products (Equations 3 and 4).

$$EO + O_2 \xrightarrow{\text{catalytic incineration}} CO_2 + H_2O \qquad (3)$$

$$CF_2Cl_2 + O_2 \xrightarrow{\text{catalytic incineration}} \text{no reaction} \qquad (4)$$

4.2.2 Hydrolysis

Ethylene oxide can be hydrolyzed under relatively mild conditions to non-toxic products; the CFC is unaffected by these conditions. Ethylene glycol is prepared industrially by the hydrolysis of EO (Equation 5).

$$\text{EO} \xrightarrow[H^+]{H_2O} \begin{array}{ll} HOCH_2CH_2OH & \text{Ethylene glycol} \\ HO(CH_2CH_2O)_nH & \text{Poly(ethylene glycols)} \\ (n = 2, 3, 4) & \end{array} \qquad (5)$$

The reaction is conducted in a large excess of water at moderate temperatures to obtain 85-90% ethylene glycol selectivity. The lower polyglycols, diethylene, triethylene, and tetraethylene glycols account for the remainder, the primary by-product being diethylene glycol. The hydrolysis reaction is slow at ambient temperatures, but the speed of the reaction can be increased by addition of heat or acid or basic catalysts.

Other reactions of EO that were considered for potential control technology options are reviewed in Appendix A.

4.3 REFERENCES FOR SECTION 4

1. Sax, N. I. 1984. Dangerous properties of industrial materials.

2. Zborzinet, J. V., et al. 1985. State of the art review of combustion and pyrolysis by-products of PCB substitutes. SCS Engineer, Long Beach, California, Draft Final Report.

SECTION 5.0

CONTROL TECHNOLOGY CONCEPTS

Nine techniques were assessed as possible candidates for control of EO emissions from hospital sterilizers. Each technique was examined in terms of its mode of operation, expected efficiency, probable by-products, safety hazards, and general technical feasibility. The data gathered on each technique were evaluated with respect to the selection criteria described in Section 4. Table 5-1 provides a list of the nine criteria evaluated and the results of the evaluation. Based on this evaluation, six concepts were eliminated. A detailed review of these six concepts is presented in Appendix B. The information gathered on the three remaining concepts is presented in Table 5-2. Further details of each concept are described below.

TABLE 5-1. POTENTIAL ETHYLENE OXIDE CONTROL CONCEPTS AND MAJOR OBJECTION FOR HOSPITAL STERILIZER APPLICATION

Control concept	Objection
Acid hydrolysis (scrubbing)	None
Catalytic oxidation	None
Carbon adsorption	High operating cost
Adsorption/reaction	No data
Thermal incineration	Toxic by-product
Condensation	Explosion hazard
Ozonation	High cost
Corona discharge (controlled plasma)	Toxic by-product
Ultraviolet photolysis	Toxic by-product

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TABLE 5-2. ETHYLENE OXIDE CONTROL TECHNOLOGIES SUMMARY

Control	Company and location	No. of installations (no. in hospitals)	Primary effluent	Operating principles	Comments
Acid hydrolysis	Chemrox Bridgeport, Conn.	20 (0)	40 wt % ethylene glycol with some sodium sulfate	Countercurrent packed column--acid hydrolysis at pH 1.0 to ethylene glycol accumulation of glycol until 40 wt %, then neutralize and dump.	First hospital system operated July 1987. Design criteria are $10 to 15K, 3 ft x 3 ft x 7 ft, self-sufficient, 99.9% efficient. Whether these will be met is the question. Chemrox has installed many industrial-sized units and have test data showing 99+% efficiency. EO control is their only business.
	Damas S. Hackensak, N.J.	27 (0)	30 wt % glycol with some sodium sulfate	Bubbles gas through sulfuric acid solution at pH 1.0. Patented diffuser said to maximize EO transfer into solution where it reacts to form glycol. Accumulation of glycol until 30 wt %, then neutralize and dump.	Does not market a unit for hospitals. Could possibly scale down their current system. They claim efficiency 99.2% EO capture for gas on current models.
	Ceilcote	Many (0)	None; glycol sold for credit	Countercurrent packed column--for industrial applications.	Currently only large-scale application. EO producers on contract sterilizers; not interested in hospital market.

(continued)

TABLE 5-2. (continued)

Control	Company and location	No. of installations (no. in hospitals)	Primary effluent	Operating principles	Comments
	Croll-Reynolds	Many (0)	None, glycol sold for credit.	Countercurrent packed column--for industrial applications.	Not interested in the hospital market.
	Heat Systems Ultrasonics Farmingdale, N.Y.	None for EO control Many for other gases	Ethylene glycol with some sodium sulfate	Venturi scrubber first stage. Then intimate vapor-liquid contact on demisting pad. Acid hydrolysis to glycol, which accumulates. Then neutralize and dump.	Marketed as a "laboratory scrubber" for small-scale $4K price. Limited to scrubbing 1,000 ppm or less in air. Have been working on an EO unit but it is not ready.
Catalytic oxidation	Mine Safety Appliances Evans City, Pa.	5 (5) Not all up yet	CO_2 + H_2O	Gas flows through catalyst bed oxidizing EO to CO_2 and H_2O. CFC passes through unreacted. Operating temperature of 300 to 350°F.	Operated since 1986 at Children's Hospital in Philadelphia, Pa. No detectable levels of EO at outlet as measured by GC analysis (0.5-ppm limit).
	DM3 Corporation Santa Ana, Calif.	0 (0)	CO_2 + H_2O	Similar to MSA's unit.	DM3 has a marketing agreement with MSA, where they purchase the catalyst from MSA and fabricate the remainder. They provided test data on the MSA unit in Philadelphia. They have not sold any units for hospitals as yet. DM3 also offers a catalytic unit for large

(continued)

TABLE 5-2. (continued)

Control	Company and location	No. of installations (no. in hospitals)	Primary effluent	Operating principles	Comments
					commercial sterilizers wholly manufactured by MSA.
Adsorption	Tigg Corporation Pittsburgh, Pa.	? (0)	Virtually none. Carbon bed must be disposed of. No by-products.	EO trapped as gas flows through activated carbon bed. Can be regenerated for large-scale operations, but not economical for small hospital scale. Designed to be disposable for small scale.	Tigg has had EO control program with "promising results." Have had industrial-scale in mind but say small-scale is possible with their smallest unit of 100 ft^3/min maximum.

5.1 CATALYTIC INCINERATION

The EtO ABATOR™ produced by Mine Safety Appliances Company (MSA) uses an oxidation catalyst to convert EO to carbon dioxide and water (see Figure 5-1). The catalyst has been available commercially for many years and is used for a variety of applications. The reaction with EO takes place catalytically at relatively low temperatures (300°-350°F). Spent sterilizer gas is mixed with a high volume of dilution air to reduce the inlet concentration to 5,000 ppm or less. (This limit is to prevent excessive catalyst bed temperatures from the exotherm of oxidation.) The mixture passes through a filter for dust removal and then is preheated with steam or electricity to the reaction temperature. The gas then enters the catalyst beds, and the EO is oxidized. Before being vented to the atmosphere, part of the stream may be recycled for heat recovery. At the start of the vent cycle, the steam use is minimal since the reaction exotherm provides most of the heat to maintain the operating temperature. As the venting continues and the EO concentration is reduced, the steam use increases to make up the lost heating value. The catalyst unit is illustrated in Figure 5-2.

MSA claims that the EtO ABATOR™ achieves an efficiency of 99.9+%. There are currently six units in operation, three of which are installed in hospitals. The customer list is shown in Table 5-3. This unit can potentially control multiple EO emission sources because the dilution air it requires can be taken from the aeration room air, aeration chamber air, and core room ventilation. Ethylene oxide from these "nonsterilizer" sources may vary from 5-25% of total EO emissions depending on the product being sterilized.

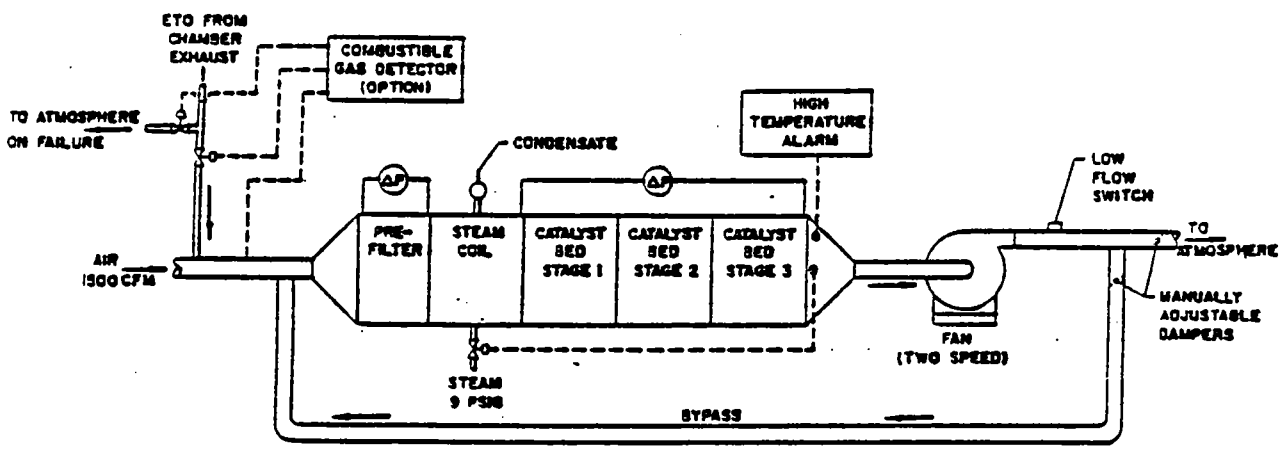

Figure 5-1. Schematic: MSA EtO ABATOR™.

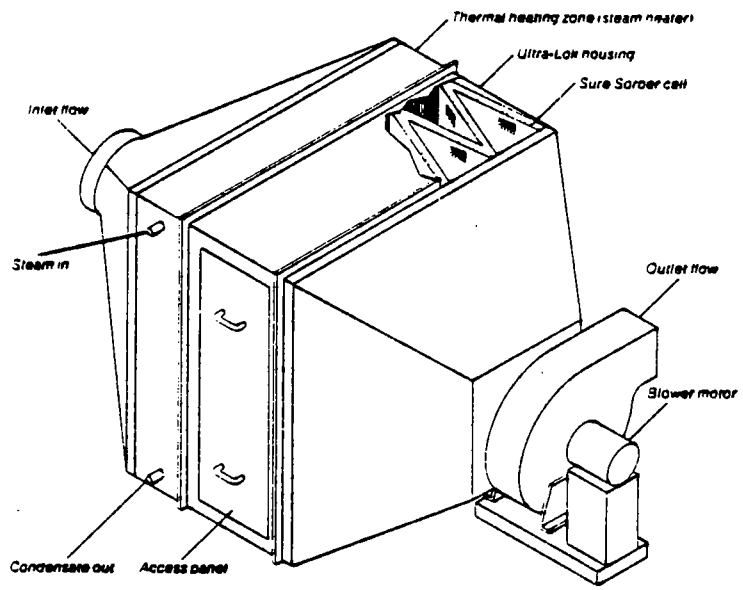

Figure 5-2. Catalyst unit: The MSA EtO ABATOR™.

TABLE 5-3. PURCHASERS OF MSA EtO ABATOR™ SYSTEMS

The Children's Hospital of Philadelphia One Children's Center 34th Street and Civic Center Boulevard Philadelphia, Pennsylvania 19104
Paoli Memorial Hospital Lancaster Pike Paoli, Pennsylvania 19301
American Cyanamid Company Lederle Laboratories Division Pearl River, New York 10965
Seamless Hospital Products Division of Dart Industries 9660 Plaza Circle El Paso, Texas 77927
Seamless Hospital Products Division of Dart Industries 1909 Northeast 25th Avenue Ocala, Florida 32670
Logansport Memorial Hospital Logansport, Indiana 46947

5.2 ACID HYDROLYSIS

Ethylene oxide will hydrolyze in the presence of water, but this reaction is very slow at neutral pH. The half-life of EO in water is approximately 14 days.[1] On either side of neutral, the reaction rate increases, but the reaction under alkaline conditions is a net consumer of alkali, and to maintain the reaction rate, caustic must be added continuously. The reaction under acidic conditions is approximately two orders of magnitude faster than the alkaline reaction and is acid-catalyzed; i.e., it is not a net consumer of acid.[2] Therefore, the pH of the solution remains constant, and no acid addition is necessary. This fact, plus the faster reaction rate, makes acid hydrolysis the choice for hydrolyzing EO.

There are four manufacturers of scrubbing controls specifically for EO emissions. Two of the makers are interested in the hospital sterilizer control market (Chemrox and Damas). The others (Ceilcote and Croll-Reynolds) manufacture systems only for industrial and large contract sterilizer use and do not plan to enter the hospital market. The approaches of Chemrox and Damas are described below.

5.2.1 The Chemrox System

Chemrox, Inc., has installed more than 25 Deoxx™ EO control systems at large contract sterilizers and spice companies. A schematic of the Deoxx™ system is shown in Figure 5-3. The system controls sterilizers having capacities from a few hundred to thousands of cubic feet. These units use a sulfuric acid solution at pH of 1.0 flowing in a countercurrent packed tower to absorb the gaseous EO into the liquid phase where it reacts to form ethylene glycol. The gas is drawn from the sterilizer by a water-ring vacuum pump. The sealant water and 12/88 gas are then separated, and the sealant water, after cooling in a heat exchanger, is returned for reuse as sealant in the pump. This recycle eliminates the discharge of water and prevents drain area EO emissions. The 12/88 gas exits the separator and enters the bottom of the packed tower. At this point, all of the gas from the sterilizer has reached the control device and no fraction has been discharged down the

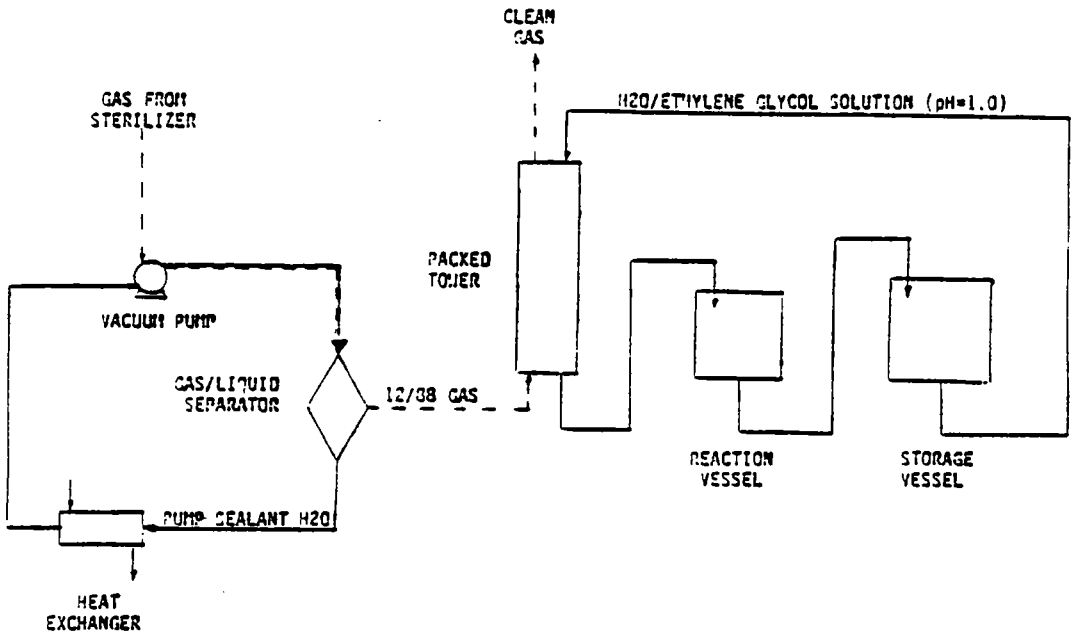

Figure 5-3. The Chemrox Deoxx™ system for scrubbing EO.

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drain. The two-step absorption/reaction process begins in the packed tower as the highly soluble EO is absorbed into the water and is hydrolyzed to ethylene glycol. Almost all of the CFC remains in the gas stream because of its relative insolubility in water. Clean, almost EO-free gas exits the top of the column, and the acid/water/glycol solution exits the bottom to a reaction vessel where there is sufficient retention time for the EO to completely hydrolyze. The solution then flows to the storage vessel, which serves as a reservoir for fresh EO-free solution which is recycled to the top of the column (still at pH 1.0). The ethylene glycol slowly builds up in the scrubbing liquor to approximately 40 wt %. At that time, caustic is pumped into the system to neutralize the acid, and the liquor is disposed of or, less often, sold for credit.

Chemrox claims a 99.9% efficiency for their Deoxx™ system when used with pure EO. This figure has been supported by tests.[3] Spice producers and contract sterilization firms have purchased the Deoxx™ system to meet state regulations. In anticipation of regulations on hospitals, Chemrox has been developing a unit for that market. The hospital Deoxx™ is scaled to smaller sterilizers but uses the same process principles as the larger units. Chemrox claims a 99% minimum efficiency for the unit. To achieve this efficiency, the gas flow rate to the unit must be no more than 10 scfm, and Chemrox has a restriction valve in place to ensure this condition. This feature should only affect large hospital sterilizers, where flows normally exceed 10 scfm. The restriction valve will add a few minutes to the evacuation cycle of these sterilizers but should not affect their performance otherwise. The system should fit in a floor space of 4.5 ft x 5 ft x 9 ft.

Chemrox believes that hospital units can operate efficiently until a glycol level of 60 wt % is reached (not 40% as in the former units). The 60% limit should extend the time between fluid changes but is also expected to reduce the cost of distilling the glycol.

5.2.2 The Damas System

Damas Corporation has installed more than 25 EO control units at various sterilizing facilities. The Damas Corporation holds the exclusive license to market an EO-scrubbing technology based on a patent held by Johnson & Johnson. The system is a bubble diffusion scrubber which also uses sulfuric acid to hydrolyze EO to ethylene glycol. A process schematic of the system referred to as the Tri-Phase™ scrubber is shown in Figure 5-4. The 12/88 gas is drawn from the sterilizer by a vacuum pump (Damas, like Chemrox, recommends a recycling vacuum pump system to eliminate drain emissions). The pressure of the mixture is controlled to tight tolerances by a pressure control valve and is sent to the Tri-Phase™ reaction vessel. Inside the vessel is a sulfuric acid solution at a pH of 0.5-1.0. The 12/88 is sparged through a diffuser to create very small bubbles which percolate through the acid solution. The small bubbles maximize mass transfer area, and the EO is absorbed into solution, where it hydrolyzes to ethylene glycol. A demisting pad prevents acid mist from exiting with the clean gas and provides a final polish to the gas stream. The CFC again remains unreacted and is exhausted to the atmosphere. Ethylene glycol builds up in the system to a recommended level of 60%, when it is neutralized and discarded. Damas claims 99.2% efficiency for this system.

Damas currently markets units for flow rates from 100-760 ft^3/min--the range found in industrial sterilizers. Damas has designed a unit for hospital sterilizers which has been tested to be greater than 99% efficient.

5.3 REFERENCES FOR SECTION 5

1. Conway, R. A., et al. 1983. Environmental fate and effects of ethylene oxide. Environmental Science Technology, 17:2, pp. 107-112.

2. Kirk-Othmer. 1980. Encyclopedia of Chemical Technology, 3rd Edition, Vol. 9, p. 436.

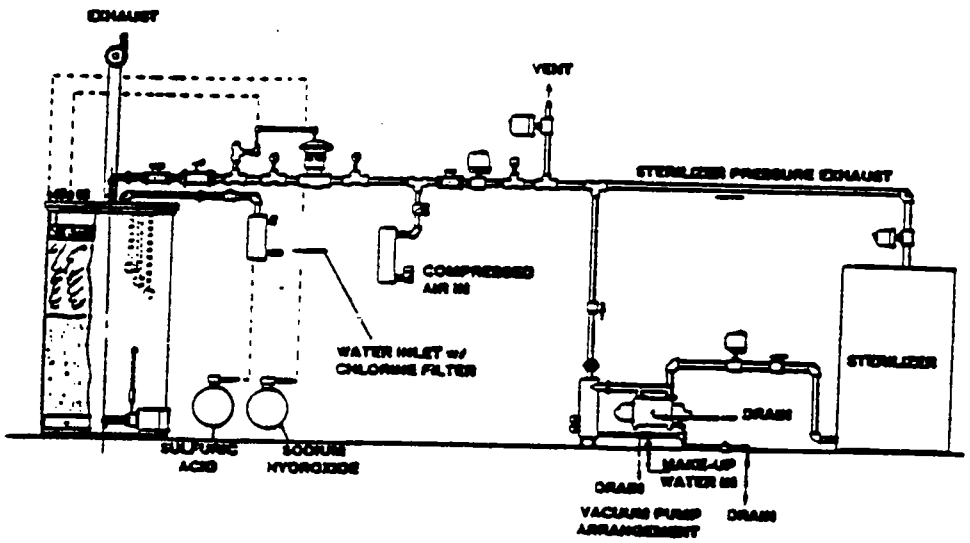

Figure 5-4. The Damas Tri-Phase™ scrubbing system.

3. Chemrox, Inc. 1985. Performance testing report Deoxx™ ethylene oxide detoxification system.

SECTION 6.0

TESTS OF CATALYTIC OXIDATION SYSTEM

A catalytic oxidation system installed at the Paoli Hospital, Paoli, Pennsylvania, was tested in June 1987. The system had been in operation at the hospital for about 6 months.

The primary goal of the test program was to determine the EO destruction efficiency of the catalyst system. A secondary goal was to measure the extent of chlorofluorocarbon decomposition during the catalytic oxidation process. Two types of experiments were performed; one type involved the treatment of the sterilizer discharge and another type involved adding the sterilizer gas directly to the system.

In all of the experiments, the observed EO destruction efficiency was high, greater than 99%. However, in the sterilizer discharge experiments, only about 10-13% of the EO in the sterilizer actually reached the catalyst system. A major fraction of the EO was absorbed by the water which was used in the once-through vacuum pump. The experiments in which EO was added directly to the system indicated that the system was capable of operating efficiently at concentrations comparable to those developed if the total discharge from the sterilizer were directed into the system. No chlorofluorocarbon decomposition was detected in any of the tests.

A summary of the catalytic oxidation system experiments is presented in Table 6-1.

TABLE 6-1. SUMMARY OF EXPERIMENTS - CATALYTIC OXIDATION SYSTEM[a]

Run no.	Objective	EO concentration in inlet at 500 cfm (ppm)	EO destruction efficiency (%)	Maximum possible CF_2Cl_2 decomposition[b] (%)
1	Sterilizer discharge study	430-0.01	99.40	$< 4 \times 10^{-5}$
2	EO addition study	125-250	99.89	$< 6 \times 10^{-5}$
3	EO addition study	400-600	99.93	NA
4	Sterilizer discharge study (replicate of Run No. 1)	429-0.01	99.16	$< 3 \times 10^{-5}$
5	EO addition study	750-1,100	99.97	$< 4 \times 10^{-6}$
6	EO addition study (replicate of Run No. 5)	750-1,000	99.98	NA
7	Sterilizer discharge study	475-0.27	99.36	$< 2 \times 10^{-5}$

a Two kinds of experiments were performed. In the sterilizer discharge studies the sterilizer was allowed to discharge into the catalytic oxidation system. In the EO addition studies, EO (12/88) was introduced from a cylinder into the catalytic oxidation system.

b No chloride was detected at a limit of detection of 200 ppb.

6.1 THE CATALYTIC OXIDATION SYSTEM

The catalytic oxidation system uses an oxidation catalyst to convert EO to carbon dioxide and water. The catalyst has been available commercially for many years and is used for a variety of applications. The reaction with EO takes place catalytically at relatively low temperatures (300°-350°F). Spent sterilizer gas is mixed with a high volume of dilution air to reduce the inlet concentration to 5,000 ppm or less. This limit is to prevent excessive catalyst bed temperatures from the exotherm of oxidation. The mixture passes through a filter for dust removal and then is preheated with steam to the reaction temperature. The gas then enters the catalyst beds, and the EO is oxidized. At the start of the sterilizer discharge cycle, the steam use is minimal as the exothermic reaction provides most of the heat to maintain the operating temperature. As the venting continues and the EO concentration is reduced, the steam use increases. When the vent cycle stops, steam use is a maximum.

The Paoli Memorial Hospital operates one EO sterilizer and one EO aerator. The EO sterilizer is a 9-ft^3 sterilizer that is approximately 4 years old. Operation is automatic, but the length of each phase of the sterilization cycle can be adjusted by timers. The current cycle is as follows:

1. The sterilizer is preheated for 30 min.

2. The initial vacuum is drawn to 26 in. of mercury (in. Hg).

3. Steam is injected for 10 min to raise humidity.

4. The 12/88 is introduced and held at 10 psig for 3 hr for complete sterilization.

5. The vacuum pump evacuates chamber to 26 in. Hg vacuum (requires about 5 min).

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6. Pulse purges continue for 30 min until cycle ends.

Currently there are 10 pulse purges during which the chamber is repeatedly drawn down and then flooded back to atmospheric pressure. The pulse purges are set on a timer for 30 sec of draw-down, followed by 30 sec of flooding.

For testing purposes, the entire sterilization cycle was shortened to 30 min by eliminating preheating and steam injection, reducing exposure time from 3 hr to 15 min, and eliminating the pulse purges.

The hospital usually starts the sterilization cycle at about 4 p.m. and removes the sterilized items at approximately 8 p.m. They are immediately placed in the aerator, remain there for 12 hr, and are then removed.

Figure 6-1 is a diagram showing the site layout. The sterilizer, aerator, and EO tanks are located in one room. These devices are all ducted to a common galvanized steel duct (10 x 16 in.) in the ceiling. The duct passes through a wall into the next room (approximately 8 x 15 ft) where the catalytic oxidation system is located. The duct leaves the oxidation system and passes through the next two rooms before exiting out a louvered vent in the exterior wall. Testing was only possible in the room where the oxidation system is located because of space limitations and sterility requirements. While in the area of the sterilizer, test personnel were required to wear sterile gowns, caps, and shoe covers.

Sampling ports were installed at the inlet to and outlet of the oxidation system. Direct EO addition experiments were performed by adding 12/88 directly to the duct at the hood over the EO tanks.

The vacuum pump drain is in the floor next to the sterilizer. The drain is not "hard.piped," and high levels of EO may be present in the vicinity of the drain when the vacuum pump is running. The design flow rate of the pump is 2.6 gal/min.

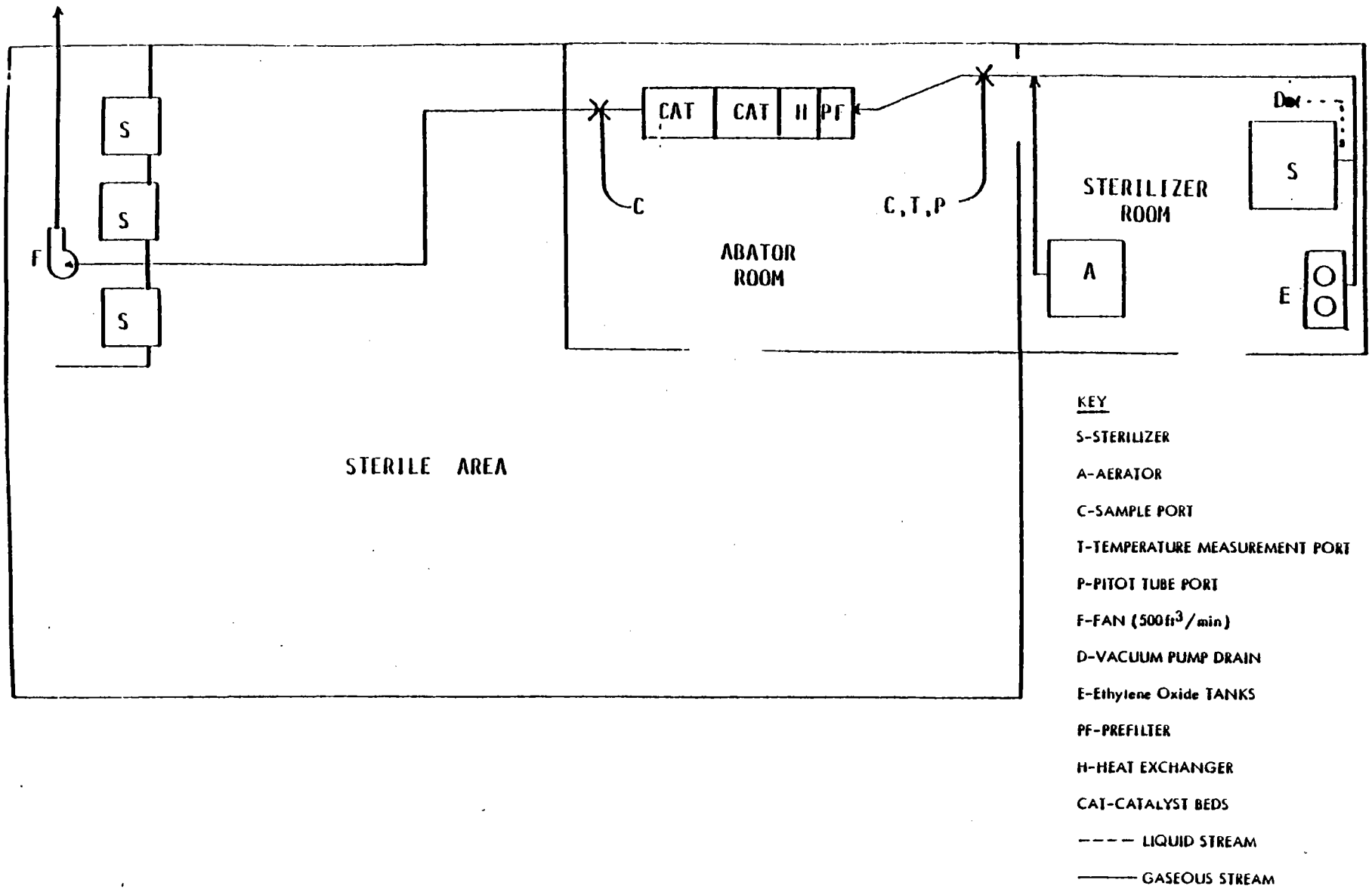

Figure 6-1. Site plan for the Paoli Memorial Hospital sterilization section.

The catalytic oxidation system consists of a prefilter section and a steam heater section followed by two catalyst beds. The heater uses 50 psi steam to heat the incoming air to approximately 300°F before it enters the catalyst beds. The control panel for the system has temperature indicators for both stages of the catalyst beds. Also, pressure gauges indicate the differential pressure across the prefilter and catalyst beds. The system also has a low-flow alarm that sounds when the differential pressure drops below a set point. This protects the unit from overheating in the event of fan failure.

6.2 DESCRIPTION OF STERILIZER DISCHARGE EXPERIMENTS

A diagram of the sampling and analysis system is shown in Figure 6-2. The primary sampling points were located on either side of the catalyst at points labeled 1 and 2. The sample streams were drawn from the ducts through polytetrafluoroethylene tubing.

In order to establish the shape of the concentration versus time curve, it was necessary to sample very rapidly, about every 40 sec. The response time of the GC, which is about 3.0 min, did not allow all of the samples to be taken and analyzed immediately. Therefore, samples were taken at each location and analyzed as soon as possible after collection in the order sampled. Glass syringes (10 mL) were used. The sample ports consisted of rubber septums installed in tees located in the sampling lines. Details of the analytical procedures are presented in Appendix C.

In addition, the EO concentration approaching the catalyst bed was monitored continuously using a total hydrocarbon (THC) analyzer equipped with a flame-ionization detector (FID) (see Figure 6-2). This device indicated when the maximum concentration of EO approached the catalyst bed and facilitated the timing of the multiple GC samples taken on both sides of the catalyst. The THC results also provided the general shape of the concentration versus time curves.

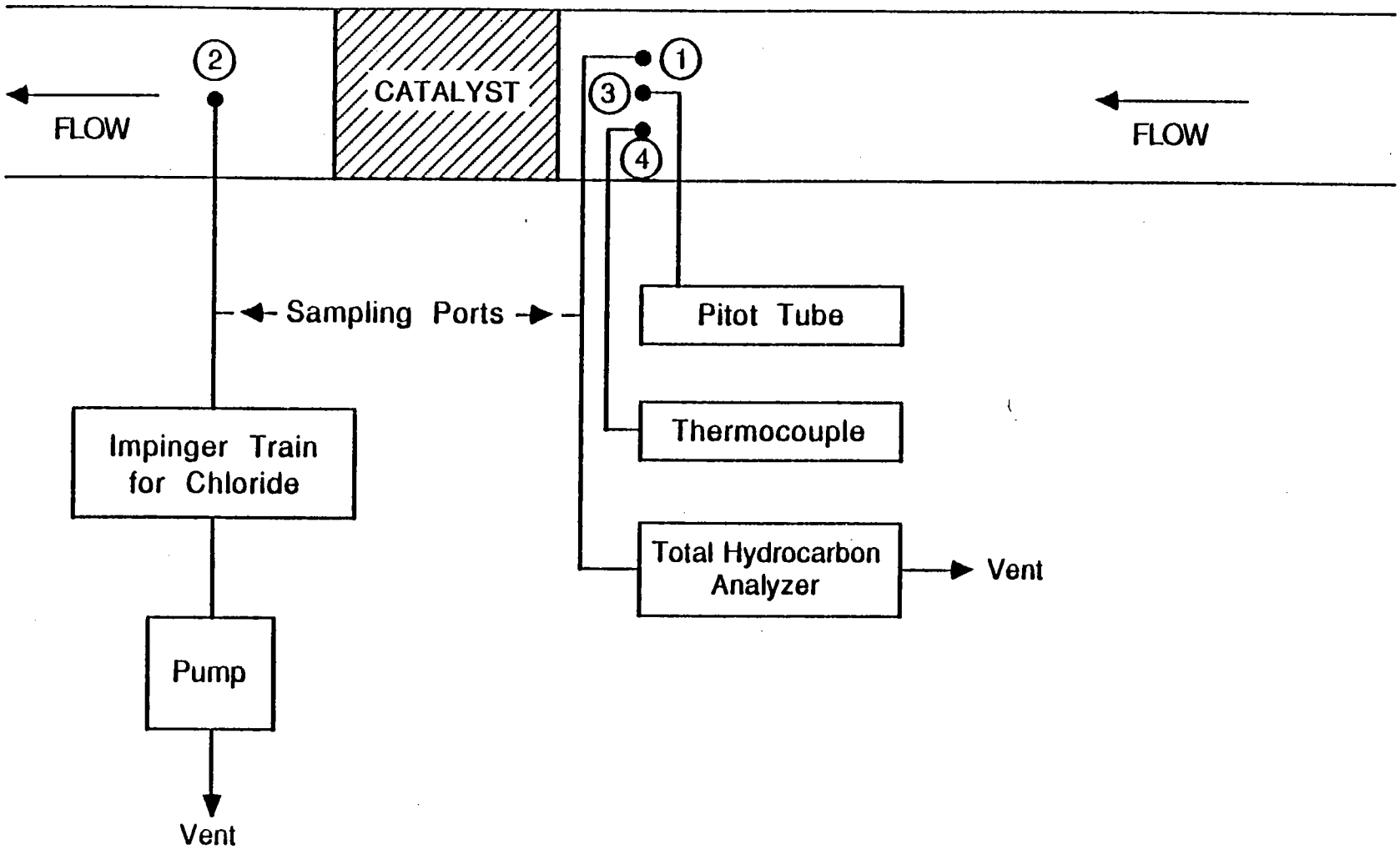

Figure 6-2. Schematic for sampling and analysis of catalytic oxidation system.

The first series of tests involved sampling the inlet and outlet streams of the catalyst system during the evacuation of the sterilizer. In a second series of tests, EO was added to the stream to simulate EO discharges from the sterilizer.

The extent of chlorofluorocarbon decomposition was determined by sampling the exhaust from the catalyst system and analyzing for chloride.

Drain water was sampled during sterilizer discharge and analyzed for EO. Attempts were made to determine the relative amounts of EO discharged from the sterilizer in both the air and water discharges.

Flow rate measurement was accomplished by employing standard, L-shaped pitot tubes, point 3. Prior to the testing of the catalyst system, the pitot tube was used to measure velocities along a traverse of the rectangular duct; velocity determinations were made at four points across the width of the duct. Although the flow volume from the sterilizer decreases during evacuation, the flow at the test point does not change significantly. Thus, the pitot tube-measured velocities are not significantly affected by this change in flow volume. An average flow rate was calculated based on these measurements. During the tests of the catalyst system, the pitot tube was placed at the center of the duct and velocity determinations were made at this point and correlated to the average flow rates. Temperature was measured by installing a thermocouple at point 4 (Figure 6-2).

From the measurements of EO concentration, temperature and flow rate, the EO destruction efficiency (E) was calculated based on the total amount of EO in the exhaust and the total amount of EO in the input stream. The EO destruction efficiency was calculated based upon the total mass of EO which entered the catalyst system and the total mass of EO which left the system:

$$E = \frac{(\text{Mass of EO}) \text{ in} - (\text{Mass of EO}) \text{ out}}{(\text{Mass of EO}) \text{ in}} \times 100$$

The mass of EO entering the system was determined from plots of EO concentration versus time, and flow rate, measured during the 10- to 15-min period when the exhaust gas from the sterilizer passed through the catalyst system. From these plots the total amount of EO entering the system was calculated.

6.3 RESULTS OF STERILIZER DISCHARGE EXPERIMENTS

The results of a representative sterilizer discharge experiment are shown in Figure 6-3, 6-4, and 6-5. Figure 6-3 shows the rapid buildup and decrease of the concentration observed at the inlet during the first sterilizer discharge. Very little EO was observed during the second sterilizer discharge because the sterilizer was very throughly evacuated during the first discharge. The shape of the EO concentration curve was verified using the THC data, which is presented in Figure 6-4.

The observed outlet concentrations are shown in Figure 6-5. Many of these concentrations were near the limit of detection which was 0.1 ppm.

The results of the sterilizer discharge experiments are summarized in Table 6-2. Detailed experimental results are presented in Appendix D and analytical procedures are presented in Appendix C.

The experiments indicated that the catalytic oxidation system operated at high efficiency, greater than 99%. However, as pointed out in the following section (Section 6.4) only about 10-13% of the EO in the sterilizer actually reached the oxidation system. A major fraction of the EO was apparently absorbed by the water which was used in the once-through vacuum pump.

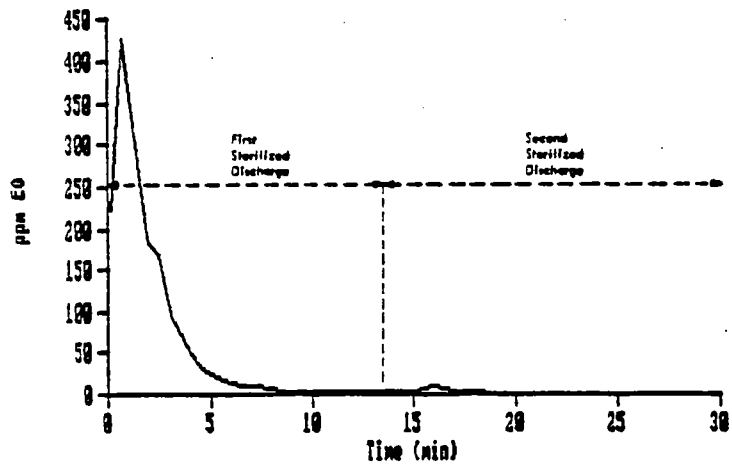

Figure 6-3. Catalytic oxidation system--sterilizer discharge study--inlet concentrations (run 4).

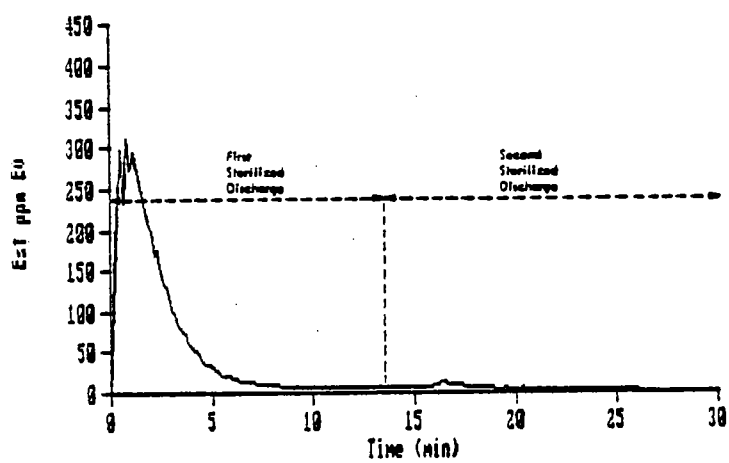

Figure 6-4. Catalytic oxidation system--sterilizer discharge study--inlet concentrations detected by total hydrocarbon analyzer (run 4).

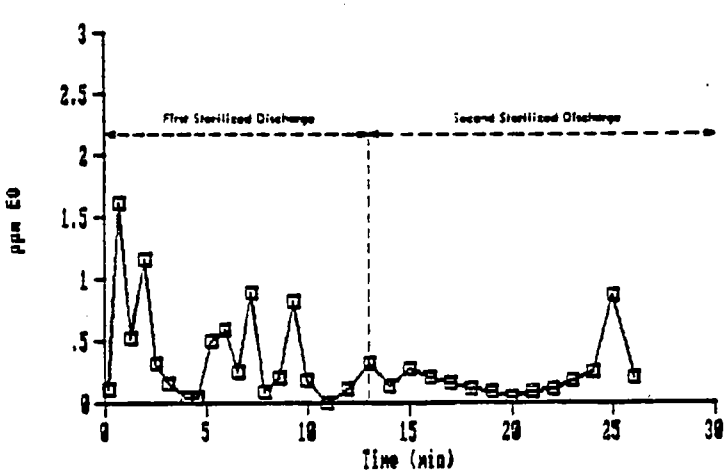

Figure 6-5. Catalytic oxidation system--sterilizer discharge study--outlet concentrations (run 4).

TABLE 6-2. RESULTS OF STERILIZER DISCHARGE STUDIES

Run No.	Total ethylene oxide to inlet (g)[a]	Total ethylene oxide from outlet (g)[a]	EO destruction efficiency
1	20.93	0.125	99.40
4	17.65	0.148	99.16
7	18.89	0.120	99.36

a The data from which these calculations were made are presented in Appendix D.

6.4 DETERMINATION OF ETHYLENE OXIDE IN VACUUM PUMP DRAIN WATER

Samples of water were collected at the sterilizer drain during the discharge of the sterilant gas. Since the concentration of EO was expected to vary widely with time, samples were taken frequently (about one per minute) during the first 5 min of the sterilizer discharge, and less frequently during the remainder of the sterilizer discharge. The water samples were placed in glass vials having lids equipped with polytetrafluoroethane seals. These samples were analyzed on-site by GC. Analytical procedures are presented in Appendix C.

The results of one of these experiments (run 1) are presented in Figure 6-6. The EO concentrations in the water were very much higher than expected (about 15,000 ppm maximum). The overall plot very closely paralleled the shape of the curve of the EO at the inlet of the catalytic oxidation system (see Figure 6-3).

These experiments are summarized in Table 6-3. Experimental details are presented in Appendix D and the analytical procedures are presented in Appendix C.

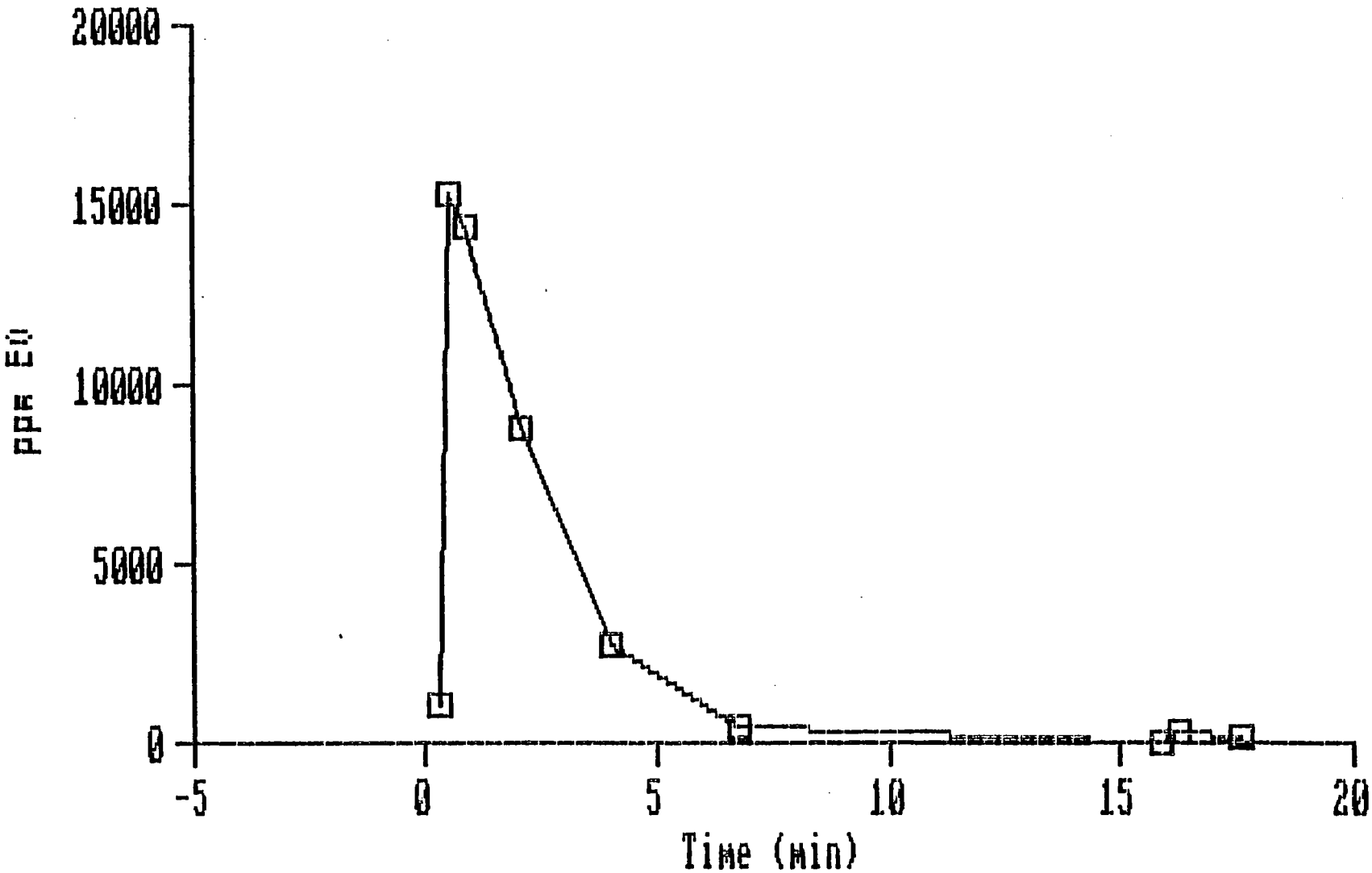

Figure 6-6. Catalytic oxidation system--sterilizer discharge studies. Concentrations of ethylene oxide in vacuum pump water discharge (run 1).

TABLE 6-3. ESTIMATED MATERIAL BALANCE (STERILIZER DISCHARGE STUDIES)

Run no.	Ethylene oxide in sterilizer (g)	Ethylene oxide to inlet (g)	Ethylene oxide to inlet (%)[a]	Ethylene oxide in water discharge (g)	Ethylene oxide in water discharge (%)[b]
1	163	20.93	12.8	127	78
4	165	17.65	10.7	101	61
7	168	18.89	11.2	-[c]	-[c]

a The data from which these calculations were made are presented in Appendix D.

b The percentages are based on the amount of ethylene oxide in the sterilizer.

c No water samples were taken in run 7.

The data in Table 6-3 indicate that, during the sterilizer discharge, only 10.7-12.6% of the EO in the sterilizer reached the oxidation system. An unexpectedly large proportion of the EO (61-78%) was discharged to the sewer in the water from the vacuum pump. Although during these tests the control unit did not process the total sterilizer EO charge, the determination of control efficiency was not affected. Later tests were conducted where EO equivalents to the total sterilizer charge were discharged through the control unit.

During these experiments, an examination of the sterilizer revealed that a gas-liquid separator had been installed in the line conducting water from the vacuum pump to the sewer. An unexpected observation was that the gaseous discharge from this separator, although originally designed to be ducted to the control device, was actually vented outside the hospital, bypassing the control device. It was not feasible to determine how much EO, if any, was discharged through this vent. However, the mass balance accounted for 72-91% of the EO, indicating that only a small fraction could have been vented.

A further unexpected observation was that the water flow rate from the vacuum pump was substantially lower than expected. The design flow rate of the vacuum pump is 2.6 gallons per minute (gpm), and the measured flow rate was approximately 0.9 gpm.

6.5 DETERMINATION OF CATALYST EFFICIENCY BY ADDING ETHYLENE OXIDE TO SYSTEM

Additional experiments were performed in order to supplement the analytical data obtained during sterilizer discharge. EO was added (at a controlled rate) to the system at a point located upstream from the catalyst system. Sufficient EO was added to bring the concentration of the stream to selected levels of EO. Three levels, 125-250 ppm, 400-600 ppm, and 750-1,500 ppm were tested. These concentrations were maintained for 3-5 min, allowing multiple samples to be taken on each side of the catalyst. The feed stock for the EO additions was the sterilizing mixture (12/88).

The experimental procedures were practically identical to those described for the test of the catalyst system during sterilizer discharge (refer to Section 6.2). The EO was added to the system using a calibrated rotameter and the THC analyzer was used as before. As in the other studies, samples were taken on each side of the catalyst at approximately 40-sec intervals. Temperature and flow rate were also determined as in the sterilizer discharge studies.

The results of a representative EO-addition experiment (run 5) are presented in Figures 6-7, 6-8, and 6-9. Figure 6-7 shows the inlet concentrations detected by the GC analyses; Figure 6-8 shows the analogous THC data. Figure 6-9 shows the outlet concentrations detected by GC.

The results of this experiment and the other EO-addition experiments are summarized in Table 6-4. All of the experiments indicated high EO destruction efficiencies, 99.8% or better.

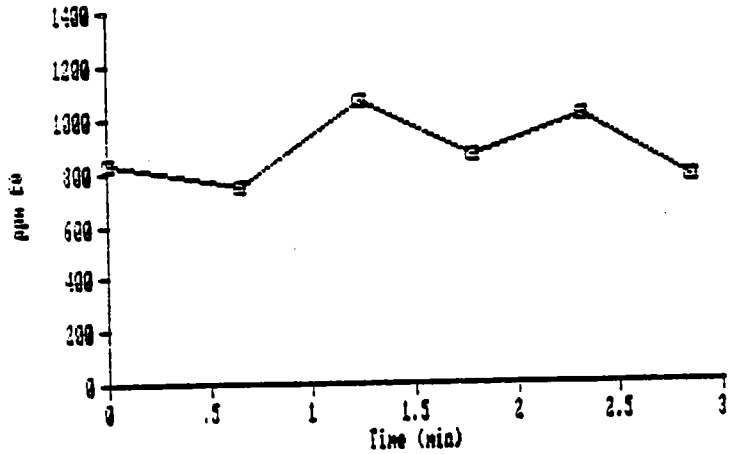

Figure 6-7. Catalytic oxidation system--ethylene oxide addition studies--inlet concentrations (run 5).

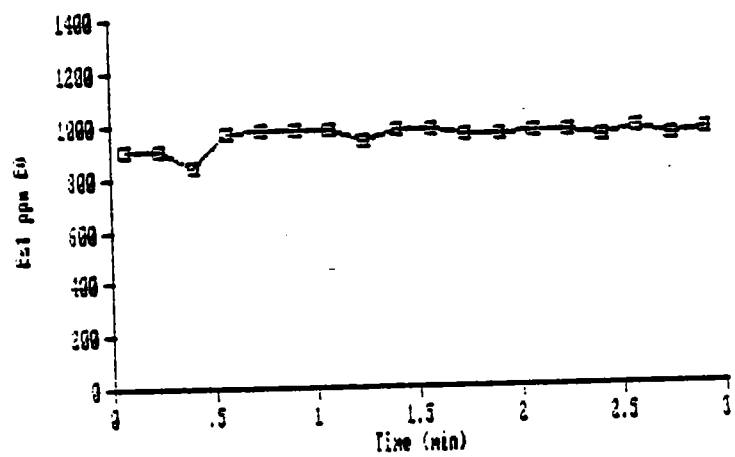

Figure 6-8. Catalytic oxidation system--ethylene oxide addition studies--inlet concentrations detected by total hydrocarbon analyzer (run 5).

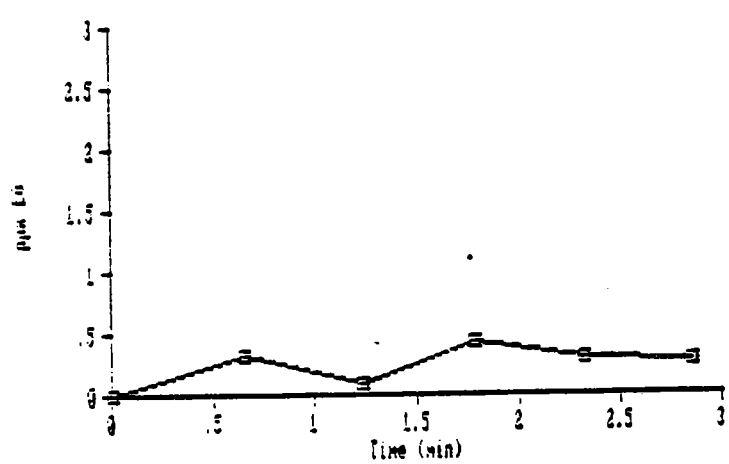

Figure 6-9. Catalytic oxidation system--ethylene oxide addition studies--outlet concentrations (run 5).

TABLE 6-4. ETHYLENE OXIDE DESTRUCTION EFFICIENCY DETERMINED BY ADDING ETHYLENE OXIDE (EO) TO SYSTEM

Run no.	EO concentration at inlet (ppm)	Total EO to inlet (g)[a]	Total EO from outlet (g)[a]	EO destruction efficiency (%)
2	125-250	12.43	0.014	99.89
3	400-600	40.53	0.039	99.93
5	750-1,100	48.67	0.014	99.97
6	750-1,500	52.24	0.012	99.98

a The data from which these calculations were made are presented in Appendix E.

An important significance of these experiments is that they demonstrate that the catalytic oxidation system was capable of operating very efficiently at concentrations of sterilizer gases comparable to those developed if the total discharge from the sterilizer were directed into the system. (The results of the sterilizer discharge studies (Table 6-3) showed that less than 13% of the sterilizer discharge had reached the catalytic oxidation system.)

Additional details concerning these experiments are presented in Appendix E and the analytical procedures are described in Appendix C.

6.6 TESTS FOR CHLOROFLUOROCARBON DECOMPOSITION

The EO used for sterilization contains 88% by volume of the chlorofluorocarbon (CFC) dichlorodifluoromethane (CF_2Cl_2). The possible thermal decomposition of the CFC at excessively high catalyst temperatures could result in the emission of several highly toxic and highly corrosive materials such as hydrogen chloride, hydrogen fluoride, phosgene ($COCl_2$), and chlorine. The extent of this decomposition was tested by analyzing samples of the catalyst exhaust stream for chloride during periods when the catalyst temperature was

high. Maximum catalyst temperatures occur immediately after the highest concentrations of EO pass through the catalyst.

The sample stream was the same as that used to measure EO on the exhaust side of the catalyst (see point 2, Figure 6-2). The stream was passed through an impinger containing 0.1 N sodium carbonate. The alkaline samples were analyzed for chloride using ion chromatography (analytical procedures are presented in Appendix C).

The results of the chlorofluorocarbon decomposition tests are presented in Table 6-5. No chloride was detected in any of the samples; the detection limit was 200 ppb. Apparently no decomposition of the CF_2Cl_2 occurred. Additional experimental details are presented in Appendix F.

TABLE 6-5. RESULTS OF CHLOROFLUOROCARBON DECOMPOSITION TESTS

Run no.	Maximum catalyst temperature (°F)	Total weight of CF_2Cl_2 through system (kg)	Maximum possible CF_2Cl_2 decomposition (µg)	Maximum possible CF_2Cl_2 decomposition (%)[a]
1	283	1.20	< 518	$< 4 \times 10^{-5}$
2	287	0.104	< 67	$< 6 \times 10^{-5}$
4	299	1.21	< 408	$< 3 \times 10^{-5}$
5	311	0.41	< 16	$< 4 \times 10^{-6}$
7	282	1.24	< 262	$< 2 \times 10^{-5}$

a No chloride was detected at a limit of detection of 200 ppb. Apparently no decomposition of the CF_2Cl_2 occurred. Additional experimental details are presented in Appendix F.

SECTION 7.0

COST ESTIMATES FOR CATALYTIC OXIDATION SYSTEM

Capital and operating costs for the catalytic oxidation system have been estimated from data provided by the hospitals where they have been installed, other hospital contacts, the control device vendors, and observations made during site visits to the installation. A summary of the projected costs is presented in Table 7-1.

Because there are only two hospital installations available for study (Children's Hospital of Philadelphia and Paoli Memorial Hospital, Paoli, PA), and the technology in question is very new, the cost estimates presented here remain approximate and may not accurately reflect the costs for future installations. A discussion of both capital and operating costs is presented below.

7.1 CAPITAL COSTS

Capital cost estimates for this control device vary widely from source to source. The equipment costs estimate provided for the unit at the Children's Hospital of Philadelphia (a 1,500-cfm unit with an economizer) is $25,000. The estimate provided by Paoli Memorial Hospital for their unit (a 500-cfm unit without an economizer) is $40,000. Installation costs depend entirely on the specific site. Thus, based on these installations, absolute flow rate is not necessarily indicative of total system costs. Installation cost factors include: the design airflow of the unit's fan (determines duct size), the availability of space near the sterilizer, proximity of the unit to an outside wall (determines the length of duct work required), the number of sterilizers

TABLE 7-1. COST ESTIMATES FOR THE CATALYTIC OXIDATION SYSTEM

Capital Costs	
Equipment Cost:	$25,000 to $40,000
Installation Costs:	$ 5,000 to $10,000
Total Equipment Cost:	$30,000 to $50,000
Annual Operating Costs	
Steam for Preheater:	$3,900 to $12,300
Electricity for Fan:	$ 580 to $ 1,740
Annualized Catalyst Replacement:	$ 800 to $ 1,330
Annualized Prefilter Replacement:	$ 25
Maintenance Labor (12 hr @ $35/hr):	$ 420
Estimated Total Annual Operating Cost:	$5,725 to $15,815

and aerators connected to the system, the materials of construction, and Table 7-1 other factors. The costs of installation presented in Table 7-1 are based on estimates provided by the hospitals that have installed the unit and are approximately 20-25% of the purchased equipment cost.

7.2 OPERATING COSTS

An analysis of the catalytic oxidation unit's operating costs has identified four major cost items: (1) the cost of steam to preheat the incoming air, (2) the cost of electricity to run the fan, (3) the cost of catalyst and prefilter replacement, and (4) the labor cost of maintenance. A summary of operating costs is presented in Table 7-1, and a more detailed discussion of each follows.

7.2.1 Cost of Steam

In both hospital installations the catalytic oxidation unit requires steam supplied to a heat exchanger to preheat the incoming air to proper temperatures for catalysis. The recommended operating temperature is 275° to 300°F (135°-150°C). The units in both hospitals are kept at this operating temperature 24 hr/day, 360 days/year. The cost to the hospital for steam generation varies depending on the type and size of steam generating process, and the cost of fuel. The cost to produce steam at the Children's Hospital of Philadelphia is approximately $9/1,000 lb of steam.[1] Another estimate from Rex Hospital in Raleigh, North Carolina was $5.20/1,000 lb.[2] The smaller Paoli Hospital unit (500 ft^3/min) requires approximately 1.5 lb of steam to heat 500 ft^3 of air every minute of operation.[3] For the Children's Hospital unit (1,500 ft^3/min), which must heat three times the amount of air, the steam usage is greater. However, the Children's Hospital unit also has had an economizer installed as an option. The economizer is a heat exchanger that uses the waste heat from the outlet gases to preheat the incoming air. This reduces steam usage by an estimated 40%.[3] Thus, the Children's Hospital unit uses approximately 2.6 lb of steam per minute to heat the incoming air. These steam usage figures were multiplied by the range of steam costs ($5.20 and $9/1,000 lb of steam) to determine the range of expected steam costs for both units presented in Table 7-1.

7.2.2 Cost of Fan Power

The cost of moving 500-1,500 ft^3 of air per minute was calculated using the cost equations contained in Reference 4. The range presented in Table 7-1 represents the Paoli Hospital unit and the Children's Hospital unit, respectively.

7.2.3 Annualized Catalyst and Prefilter Replacement Costs

The cost of catalyst for the catalytic oxidation unit is approximately $2,000/cell, installed.[5] Both hospital units have two catalyst cells. Thus, the replacement cost is estimated to be $4,000/unit. Neither hospital has had

to replace the catalyst beds as of yet with more than a year of operating time in the case of the Children's Hospital unit. The estimated catalyst life, provided normal operating parameters are maintained, is from 3-5 years.[5] Therefore, range of costs in Table 7-1 were calculated by annualizing the catalyst replacement cost over the expected 3- to 5-year catalyst life.

In addition, the units prefilter will need replacement every 3 years at a cost of $75.[5] This adds approximately $25 to the annual operating costs of the unit.

7.2.4 Maintenance Labor Costs

According to hospital sources at hospitals where the catalytic oxidation system has been installed, the unit has required virtually no time for maintenance.[1,6] However, as the units require catalyst or prefilter replacements or normal fan maintenance, a nominal maintenance estimate of 1 hr per operating month was applied to the annual operating cost. The net cost of 12 hr of labor at $35/hr is reflected in Table 7-1.

7.3 REFERENCES FOR SECTION 7.0

1. Telecon. B. Nicholson, MRI, with R. Ewing, Children's Hospital of Philadelphia. August 5, 1987. Capital costs and energy requirements of the catalytic oxidation system.

2. Telecon. B. Nicholson, MRI, with W. Tice, Rex Hospital, Raleigh, North Carolina. August 10, 1987. Cost of steam at Rex Hospital.

3. Memorandum from B. Nicholson to Ethylene Oxide Demonstration Project Files. August 13, 1987. Calculations for cost estimation.

4. Neveril, R. B., GARD, Inc. Capital and Operating Costs of Selected Air Pollution Control Systems. Prepared for U.S. Environmental Protection

Agency, Research Triangle Park, North Carolina. Publication No. EPA-450/5-80-002. December 1978.

5. Telecon. B. Nicholson, MRI, with P. Coward, Coward-Eastman, Inc., Gloucester, New Jersey. August 11, 1987. Costs and replacement schedules for the catalytic oxidation system.

6. Telecon. B. Nicholson, MRI, with B. Fahey, Paoli Memorial Hospital, Paoli, Pennsylvania. August 10, 1987. Capital and operating cost of the catalytic oxidation system.

SECTION 8.0

TESTS OF ACID-HYDROLYSIS SYSTEM

A full-scale acid-hydrolysis system was tested under laboratory conditions which closely simulated a system which could be used for hospital sterilizers. The primary goal was to determine the EO destruction efficiency of the system. Experiments were performed in which a sterilizer discharge was conducted through the system, and in other experiments, the sterilizer gas (12/88) was added directly to the system. In both types of tests, the observed EO destruction efficiency was very high, greater than 99.99% in all of the experiments. When the sterilizer was discharged to the system, the data indicate that substantial quantities of EO were being absorbed by the sealant liquid of the vacuum pump and subsequently released when the pump was purged with air on the second sterilizer evacuation. A summary of the acid-hydrolysis system experiments is presented in Table 8-1.

8.1 THE ACID-HYDROLYSIS SYSTEM

A schematic of the acid-hydrolysis system is shown in Figure 8-1. The system uses sulfuric acid solution at pH 1.0 to absorb gaseous EO into the liquid phase, where it reacts to form ethylene glycol (EG). The reaction is acid-catalyzed, so there is no net loss of acid as the EO is reacted to form EG. The gas is drawn from the sterilizer using a two-stage liquid-ring vacuum pump which uses EG as the sealant liquid. The sealant liquid and 12/88 gas are then separated, and the sealant liquid is conducted to a reservoir and returned for reuse as sealant in the pump. This recycle eliminates the discharge of liquid and prevents drain area EO emissions. The 12/88 gas exits

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TABLE 8-1. SUMMARY OF EXPERIMENTS - ACID HYDROLYSIS SYSTEM[a]

Run no.	Objective	EO concentrations at inlet (%)[b]	Observed EO destruction Flow rate (scfm)[c]	efficiency (%)
1	EO addition study	17.55-24.37	2.5	> 99.999
2	EO addition study	19.22-22.67	2.5	> 99.999
3	EO addition study	21.05-24.38	2.5	> 99.999
4	Sterilizer discharge study	3.40-8.38	0.31-1.52	> 99.998
5	Sterilizer discharge study	1.92-10.92	0.34-1.56	> 99.998
6	Sterilizer discharge study	4.21-13.95	0.11-1.56	> 99.995
7	Sterilizer discharge study	5.16-10.66	0.33-1.41	> 99.998

a Two kinds of experiments were performed. In the sterilizer discharge studies the sterilizer was allowed to discharge into the acid-hydrolysis system. In the EO addition studies, EO (12/88) was introduced from a cylinder into the acid hydrolysis system.

b In the EO addition studies, the EO concentrations were selected to simulate typical sterilizer discharge concentrations. These concentrations were not realized in the sterilizer discharge studies because of EO absorption by the fluid in the vacuum pump (see text).

c In the EO addition studies, the flow rate was selected based upon the flow rate capacity of the acid hydrolysis system. In the sterilizer discharge studies, the flow rates varied because the sterilizer was being gradually evacuated.

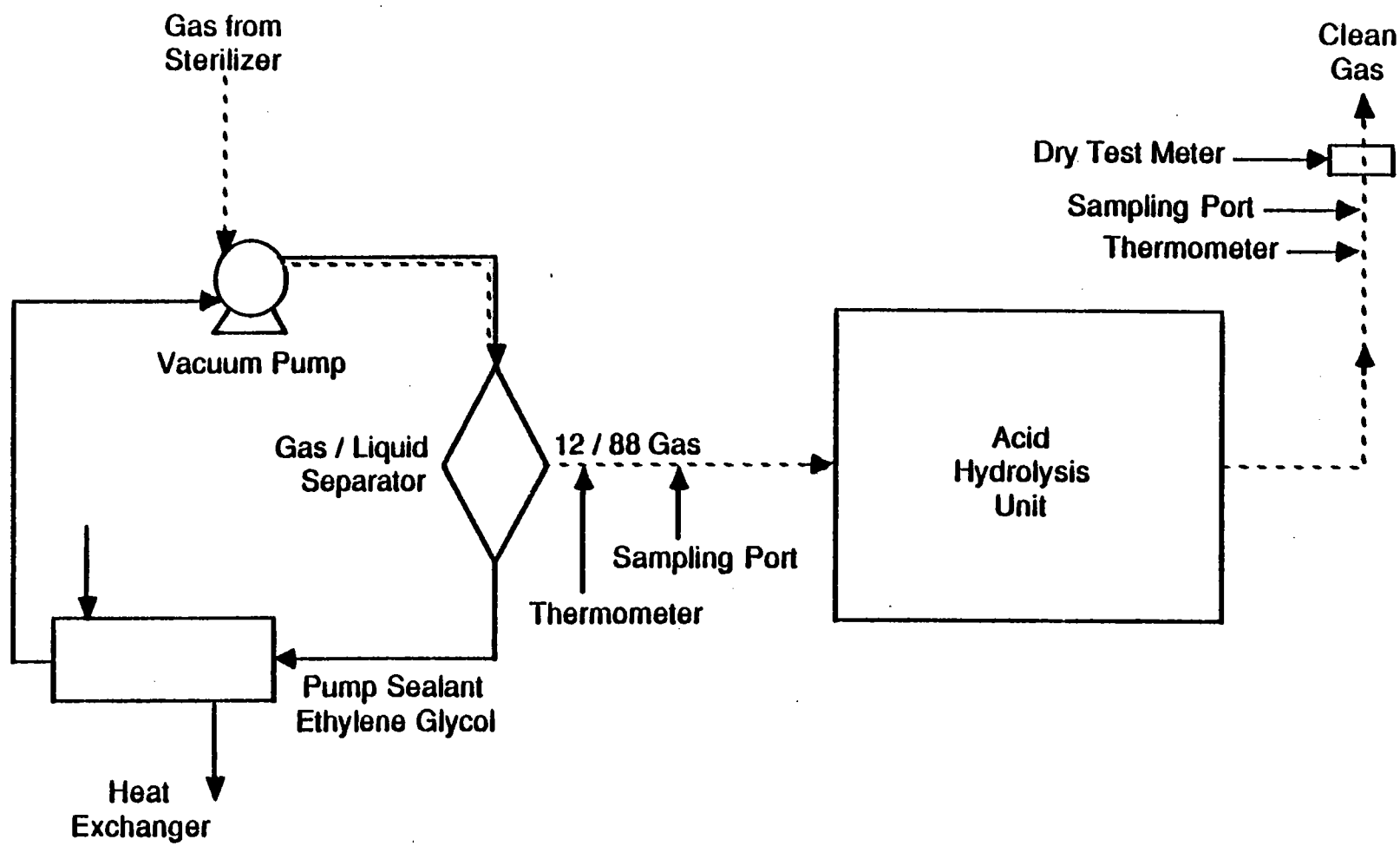

Figure 8-1. Schematic of acid-hydrolysis system showing sampling and analysis locations.

the pump and is conducted to the bottom of a packed tower. All of the gas from the sterilizer is conducted into the control device, and no fraction is discharged down the drain. The two-step absorption/reaction process begins in the packed tower, as the highly soluble EO is absorbed into the water and is hydrolyzed to EG. Almost all of the chlorofluorocarbon (CFC) remains in the gas stream because of its relative insolubility in water. Clean, almost EO-free gas exits the top of the column, and the acid/water/glycol solution exits the bottom to a reaction/storage vessel where there is sufficient retention time for the EO to completely hydrolyze. Fresh, EO-free solution is recycled to the top of column (still at pH = 1.0). The ethylene glycol slowly builds up in the liquor to approximately 60 wt %.

For maximum efficiency, the gas flow rate to the system is limited to a selected maximum flow, in this case, 2.5 scfm.

8.2 DESCRIPTION OF THE EXPERIMENTS

The objectives of the experiments were to determine flow rates and EO concentrations immediately upstream and downstream of the system in order to calculate the EO destruction efficiency of the system.

Seven experimental measurements of the effectiveness of the system were conducted. Four experiments involved system operation during sterilizer discharge, and three were done in which 12/88 was added to the system. A schematic of the sampling and analysis system is shown in Figure 8-1. The primary sampling points were located on either side of the system. The sample streams were drawn through polytetrafluoroethylene tubing to sample ports, which consisted of rubber septums located in the lines.

Determination of the total EO mass flow required simultaneous measurement of EO concentration and total gas stream flow rate. EO concentrations were measured by pulling syringe samples from the stream and analyzing them on site using a gas chromatograph (GC).

In all of the experiments, it was necessary to sample very rapidly, as often as every 40 sec. The response time of the GC, which was about 3.0 min, did not allow all of the samples to be taken and analyzed immediately. Therefore, samples were taken at each location and analyzed as soon as possible after collection in the order sampled. Glass syringes were used.

The analysts took samples from each side of the system, beginning when the sterilizer gas reached the system. Sampling stopped when the gas flow stopped.

The flow rate through the scrubber was measured using a calibrated dry test meter (Figure 8-1). The flow rate at the inlet was calculated based on the flow rate at the outlet, subtracting the amount of EO removed. The dry test meter was read at the same time that the samples were taken.

From the measurements of EO concentration, temperature, and flow rate, the EO destruction efficiency was calculated based on the total amount of EO which entered the system and the total amount which left the system.

8.3 RESULTS OF STERILIZER DISCHARGE EXPERIMENTS

The results of the sterilizer discharge experiments are summarized in Table 8-2, and additional details are presented in Appendix G. Four runs were made, and the results of a typical run (run 4) are presented in Figures 8-2 and 8-3. Figure 8-2 shows the EO concentrations detected in the inlet samples. Figure 8-3 shows the flow rate from the sterilizer to the inlet during the two evacuation cycles. A combination of the data in Figures 8-2 and 8-3 yields the total amount of EO which went into the system (see Table 8-2). No EO was detected in the outlet (except for an anomaly discussed below) where the detection limit was 1 ppm. As shown in Table 8-1, the observed EO destruction efficiency was greater than 99.99% in all experiments.

TABLE 8-2. SUMMARY OF STERILIZER DISCHARGE EXPERIMENTS[a]

Run no.	EO concentrations at inlet (%)	Flow rate (scfm)	EO into system (g)	EO emissions from system		Observed EO destruction efficiency (%)
				ppm	mg	
4	3.40-8.38	0.31-1.52	38.8	< 1	< 0.8	> 99.998
5	1.92-10.92	0.34-1.56	51.3	< 1	< 0.7	> 99.998
6	4.21-13.95	0.11-1.56	86.2	< 1	< 4.4	> 99.995
7	5.16-10.66	0.33-1.41	58.3	< 1	< 0.8	> 99.998

a Additional experimental data are presented in Appendix G.

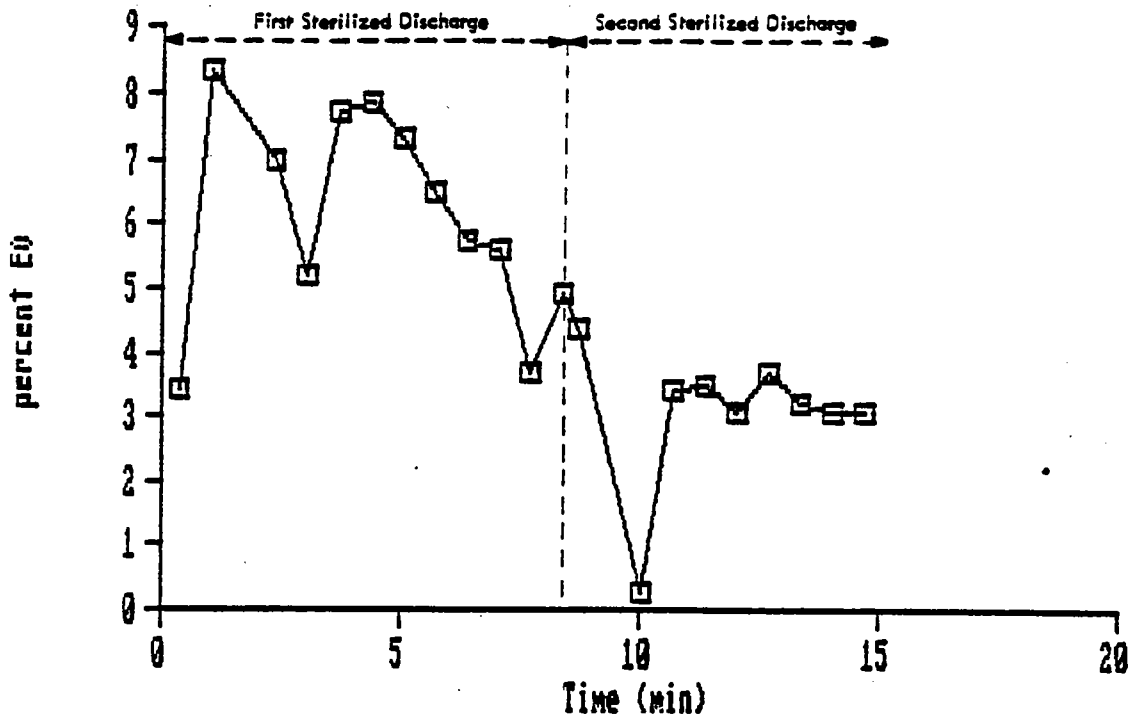

Figure 8-2. Acid hydrolysis system--sterilizer discharge studies--inlet concentration (run 4).

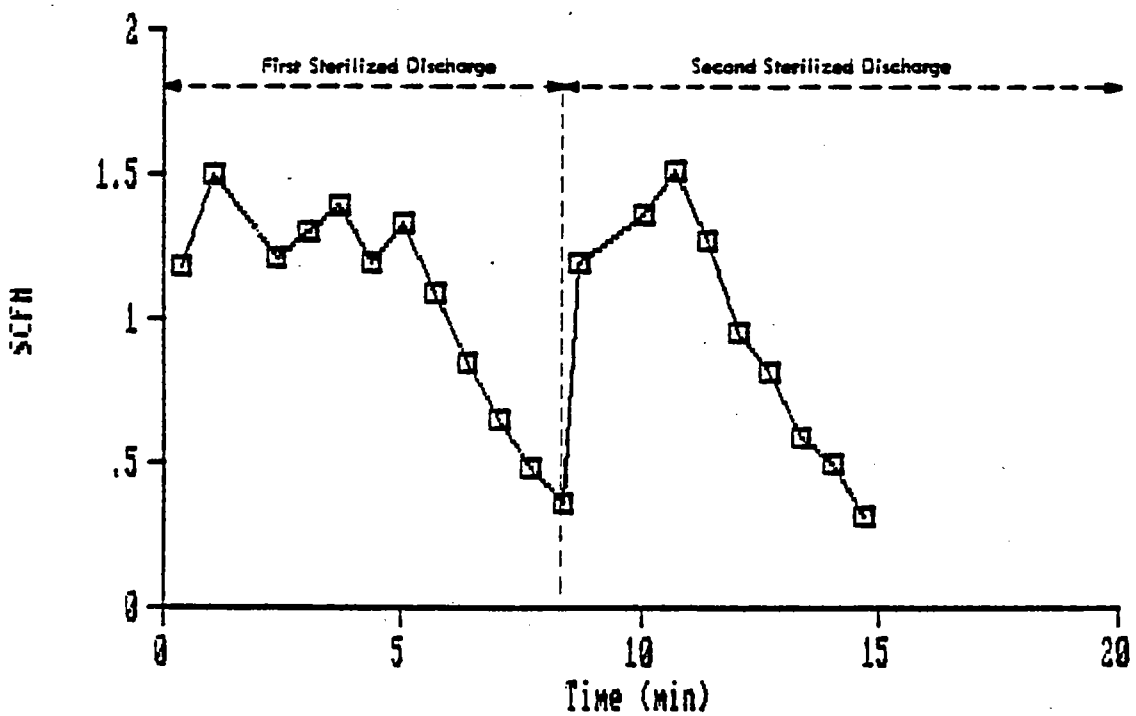

Figure 8-3. Acid hydrolysis system--sterilizer discharge studies--inlet flow rate (run 4).

There were several unexpected observations which indicated that EO was being absorbed by and released from the sealant liquid of the vacuum pump. The pump was a recirculating, liquid-ring vacuum pump which used ethylene glycol (16 gal.) as the sealant liquid.

The first observation was the fact that the EO concentration at the inlet during the first evacuation cycle did not approach the expected concentration of 12/88, which is about 26%. This concentration should have been relatively constant during the sterilizer discharge. In a typical experiment, as shown in Figure 8-3, this concentration varied widely between about 3 and 8.5%. Similar observations were made in all of the sterilizer discharge experiments and indicate that EO was being absorbed by the sealant liquid. The vacuum pump was serving as a scrubber during the first evacuation by mechanically mixing the EO with the sealant liquid.

During the second evacuation, the EO concentration would also be expected to be constant, but less than about 0.1%, because the sterilizer had been thoroughly evacuated during the first evacuation cycle, then returned to atmospheric pressure by allowing air to reenter the sterilizer chamber. As seen in Figure 8-3, the EO concentrations during the second evacuation were unexpectedly high and variable, between 0.24 and 3.7%. Similar observations were made in all of the experiments (see Appendix G) and can best be explained by release of EO from the sealant liquid. During the second evacuation, the sealant liquid (rich in EO from the first evacuation) is mechanically mixed with the incoming air (very lean in EO). Thus the pump serves to strip the EO from the pump sealant during the second evacuation.

There are two other facts which support the concept that substantial quantities of EO became dissolved in the pump fluid:

1. In all of the experiments, the total amount of EO that reached the inlet of the scrubber represented only 25-56% of the EO charged to the sterilizer. These data are presented in Table 8-3. There appears to be no other explanation for this loss of EO.

TABLE 8-3. STERILIZER DISCHARGE STUDIES--ETHYLENE OXIDE MATERIAL BALANCE[a]

Run No.	EO into sterilizer (g)	EO into system: First evacuation (g)	EO into system: Second evacuation (g)	EO into system: Total (g)	Percent of sterilizer charge (%)
4	150	29.5	9.3	38.8	25.4
5	153	34.7	16.5	51.3	33.5
6	153	58.7	27.3	86.2[b]	56.3
7	155	40.0	18.8	58.3	37.9

a Additional experimental data are presented in Appendix G.

b At the end of run 6, the pump was allowed to run for an additional 30 min with the sterilizer open to the atmosphere. This procedure allowed air to pass through the vacuum pump and into the inlet of the system. Analytical data from samples taken at the inlet show that 116 g of EO had been eluted from the sealant liquid (ethylene glycol) of the pump (see Appendix G).

2. Elution of the pump liquid with pure air resulted in high concentrations of EO in the outlet gases and relatively large total quantities of EO (see footnote to Table 8-3). The source of this EO must be release of EO by the sealant liquid.

Before the start of run 6, the sterilizer was inadvertently allowed to discharge at a time when the system was not operating. This allowed high concentrations of EO (5-10%) to come in contact with the outlet area of the system. This EO dissolved in moisture known to be present in the outlet area and resulted in contamination of subsequent outlet samples taken during run 6 (see Appendix G). EO concentrations in the range 5-25 ppm were detected during this run; no EO had been detected in the outlet during the previous runs.

The outlet area was thoroughly purged with nitrogen gas and air, and run 6 was repeated (run 7). As in runs 4 and 5, no EO was detected in the outlet during run 7.

8.4 RESULTS OF EXPERIMENTS IN WHICH ETHYLENE OXIDE WAS ADDED DIRECTLY TO ACID-HYDROLYSIS SYSTEM

Additional experiments were performed to supplement the analytical data obtained during sterilizer discharge. Ethylene oxide was added (at a controlled rate) to the system at a point located upstream from the system. The flow rate was maintained for approximately 7 min, allowing multiple samples to be taken on each side of the system.

The selected flow rate level was based upon the flow rate capacity of the system, which was approximately 2.5 cfm. The feedstock for the EO additions was the sterilizing mixture (12/88). The test procedures were very similar to the tests of the system during sterilizer discharge. The EO was added to the system using an evaporator device and a calibrated rotameter. As in the other studies, samples were taken on each side of the system at approximately 40-sec intervals. Temperature and flow rate were also determined as in the sterilizer discharge studies.

The results of these studies are presented in Table 8-4 and in Appendix H. As indicated in Table 8-4, all of the tests showed very high EO destruction efficiencies, greater than 99.999%. No EO was detected in the outlet of the scrubber, and the limit of detection was 1 ppm.

TABLE 8-4. SUMMARY OF EXPERIMENTS IN WHICH ETHYLENE OXIDE WAS ADDED DIRECTLY TO THE ACID-HYDROLYSIS SYSTEM[a]

Run No.	EO concentration at inlet (%)	Flow rate (scfm)	EO into system (g)	EO emissions from system (ppm)	EO emissions from system (mg)	Observed EO destruction efficiency (%)
1	17.55-24.37	2.5	190	< 1	< 0.8	> 99.999
2	19.22-22.67	2.5	56	< 1	< 0.2	> 99.999
3	21.05-24.38	2.5	213	< 1	< 0.8	> 99.999

a Additional data are presented in Appendix H.

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SECTION 9.0

COST ESTIMATE FOR ACID-HYDROLYSIS SCRUBBING SYSTEM

This type of control device is less developed than catalytic oxidation, and although a pilot unit is installed at a hospital, the final design of the hospital unit remains unfixed at this date. Therefore, the costs estimated here are primarily costs provided by the system vendors. A summary of the operating cost estimates is presented in Table 9-1.

9.1 CAPITAL COSTS

A base equipment cost estimate of $15,000 has been supplied by the vendor of the hospital scrubber which was tested.[1] However, the vendor recommends installing a recirculating vacuum pump to replace the current once-through vacuum pump or water ejector currently on most sterilizers. Doing so eliminates drain emissions which, as shown by test data presented in Section 6.0, can be a significant EO emission source. With a recirculating vacuum pump the equipment cost is estimated to be approximately $20,000.[1] These cost estimates represent target prices for the vendor and have not yet been firmly established. Installation cost was estimated at 20-30% of the equipment cost. The hospital system can only treat the discharge of one sterilizer at a time. However, if a hospital has multiple sterilizers they can all be ducted to the system as long as the sterilizers are timed so as not to discharge simultaneously.

TABLE 9-1. COST ESTIMATES FOR ACID-HYDROLYSIS SYSTEM

	Small	Large
Capital Costs		
Equipment Cost:	$15,000 - 20,000	$15,000 - 20,000
Installation Cost:	4,000 - 6,000	4,000 - 6,000
Total Equipment Cost:	$19,000 - 26,000	$19,000 - 26,000
Annual Operating Cost		
Shipping Spent Solution to Vendor for Disposal:[a]	32 - 114	590 - 2,125
Replacement Solution (Materials and Shipping):[a]	35 - 117	648 - 2,183
Maintenance Labor Cost (Estimated):	500	1,675
Pump Electricity:	8	40
Estimated Total Annual Operating Cost:	$ 575 - 739	$ 2,953 - 6,023

a Shipping costs estimated using information from Reference 3.

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9.2 ANNUAL OPERATING COSTS

As shown in Table 9-1, the operating costs associated with the hospital system include the costs of spent solution disposal, the cost of Table 9-1 solution replacement, the cost of labor for maintenance and operation, and the cost of electricity for the pump that recirculates the fluid in the system. Each of the operating costs is discussed in more detail below.

9.2.1 Disposal and Replacement Costs

The predominant operating costs for the acid-hydrolysis system are for replacement solution and disposal of spent liquor. The cost of these functions is directly related to the amount of EO used by the hospital. In order to produce a range of operating costs, model hospitals were developed for evaluation (see Table 9-2). The small hospital model is represented by one small sterilizer (9.0 ft^3) operating once per day 360 times per year. This sterilizer is typically charged with 2.5 lb of 12/88 (0.3 lb of which is EO). Thus, total annual EO consumption is 108 lb/year. For the large model hospital, represented by two large sterilizers (30 ft^3) and one small sterilizer (9.0 ft^3), the EO consumption is approximately 2,016 lb annually.

The system can absorb and convert approximately 450 lb of EO to ethylene glycol before the scrubbing solution must be replaced.[1] The number of replacements required annually can be determined by dividing the annual EO consumption by the system capacity. Once the recirculating solution reaches approximately 60% ethylene glycol by weight, the spent solution must be disposed of and fresh solution replaced.

Although the solution at the time of disposal is not classified as a hazardous waste, it is still highly acidic and must be neutralized prior to discharge. However, most hospitals will lack the capability for performing the neutralization and discharge themselves. For this reason, the vendor of the technology investigated an approach to both disposal and replacement that will place a minimum of technical capability burden on hospitals. According to this approach, hospitals will ship the spent solution back to the vendor

TABLE 9-2. MODEL HOSPITAL PARAMETERS FOR ACID-HYDROLYSIS OPERATING COST ESTIMATION

Type of model EO consumer	Chamber size (ft^3)	Number of chambers	EO emissions per cycle per chamber (lb)	Cycles per year per chamber	Annual EO consumption (lb/yr)
Small	9	1	0.3	360	108
Large	30	2	1.0	900	1,800
	9	1	0.3	720	216
		3			2,016

where the neutralization and either reuse or disposal operations will take place. This approach avoids the necessity of hospital personnel neutralizing the highly acidic solution with concentrated caustic. If this disposal solution is not available, then each hospital must be prepared to accept disposal responsibility for waste scrubbing liquid.

In the past, solutions of this kind have been accepted by publicly owned treatment works (POTWs), provided that a chemical analysis of the spent solution is completed prior to discharge.[1] At large hospitals, where frequent solution replacements will be necessary, the shipping costs may become high enough to encourage the hospital to neutralize their own solution and discharge it to their local POTW.

The cost ranges presented in Table 9-1 only represent the case where a hospital will ship the solution to the vendor for disposal. However, even if the hospital disposed of the solution themselves, the hospital would need to pay the cost of a fresh solution. Since the raw materials for the solution are inexpensive, the cost of the replacement solution will almost equal the cost to ship the solution from the vendor to the hospital. Thus the shipping expenses cannot be eliminated by on-site neutralization and disposal.

9.2.2 Maintenance Labor Costs

The labor cost associated with the hospital acid-hydrolysis system was estimated using two components, a monthly inspection, and labor associated with solution replacement. Inspection time of 1 hr monthly was estimated to be necessary. For solution replacement, the labor required to ship the spent solution and order and receive the fresh solution was estimated to be 8 hr.

9.2.3 Pump Electricity

The energy costs for the acid-hydrolysis system are very low compared to the catalytic oxidation system. Essentially, the only energy cost is the

electricity for the pump which circulates the acid solution. The pump capacity is 1 hp or less according to the vendor, and it runs only during the sterilizer discharge. Electricity requirements for this pump were estimated to be $8 annually for the small model hospital and $40 annually for the large hospital.[2]

9.3 REFERENCES FOR SECTION 9.0

1. Telecon. B. Nicholson, MRI, with confidential vendor. August 17, 1987.

2. Neveril, R. B., GARD, Inc. Capital and Operating Costs of Selected Air Pollution Control Systems. Prepared for U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. Publication No. EPA-450/5-80-002. December 1978.

3. Telecon. B. Nicholson, MRI, with D. McCollen, Yellow Freight Systems, Inc., Durham, North Carolina. August 17, 1987. Shipping costs for ethylene glycol.

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APPENDIX A

CHEMICAL REACTIONS OF ETHYLENE OXIDE RELEVANT TO POTENTIAL STERILIZER EMISSION CONTROL OPTIONS

Oxidation and hydrolysis are discussed in the body of this report as important chemical reactions for potential emission control options for hospital sterilizers. Other reactions that were considered are discussed below.

1. Industrial Products from Ethylene Oxide

A general review was made of all potentially important chemical reactions of EO which might form the basis for a sterilizer control technology.[1] Special emphasis was placed on those reactions which form the basis of industrial production technology based on EO.

Almost all (98 percent) of the EO produced in the U.S. (3×10^9 kg/yr, 1983) is used in the production of other chemicals.[2] Table A-1 lists the products produced from EO and the percentages of total production that each product represents.

In the following paragraphs, a very brief review is presented of the reactions upon which these products are based as well as other related EO reactions which were considered.

2. Reaction with Alcohols

Ethylene oxide reacts with alcohols (Equation 1) to produce the monoethers of ethylene glycol,

$$EO + ROH \longrightarrow RCH_2CH_2OH \quad (R = C_2H_5 = \text{cellosolve}) \qquad (1)$$

1 The sources of information were basically the "Kirk-Othmer Encyclopedia of Chemical Technology," First, Second and Third Editions, 1950, 1966, and 1980. Subject topics that were examined included "Ethylene Oxide" plus entries concerning various EO products. Other references cited by this source were also examined.

2 Source: R. Conway et al. Environmental Science and Technology, 17, 107-112 (1983).

TABLE A-1. INDUSTRIAL PRODUCTS PRODUCED FROM EO

Product	Percent of total EO production
Ethylene glycol	60
Surfactants	11
Ethanolamines	7
Glycol ethers	7
Others	15

alcohols. Since hydrolysis is a competing reaction, the processes are carried out under anhydrous conditions. Because of the high humidity required for sterilization, anhydrous conditions would be troublesome to obtain, and this reaction would probably not be applicable for EO control.

3. Reaction with Ethylene Glycol

Ethylene oxide reacts with ethylene glycol to produce poly(ethylene glycols) (Equation 2).

$$EO + HOCH_2CH_2OH \xrightarrow[\text{NaOH, 4 ATM}]{130°C} HOCH_2(CH_2OCH_2)_nCH_2OH \quad (2)$$

Polyoxyethylene
Poly(ethylene glycol)
n = 5-10

The products are used in pharmaceutical ointments, topical formulations, and cosmetics. Although the products are harmless, the relatively high temperature and high pressure of this reaction probably preclude its use in control technology.

4. Reaction with Ammonia

Ethylene oxide reacts with ammonia to produce the ethanolamines (Equation 3) and similarly with amines to produce substituted ethanolamines (Equation 4).

$$EO + \underset{\text{(Ammonia)}}{NH_3} \longrightarrow \begin{array}{ll} HOCH_2CH_2NH_2 & \text{Ethanolamine} \\ (HOCH_2CH_2)_2NH & \text{Diethanolamine} \\ (HOCH_2CH_2)_3N & \text{Triethanolamine} \end{array} \quad (3)$$

$$EO + \underset{\text{(Amines)}}{R_2NH} \longrightarrow R_2NCH_2CH_2OH \quad \text{Substituted ethanolamine} \quad (4)$$

All of these materials are important commercial products used in the manufacturer of detergents and other applications. These reactions were not

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considered useful for EO control technology because of the objectional odors involved (ammonia and the amines) and the fact that the products might be converted to carcinogenic nitrosamines in the environment.

5. Reduction

Ethylene oxide can be reduced to ethanol (Equation 5), a harmless product, but this reaction requires hydrogen under high pressure, or the handling of metallic sodium which is hazardous.

$$EO \xrightarrow[\text{or sodium amalgam (reduction)}]{\text{catalytic hydrogenation}} \underset{\text{(ethanol)}}{CH_3CH_2OH} \qquad (5)$$

6. Reactions with Mineral Acids

Ethylene oxide reacts with minerals acids to produce ethylene halohydrins (Equation 6).

$$EO + \underset{\text{(anhydrous)}}{\text{mineral acids}} \xrightarrow[X = CL,\ CN]{HX} \underset{\text{(ethylene halohydrin)}}{HOCH_2CH_2X} \qquad (6)$$

These reactions are performed under anhydrous conditions, and the products would be expected to be relatively toxic.

7. Reaction with Organic Acids

Organic acids also react with EO (Equation 7) to produce important industrial products that are not toxic. However, the reactions are performed under anhydrous conditions because of the competing reaction of hydrolysis.

$$EO + RCO_2H \longrightarrow HOCH_2CH_2OCOR \quad (7)$$

(organic acid) → (ethylene glycol ester)

8. Thermal Decomposition and Polymerization

Ethylene oxide undergoes thermal decomposition (Equation 8) and polymerization (Equation 9), but these reactions are probably not suitable for control technology.

$$EO \xrightarrow[\text{thermal decomposition}]{500°C} \begin{array}{ll} CH_4 & \text{Methane} \\ CO & \text{Carbon monoxide} \\ C_2H_6 & \text{Ethane} \\ H_2 & \text{Hydrogen} \\ C & \text{Carbon} \end{array} \quad (8)$$

$$EO \xrightarrow[\text{polymerization (explosive hazard)}]{\text{catalyst}} \text{Dioxane and polymers (MW 10,000 - 70,000) (carbowax)} \quad (9)$$

APPENDIX B

REVIEWS OF CONTROL TECHNOLOGY CONCEPTS WHICH WERE ELIMINATED

Of the eight control technologies which were selected for evaluation, five were eliminated. These concepts, and the reasons that they are not acceptable, are discussed below.

1. Thermal Incineration

This concept was eliminated on the basis that incineration of chlorinated fluorocarbons (CFC) would produce toxic and corrosive by-products including phosgene, hydrochloric acid, hydrofluoric acid, and other products equally unacceptable. Thermal incineration could not be used without a pretreatment step that separates EO from CFC. Since this would necessitate another process and an additional costly unit operation, incineration was not considered further.

2. Condensation

This concept was eliminated on the basis that an explosion hazard would be created. Condensing the sterilizer gas to a liquid would require that the unit be operated in the explosive range of ethylene oxide. Condensation is employed for EO recovery in a commercial sterilizing facility, but the process requires all explosion-proof hardware in a separate room. The expense to achieve this level of safety would be prohibitive for hospital sterilizers. Other disadvantages include low recovery efficiency (60 to 70 percent) and the required reformulation to achieve the 12:88 ratio before reuse is possible.

3. Corona Discharge

This technique employs a high-voltage, low- current electric field across a gap between a microneedle and a plate. This field strips electrons from the passing gas molecules. The resulting free electron bombardment breaks molecular bonds. The new molecules recombine downstream in a random fashion creating many by-products. The chemistry of gases undergoing a controlled plasma reaction is not yet fully understood. As Table 2 shows, Westinghouse is currently developing this technique for NO_x and SO_x removal in boiler stacks. Efficiencies are low, and products can be new and unknown compounds. Westinghouse representatives said that they have enough experience to predict that the decomposition products of Freon are likely to be hydrochloric and

hydrofluoric acids among other things. According to Westinghouse, at least 3 years of further study are needed before the technique would be commercially available. Thus, based on the information provided by Westinghouse concerning toxic by-products, corona discharge was eliminated from further consideration.

4. Ultraviolet Photolysis

This process was also eliminated because of toxic by-product formation. Ethylene oxide spontaneously decomposes when irradiated by ultraviolet (UV) light. Unfortunately, Freon also decomposes under these conditions to form free-radical chlorine and fluorine. Developers of this technique have had success if the gas treated is pure EO, but if Freon is present, a sticky polymeric substance is formed which coats the UV tubes and blocks further UV radiation from reaching the gas stream. Thus, since all hospitals use 12/88, this technique cannot be used unless further refinements are made.

5. Ozonation

In this process, ozone would oxidize EO and leave the CFC unreacted. However, ozonation is generally used commercially only in situations requiring the destruction of very small quantities of an odorous gas. The largest ozone generator readily available, beside being economically infeasible, could not provide enough ozone to oxidize the entire sterilizer load as fast as it exited the sterilizer. An alternate plan was considered in which the spent 12/88 was stored and gradually released to the ozonator. However, the ancillary equipment required, plus the high capital cost of the ozonator, still did not make this method economically attractive. Further, it was felt there were too many unknown factors involved with this technique: the exotherm from the EO/O_3 reaction, Freon stability under all reaction conditions, control equipment with feedback loops to check O_3 emissions were required, and the equipment itself requires moderate to high maintenance.

APPENDIX C

ANALYTICAL PROCEDURES

APPENDIX C

ANALYTICAL PROCEDURES

1.0 DETERMINATIONS OF ETHYLENE OXIDE DESTRUCTION EFFICIENCY

The sampling and analysis methods were identical for both the sterilizer discharge tests and the EO addition tests. The THC analyzer was placed in line upstream of the catalyst system. The GC samples were taken from septum ports installed preceding and following the catalyst system, using 2.5-mL locking, gas-tight syringes. The actual septum ports were located in the lines to the THC and chloride trains. The pumps maintained a purge rate of > 1 L/min. Preliminary tests at MRI indicated that the replaceable needle/syringe lock/gas-tight syringe arrangement used allowed samples to be stored in the syringes for up to 3 hr with a loss in concentration of less than 5%. Samples were taken every 40 sec during the EO addition runs and the first half of the sterilizer discharge runs, and 1-min intervals during the second half of the sterilizer discharge runs.

The samples were injected immediately following each test into a Varian gas chromatograph, which contained two flame ionization detectors. The GC conditions are shown here:

Gas Chromatograph	Varian 2400 with dual FIDs
Separation columns	6 ft x 1/8 in. O.D. SP-Alloy packed with 80/100 Porapak PS
Oven temperature	100°C
Carrier gas/flow rate	Helium, 30 mL/min
Detector temperature	260°C
Injector temperature A/B	190/210°C

Both inlet and outlet sides of the system were calibrated twice daily with 90.7 ppm and 1035 ppm EO in nitrogen standards prepared by Scott gases (see Table C-1). The THC analyzer was calibrated twice daily with zero air and 1,035 ppm EO.

All data was recorded on both computer diskettes and a strip chart recorder. The sample concentrations were determined by dividing the actual peak area by a reference factor based on that day's calibration data. The initial and final averages for each calibration gas were entered in a regression curve fit program forcing the y-intercept through the origin. The slope of this line was used as the reference factor.

2.0 CHLOROFLUOROCARBON DECOMPOSITION STUDIES

A midget impinger sampling train was used to trap any chloride which may have resulted from CF_2Cl_2 degradation in the catalyst bed. The train consisted of two impingers containing 0.1 N sodium carbonate solution. The sample gas volume through the train was measured using a dry test meter. The samples were recovered into Nalgene bottles and returned to MRI for analysis using ion chromatography, according to ASTM D4327-84.

Prior to making new calibration standards for the ion chromatograph, several samples were analyzed to determined an approximate concentration range. None of the samples indicated any chloride present, with the instrument running at a detection limit of 200 ppb. The detection limit was determined using standards prepared for a previous project. The limit was based on the chloride concentration corresponding to a peak at 40% of the lowest calibration standard of 500 ppb. The carbonate peak coincided with the retention time of fluoride, so no fluoride could have been detected, had it been present. To verify that the standard concentrations used had not varied significantly, very low concentration performance samples were prepared and analyzed. Although the results of this analysis were outside the Data Quality Objectives of 95% accuracy specified in the QAPP, the actual deviations were very small. The results of the analysis are shown below:

TABLE C-1. SUMMARY OF CALIBRATION RESULTS
Catalytic Oxidation System

Run, channel	Calibration gas (ppm)	Initial peak area (1000 counts)	Final peak area (1000 counts)	RPD (%)[a]	Reference factor[b]
1-A	90.7	197.3	192.0	2.7	2,112
	1,035	2,225	2,146	3.6	
1-B	90.7	232.2	224.3	3.5	2,468
	1,035	2,605	2,503	4.0	
Drain 1-A	50	75.7			2,060
	500	1,033			
2,3-A	90.7	178.1	166.6	3.3	1,776
	1,035	1,963	1,712	13.7	
2,3-B	90.7	214.3	217.9	1.7	2,278
	1,035	2,357	2,356	0.03	
4-A	90.7	163.0	151.5	7.3	1,691
	1,035	1,806	1,693	6.5	
4-B	90.7	201.8	206.2	2.2	2,164
	1,035	2,196	2,282	3.8	
Drain 4-A	50	74.0			2,141
	500	1,074			
5,6-A	90.7	210.5	232.9	10.1	2,386
	1,035	2,326	2,613	11.6	
5,6-B	90.7	229.3	244.9	6.6	2,499
	1,035	2,534	2,636	3.9	
7-A	1,035	1,993	2,300	14.3	2,075
7-B	90.7	241.5	248.4	2.8	2,538

a Relative Percent Deviation, $\left|\frac{\text{Initial-Final}}{\text{Average}}\right| \times 100$

b Calculated using Linear Least Squares Fit forcing a zero-intercept or

$$m = \sum \frac{x_i y_i}{x_i^2}$$

100

Actual concentration	Found concentration	Percent accuracy
2.83 ppm	2.43 ppm	86%
1.42 ppm	1.21 ppm	85%

The results did not indicate sufficient need to prepare new calibration standards since no detectable levels of chlorides were found in the samples.

3.0 DETERMINATION OF ETHYLENE OXIDE IN VACUUM PUMP DRAIN WATER

Samples of the water discharge from the vacuum pump were taken using a dipper. Respiratory protective equipment was used during the sampling and transfer to 40-mL vials. Notation was made of the exact time that the samples were taken. The vials were equipped with septa-lined caps and were filled to the top of the vial.

One microliter of these samples was injected into the inlet side of the GC under the conditions specified earlier. The standards were prepared by injecting a known volume of 12/88 gas into a known volume of water in an air-tight vial. The standards were prepared at 50 and 500 ppm levels and stored on ice between injections. The data were treated in the same manner as previously described GC samples.

4.0 DETERMINATIONS OF ACID SCRUBBER EFFICIENCY

The sampling and analysis methods were identical for both the sterilizer discharge tests and the EO addition tests. The inlet samples were taken from septum ports installed just prior to the scrubber system, using procedures described earlier. The outlet samples were taken from an injection tee installed on a gas circulating loop which withdrew about 1 L/min from the system, past the sample port, through a pump and then returned to the system about 1 ft downstream. All components between the port and system were Teflon or stainless steel. Dry gas meter readings and samples were taken every 40 sec during Runs 1 through 6 and at 1 min intervals during Run 7.

The samples were analyzed immediately following each test using the Varian gas chromatograph described earlier. Both inlet and outlet detectors were calibrated twice daily: 1% and 2% EO standards were used for the inlet side and 49.3 and 90.7 ppm standards were used for the outlet side (see Table C-2). The differences in GC conditions are listed below:

Injector temperatures	185-210°C
Detector temperatures	188-220°C

The concentrations of the inlet samples were substantially higher (15,000 ppm) than those obtained from the inlet of the catalytic oxidation system (200-1,500 ppm). The inlet samples were diluted in the syringes in order to bring the concentrations down to the range of the calibration standards. The technique involved diluting 0.25 mL of sample to 2.5 mL with ambient air. The syringe was then locked and the plunger depressed and returned to the 2.5 mL mark to assure even mixing. Then 2.07 mL of this mixture was expelled into a waste bag. The remaining 0.43 mL was then diluted to 1.0 mL with ambient air.

A verification of this technique was performed by diluting one of the calibration standards with three different syringes at the beginning of each day, and the average of those dilutions was used to calculate actual sample concentrations. A more detailed description, including actual calculations is shown below.

5.0 DILUTION METHODOLOGY AND CALCULATIONS

The dilution scheme described above was developed to provide an efficient, accurate method of bringing the samples to the range of the standards. The first step in determining the exact volumes needed was to measure the dead volume in the needle, syringe lock, and syringe. This was done by diluting an apparently known volume of calibration gas with a known volume of ambient air. If the dead volume were zero, the dilution would indicated 10% of the original peak area of the calibration gas, using 0.25 mL calibration gas diluted to 2.5 mL with ambient air. However, since the dead volume filled with calibration gas is pulled into the syringe body with the ambient air, the

TABLE C-2. SUMMARY OF CALIBRATION RESULTS
Acid Hydrolysis System

Run, channel	Initial Calibration gas	Final peak area (1000 counts)	peak area (1000 counts)	RPD (%)[a]	Reference factor[b,c]
1,3-A	1.0%	28,261	28,656	1.4	2,705
	2.0%	51,626	55,020	6.4	
1,3-B	48.3 ppm	162.4	154.7	4.9	3,394
	90.7 ppm	308.0	313.4	1.7	
1,3-A	Dilution check - 1.0% in syringe A	2,420			2,393 (8.5%)
	B	2,419			
	C	2,341			
4-A	1.0%	25,261	28,075	10.6	2,524
	2.0%	47,858	51,566	7.5	
4-B	48.3 ppm	161.2	155.5	3.6	3,421
	90.7 ppm	319.3	308.7	3.4	
4-A	Dilution check - 1.0% in syringe A	2,295			2,203 (8.8%)
	B	2,292			
	C	2,023			
5,6-A	1.0%	24,490	22,568	8.2	2,238
	2.0%	45,394	42,865	5.7	
5,6-B	48.3 ppm	158.0	154.9	2.0	3,377
	90.7 ppm	312.5	307.3	1.7	
5,6-A	Dilution check - 1.0% in syringe A	2,083			2,093 (8.6%)
	B	2,254			
	C	1,942			
7-A	1.0%	23,392	21,489	8.5	2,152
	2.0%	43,909	41,144	6.5	
7-B	48.3 ppm	155.2	154.7	0.3	3,319
	90.7 ppm	306.9	300.9	2.0	
7-A	Dilution check - 1.0% in syringe A	1,986			1,982 (8.5%)
	B	2,046			
	C	1,914			

a Relative Percent Deviation, $\left/\frac{\text{Initial-Final}}{\text{Average}}\right/ \times 100$

b Calculated using Linear Least Squares Fit forcing a zero-intercept or

$$m = \sum \frac{x_i y_i}{x_i^2}$$

c Number in parentheses is an average dilution value from three syringes, three injections each, used to determine concentrations of diluted high level samples.

dilution is lower than 10%. The actual value of the dilution allows the dead volume contribution to be calculated, according to the equation shown here:

(initial vol) (conc) + (vol air added) (conc) = (final vol) (conc)

Where: conc = concentration of calibration gas in percent relative to initial calibration gas concentration

$$(0.25 + x)\ (100\%) + (2.25)\ (0\%) = (2.5 + x)\ (18.4\%)$$

Where: x = Dead volume

18.4% = Actual concentration determined from triplicate analysis conducted immediately prior to field tests (after diluting 0.25 mL of calibration gas to 2.5 mL with ambient air)

The second calculation, utilizing the value calculated above for the dead volume, determines what volume of this calibration gas/air mixture is needed in 1 mL of sample to give a final concentration equal to 10% of the original calibration gas, 1 mL being the injection volume. This equation also follows the generic formula shown above. With actual values substituted, it is:

$$(y + 0.25)\ (18.4\%) + (1-y)\ (0\%) = (1 + 0.25)\ (10\%)$$

Where: y = Volume of calibration gas needed for 10% dilution

0.25 = Dead volume from first equation

10% = Desired final concentrations

Solving the above equation for y gives an initial desired volume of 0.43 mL for the second portion of the dilution. As mentioned previously in the text, this two-step process was performed using three different syringes, three times each, as part of the daily initial instrument calibration process. An average dilution value was used in conjunction with the standard reference factor to calculate the actual sample volumes.

APPENDIX D

EXPERIMENTAL DATA
CATALYTIC OXIDATION SYSTEM
STERILIZER DISCHARGE EXPERIMENTS

NOTES TO APPENDIX D

1. GC CALCULATIONS

a. The area under the curve is the average of the current and previous points times the time interval since the GC samples are near instantaneous grab samples.

b. The EO emissions in grams are the area in ppm*min times 0.019 obtained from the equation:

$$g\ EO = \frac{ppm(\mu L/L) * min * 370\ ft^3/min * 28.32\ L/ft^3 * 1.83\ g/L}{10^6\ \mu L/L}$$

The catalyst is assumed to be leak-free, thus the outlet flow is the same as the inlet flow.

c. For the water samples, the emission factor is 0.0033 times the curve area from:

$$g\ EO = \frac{ppm\ (mg/L) * min * 3.3\ L/min}{1{,}000\ mg/g}$$

2. THC CALCULATIONS

a. The THC responds to the sum of all organics. The correction from ppm as EO to Est EO (ppm) uses measured response factors for 1000 ppm mixtures of EO and CF_2Cl_2 in nitrogen. Assuming that the inlet vapor remains at 12% EO, 88% R-12 (w/w) the EO fraction would be 64% of the total signal. A moderate nonlinearity of CF_2Cl_2 response was ignored. Also, in runs 1, 4, and 7 the losses into the water probably have shifted the ratio to some extent because of the high solubility of EO and the low solubility of CF_2Cl_2.

b. The area under the curve calculation is the time from the previous reading times the logger reading in ppm. This is because the logger records the average of all scans since the previous entry. Where noise problems

caused skipped points the average covers the entire period, not just the last 10 sec.

c. The same 0.019 factor for Est EO emissions is used.

3. NOTE ON FLOW MEASUREMENTS

Because of the difficulty of measuring the low delta P across the pitot, no attempt to correct the flow according to the delta P measured during each run was made. The inlet flow is assumed equal to the traverse run on June 8 (370 ft^3/min). The measurement precision is about ±50 cfm. The catalyst bed had Magnehelic gauges monitoring the pressure drop across each stage. These gauges never varied during any test.

The water flow rate is an average of four measurements on June 9 and 10. The flow rate was never constant. The measured average has an error limit of about 20%.

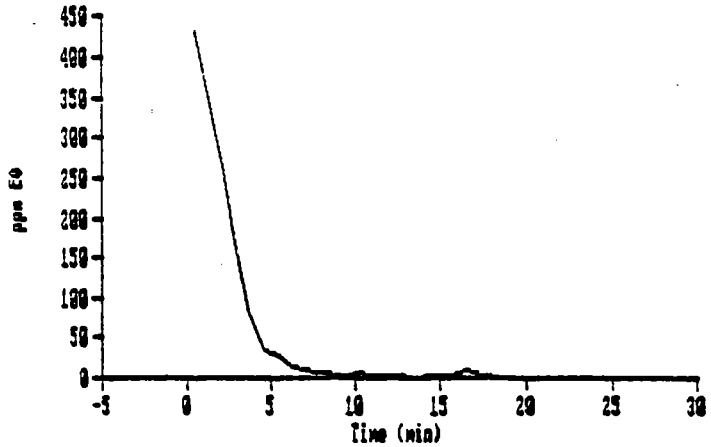
RUN 1
GC DATA - INLET

Sample No.	Time (min.sec)	ppm EO	Time (dec.)	Time from start	EO Area (ppm*min)	EO (g)
Start	1155.54		1155.9	-.0		
I-1	1156.20	430.11	1156.3	.4	93.2	1.771
I-3	1158.00	265.69	1158.0	2.1	579.8	11.017
I-4	1158.40	177.84	1158.7	2.8	147.8	2.809
I-5	1159.30	84.66	1159.5	3.6	109.4	2.078
I-6	1200.30	35.11	1200.5	4.6	59.9	1.138
I-7	1201.19	25.68	1201.3	5.4	24.8	.472
I-8	1202.07	14.21	1202.1	6.2	16.0	.303
I-9	1202.48	11.18	1202.8	6.9	8.7	.165
I-10	1203.28	8.34	1203.5	7.6	6.5	.124
I-11	1204.06	8.07	1204.1	8.2	5.2	.099
I-12	1204.45	4.70	1204.8	8.8	4.2	.079
I-13	1205.27	4.61	1205.5	9.5	3.3	.062
I-14	1206.04	6.21	1206.1	10.2	3.3	.063
I-15	1206.43	4.43	1206.7	10.8	3.5	.066
I-16	1207.20	2.46	1207.3	11.4	2.1	.040
I-17	1208.20	3.77	1208.3	12.4	3.1	.059
I-18	1209.21	1.56	1209.4	13.5	2.7	.051
I-19	1210.20	4.99	1210.3	14.4	3.2	.061
I-20	1211.25	2.11	1211.4	15.5	3.8	.073
I-21	1212.21	9.24	1212.4	16.5	5.3	.101
I-22	1213.20	3.50	1213.3	17.4	6.3	.119
I-23	1214.20	1.09	1214.3	18.4	2.3	.044
I-24	1215.20	1.06	1215.3	19.4	1.1	.020
I-25	1216.20	.84	1216.3	20.4	1.0	.018
I-26	1217.20	.82	1217.3	21.4	.8	.016
I-27	1218.20	.75	1218.3	22.4	.8	.015
I-28	1219.20	.70	1219.3	23.4	.7	.014
I-29	1220.20	1.05	1220.3	24.4	.9	.017
I-30	1221.20	.30	1221.3	25.4	.7	.013
I-31	1222.20	.30	1222.3	26.4	.3	.006
I-32	1223.21	.51	1223.4	27.5	.4	.008
I-33	1224.20	.77	1224.3	28.4	.6	.012
				Totals=	1101.6	20.93

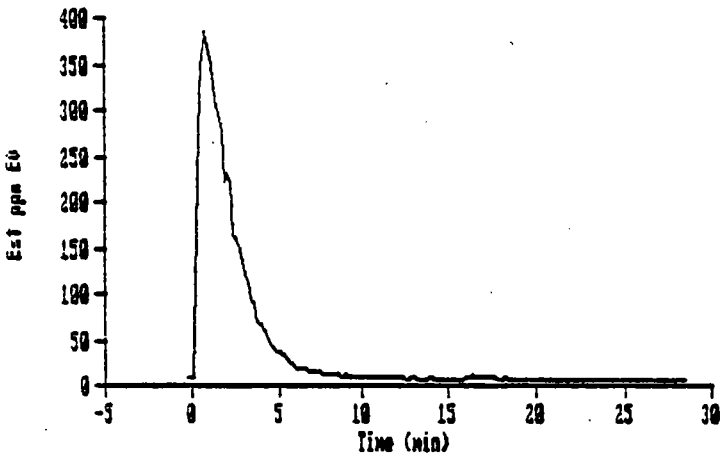
RUN 1
GC DATA - OUTLET

Sample No.	Time (min.sec)	ppm EO	Time (dec.)	Time from start	EO Area (ppm*min	EO (g)
Start	1155.54		1155.9	-.0		
O-1	1156.20	0.00	1156.3	.4	.0	.000
O-2	1157.07	.62	1157.1	1.2	.2	.005
O-3	1158.00	0.00	1158.0	2.1	.3	.005
O-4	1158.40	0.00	1158.7	2.8	.0	.000
O-5	1159.30	.08	1159.5	3.6	.1	.001
O-6	1200.17	.37	1200.3	4.4	.2	.003
O-7	1201.19	.24	1201.3	5.4	.3	.006
O-8	1202.07	.18	1202.1	6.2	.2	.003
O-9	1202.48	.22	1202.8	6.9	.1	.003
O-10	1203.28	.26	1203.5	7.6	.2	.003
O-11	1204.06	.59	1204.1	8.2	.3	.005
O-12	1204.45	.26	1204.8	8.8	.3	.005
O-13	1205.27	.17	1205.5	9.5	.2	.003
O-14	1206.04	.40	1206.1	10.2	.2	.003
O-15	1206.43	.07	1206.7	10.8	.2	.003
O-16	1207.20	.17	1207.3	11.4	.1	.001
O-17	1208.20	.50	1208.3	12.4	.3	.006
O-18	1209.21	.03	1209.4	13.5	.3	.005
O-19	1210.20	.40	1210.3	14.4	.2	.004
O-20	1211.25	.22	1211.4	15.5	.3	.006
O-21	1212.21	.30	1212.4	16.5	.2	.005
O-22	1213.20	.06	1213.3	17.4	.2	.003
O-23	1214.20	.12	1214.3	18.4	.1	.002
O-24	1215.20	.46	1215.3	19.4	.3	.006
O-25	1216.20	.09	1216.3	20.4	.3	.005
O-26	1217.20	1.01	1217.3	21.4	.6	.010
O-27	1218.20	.38	1218.3	22.4	.7	.013
O-28	1219.20	.21	1219.3	23.4	.3	.006
O-29	1220.20	.01	1220.3	24.4	.1	.002
O-30	1221.20	.07	1221.3	25.4	.0	.001
O-31	1222.20	0.00	1222.3	26.4	.0	.001
O-32	1223.21	0.00	1223.4	27.5	.0	.000
O-33	1224.20	0.00	1224.3	28.4	.0	.000
				Totals=	6.6	.125

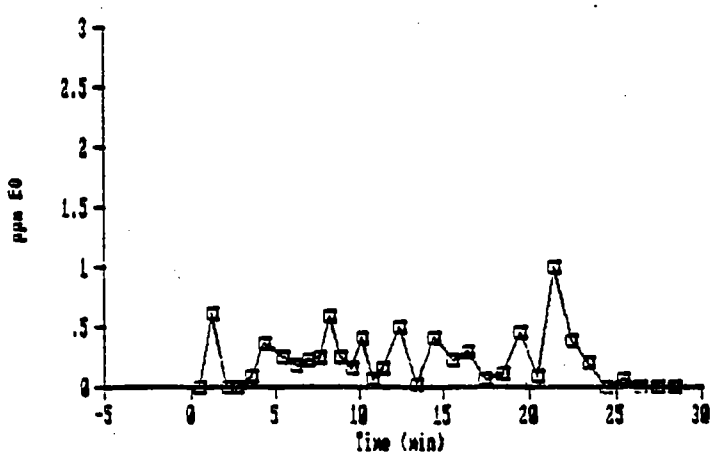
RUN #1 EO INLET CONCENTRATION



RUN #1 THC CONCENTRATION

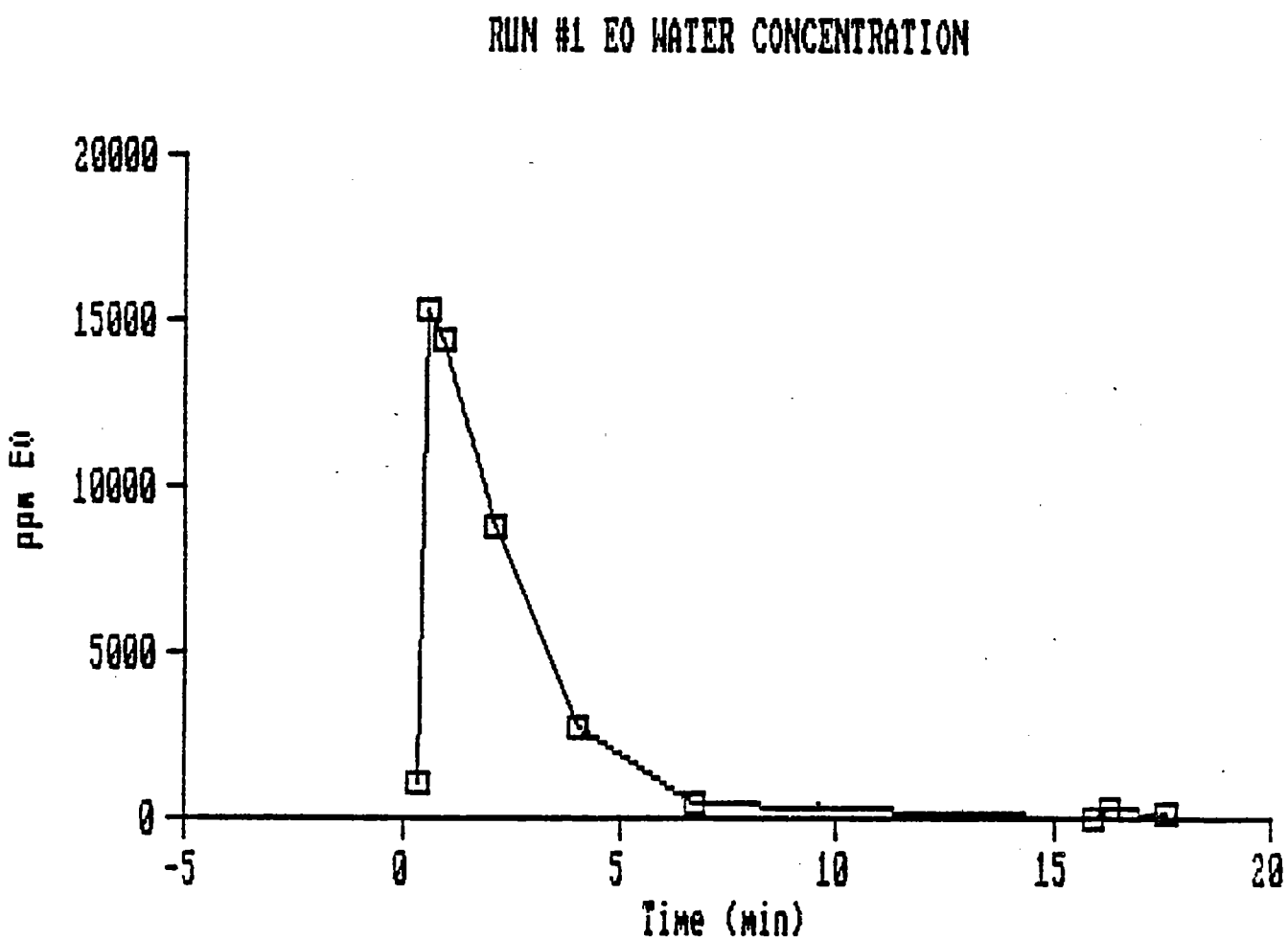


RUN #1 EO OUTLET CONCENTRATION



RUN 1
GC DATA - WATER DISCHARGE

Sample No.	Time (min.sec)	ppm EO	Time (dec.)	Time from start	EO Area (ppm*min	EO (g)
Start	1155.54		1155.9	-.0		
D1003	1156.15	1027.0	1156.3	.4	179.7	.59
D1004	1156.29	15430.0	1156.5	.6	1920.0	6.34
D1005	1156.50	14394.0	1156.8	.9	5219.2	17.22
D1006	1158.00	8864.0	1158.0	2.1	13567.2	44.77
D1007	1159.55	2729.0	1159.9	4.0	11110.0	36.66
D1008	1202.39	412.6	1202.7	6.8	4293.5	14.17
D1009	1211.47	22.5	1211.8	15.9	1987.0	6.56
D1010	1212.10	322.3	1212.2	16.3	66.1	.22
D1011	1213.29	109.1	1213.5	17.6	284.0	.94
				Totals=	38626.6	127.5



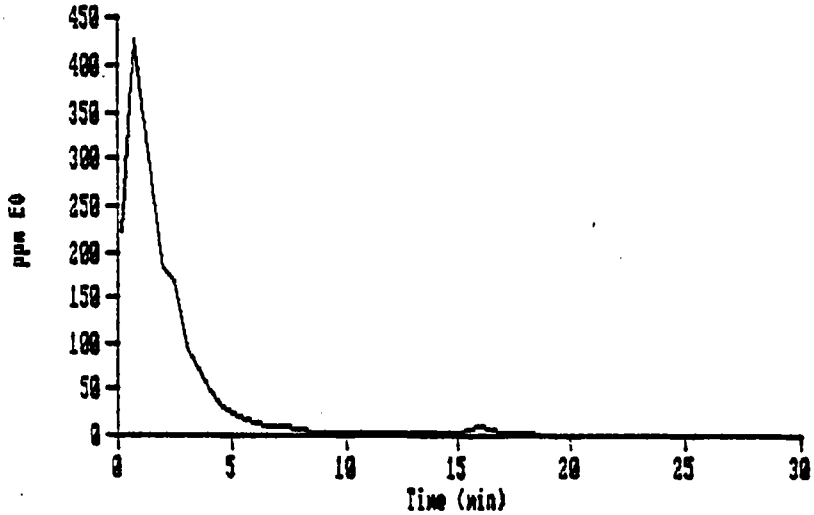
RUN 4
GC DATA - INLET

Sample No.	Time (min.sec)	ppm EO	Time (dec.)	Time from start	EO Area (ppm*min	EO (g)
Start	1128.00		1128.0	.0		
I-1	1128.10	223.00	1128.2	.2	18.6	.353
I-2	1128.43	428.90	1128.7	.7	179.3	3.406
I-3	1129.17	312.58	1129.3	1.3	210.1	3.992
I-4	1129.57	181.14	1130.0	1.9	164.6	3.127
I-5	1130.30	167.65	1130.5	2.5	95.9	1.822
I-6	1131.07	91.94	1131.1	3.1	80.0	1.521
I-7	1132.00	51.24	1132.0	4.0	63.2	1.202
I-8	1132.35	30.22	1132.6	4.6	23.8	.451
I-9	1133.15	19.47	1133.3	5.3	16.6	.315
I-10	1133.55	12.61	1133.9	5.9	10.7	.203
I-11	1134.34	10.04	1134.6	6.6	7.4	.140
I-12	1135.14	9.42	1135.2	7.2	6.5	.123
I-13	1135.51	6.16	1135.9	7.8	4.8	.091
I-14	1136.35	4.83	1136.6	8.6	4.0	.077
I-15	1137.17	4.28	1137.3	9.3	3.2	.061
I-16	1137.55	3.68	1137.9	9.9	2.5	.048
I-17	1138.55	3.56	1138.9	10.9	3.6	.069
I-18	1139.55	2.55	1139.9	11.9	3.1	.058
I-19	1141.00	3.83	1141.0	13.0	3.5	.066
I-20	1142.00	2.41	1142.0	14.0	3.1	.059
I-21	1143.00	3.30	1143.0	15.0	2.9	.054
I-22	1144.00	8.66	1144.0	16.0	6.0	.114
I-23	1145.00	4.66	1145.0	17.0	6.7	.127
I-24	1146.00	2.75	1146.0	18.0	3.7	.070
I-25	1147.00	1.27	1147.0	19.0	2.0	.038
I-26	1148.00	.38	1148.0	20.0	.8	.016
I-27	1149.00	.53	1149.0	21.0	.5	.009
I-28	1150.00	.62	1150.0	22.0	.6	.011
I-29	1151.00	.39	1151.0	23.0	.5	.010
I-30	1152.00	.45	1152.0	24.0	.4	.008
I-31	1153.00	.24	1153.0	25.0	.3	.007
I-32	1154.00	.40	1154.0	26.0	.3	.006
				Totals=	929.0	17.65

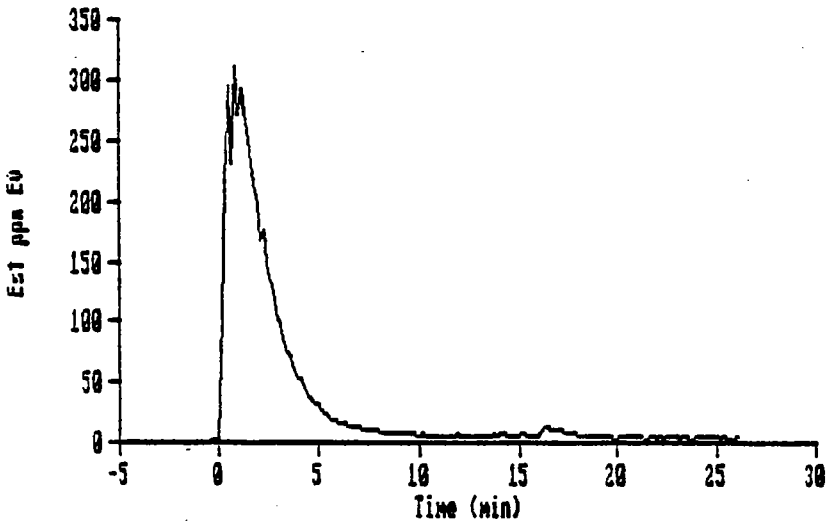
RUN 4
GC DATA - OUTLET

Sample No.	Time (min.sec)	ppm EO	Time (dec.)	Time from start	EO Area (ppm*min	EO (g)
Start	1128.00		1128.0	.0		
O-1	1128.10	.12	1128.2	.2	.0	.000
O-2	1128.43	1.62	1128.7	.7	.5	.009
O-3	1129.17	.52	1129.3	1.3	.6	.012
O-4	1129.57	1.17	1130.0	1.9	.6	.011
O-5	1130.30	.33	1130.5	2.5	.4	.008
O-6	1131.07	.16	1131.1	3.1	.2	.003
O-7	1132.00	.05	1132.0	4.0	.1	.002
O-8	1132.35	.04	1132.6	4.6	.0	.000
O-9	1133.15	.51	1133.3	5.3	.2	.003
O-10	1133.55	.59	1133.9	5.9	.4	.007
O-11	1134.34	.26	1134.6	6.6	.3	.005
O-12	1135.14	.88	1135.2	7.2	.4	.007
O-13	1135.51	.09	1135.9	7.8	.3	.006
O-14	1136.35	.21	1136.6	8.6	.1	.002
O-15	1137.17	.81	1137.3	9.3	.4	.007
O-16	1137.55	.18	1137.9	9.9	.3	.006
O-17	1138.55	.01	1138.9	10.9	.1	.002
O-18	1139.55	.11	1139.9	11.9	.1	.001
O-19	1141.00	.31	1141.0	13.0	.2	.004
O-20	1142.00	.14	1142.0	14.0	.2	.004
O-21	1143.00	.27	1143.0	15.0	.2	.004
O-22	1144.00	.21	1144.0	16.0	.2	.005
O-23	1145.00	.17	1145.0	17.0	.2	.004
O-24	1146.00	.12	1146.0	18.0	.1	.003
O-25	1147.00	.10	1147.0	19.0	.1	.002
O-26	1148.00	.05	1148.0	20.0	.1	.001
O-27	1149.00	.09	1149.0	21.0	.1	.001
O-28	1150.00	.11	1150.0	22.0	.1	.002
O-29	1151.00	.19	1151.0	23.0	.2	.003
O-30	1152.00	.24	1152.0	24.0	.2	.004
O-31	1153.00	.86	1153.0	25.0	.6	.010
O-32	1154.00	.20	1154.0	26.0	.5	.010
				Totals=	7.8	.148

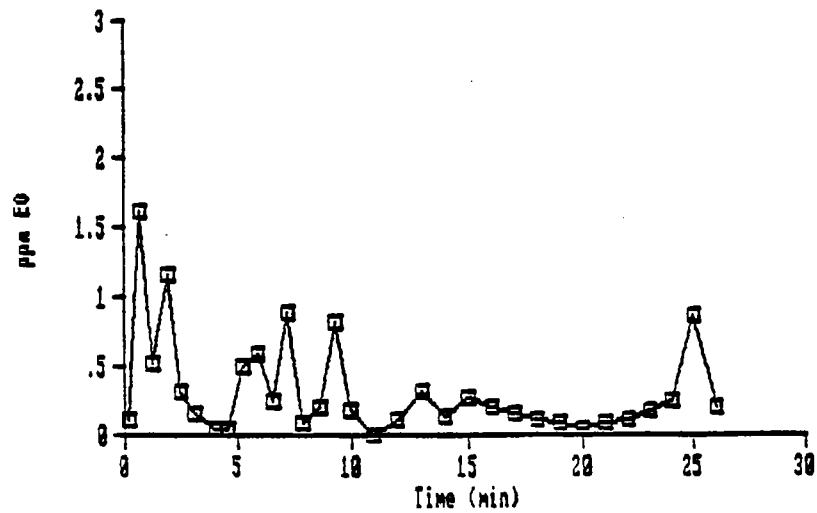
RUN #4 EO INLET CONCENTRATION



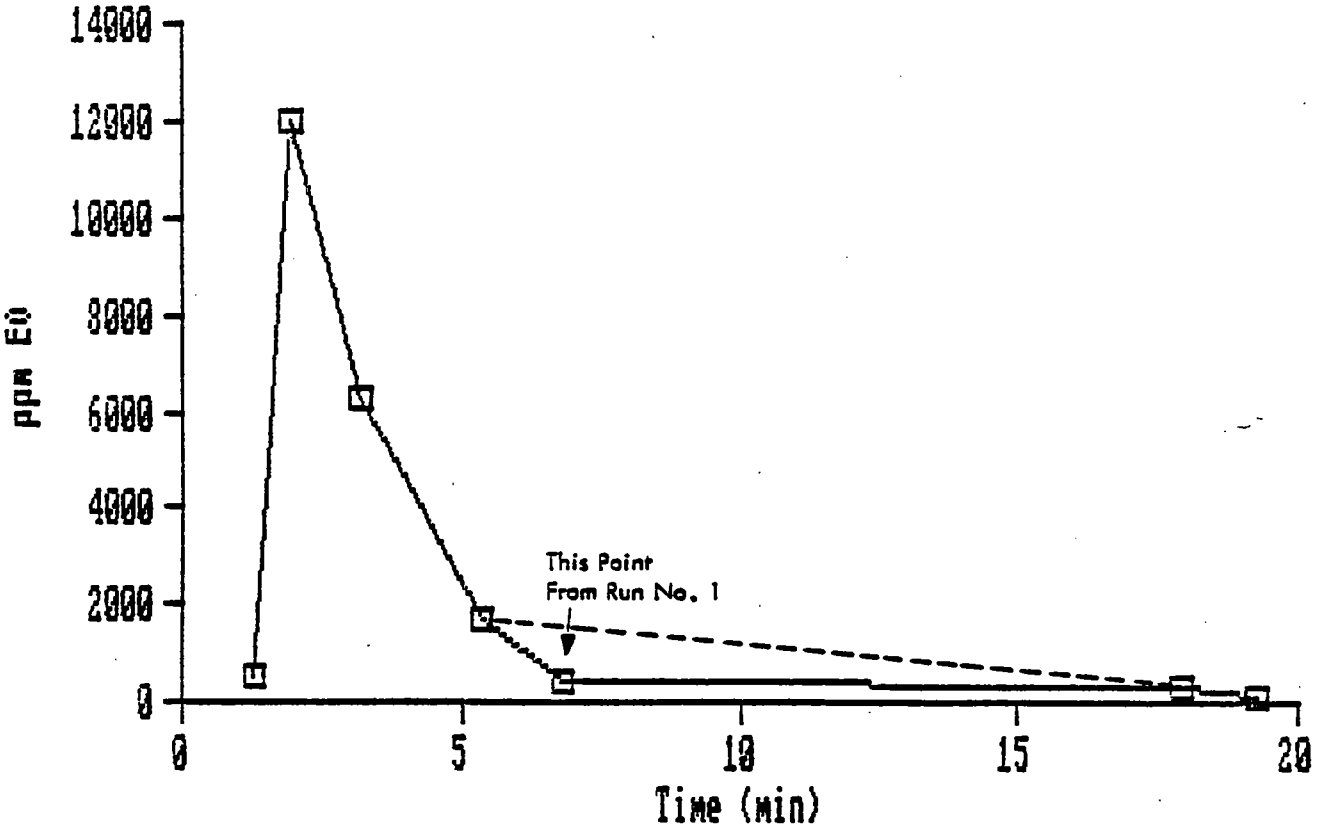
RUN #4 THC CONCENTRATION



RUN #4 EO OUTLET CONCENTRATION



RUN #4 EO WATER CONCENTRATION



RUN 4
GC DATA - WATER DISCHARGE

Sample No.	Time (min.sec)	ppm EO	Time (dec.)	Time from start	EO Area (ppm*min	EO (g)
Start	1128.00		1128.0	.0		
D4003	1129.17	565.5	1129.3	1.3	362.9	1.20
D4004	1129.57	12019.0	1130.0	1.9	4194.8	13.84
D4005	1131.12	6317.0	1131.2	3.2	11460.0	37.82
D4006	1133.20	1713.0	1133.3	5.3	8565.3	28.27
D1008	1134.45	412.6	1134.8	6.8	1505.6	4.97
D4007	1145.56	330.7	1145.9	17.9	4156.3	13.72
D4008	1147.16	76.7	1147.3	19.3	271.6	.90
				Totals=	30516.5	100.7

Note: No sample was available at time = 6.8. The integration of these data would result in excessively high amounts of EO because of the large area between time = 5.3 and time = 17.9 (see figure, run 4, water concentration). Therefore, the concentration obtained in run 1 at this time (see sample No. D1008 above) was used in the calculations.

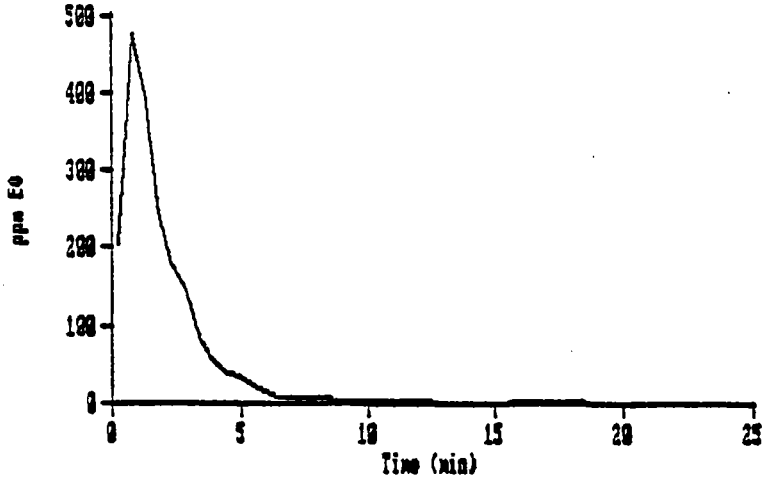
RUN 7
GC DATA - INLET

Sample No.	Time (min.sec)	ppm EO	Time (dec.)	Time from start	EO Area (ppm*min)	EO (g)
Start	1157.30		1157.5	.0		
I-1	1157.43	204.63	1157.7	.2	22.2	.421
I-2	1158.16	475.37	1158.3	.8	187.0	3.553
I-3	1158.46	398.73	1158.8	1.3	218.5	4.152
I-4	1159.16	244.77	1159.3	1.8	160.9	3.057
I-5	1159.46	177.20	1159.8	2.3	105.5	2.004
I-6	1200.20	143.06	1200.3	2.8	90.7	1.724
I-7	1200.55	78.88	1200.9	3.4	64.7	1.230
I-8	1201.25	52.08	1201.4	3.9	32.7	.622
I-9	1201.55	38.91	1201.9	4.4	22.7	.432
I-10	1202.25	32.84	1202.4	4.9	17.9	.341
I-11	1202.55	22.18	1202.9	5.4	13.8	.261
I-12	1203.25	15.77	1203.4	5.9	9.5	.180
I-13	1203.55	9.18	1203.9	6.4	6.2	.119
I-14	1204.25	7.85	1204.4	6.9	4.3	.081
I-15	1204.55	6.35	1204.9	7.4	3.5	.067
I-16	1205.28	6.22	1205.5	8.0	3.5	.066
I-17	1206.30	3.26	1206.5	9.0	4.9	.093
I-18	1207.30	2.65	1207.5	10.0	3.0	.056
I-20	1209.30	1.98	1209.5	12.0	4.6	.088
I-21	1210.30	1.15	1210.5	13.0	1.6	.030
I-22	1211.30	.83	1211.5	14.0	1.0	.019
I-23	1212.30	1.04	1212.5	15.0	.9	.018
I-24	1213.30	5.04	1213.5	16.0	3.0	.058
I-25	1214.30	3.13	1214.5	17.0	4.1	.078
I-26	1215.30	2.49	1215.5	18.0	2.8	.053
I-27	1216.30	.82	1216.5	19.0	1.7	.031
I-28	1217.30	.80	1217.5	20.0	.8	.015
I-29	1218.30	.43	1218.5	21.0	.6	.012
I-30	1219.30	.95	1219.5	22.0	.7	.013
I-31	1220.30	.27	1220.5	23.0	.6	.012
				Totals=	994.0	18.89

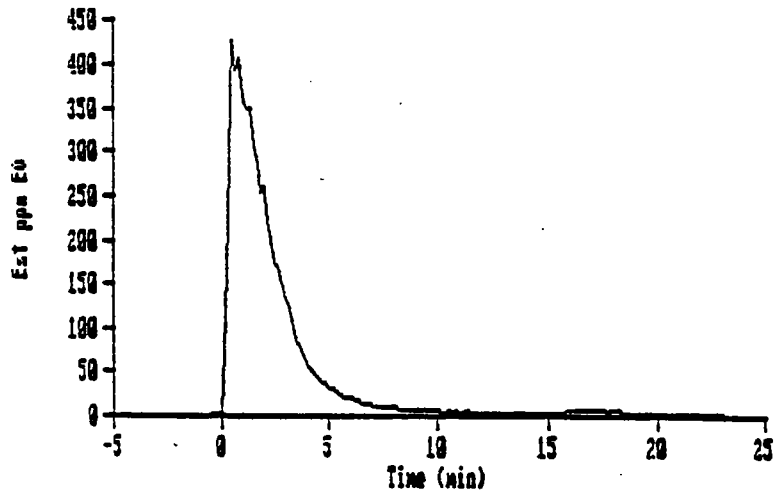
RUN 7
GC DATA - OUTLET

Sample No.	Time (min.sec)	ppm EO	Time (dec.)	Time from start	EO Area (ppm*min	EO (g)
Start	1157.30		1157.5	.0		
O-1	1157.43	0.00	1157.7	.2	.0	.000
O-2	1158.16	.13	1158.3	.8	.0	.001
O-3	1158.46	.22	1158.8	1.3	.1	.002
O-4	1159.16	.17	1159.3	1.8	.1	.002
O-5	1159.46	.32	1159.8	2.3	.1	.002
O-6	1200.20	.15	1200.3	2.8	.1	.003
O-7	1200.55	.31	1200.9	3.4	.1	.003
O-8	1201.25	.74	1201.4	3.9	.3	.005
O-9	1201.55	.25	1201.9	4.4	.2	.005
O-10	1202.25	0.00	1202.4	4.9	.1	.001
O-11	1202.55	0.00	1202.9	5.4	.0	.000
O-12	1203.25	.24	1203.4	5.9	.1	.001
O-13	1203.55	0.00	1203.9	6.4	.1	.001
O-14	1204.25	0.00	1204.4	6.9	.0	.000
O-15	1204.55	0.00	1204.9	7.4	.0	.000
O-16	1205.28	0.00	1205.5	8.0	.0	.000
O-17	1206.30	.20	1206.5	9.0	.1	.002
O-18	1207.30	.42	1207.5	10.0	.3	.006
O-19	1208.30	.31	1208.5	11.0	.4	.007
O-20	1209.30	.33	1209.5	12.0	.8	.014
O-21	1210.30	.41	1210.5	13.0	.4	.007
O-22	1211.30	.09	1211.5	14.0	.3	.005
O-23	1212.30	.06	1212.5	15.0	.1	.001
O-24	1213.30	.18	1213.5	16.0	.1	.002
O-25	1214.30	.53	1214.5	17.0	.4	.007
O-26	1215.30	.34	1215.5	18.0	.4	.008
O-27	1216.30	.71	1216.5	19.0	.5	.010
O-28	1217.30	.25	1217.5	20.0	.5	.009
O-29	1218.30	.58	1218.5	21.0	.4	.008
O-30	1219.30	.17	1219.5	22.0	.4	.007
O-31	1220.30	.05	1220.5	23.0	.1	.002
				Totals=	6.3	.120

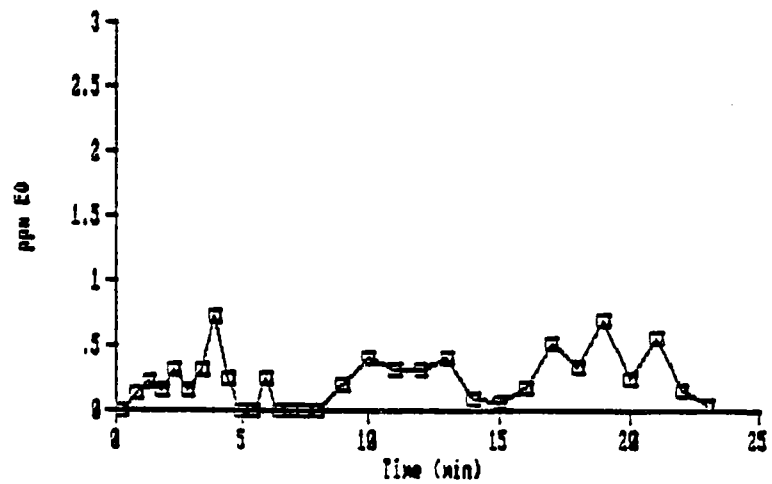
RUN #7 EO INLET CONCENTRATION



RUN #7 THC CONCENTRATION



RUN #7 EO OUTLET CONCENTRATION



APPENDIX E

EXPERIMENTAL DATA
CATALYTIC OXIDATION SYSTEM
ETHYLENE OXIDE ADDITION EXPERIMENTS

NOTES TO APPENDIX E

1. GC CALCULATIONS

a. The area under the curve is the average of the current and previous points times the time interval since the GC samples are near instantaneous grab samples.

b. The EO emissions in grams are the area in ppm*min times 0.019 obtained from the equation:

$$g\ EO = \frac{ppm\ (\mu L/L) * min * 370\ ft^3/min * 28.32\ L/ft^3 * 1.83\ g/L}{10^6\ \mu L/L}$$

The catalyst is assumed to be leak-free, thus the outlet flow is the same as the inlet flow.

c. For the water samples, the emission factor is 0.0033 times the curve area from:

$$g\ EO = \frac{ppm\ (mg/L) * min * 3.3\ L/min}{1{,}000\ mg/g}$$

2. THC CALCULATIONS

a. The THC responds to the sum of all organics. The correction from ppm as EO to Est EO (ppm) uses measured response factors for 1000 ppm mixtures of EO and CF_2Cl_2 in nitrogen. Assuming that the inlet vapor remains at 12% EO, 88% R-12 (w/w) the EO fraction would be 64% of the total signal. A moderate nonlinearity of CF_2Cl_2 response was ignored. Also, in runs 1, 4, and 7 the losses into the water probably have shifted the ratio to some extent because of the high solubility of EO and the low solubility of CF_2Cl_2.

b. The area under the curve calculation is the time from the previous reading times the logger reading in ppm. This is because the logger records the average of all scans since the previous entry. Where noise problems caused skipped points the average covers the entire period, not just the last 10 sec.

c. The same 0.019 factor for Est EO emissions is used.

3. NOTE ON FLOW MEASUREMENTS

Because of the difficulty of measuring the low delta P across the pitot, no attempt to correct the flow according to the delta P measured during each run was made. The inlet flow is assumed equal to the traverse run on June 8 (370 ft^3/min). The measurement precision is about ±50 cfm. The catalyst bed had Magnehelic gauges monitoring the pressure drop across each stage. These gauges never varied during any test.

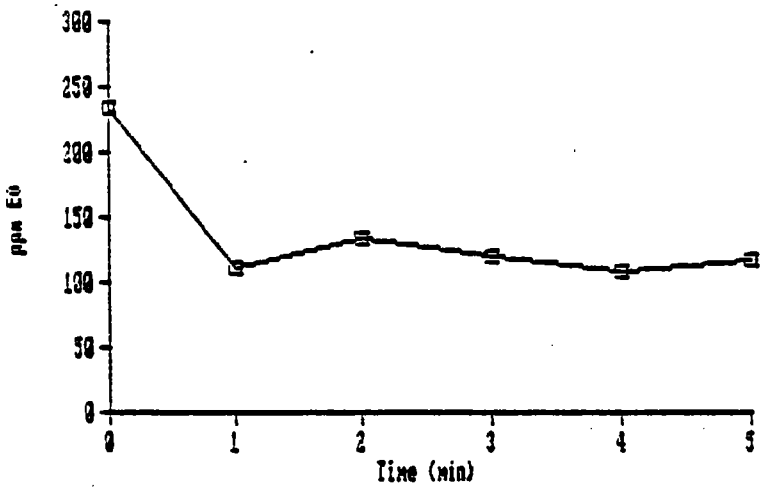
RUN 2
GC DATA - INLET

Sample No.	Time (min.sec)	ppm EO	Time (dec.)	Time from start	EO Area (ppm*min)	EO (g)
I-1	1044.00	234.15	1044.0	.0		
I-2	1045.00	112.09	1045.0	1.0	173.1	3.29
I-3	1046.00	135.08	1046.0	2.0	123.6	2.35
I-4	1047.00	121.11	1047.0	3.0	128.1	2.43
I-5	1048.00	110.19	1048.0	4.0	115.7	2.20
I-6	1049.00	117.51	1049.0	5.0	113.9	2.16
				Totals=	654.3	12.43

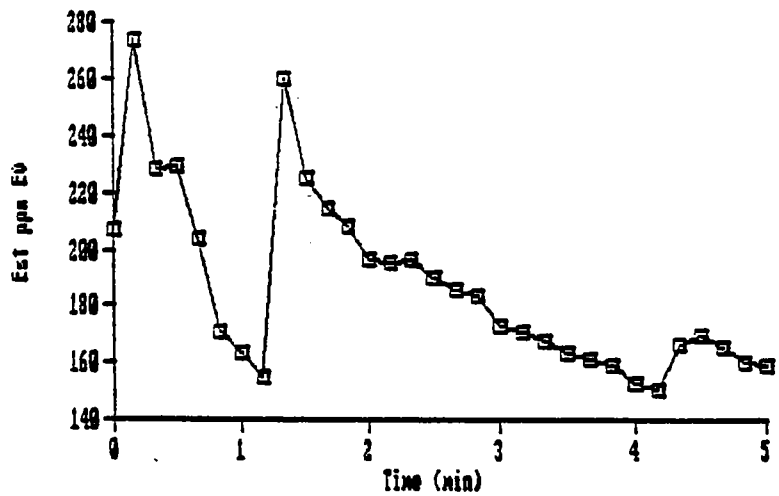
RUN 2
GC DATA - OUTLET

Sample No.	Time (min.sec)	ppm EO	Time (dec.)	Time from start	EO Area (ppm*min	EO (g)
O-1	1044.00	.20	1044.0	.0		
O-2	1045.00	.47	1045.0	1.0	.3	.006
O-3	1046.00	0.00	1046.0	2.0	.2	.004
O-4	1047.00	0.00	1047.0	3.0	.0	.000
O-5	1048.00	.09	1048.0	4.0	.0	.001
O-6	1049.00	.20	1049.0	5.0	.1	.003
				Totals=	.8	.014

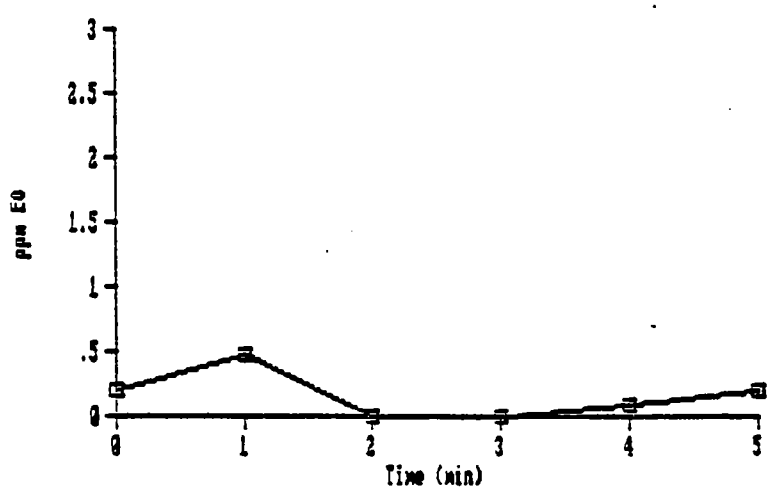
RUN #2 EO INLET CONCENTRATION



RUN #2 THC CONCENTRATION



RUN #2 EO OUTLET CONCENTRATION



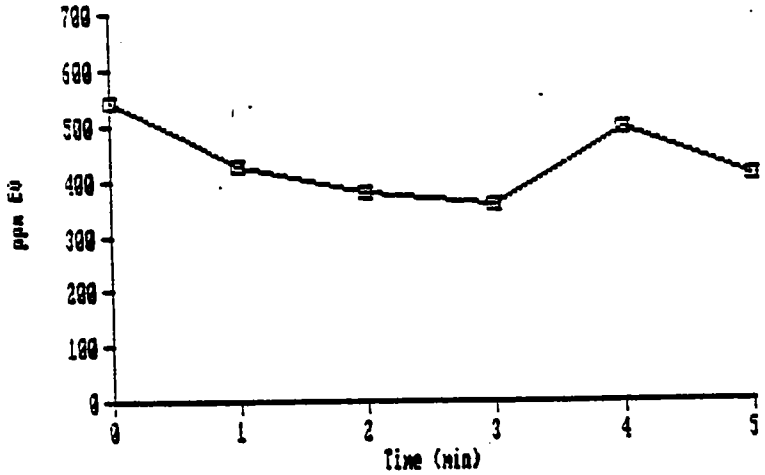
RUN 3
GC DATA - OUTLET

Sample No.	Time (min.sec)	ppm EO	Time (dec.)	Time from start	EO Area (ppm*min	EO (g)
O-7	1110.00	.56	1110.0	.0		
O-8	1111.00	.61	1111.0	1.0	.6	.011
O-9	1112.00	.06	1112.0	2.0	.3	.006
O-10	1113.00	.06	1113.0	3.0	.1	.001
O-11	1114.00	.86	1114.0	4.0	.5	.009
O-12	1115.00	.33	1115.0	5.0	.6	.011
				Totals=	2.0	.039

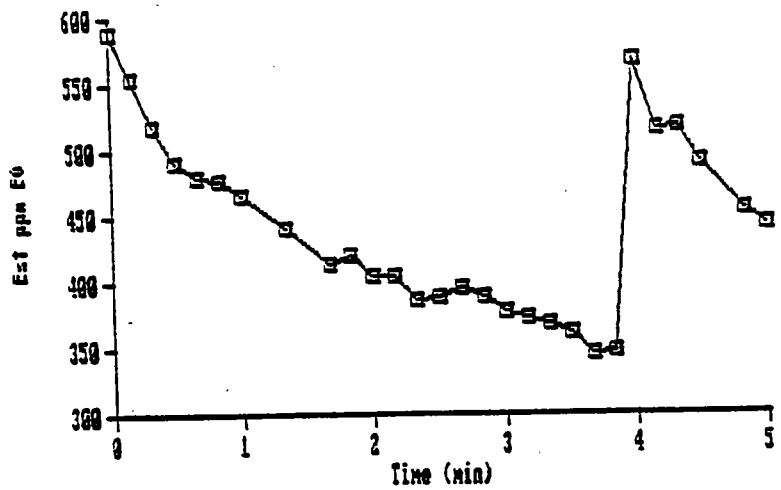
RUN 3
GC DATA - INLET

Sample No.	Time (min.sec)	ppm EO	Time (dec.)	Time from start	EO Area (ppm*min)	EO (g)
I-7	1110.00	541.67	1110.0	.0		
I-8	1111.00	425.19	1111.0	1.0	483.4	9.19
I-9	1112.00	379.39	1112.0	2.0	402.3	7.64
I-10	1113.00	358.13	1113.0	3.0	368.8	7.01
I-11	1114.00	494.48	1114.0	4.0	426.3	8.10
I-12	1115.00	410.56	1115.0	5.0	452.5	8.60
				Totals=	2133.3	40.53

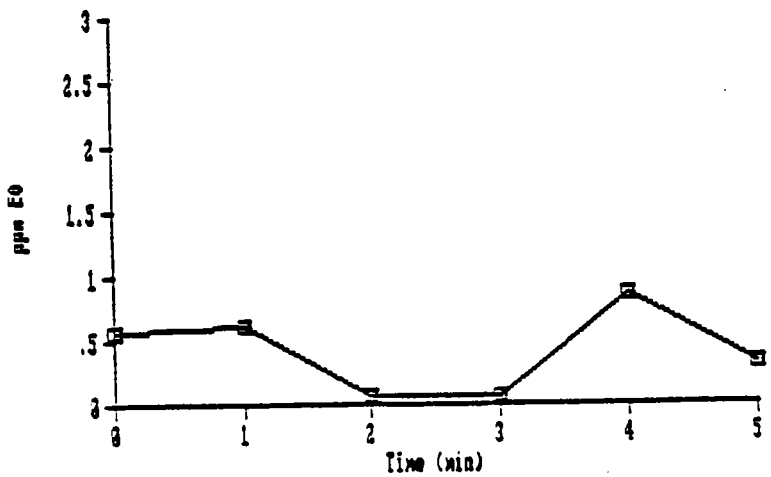
RUN #3 EO INLET CONCENTRATION



RUN #3 THC CONCENTRATION



RUN #3 EO OUTLET CONCENTRATION



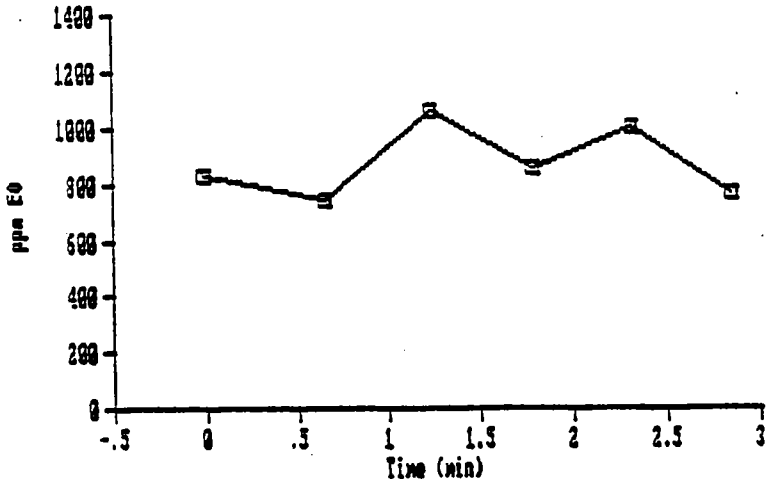
RUN 5
GC DATA - INLET

Sample No.	Time (min.sec)	ppm EO	Time (dec.)	Time from start	EO Area (ppm*min)	EO (g)
I-1	939.05	832.61	939.1	-.0		
I-2	939.45	750.43	939.8	.7	527.7	10.03
I-3	940.20	1066.83	940.3	1.2	530.0	10.07
I-4	940.53	858.80	940.9	1.8	529.5	10.06
I-5	941.25	1006.97	941.4	2.3	497.5	9.45
I-6	941.57	780.08	942.0	2.9	476.5	9.05
				Totals=	2561.3	48.67

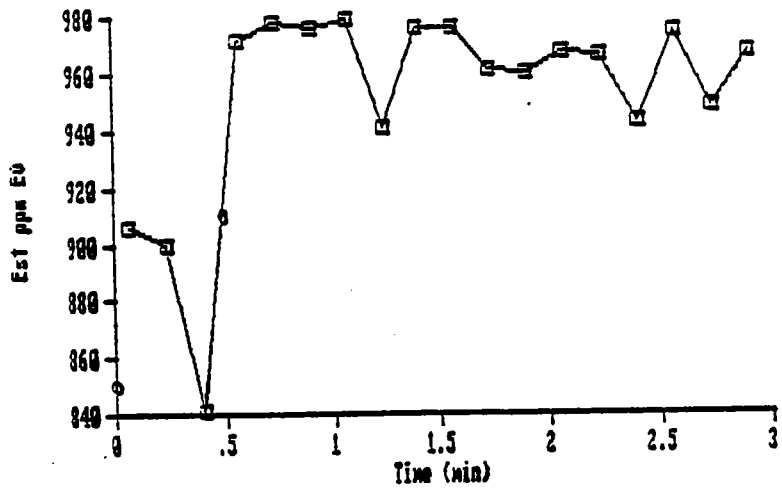
RUN 5
GC DATA - OUTLET

Sample No.	Time (min.sec)	ppm EO	Time (dec.)	Time from start	EO Area (ppm*min	EO (g)
O-1	939.05	0.00	939.1	-.0		
O-2	939.45	.31	939.8	.7	.1	.002
O-3	940.20	.09	940.3	1.2	.1	.002
O-4	940.53	.44	940.9	1.8	.1	.003
O-5	941.25	.30	941.4	2.3	.2	.004
O-6	941.57	.27	942.0	2.9	.2	.003
				Totals=	.7	.014

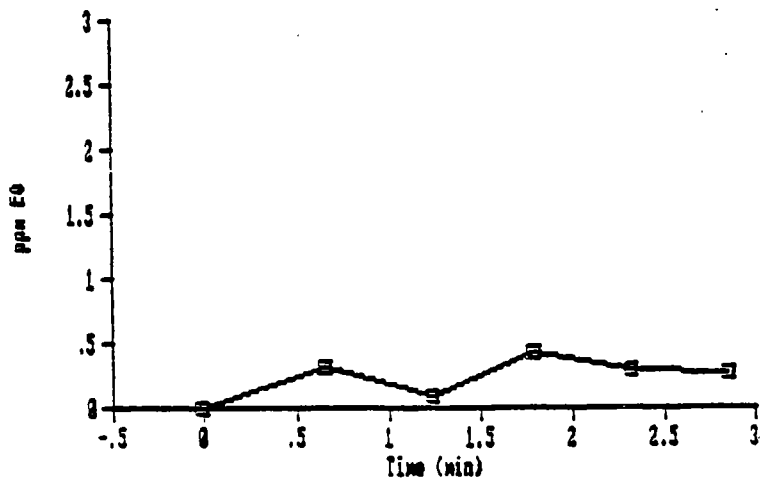
RUN #5 EO INLET CONCENTRATION



RUN #5 THC CONCENTRATION



RUN #5 EO OUTLET CONCENTRATION



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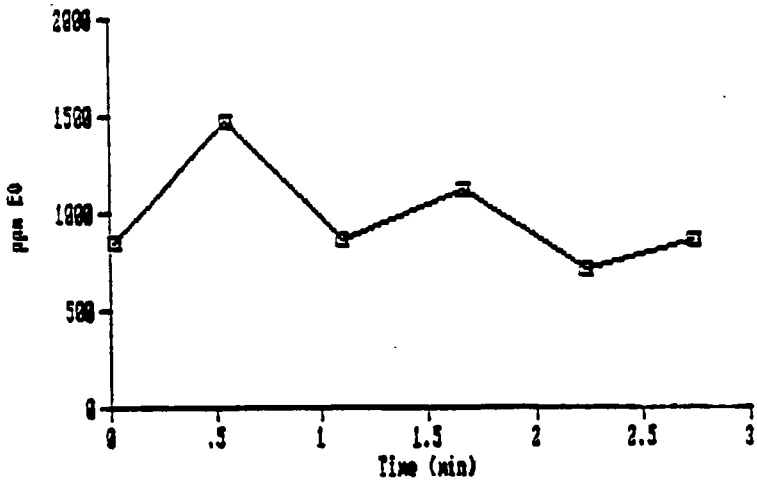
RUN 6
GC DATA - INLET

Sample No.	Time (min.sec)	ppm EO	Time (dec.)	Time from start	EO Area (ppm*min)	EO (g)
I-7	949.49	849.71	949.8	.0		
I-8	950.21	1482.43	950.4	.6	621.9	11.82
I-9	950.54	872.25	950.9	1.1	647.5	12.30
I-10	951.28	1125.50	951.5	1.7	566.0	10.75
I-11	952.02	708.87	952.0	2.2	519.7	9.88
I-12	952.32	867.70	952.5	2.7	394.1	7.49
				Totals=	2749.4	52.24

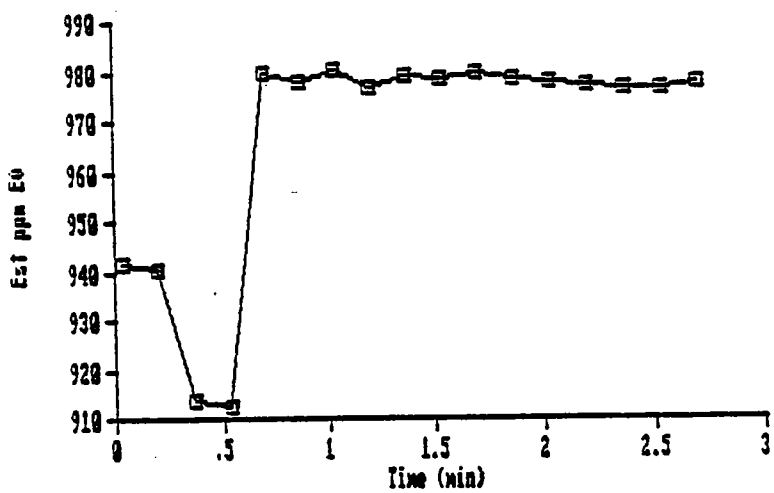
RUN 6
GC DATA - OUTLET

Sample No.	Time (min.sec)	ppm EO	Time (dec.)	Time from start	EO Area (ppm*min	EO (g)
O-7	949.49	0.00	949.8	.0		
O-8	950.21	.27	950.4	.6	.1	.001
O-9	950.54	.14	950.9	1.1	.1	.002
O-10	951.28	.06	951.5	1.7	.1	.001
O-11	952.02	.42	952.0	2.2	.1	.003
O-12	952.32	.52	952.5	2.7	.2	.004
				Totals=	.6	.012

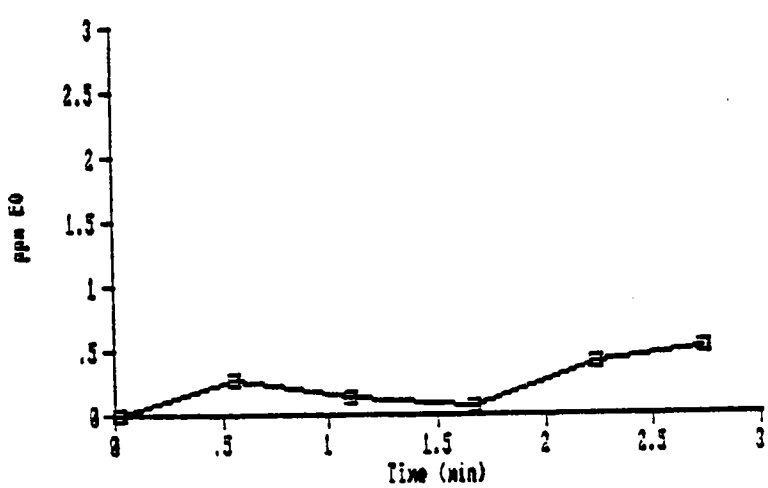
RUN #6 EO INLET CONCENTRATION



RUN #6 THC CONCENTRATION



RUN #6 EO OUTLET CONCENTRATION



APPENDIX F

EXPERIMENTAL DATA
CATALYTIC OXIDATION SYSTEM
CHLOROFLUOROCARBON DECOMPOSITION EXPERIMENTS

SUMMARY OF CHLOROFLUOROCARBON DECOMPOSITION STUDIES

Run no.	Chloride concentration (ng/mL)[a]	Impinger volume (mL)	Sample volume (dscf)	System flow rate (dscfm)[b]	Maximum chloride emissions (µg/min)	Maximum possible Freon decomposition (µg/min)[c]	Sampling time (min)	Maximum possible Freon decomposition (µg)	Freon input (kg)[d]	Maximum Freon decomposition (%)	Maximum catalyst temperature (°F)
1	< 200	20	1.5	370	< 5	< 18	28.0	< 520	1.20	$< 4 \times 10^{-5}$	283
2	< 200	20	1.1		< 4	< 13	5.0	< 67	0.104	$< 6 \times 10^{-5}$	287
4	< 200	20	1.3		< 5	< 16	25.8	< 400	1.21	$< 3 \times 10^{-5}$	299
5	< 200	20	0.46		< 2	< 5.8	2.8	< 16	0.407	$< 4 \times 10^{-6}$	311
7	< 200	20	0.92		< 3	< 12	22.8	< 260	1.24	$< 2 \times 10^{-5}$	282

a No chloride was detected in the samples. These results are calculated using the detection limit concentration of 200 ng/mL.

b See note on flow measurements in Appendix D.

c The assumption of one Cl^- per CF_2Cl_2 molecule was used to calculate possible CF_2Cl_2 emissions.

d The CF_2Cl_2 input values for the sterilizer discharge tests, Runs 1, 4, 7 were determined by measuring a change in cylinder weight and correcting for 12/88% by weight EO/CF_2Cl_2 concentrations. Since a large portion of the EO was lost to the water discharge, and some of the 12/88 mixture may have been lost to the vent, the percent decomposition values may be artificially low because it is not possible to quantitate the amount of CF_2Cl_2 input into the catalyst. The CF_2Cl_2 input values for the steady state tests, Runs 2, 5, were in proportion (12/88) to the detected EO input levels.

APPENDIX G

EXPERIMENTAL DATA
ACID SCRUBBER SYSTEM
STERILIZER DISCHARGE STUDIES

NOTES TO APPENDIX G

The dry gas meter readings are converted to flow rates by correcting to scfm using the meter calibration factor, temperature, pressure, and interval to previous reading:

$$\text{Flow rate (scfm)} = \frac{(\text{current DGM - previous DGM [ft}^3\text{])}}{\text{time from previous reading (min)}} \times M_f \times \frac{528}{460 + T} \times \frac{\text{pressure}}{29.92}$$

During run 6:

$M_f = 0.9131$

$T = 82°F$

$$\text{Flow rate (scfm)} = \frac{0.8999 \times \text{net ft}^3}{\text{net time}}$$

$$P = 30.20 + \frac{1 \text{ in. w.c.}}{13.6} = 30.27$$

Inlet Flows

For the inlet, the same flow rate equation is used, but with an additional term to correct for the EO absorbed = outlet flow x $\frac{100}{(100 - \%\ EO)}$

Outlet Emissions

$$EO\ (mg) = \frac{\text{flow rate (scfm)} \times 28.32\ L/ft^3 \times 1.83\ g/L}{10^3\ mL/L} \times \text{ppm} \times \text{min}$$

or flow rate x ppm x min x 0.0518

Inlet Emissions

$$EO\ (g) = \frac{\text{flow rate (scfm} \times 28.32\ L/ft^3 \times 1.83\ g/L \times \% \times \text{min)}}{100}$$

or flow rate x % EO x min x 0.518

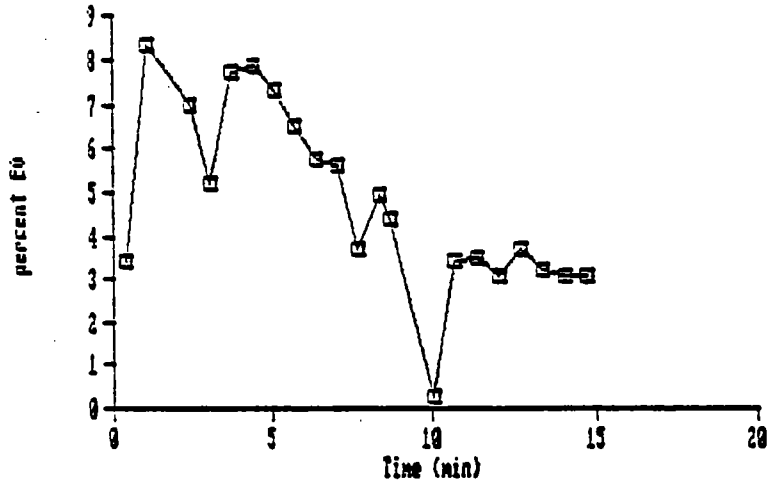
RUN 4
GC DATA - INLET

Sample No.	Time (min.sec)	DGM (cu. ft.)	percent EO	Time from start	Gas Flow (SCFM)	EO (g)	Rate (g/min)
Start	1328.49	419.43		.0			
I-1	1329.10	419.87	3.40	.4	1.19	.37	1.1
I-2	1329.50	420.87	8.38	1.0	1.50	3.05	4.6
I-4	1331.10	422.52	6.99	2.4	1.22	6.48	4.9
I-5	1331.50	423.42	5.23	3.0	1.31	2.76	4.1
I-6	1332.30	424.36	7.72	3.7	1.40	3.13	4.7
I-7	1333.10	425.16	7.87	4.4	1.19	3.22	4.8
I-8	1333.50	426.06	7.29	5.0	1.34	3.50	5.2
I-9	1334.30	426.80	6.47	5.7	1.09	2.59	3.9
I-10	1335.10	427.38	5.75	6.4	.85	1.79	2.7
I-11	1335.50	427.83	5.58	7.0	.66	1.28	1.9
I-12	1336.30	428.17	3.70	7.7	.49	.78	1.2
I-13	1337.10	428.42	4.91	8.4	.36	.54	.8
I-14	1345.30	428.84	4.41	8.7	1.21	.97	2.9
I-16	1346.50	430.82	.24	10.0	1.37	2.19	1.6
I-17	1347.30	431.89	3.43	10.7	1.52	.97	1.4
I-18	1348.10	432.79	3.47	11.4	1.28	1.53	2.3
I-19	1348.50	433.47	3.08	12.0	.97	1.09	1.6
I-20	1349.30	434.05	3.71	12.7	.83	.97	1.5
I-21	1350.10	434.47	3.24	13.4	.60	.72	1.1
I-22	1350.50	434.82	3.07	14.0	.50	.54	.8
I-23	1351.30	435.04	3.07	14.7	.31	.33	.5
				Totals=		38.79	

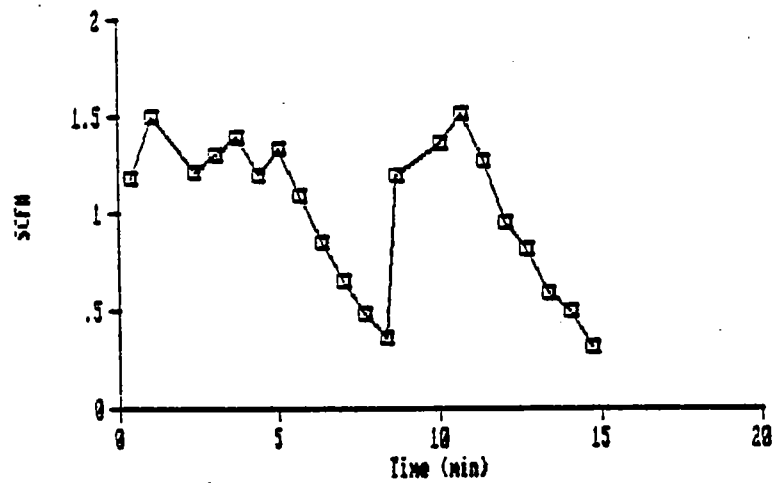
RUN 5
GC DATA - INLET

Sample No.	Time (min.sec)	DGM (cu. ft.)	percent EO	Time from start	Gas Flow (SCFM)	EO (g)	Rate (g/min)
Start	1002.38	443.80					
I-1	1004.00	444.93	10.26	1.4	.81	3.02	2.2
I-2	1004.40	445.78	10.92	2.1	1.29	4.73	7.1
I-3	1005.20	446.62	10.10	2.7	1.27	4.60	6.9
I-4	1006.00	447.47	8.08	3.4	1.25	3.93	5.9
I-5	1006.40	448.35	9.73	4.1	1.32	4.06	6.1
I-6	1007.20	449.20	9.46	4.7	1.27	4.22	6.3
I-7	1008.00	449.98	8.90	5.4	1.16	3.68	5.5
I-8	1008.40	450.60	8.24	6.1	.92	2.71	4.1
I-9	1009.20	451.06	7.21	6.7	.67	1.79	2.7
I-10	1010.00	451.40	6.55	7.4	.49	1.17	1.8
I-11	1010.40	451.65	1.92	8.1	.35	.51	.8
I-12	1011.07	451.81	6.12	8.5	.34	.32	.7
I-13	1019.10	452.12	5.39	9.1	.54	.88	1.6
I-14	1019.50	453.07	6.22	9.7	1.37	2.75	4.1
I-15	1020.30	454.08	5.02	10.4	1.44	2.80	4.2
I-16	1021.10	455.17	5.20	11.1	1.56	2.75	4.1
I-17	1021.50	456.06	4.45	11.7	1.26	2.10	3.2
I-18	1022.30	456.74	4.95	12.4	.97	1.57	2.4
I-19	1023.10	457.29	4.43	13.1	.78	1.26	1.9
I-20	1023.50	457.73	5.42	13.7	.63	1.07	1.6
I-22	1025.10	458.26	4.99	15.1	.38	1.36	1.0
				Totals=		51.30	

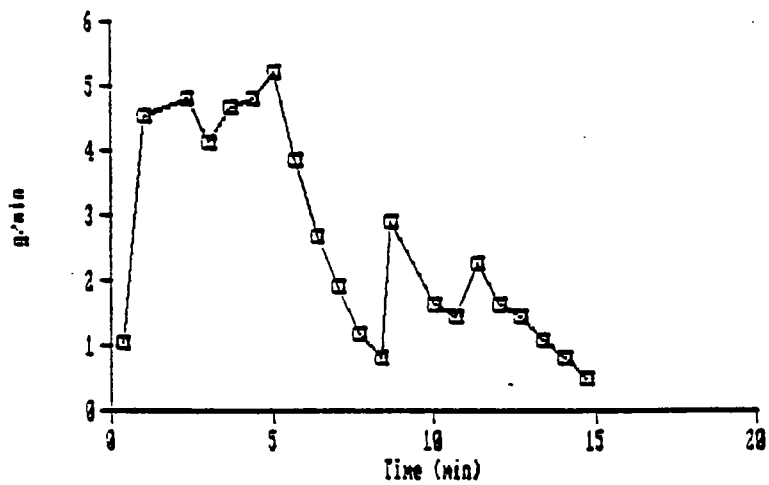
RUN #4 EO INLET CONCENTRATION



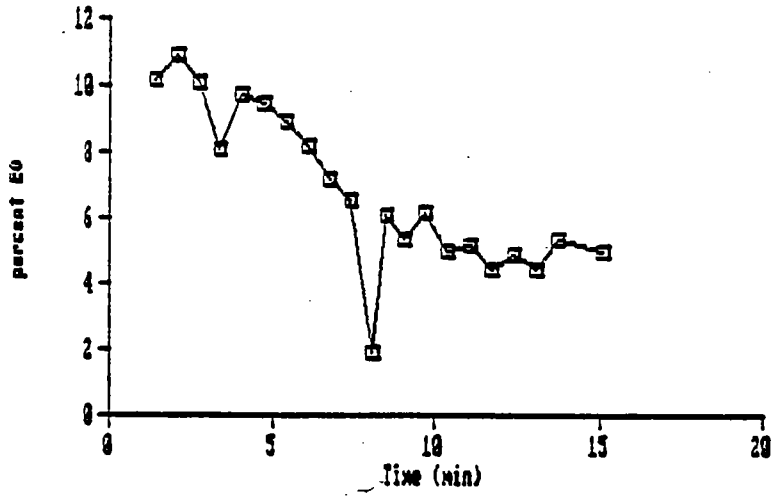
RUN #4 INLET FLOW RATE



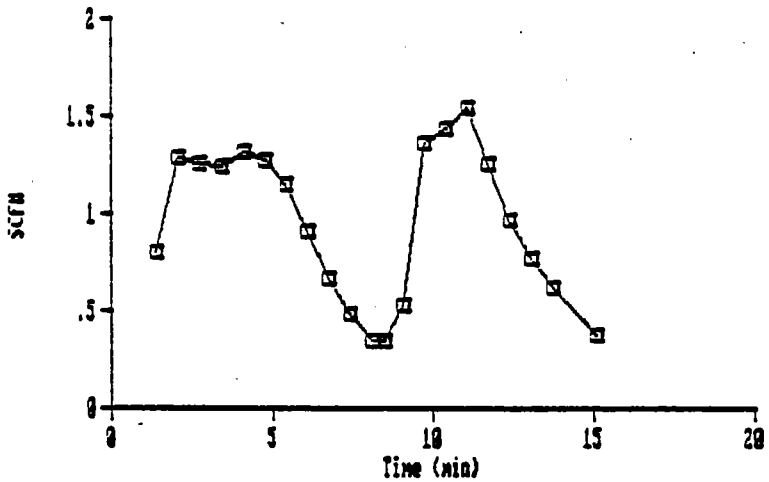
RUN #4 EO INLET EMISSION RATE



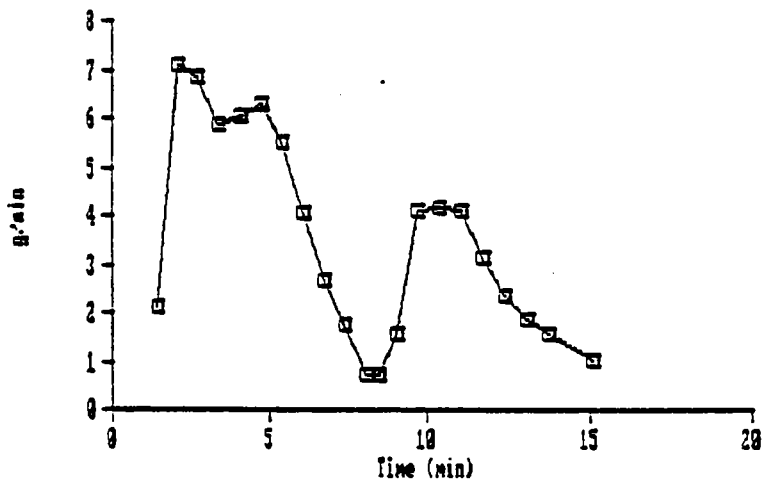
RUN #5 EO INLET CONCENTRATION



RUN #5 INLET FLOW RATE



RUN #5 EO INLET EMISSION RATE



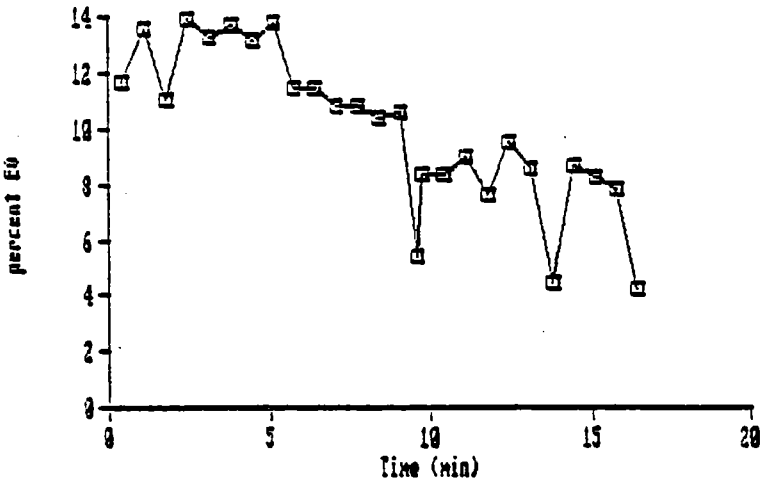
RUN 6
GC DATA - INLET

Sample No.	Time (min.sec)	DGM (cu. ft.)	percent EO	Time from start	Gas Flow (SCFM)	EO (g)	Rate (g/min)
Start	1433.26	485.34					
I-1	1433.50	485.82	11.76	.4	1.13	1.49	3.4
I-2	1434.30	486.69	13.60	1.1	1.36	5.95	8.9
I-3	1435.10	487.53	11.12	1.8	1.28	5.45	8.2
I-4	1435.50	488.36	13.95	2.4	1.30	5.64	8.5
I-5	1436.30	489.24	13.27	3.1	1.37	6.44	9.7
I-6	1437.10	490.15	13.70	3.8	1.42	6.63	9.9
I-7	1437.50	491.02	13.16	4.4	1.35	6.27	9.4
I-8	1438.30	491.87	13.88	5.1	1.33	6.22	9.3
I-9	1439.10	492.62	11.52	5.8	1.14	5.02	7.5
I-10	1439.50	493.14	11.55	6.4	.79	3.16	4.7
I-11	1440.30	493.54	10.82	7.1	.61	2.34	3.5
I-12	1441.10	493.85	10.91	7.8	.47	1.76	2.6
I-13	1441.50	494.18	10.40	8.4	.50	1.83	2.7
I-14	1442.30	494.26	10.64	9.1	.12	.44	.7
I-15	1443.00	494.32	5.39	9.6	.11	.24	.5
I-16	1450.40	494.53	8.41	9.8	1.24	.74	4.4
I-17	1451.20	495.46	8.46	10.4	1.37	3.99	6.0
I-18	1452.00	496.50	9.09	11.1	1.54	4.68	7.0
I-19	1452.40	497.57	7.65	11.8	1.56	4.52	6.8
I-20	1453.20	498.44	9.55	12.4	1.30	3.86	5.8
I-21	1454.00	499.13	8.63	13.1	1.02	3.20	4.8
I-22	1454.40	499.67	4.51	13.8	.76	1.73	2.6
I-23	1455.20	500.08	8.77	14.4	.61	1.39	2.1
I-24	1456.00	500.43	8.34	15.1	.52	1.52	2.3
I-25	1456.40	500.71	7.90	15.8	.41	1.15	1.7
I-26	1457.20	500.89	4.21	16.4	.25	.53	.8
I-30	1509.15	502.30	3.94	16.9	3.17	2.79	6.7
I-31	1510.15	504.90	3.46	17.9	2.42	4.65	4.6
I-32	1511.15	507.90	3.28	18.9	2.79	4.87	4.9
I-33	1512.15	510.70	1.64	19.3	2.56	3.26	3.3
I-34	1513.15	513.60	3.48	20.9	2.70	3.59	3.6
I-35	1514.15	516.45	3.28	21.9	2.65	4.64	4.6
I-36	1519.15	530.90	2.96	26.9	2.68	21.66	4.3
I-37	1524.15	545.50	2.84	31.9	2.70	20.31	4.1
I-38	1529.15	560.00	2.61	36.9	2.68	18.91	3.8
I-39	1534.15	574.50	2.39	41.9	2.67	17.31	3.5
I-40	1538.30	587.50	2.23	46.1	2.82	14.32	3.4
				Totals=		202.49	

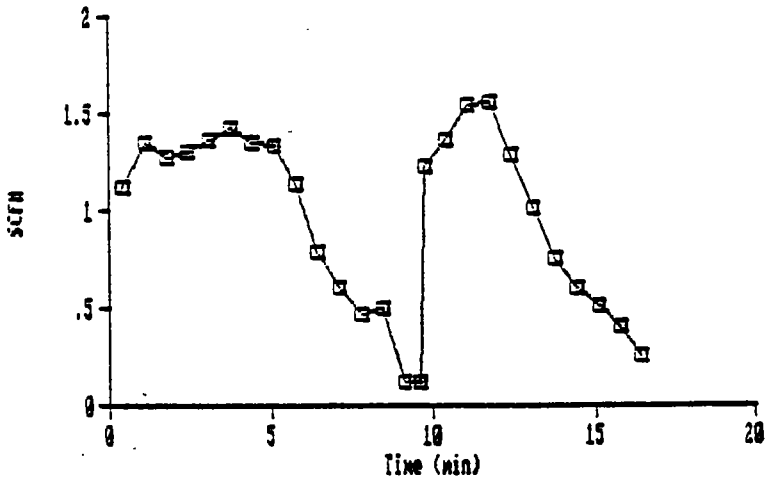
RUN 6
GC DATA - OUTLET

Sample No.	Time (min.sec)	DGM (cu. ft.)	ppm EO	Time from start	Gas Flow (SCFM)	EO (mg)	Rate (mg/min)
Start	1433.26	485.34					
O-1	1433.50	485.82	24.42	.4	1.00	.273	.63
O-2	1434.30	486.69	13.87	1.1	1.17	.776	1.16
O-3	1435.10	487.53	11.96	1.8	1.13	.506	.76
O-4	1435.50	488.36	14.10	2.4	1.12	.504	.76
O-5	1436.30	489.24	8.65	3.1	1.19	.467	.70
O-6	1437.10	490.15	8.95	3.8	1.23	.373	.56
O-7	1437.50	491.02	4.65	4.4	1.17	.276	.41
O-8	1438.30	491.87	4.03	5.1	1.15	.172	.26
O-9	1439.10	492.62	3.13	5.8	1.01	.125	.19
O-10	1439.50	493.14	3.28	6.4	.70	.078	.12
O-11	1440.30	493.54	3.11	7.1	.54	.060	.09
O-12	1441.10	493.85	3.98	7.8	.42	.051	.08
O-13	1441.50	494.18	5.61	8.4	.45	.074	.11
O-14	1442.30	494.26	5.01	9.1	.11	.020	.03
O-15	1443.00	494.32	7.70	9.6	.11	.013	.04
O-16	1450.40	494.53	3.78	9.8	1.13	.056	.34
O-17	1451.20	495.46	3.43	10.4	1.26	.156	.23
O-18	1452.00	496.50	.93	11.1	1.40	.106	.16
O-19	1452.40	497.57	1.12	11.8	1.44	.051	.08
O-20	1453.20	498.44	.90	12.4	1.17	.041	.06
O-21	1454.00	499.13	.63	13.1	.93	.025	.04
O-22	1454.40	499.67	1.70	13.8	.73	.029	.04
O-23	1455.20	500.08	2.00	14.4	.55	.035	.05
O-24	1456.00	500.43	.94	15.1	.47	.024	.04
O-25	1456.40	500.71	3.69	15.8	.38	.030	.05
O-26	1457.20	500.89	8.47	16.4	.24	.051	.08
				Totals=		4.38	

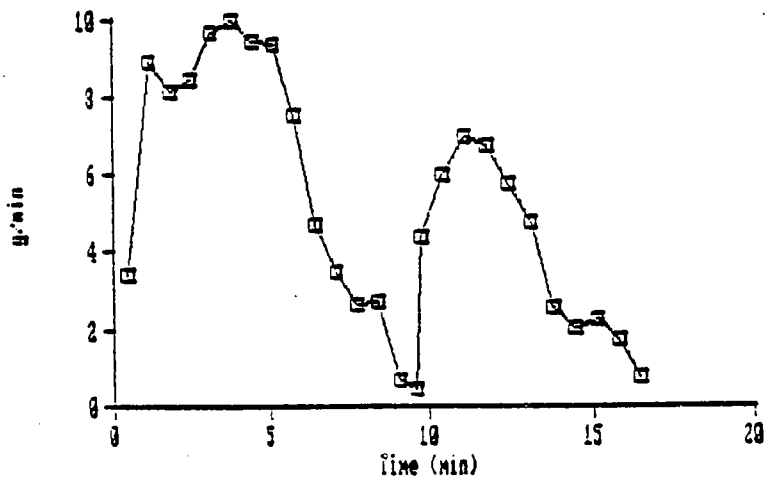
RUN #6 EO INLET CONCENTRATION



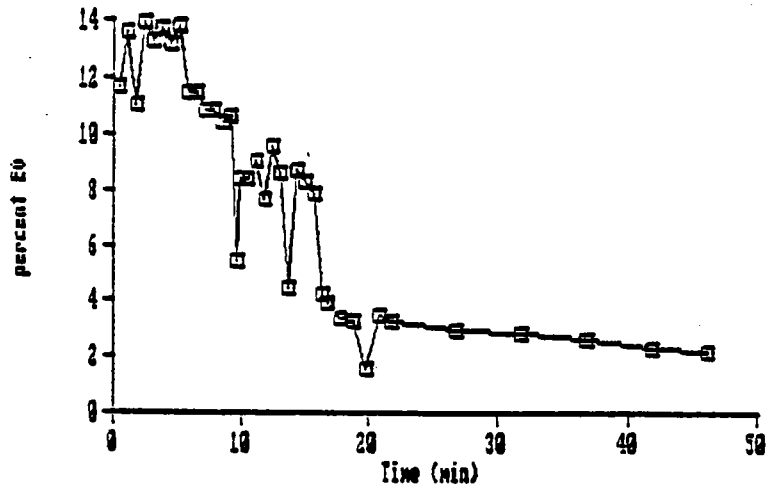
RUN #6 INLET FLOW RATE



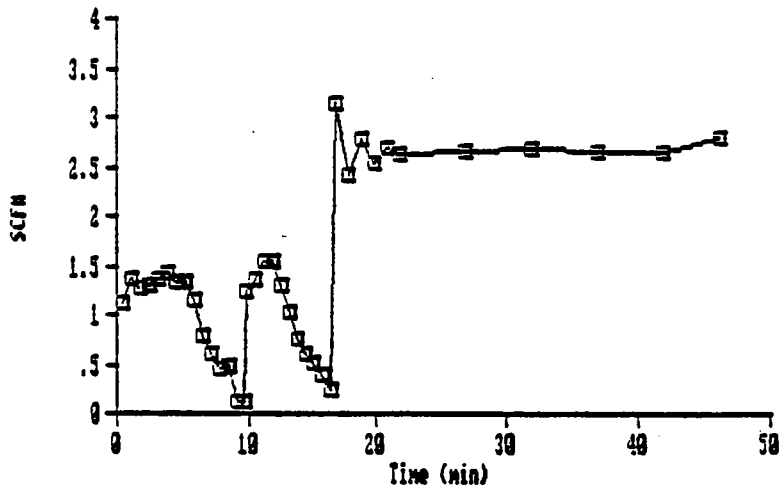
RUN #6 EO INLET EMISSION RATE



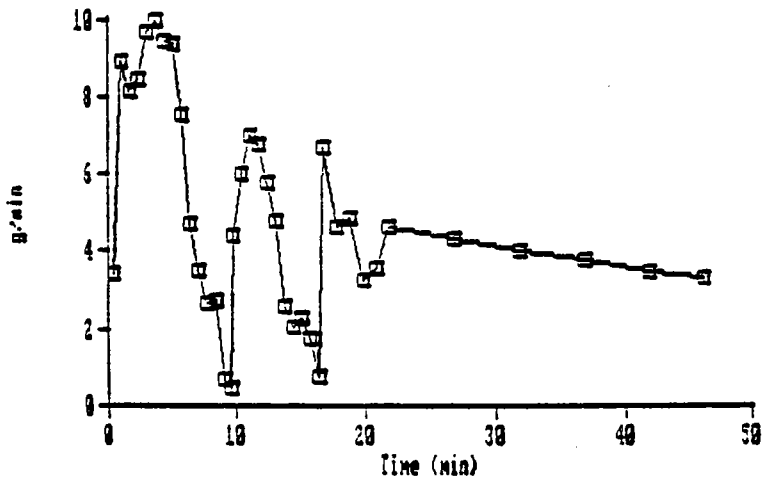
RUN #6 EO INLET CONCENTRATION



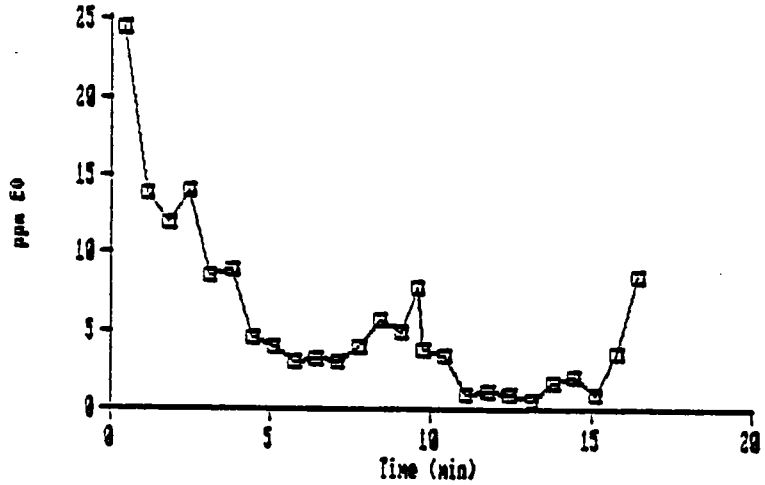
RUN #6 INLET FLOW RATE



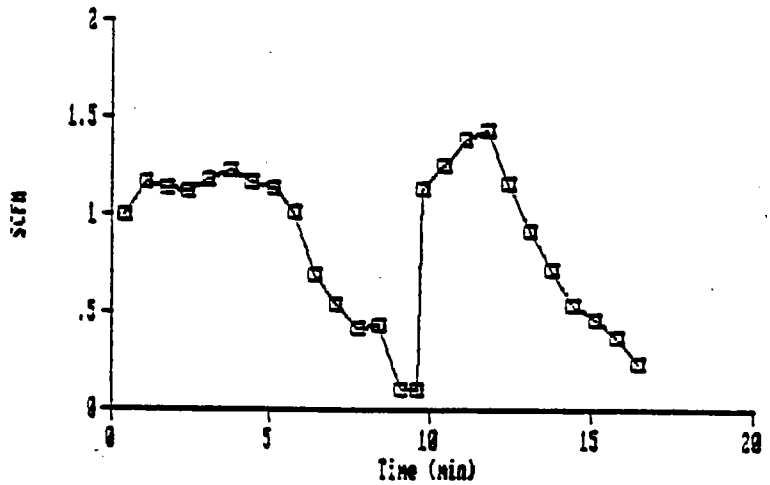
RUN #6 EO INLET EMISSION RATE



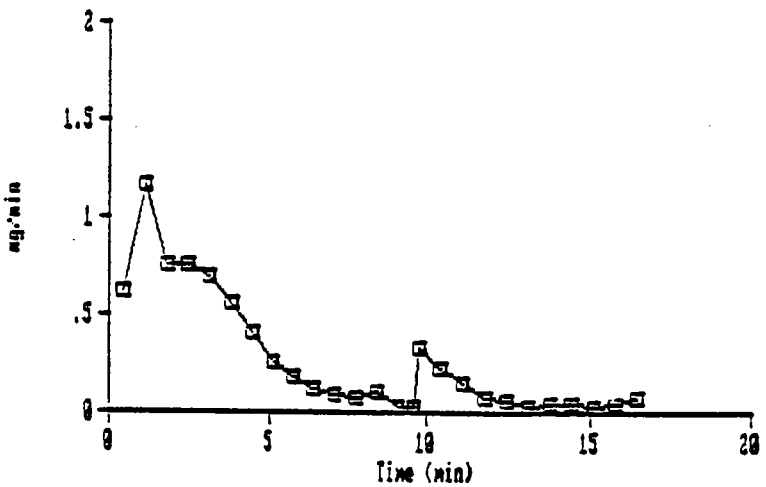
RUN #6 EO OUTLET CONCENTRATION



RUN #6 OUTLET FLOW RATE



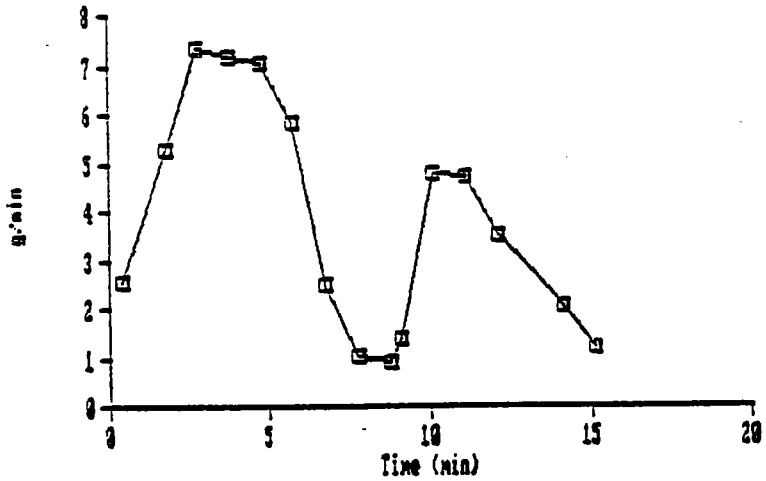
RUN #6 EO OUTLET EMISSION RATE



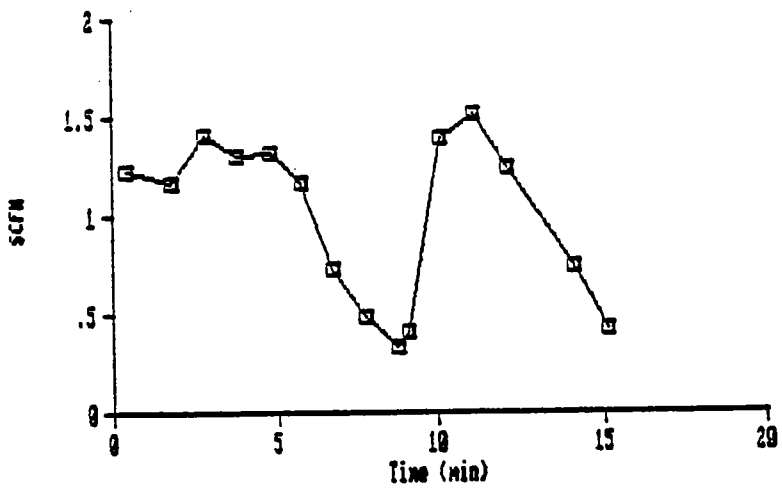
RUN 7
GC DATA - INLET

Sample No.	Time (min.sec)	DGM (cu. ft.)	percent EO	Time from start	Gas Flow (SCFM)	EO (g)	Rate (g/min)
Start	954.56	661.51					
I-1	955.20	662.05	8.07	.4	1.23	1.11	2.6
I-2	956.40	663.62	9.27	1.8	1.18	7.05	5.3
I-3	957.40	665.02	10.66	2.8	1.42	7.34	7.3
I-4	958.40	666.32	10.33	3.8	1.32	7.15	7.1
I-5	959.40	667.63	10.20	4.8	1.32	7.04	7.0
I-6	1000.40	668.80	9.10	5.8	1.17	5.84	5.8
I-7	1001.40	669.57	4.11	6.8	.73	2.49	2.5
I-8	1002.40	670.09	4.13	7.8	.49	1.05	1.1
I-9	1003.40	670.43	6.56	8.8	.33	.91	.9
I-10	1011.30	670.57	6.79	9.1	.41	.47	1.4
I-11	1012.30	672.02	6.40	10.1	1.41	4.80	4.8
I-12	1013.30	673.60	5.69	11.1	1.52	4.76	4.8
I-13	1014.30	674.91	5.16	12.1	1.25	3.52	3.5
I-15	1016.30	676.47	5.44	14.1	.75	4.11	2.1
I-16	1017.30	676.91	5.55	15.1	.42	1.20	1.2
				Totals=		58.84	

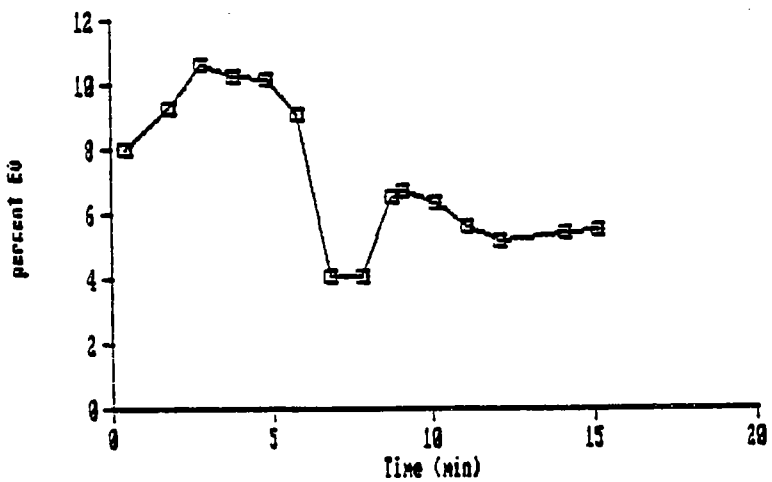
RUN #7 EO INLET EMISSION RATE



RUN #7 INLET FLOW RATE



RUN #7 EO INLET CONCENTRATION



APPENDIX H

EXPERIMENTAL DATA
ACID SCRUBBER SYSTEM
ETHYLENE OXIDE ADDITION STUDIES

NOTES TO APPENDIX H

The dry gas meter readings are converted to flow rates by correcting to scfm using the meter calibration factor, temperature, pressure, and interval to previous reading:

$$\text{Flow rate (scfm)} = \frac{(\text{current DGM} - \text{previous DGM } [ft^3])}{\text{time from previous reading (min)}} \times M_f \times \frac{528}{460 + T} \times \frac{\text{pressure}}{29.92}$$

During run 6:

$M_f = 0.9131$

$T = 82°F$

$$\text{Flow rate (scfm)} = \frac{0.8999 \times \text{net } ft^3}{\text{net time}}$$

$$P = 30.20 + \frac{1 \text{ in. w.c.}}{13.6} = 30.27$$

Inlet Flows

For the inlet, the same flow rate equation is used, but with an additional term to correct for the EO absorbed = outlet flow x $\frac{100}{(100 - \% \text{ EO})}$

Outlet Emissions

$$\text{EO (mg)} = \frac{\text{flow rate (scfm)} \times 28.32 \text{ L/ft}^3 \times 1.83 \text{ g/L}}{10^3 \text{ mL/L}} \times \text{ppm} \times \text{min}$$

or flow rate x ppm x min x 0.0518

Inlet Emissions

$$\text{EO (g)} = \frac{\text{flow rate (scfm} \times 28.32 \text{ L/ft}^3 \times 1.83 \text{ g/L} \times \% \times \text{min)}}{100}$$

or flow rate x % EO x min x 0.518

RUN 1
GC DATA - INLET

Sample No.	Time (min.sec)	DGM (cu. ft.)	percent EO	Time from start	Gas Flow (SCFM)	EO (g)	Rate (g/min)
I-1	1058.00	302.02	15.00	.0			
I-2	1059.00	304.23	24.00	1.0	2.63	26.52	26.5
I-3	1100.00	306.56	19.22	2.0	2.60	29.15	29.1
I-4	1101.00	308.76	17.55	3.0	2.41	22.94	22.9
I-5	1102.00	310.91	24.37	4.0	2.57	27.86	27.9
I-7	1104.00	315.31	19.23	6.0	2.46	55.54	27.8
I-8	1105.00	317.53	22.80	7.0	2.60	28.26	28.3
				Totals=		190.27	

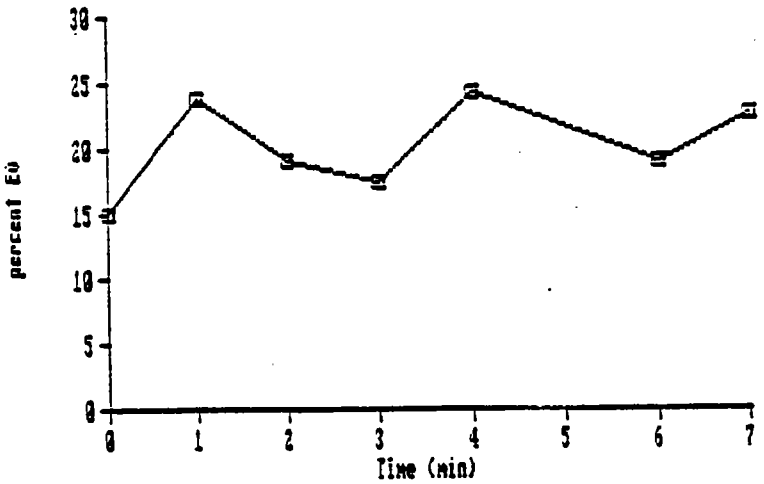
RUN 2
GC DATA - INLET

Sample No.	Time (min.sec)	DGM (cu. ft.)	percent EO	Time from start	Gas Flow (SCFM)	EO (g)	Rate (g/min)
I-1	1349.00	326.70	22.08	.0			
I-2	1350.00	328.98	22.67	1.0	2.66	30.85	30.9
I-3	1351.00	331.06	19.22	2.0	2.32	25.22	25.2
				Totals=		56.07	

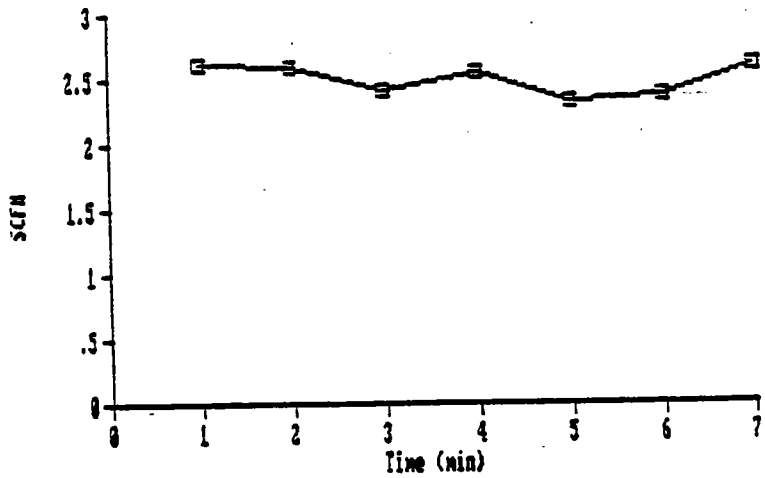
RUN 3
GC DATA - INLET

Sample No.	Time (min.sec)	DGM (cu. ft.)	percent EO	Time from start	Gas Flow (SCFM)	EO (g)	Rate (g/min)
I-1	1419.00	335.96	21.88	.0			
I-2	1420.00	338.26	21.05	1.0	2.67	29.71	29.7
I-3	1421.00	340.31	23.49	2.0	2.46	28.35	28.4
I-4	1422.00	342.59	22.29	3.0	2.69	31.91	31.9
I-5	1423.00	344.78	24.38	4.0	2.66	32.11	32.1
I-6	1424.00	346.82	21.57	5.0	2.39	28.40	28.4
I-7	1425.00	349.05	23.51	6.0	2.67	31.22	31.2
I-8	1426.00	351.26	22.65	7.0	2.62	31.33	31.3
				Totals=		213.04	

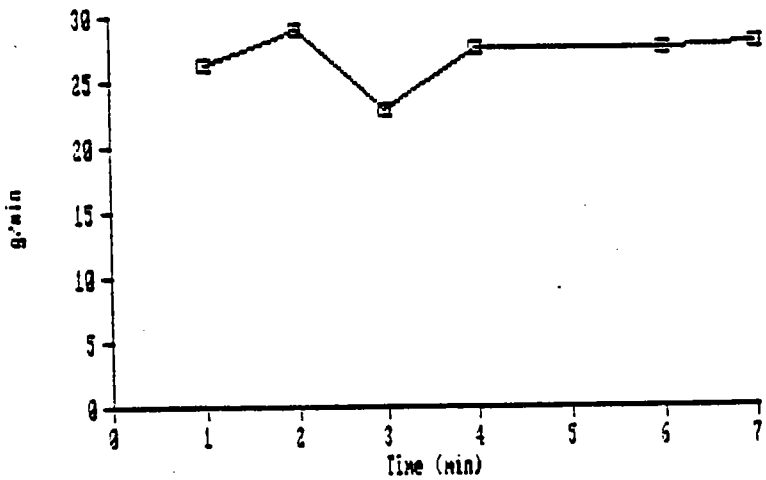
RUN #1 EO INLET CONCENTRATION



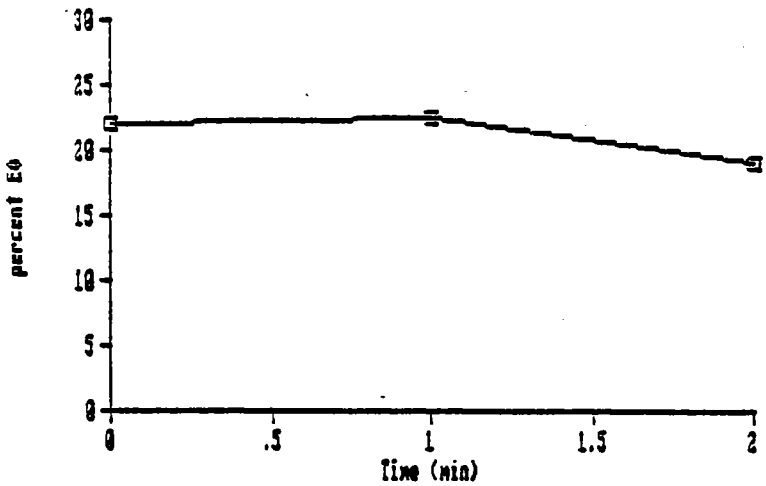
RUN #1 INLET FLOW RATE



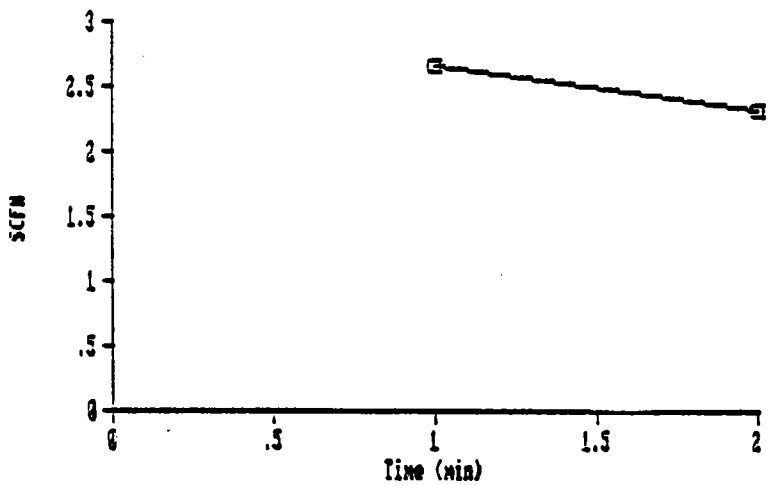
RUN #1 EO INLET EMISSION RATE



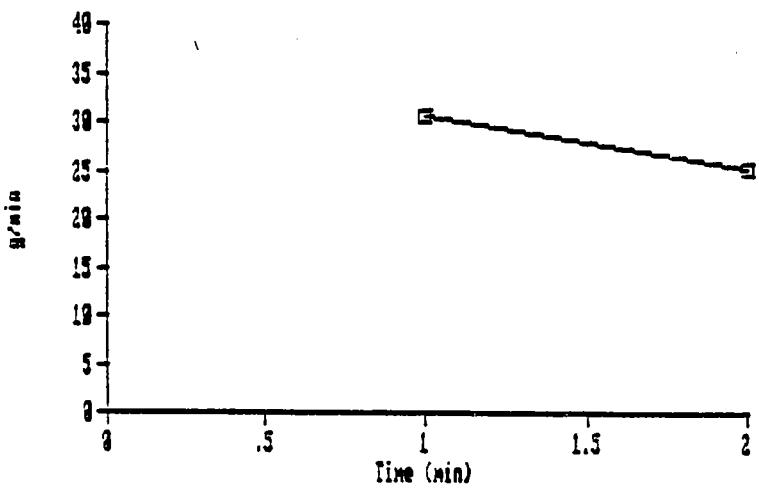
RUN #2 EO INLET CONCENTRATION



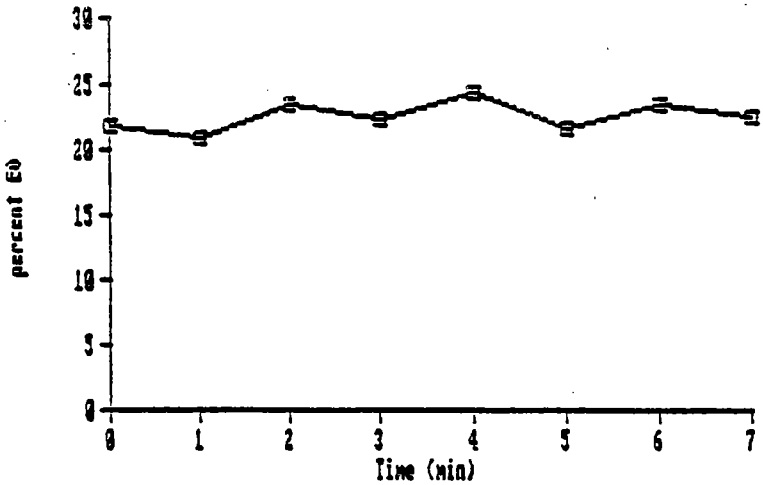
RUN #2 INLET FLOW RATE



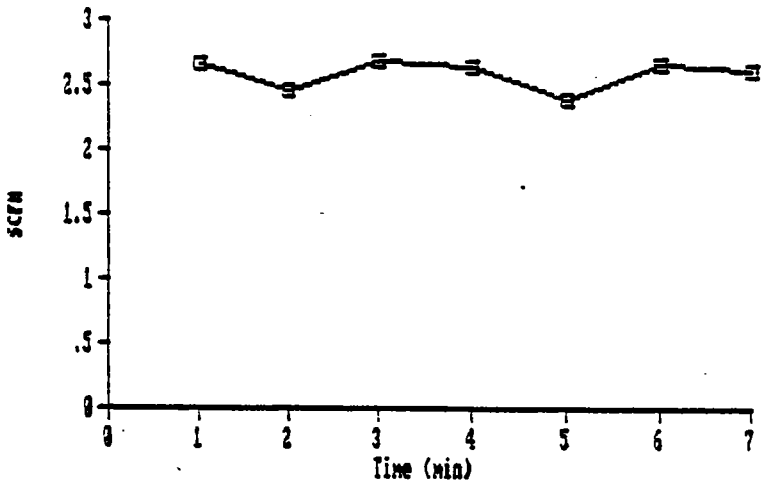
RUN #2 EO INLET EMISSION RATE



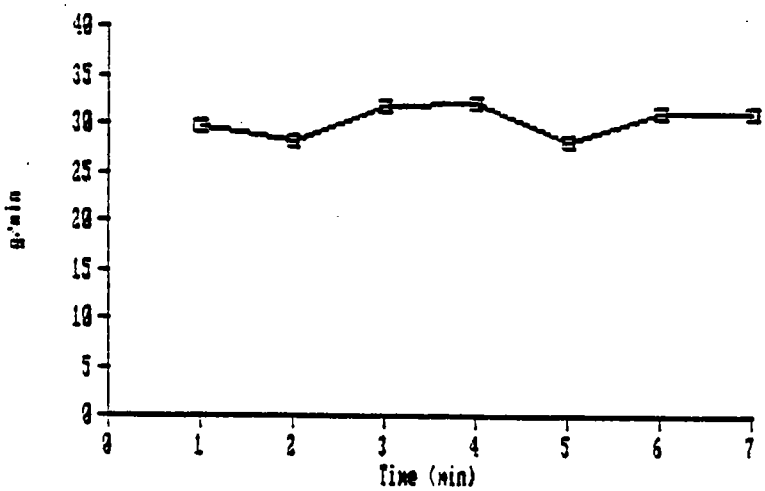
RUN #3 EO INLET CONCENTRATION



RUN #3 INLET FLOW RATE



RUN #3 EO INLET EMISSION RATE



APPENDIX I

QUALITY CONTROL EVALUATION REPORT

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APPENDIX I

September 23, 1987

Project No. 8691-L(10)

ETHYLENE OXIDE CONTROL TECHNOLOGY DEVELOPMENT
FOR HOSPITAL STERILIZERS

This report summarizes the independent QA/QC activities that were performed in conjunction with this project.

The experimental work was conducted at two test sites for the evaluation of a catalytic oxidation system and an acid-scrubber system. A separate Quality Assurance Project Plan (QAP) was written for both test sites.

The experimental work was performed by Ms. Laurie Cone and Ms. Dannette Shaw under the direction of Drs. George Scheil and Al Meiners (Project Leader). The Quality Assurance Coordinator (QAC) for this project was Mr. Dennis Hooton; Dr. Shri Kulkarni and Ms. Anne Worth of the Center for Environmental Quality Assurance, Research Triangle Institute performed audits for the U.S. EPA at the first test site.

I. Performance Audit Sample Results

A. Ethylene Oxide

An independent performance audit sample was analyzed at the Paoli test site by gas chromatography. The audit sample was a CL cylinder of ethylene oxide in nitrogen, procured by the QAC from Scott Specialty Gases; label information indicated that it was prepared on 5/22/87 and certified at ±2% accuracy. The manufacturer's listed concentration was removed from the label, a MRI sample identification number was assigned and labeled on the cylinder, then it was given to the field crew and transported to the test site for analysis. Results were initially reported via phone from the test site to confirm that the results met data quality objectives for accuracy; the audit

results were reported in writing by the analysts upon their return to Kansas City.

Overall, precision and accuracy results were good for the analysis of the MRI audit cylinder. Data Quality Objectives (DQOs) for the analysis of ethylene oxide by gas chromatography were 10% RPD (range % deviation) for precision, and 90% to 110% of the "true" value for accuracy. QC results indicated accuracies of 98% and 92% for Detectors A and B, respectively; precision was demonstrated from replicate injections analysis to be 3% RPD for Detector A and 24% RPD for Detector B. A complete summary of the audit sample results is shown in Table I-1.

TABLE I-1. ACCURACY AND PRECISION RESULTS FOR THE MRI ETHYLENE OXIDE AUDIT CYLINDER

MRI sample no.: 04428
Date analyzed: 6/4/87

Replicate analysis	Detector A Concentration found (ppm)*	Detector B Concentration found (ppm)
1	478.8	476.9
2	484.9	406.3
3	489.9	490.8
4	475.9	397.8
5	480.3	489.5
6	-	407.3
7	-	508.4
Mean:	482 ppm	454 ppm
Precision:	3% RPD	24% RPD
Expected Concentration:	492 ppm	492 ppm
Accuracy:	98%	92%

* ppm = v/v.

Precision of Detector B was outside the DQO and indicates that instrument performance was simply not as good as it was for Detector A. These precision

results are also reflected in the performance of the detectors when the EPA audit cylinder was analyzed.

As indicated in RTI's audit report of July 31, 1987, some of the performance checks of the Paoli audit were outside the DQOs. The two GC detectors (A and B) were checked by analyzing samples from an EPA audit cylinder. Results of the analyses showed that precisions were demonstrated to be 1.3% RPD for Detector A and 11.2% RPD for Detector B. Accuracy values were calculated to be 87.3% and 104.1% for Detectors A and B, respectively. Comments provided by the project officer indicate that, although the two values exceeded the DQOs in the project plan, the data obtained indicates that the objective of the project was not affected by the deviation. The typical maximum concentration in the inlet stream is 430 ppm whereas the typical maximum concentration in the outlet is 0.74 ppm. The reduction in the EO levels is so significant that the deviation in the precision and accuracy by a factor of 2 will not affect the results that indicate better than 99% control of EO in the emission stream.

B. Chlorides

Two performance audit samples were prepared for chloride analysis by ion chromatography by diluting a potassium chloride reference standard solution, certified by an independent laboratory, with project supplied Table 1 eluent (3 mM $NaHCO_3$/2.4 mM Na_2CO_3). Concentrations of the performance samples were not disclosed to the analyst; however, based on discussions with the analyst, the concentration range for preparing the performance samples was lowered to 0 to 3 ppm (µg/mL) from the originally planned 0 to 50 ppm because of the non-detected levels of chlorides found in the test samples.

Results of the duplicate analyses of the performance samples indicated 85% accuracy for the 1.42 ppm sample and 86% accuracy for the 2.83 ppm sample. Precision found for the duplicate analyses were better than or equal

to 2% RPD (range % deviation). The accuracy results do not meet the objectives listed in Table 5-1 of the QAP (April 28, 1987), i.e., ±5% of the expected value. Results for the chloride performance samples are presented in Table I-2.

TABLE I-2. ACCURACY AND PRECISION RESULTS FOR CHLORIDE PERFORMANCE SAMPLES

Date analyzed: 6/24/87

Replicate analysis	Sample no. 04430 concentration found (ppm)*	Sample no. 04431 concentration found (ppm)
1	2.41	1.20
2	2.45	1.21
Mean:	2.43 ppm	1.21 ppm
Precision:	2% RPD	1% RPD
Expected Concentration:	2.83 ppm	1.42 ppm
Accuracy:	86%	85%

* ppm = µg/mL.

II. Data and Systems Audits

The draft final report and supporting data and records were received by the QAC on September 15, 1987, for review. Selected data were chosen at random to check for systematic errors and traceability, these included:

Calculations for Run 1 of the GC sterilizer discharge studies, Run 2 of the GC ethylene oxide addition study, and the calibration data from June 9, 1987.

A systems audit on the chloride analyses by ion chromatography was conducted on June 24, 1987. The analyst had completed specialized training in

ion chromatography, and was performing the work in accordance with the protocols specified in the QAP. The standard data used for establishing the calibration curve was also verified.

In general, there were no major problems found with the GC or ion chromatographic data that were inspected.

Clarification statements were provided in the project records about the data reduction procedures used for calculating ethylene oxide results, made necessary because of the very low levels of ethylene oxide found in the inlet samples. Results were calculated using the formula defined by the analyst as the "zero-intercept LLSQ fit" equation, and expressed as:

$$\sum \frac{x_i y_i}{\Sigma x_i^2}$$

References were provided for the project records to support the use of this method of calculation.

III. Conclusion

Based on observations and results of the QA review and performance audits, the work was performed by qualified personnel, in accordance with the project quality assurance plan.

MIDWEST RESEARCH INSTITUTE

Dennis Hooton
Quality Assurance Coordinator

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DOCKET CONTROL ROOM

April 5, 1988

RADIAN
CORPORATION

DCN: 88-233-004-65-03
Radian No.: 233-004-65-01
EPA No.: 68-02-4119

FINAL REPORT

SAMPLING/ANALYTICAL METHOD EVALUATION FOR ETHYLENE OXIDE EMISSION AND CONTROL UNIT EFFICIENCY DETERMINATIONS

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James B. Homolya, Project Director	April 5, 1988 Date
Dennis R. Knisley, QA/QC Reviewer	05/04/88 Date
John H. E. Stelling, Technical Reviewer	5.04.88 Date

April 5, 1988

ess/016

DISCLAIMER

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5

b

ABSTRACT

Radian Corporation, assisting the Environmental Monitoring Systems Laboratory, Environmental Protection Agency, Research Triangle Park, North Carolina, performed a field evaluation of a method for sampling and analyzing ethylene oxide (EO) in the vent stream from a sterilization chamber and a dilute acid scrubber. The utility of the sampling method for measuring the efficiency of the control unit was also evaluated.

The evaluated sampling and analysis procedure used semi-continuous direct sampling with on-line gas chromatographic analysis. Laboratory studies of the sampling method previous to the field test showed that semi-continuous direct sampling was capable of measuring EO emissions to within 11% of the expected value with a between-trial precision of 5 percent.

Analysis of samples taken from the vent of a dilute acid hydrolytic scrubber indicated that a column that retained dichlorodifluoromethane (CFC-12) longer than EO would be desirable because low part per million by volume levels of EO were difficult to detect in the presence of percent levels of CFC-12. Studies of several types of columns indicated that a stainless steel 10 foot (3 meter) by 1/8 inch (3 millimeter) outer diameter, 5% Flurocol on 60/80 mesh Carbopack B column, provided the best conditions for separation of EO from CFC-12.

Additional studies performed showed that under the field test conditions used, adequate control unit efficiency measurements were obtained using chambers filled with product and assuming that all of the EO charged to the chamber entered the control unit. The field test conditions used included a sterilization chamber/control unit system that was a closed system (i.e. leak-free), and a control unit that had a normal operating efficiency >99.6 percent.

This report contains conclusions and recommendations based on the field test results; descriptions of the properties of EO, the sterilization industry, previously used sterilizer test methods, and the semi-continuous

direct sampling method; results of the laboratory and field evaluation of the method as well as results of related laboratory studies which were performed; and references used to prepare this report.

This report was submitted in partial fulfillment of EPA Contract No. 68-02-4119 by Radian Corporation under the sponsorship of the U.S. Environmental Protection Agency. This report covers a period from July 1986 to December 1987.

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SAMPLING/ANALYTICAL METHOD EVALUATION FOR ETHYLENE OXIDE EMISSION AND CONTROL UNIT EFFICIENCY DETERMINATIONS

SECTION 1

INTRODUCTION

The Source Branch of the Environmental Protection Agency's (EPA) Environmental Monitoring Systems Laboratory (EMSL) at Research Triangle Park, North Carolina, has a program to develop stationary source test methods of known precision and accuracy for use in determining compliance with EPA standards. While participating in this program, Radian Corporation performed a field evaluation of a method for sampling and analyzing ethylene oxide (EO) in the vent stream from a chamber and a dilute acid scrubber of a commercial sterilizer. The usefulness of the sampling and analytical method for measuring the efficiency of the control unit was also evaluated.

Because EPA has listed EO as a possible hazardous air pollutant, a standardized sampling and analytical method is needed for determining control equipment efficiency. The evaluated sampling and analysis procedure used semi-continuous direct sampling with on-line gas chromatographic analysis.

The semi-continuous direct sampling method with on-line gas chromatographic analysis was tested because this method should provide accurate emissions data regardless of the EO concentration profile of the exhaust stream. The sampling/analytical method was tested at the inlet and outlet of the control unit. At the inlet the EO concentration was in the percent range and the temperature was above ambient (120-140°F, 49-60°C) while EO concentrations were in the ppmv range and at ambient temperatures at the outlet.

The measurement of the emissions were used to calculate the EO control unit efficiency. Two calculational methods were evaluated. The first method calculated a through-put efficiency using the EO emissions measured at the inlet and outlet of the control unit. This method calculated a true-efficiency because the EO actually entering the control unit was used in

the efficiency calculation. However, there was a greater possibility of error because of the necessity of accurately measuring the inlet flow rate, which entered into the calculation. Measuring the inlet flow rate was complicated by the high EO concentrations and the low flow rates at the inlet.

Measurement of the inlet flow rate was not required using the second calculational method which calculated a recovery that was equated to the control unit efficiency. The recovery was calculated from the amount (weight) of EO charged into the chamber and the measured EO emissions at the outlet of the control unit.

The purposes of the field evaluation were:

- To field test the proposed sampling method on an operating sterilizer with a dilute acid scrubber;
- To evaluate the suitability of the proposed sampling method for determining EO emissions and control unit efficiency; and
- To evaluate the applicability of the measured EO recovery as an estimator of control unit efficiency.

Section 2 reports the conclusions and recommendations based on the test results. Section 3.0 describes the properties of EO and provides a basic description of the sterilization process, the sterilization industry, and previously used test methods. Section 4 describes the method tested. Section 5 contains the results of laboratory evaluations of the method and related laboratory studies. Section 6 contains field test results. Section 7 lists references.

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SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Six conclusions were based on the field test results. First, the sampling/analytical method adequately determined EO emissions at the outlet of the uncontrolled sterilizer (i.e. the EO mass flow rate into the control unit).

Second, the sampling/analytical method adequately determined EO emissions at the outlet of the dilute acid scrubber, but identification of the EO peak in the chromatogram was complicated by EO retention times that shifted as the EO concentration decreased. The EO retention time shift was magnified due to the large range in the EO concentrations. The bias in the sampling/analytical method averaged 7.4% for EO and -2.4% for CFC-12. .

Third, the sampling/analytical method adequately determined the efficiency of the dilute acid scrubber. Measured efficiency calculated by the throughput method for empty chamber tests ranged from 99.82 to 99.98% and averaged 99.94 percent.

Fourth, the recovery method of determining control unit efficiency was comparable to the throughput method at this site. Efficiencies calculated for empty chamber tests by the throughput method ranged from 99.82 to 99.98% and averaged 99.94 percent. Efficiencies calculated for empty chamber tests by the recovery method ranged from 99.90 to 99.97% and averaged 99.95 percent. A one-way analysis of variance (ANOVA) performed on the data for the empty chamber tests showed that the methods were not different. The sterilizer chamber/control unit tested was a closed system (i.e. leak-free) so this conclusion may not be valid at an older facility where more EO may be lost from the system as fugitive emissions.

Fifth, the presence of product in the chamber did not affect the scrubber efficiency measurement. The efficiencies calculated for empty chamber tests by the throughput method ranged from 99.82 to 99.98% and averaged 99.94 percent. The efficiencies calculated for full chamber tests by the throughput method ranged from 99.92 to 99.98% and averaged 99.96 percent.

Sixth, EO emissions and control unit efficiencies calculated using flow rates based on orifice plate data did not differ significantly for EO emissions and control unit efficiencies calculated using estimates based on chamber temperatures and pressures. Ethylene oxide emissions for empty chamber tests based on orifice plate data ranged from 0.011 to 0.043 lb and averaged 0.024 lb. Estimated EO emissions for the same tests ranged from 0.006 to 0.036 lb and averaged 0.017 lb. Throughput efficiencies based on the orifice plate data ranged from 99.82 to 99.98% and averaged 99.93 percent. Throughput efficiencies based on estimated flows for the same tests ranged from 99.85 to 99.99% and averaged 99.95 percent. Again, the sterilizer chamber/control unit tested was a closed system so this conclusion may not be valid at an older facility where more EO may be lost from the system as fugitive emissions.

RECOMMENDATIONS

Six modifications based on the field test results are recommended. These include:

1. For efficiency determinations, sampling at the control unit inlet should not be required when the sterilizer chamber/control unit is a closed system. Sampling at this location is unnecessary because efficiencies calculated by the Recovery Method were comparable to efficiencies calculated by the Throughput Method. The Recovery Method used initial chamber charge and total EO emissions from the control unit outlet to calculate the efficiency.

2. For on-line analysis on a system using EO/CFC-12 sterilant gas, the analysis at the outlet should be modified by using two separate channels, one to quantitate the EO and the other to quantitate the CFC-12. Quantitation of the CFC-12 is needed to calculate the molecular weight of the vent stream. Separate analyses would eliminate the need to program the detector range and the added difficulties produced by detector range programming.

3. A minimum of six samples should be taken during each evacuation: two during the first two minutes, two between the second and ninth minute, and two between the tenth minute and the end of the evacuation. During the first two minutes of the evacuation the EO and CFC-12 concentrations should be the same as they were at the end of the previous exhaust and should be fairly constant. During the next five to seven minutes the EO and CFC-12 concentrations should change rapidly as the old chamber gas is swept out of the stack and the remaining chamber gas is diluted by the new chamber gas entering the scrubber. After 10 minutes the EO and CFC-12 concentrations should remain fairly constant at a level lower than the initial level.

4. The use of orifice plates should not be required when testing a closed chamber/control unit equipped with chamber temperature and pressure monitors. Field test data showed that the efficiencies calculated using estimated flow data were similar to efficiencies calculated using flow data based on orifice plate measurements.

5. If possible, sampling should be performed offline. Offline sampling would allow more samples to be collected because the number of samples would not be limited by the analysis time. Offline sampling would allow greater flexibility in the analytical method and improve the reliability of the identification and quantification of the components.

6. For offline sampling, 15-second grab samples should be acquired at one-minute intervals during the first two evacuations when the EO concentration is changing rapidly with time. Grab sampling should be performed during the later evacuations at two- or three-minute intervals. Grab samples could be obtained in syringes equipped with valves, small Tedlar bags or Vacusampler® cans.

SECTION 3

BACKGROUND

PROPERTIES OF ETHYLENE OXIDE

The chemical and physical properties of EO are discussed in References 1, 2 and 3. Only a brief summary is included here. Ethylene oxide, an epoxide, is also called oxirane (the International Union of Pure and Applied Chemistry name).[1] Other synonyms include: dihydrooxirene, dimethylene oxide, 1,2-epoxylethane, oxacyclopropane, oxane, oxidoethane, and α,β-oxidoethane.[1] It is usually handled as a liquid under pressure. At room temperature and pressure, EO is a gas that has a pungent, irritating, ether-like odor.[1] At 10 degrees Celsius (^{o}C) [50 degrees Fahrenheit (^{o}F)] it condenses to a colorless liquid.[1,2,3] It is completely miscible with water and with organic solvents.[1,2] The reactive and volatile properties of EO make it highly flammable and potentially explosive.[1,2] It has a flash point of <-18°C (0.4^{o}F) and is flammable in air at concentrations ranging from 3 to 100 volume percent (% [v]).[1,2] It is currently regulated by the Occupational Safety and Health Administration (OSHA) for occupational exposure of 1 part per million (ppm) over 8 hours (hr).[4] Because EO is a known reproductive hazard[2,5] and a suspected carcinogen[5], these last considerations, coupled with the fact that there is no upper explosive limit, require that special safety precautions be taken when handling and storing EO.

GENERALIZED DESCRIPTION OF THE BULK STERILIZATION PROCESS

Detailed descriptions of the sterilization process are contained in References 1 and 6. The bulk sterilization process, used by the majority of the commercial sterilization industry is described here in general terms. Hospital and medical products to be sterilized are preconditioned with steam in a separate chamber prior to sterilization. An air-tight sterilization chamber is loaded with the preconditioned products. Air inside the chamber is evacuated using steam ejectors to decrease the chamber pressure. Once the

desired vacuum level is achieved, the air inside the chamber is humidified to a predetermined value by adding steam. The sterilant is pressurized into the chamber to a predetermined level. The chamber is held at a constant pressure for a specified period, during which the products are sterilized by EO. When sterilization is complete, the sterilizer gas mixture is exhausted from the chamber until the chamber pressure is decreased to a predetermined level. Filtered air is introduced into the chamber to flush the sterilant gases from the chamber and product. These air washes may be repeated several times. After the last air wash, the door is opened and the chamber unloaded.

The gas in an EO sterilization chamber does not vent at a constant rate for two reasons. First the initial maximum venting rate is determined by the size of the chamber vacuum pump. As the chamber empties, the vent gas flow rate decreases. Second, the evacuation of the chamber is controlled by a solenoid valve which cuts on and off at regular intervals to prevent the chamber from evacuating too rapidly and damaging the products. This changing and pulsing flow rate makes sampling the gas stream more difficult for two reasons. First, calculating the total flow through the vent is an integration rather than a multiplication process and requires continuous monitoring of the flow. Second, calculating the total emissions requires taking many grab samples over the sampling period or collecting a representative sample using special techniques.

There are two models for the EO concentration profile in the chamber exhaust. In one model the chamber is considered to be a closed system at equilibrium. For this model, the EO concentration in the exhaust gas remains constant and only the vent stream flow rate varies. In the other model, the chamber is considered to be a dynamic system. For this model, both the EO concentration and flow rate of the exhaust gas change with time. If the sterilization chamber does not contain product, the exhaust stream will be characterized best by the first (static) model because equilibrium will occur quickly between evacuations. Any product present in the chamber will offgas, releasing ethylene oxide, during chamber evacuations and air washes. With a product-containing chamber, the exhaust stream will be characterized best by the second (dynamic) model.

HOSPITAL SUPPLY STERILIZATION INDUSTRY

Throughout the United States and Puerto Rico approximately two hundred facilities use EO for sterilizing heat- or moisture-sensitive products or for fumigating microorganisms and insects.[6,7] Chambers range in volume from less than 2 cubic meters (m^3) [60 cubic feet (ft^3)] to 170 m^3 (6000 ft^3).[7] Throughout the industry 76% of the chambers are charged with a mixture of 12 weight percent (% [w]) EO and 88% (w) of dichlorodifluoromethane (CFC-12).[7] Pure EO is used in 68% of the chambers and mixtures of carbon dioxide and EO are used in 10%.[7] (Some chambers are used with more than one type of sterilant gas.)

The vent streams from 17% of the EO sterilization facilities have some type of control unit, ranging from a neutral-water scrubber to an incinerator.[7] Forty-four percent of the control units chemically hydrolize the EO to ethylene glycol using dilute acid solutions, 3% use catalytic oxidation to convert the EO to carbon dioxide and water, and 19% of the control units are condensation/reclamation systems.[7] Commercial vendors of EO control units include Chemrox Incorporated, Damas Corporation, Mine Safety Appliances (MSA), and Croll Reynolds. A significant segment of the industry has custom-designed control units. Control units have been tested by the manufacturers and the industry as described below. Ethylene oxide removal efficiencies greater than 99% have been measured.[8,9,10,11]

EO CONTROL UNIT EFFICIENCY MEASUREMENTS

Several methods are currently being used in the EO sterilization industry to measure the efficiency of EO control units.[8,9,10,11] In general, the efficiency of an EO control unit is determined on a weight basis over the entire post-sterilization cycle. The post-sterilization cycle includes the initial chamber evacuation and all subsequent air washes. The units tested and reported include:

- A Chemrox unit in Pennsylvania,[12]
- A Chemrox unit in New York,[10]
- A Damas unit,[9] and
- An MSA unit.[13]

The Chemrox unit in Pennsylvania was tested using EO recovery to estimate control unit efficiency. The empty sterilization chamber was charged with a

known amount of the EO/CFC-12 sterilant gas and then vented. Grab samples of the vent gas were taken in Vacusampler® cans every 5 min and analyzed in the laboratory. After the air wash portion of the sterilization cycle was completed, an air sample was removed from the chamber. The EO input to the control unit was calculated from the difference of the amount charged to the chamber initially and the amount remaining in the chamber at the completion of the evacuation cycle. The amount of EO emitted from the control unit was calculated from the concentration of EO in the outlet grab samples, the exhaust temperature, and outlet flow rate of the vent gas.

The Chemrox unit in New York was tested using a method whereby direct semi-continuous sampling was performed at both the inlet and outlet of the control unit. Samples were directed through heat-traced lines into the gas sampling valve of a gas chromatograph (GC) at 1 min intervals. The weights of EO at the inlet and outlet of the control unit were calculated from the concentration of EO measured by the GC and the measured temperature and flow rate of the vent gas.

The Damas unit was also tested by taking inlet and outlet samples. The inlet samples were collected in six-layered aluminized bags and the outlet samples were collected on charcoal tubes. A series of inlet and outlet samples were collected at a constant sampling rate over 5 min intervals during the entire post-evacuation cycle. The charcoal tubes were desorbed using carbon disulfide. The bag samples from the inlet and the charcoal tube extracts from the outlet were then analyzed by GC. Again, the weights of EO at the inlet and outlet of the control unit were calculated from the measured EO concentrations, vent gas temperature, and vent gas flow rate during each sampling period.

The MSA unit was also tested using both inlet and outlet measurements. The samples were collected in 10 milliliter (mL) syringes at 1 min intervals. Stream flow rates and temperatures were recorded at the time of sample collection. The entire sample in the syringe was injected directly onto a GC column for analysis. The amounts of EO at the inlet and outlet of the control system were calculated from the measured EO concentrations and stream flow rates.

SECTION 4

SEMI-CONTINUOUS DIRECT SAMPLING AND ANALYTICAL METHOD DESCRIPTION

APPLICABILITY AND PRINCIPLE

Applicability

This method applies to the measurement of EO emissions from sterilization chambers. It is applicable to emissions from sterilization chambers and sterilization control units which use acid hydrolysis to remove the EO. The analytical method is capable of measuring from 0.03 parts per million by volume (ppmv) to 27.7% (v).[14]

Principle

Samples are collected from the sterilization chamber or control unit using a semi-continuous direct sampling technique and are analyzed on-line by gas chromatography with flame ionization detection (GC/FID). The total weight in pounds or kilograms of EO is calculated using the measured EO concentrations and the measured temperatures, flow rates, and pressures of the sampled stream.

APPARATUS

The following equipment is required for performing semi-continuous direct sampling with on-line GC/FID analysis.

Heat-traced Teflon® Line

A heat-traced Teflon line is used to transport the sample from the vent stream to the gas sampling valve of the GC. The line is heated to a temperature slightly higher than the temperature of the vent gas in order to prevent condensation. The length of line required depends upon the proximity of the GC to the sampling port.

Pumps

Two vacuum pumps are required. One pump, capable of pumping 1 liter per minute (L/min) [0.035 cubic feet per minute (cfm)] with a leak-free, Teflon-coated diaphragm, is used to continuously withdraw sample from the sampling port and to pump sample to the gas sampling valve of the GC. The other pump, capable of pumping 100 milliliters per minute (mL/min) [0.0035 cfm] is used to flush the sample loop.

Acid Scrubbers

Two 500 mL Erlenmeyer flasks with two-hole stoppers containing dilute sulfuric acid at a pH of 1 are used to remove EO from the sampling stream and the GC slip stream before venting them to the atmosphere. The acid scrubbers may not be required when sampling controlled emissions if the exhaust lines are vented in a well-ventilated area void of personnel.

Thermocouples

Two thermocouples are needed to monitor the temperature of the vent stream. One should be wrapped in moist material to measure the wet bulb temperature. The accompanying temperature readout devices should be capable of measuring from ambient temperature up to 200°F (93°C).

Restricted Orifice Plates and Flanges

Restricted orifice plates sized to the vent are needed to monitor the flow rate of the vent stream. Standard orifice flange plates and flanges with standard pressure taps are recommended. If CFC-12 is used in the sterilant gas, two orifice plates are required.

Vane Anemometer

A vane anemometer is needed to measure gas stream linear velocites between 20 and 150 ft/min (6-45 m/min). A digital vane anemometer capable of measuring velocity at 10-sec intervals and with an ouput jack for a strip chart recorder is recommended.

Gas Chromatograph with Flame Ionization Detectector(FID) and Heated Gas Sampling Valve

A GC with a sampling valve, column, and detector is needed for the semi-continuous analysis of the vent sample. Other detectors (Thermal

Conductivity Detector or Photoionization Detector) may be substituted for the FID if they are shown to give equivalent results.

Chromatographic Column

A stainless steel, 10 foot (ft) [3 meter (m)] x 1/8 inch (in) [3 millimeter (mm)] outside diameter (O.D.), column containing 5% Fluorcol on 60/80 mesh Carbopack B is used to separate the EO from the CFC-12 and other materials present in the vent gas. Other columns (Chromosorb 102, Porapak® Q or R, Carbowax 20M) may be used, provided that the precision and accuracy of the standards analysis are not impaired. Information confirming that adequate resolution of the EO peak must be presented. Adequate resolution is defined as an area overlap of not more than 10% of the EO peak by an interferent peak.

Recorder/Integrator

A recorder/integrator is needed to record results.

Flow Meter

A flow meter is needed to accurately monitor sample loop flow rate of 100 mL/min.

Regulators

The following regulators are required for the GC support gases and the EO standards.

CGA 580--

One regulator is needed for the nitrogen carrier gas. A second regulator may be required for the standard manifold purge if the carrier gas line cannot be tapped.

CGA 590--

One regulator is needed for the air for the FID.

CGA 350--

Five regulators are needed; one regulator for the hydrogen on the FID and four regulators for the EO and CFC-12 standards. Two regulators with stainless steel diaphragms and Teflon seats and seals are required for the low concentration standards; one should be reserved for standards under 20 ppmv EO and the other for standards between 20 and 800 ppmv EO. The other two

standard regulators must be stainless steel; one should be reserved for standards between 800 ppmv and 2.5% (v) and the other for standards above 2.5% (v).

Teflon Tubing

Teflon tubing is needed to connect the gas cylinders to the GC, the sample loop to the sampling line and standard cylinders, the sampling line to the exhaust area, and for other miscellaneous connections. The diameter and length of the tubing depend upon the requirements of the system used. A recommended amount and diameter of tubing would be 10-20 ft (3-6 m) of 1/4 inch O.D. tubing. Each standard regulator should be equipped with 4-5 ft (1-2 m) of 1/8 in O.D. Tefon tubing.

Fittings

An assortment of Swagelock® fittings is desirable to plumb the GC to the gas cylinders and the sampling line to ensure leak-tight fittings. The size and type of fittings needed depend upon the type of tubing used and the type of fittings required by the GC and the cylinder regulators. Some recommendations are:

Caps and Front and Back Ferrules--

Teflon caps and ferrules (1/4 in) are needed to plumb in the glass flask. Stainless steel caps and ferrules (1/4 in and 1/8 in) are used on the ends of the Teflon tubing.

Unions--

Teflon (1/4 in) and stainless steel (1/4 in and 1/8 in) unions are used to connect tubing to impingers, sampling valves, etc.

Reducing Unions--

Stainless steel reducing unions (3/8 in to 1/4 in and 1/4 in to 1/8 in) are needed to connect cylinders to the GC and the sampling line to the gas sampling valve.

Soap Film Flow Meter

A soap film flow meter is used to measure GC carrier and support gas flow rates. It is also needed to calibrate any rotameters, dry gas meters, and mass flow meters used.

Two- or Three-way Radio

A two- or three-way radio is helpful to simplify communications between personnel at the sampling port, in the analytical area, and in the sterilizer control room.

REAGENTS

Unless otherwise indicated, it is intended that all reagents conform to the specifications established by the Committee on Analytical Reagents of the American Chemical Society where such specifications are available; otherwise, use the best available grade.

Nitrogen Gas

A grade of nitrogen which is 99.995 percent pure is required for use as the chromatographic carrier gas and as the system blank. If lower grades of nitrogen are used, purify the gas using hydrocarbon, water, and oxygen traps.

Hydrogen Gas

A grade of hydrogen which is 99.995 percent pure is required as a support gas for the FID. If lower grades of hydrogen are used, purify the gas using a hydrocarbon trap.

Air

A grade of air which is 99.9999 percent pure is required as a support gas for the FID. If lower grades of air are used, purify the gas using a hydrocarbon trap containing activated carbon.

Ethylene Oxide Standard Cylinders

Ethylene oxide and CFC-12 standards prepared in nitrogen which are certified through direct analysis are recommended for system calibration. The following concentrations balanced in nitrogen are suggested:

- 30% (v) EO and 5% (v) CFC-12,
- 3% (v) EO and 4000 ppmv CFC-12,
- 0.3% (v) EO and 300 ppmv CFC-12,
- 400 ppmv EO and 70% (v) CFC-12,
- 40 ppmv EO and 5% (v) CFC-12,
- 5 ppmv EO and 4000 ppmv CFC-12,
- 0.5 ppmv EO and 300 ppmv CFC-12.

If testing is performed on a controlled outlet only, the percent level EO standards are not needed.

1 N Sulfuric Acid Solution

A scrubbing solution consisting of 1 N H_2SO_4 with a pH between 1 and 2 is required for removing EO from the sampling stream before venting to the atmosphere. To prepare add 30 mL of concentrated sulfuric acid to 1 L of distilled water. Mix well. A minimum of 500 mL of scrubbing solution is needed.

Quality Assurance Audit Samples

Audit samples as described in Appendix C, Procedure 2: "Procedure for Field Auditing GC Analysis," 40 CFR, Part 61 are required.

PROCEDURE

Sampling Considerations

The sampling period begins with the start of the initial chamber evacuation and ends at the completion of the final air wash. The sampling line is continuously flushed with sample during the sampling period. The number of GC injections is based on the resolution time of the chromatographic column and the length of the evacuation interval.

Flow Rate Determination--

Restricted orifice plates are used as the basis for determining the stack gas velocity and the volumetric flow rate of the sample stream at linear velocities above 150 ft/min (45 m/min). This method calls for the use of orifice plates sized to the vent and fitted in flange holders with standard pipe taps. In cases where the gas density varies significantly two orifice plates may be required. At linear velocities between 20 and 150 ft/min (6-45 m/min) the method calls for the use of a vane anemometer.

Temperature--

Record temperature every 2 min with a type-K thermocouple or equivalent.

Moisture Content--

Determine the moisture content of the vent stream using the wet bulb/dry bulb technique.

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Semi-continuous Direct Sampling Procedure

In this procedure, sample is continuously withdrawn from the vent stream using a vacuum pump. A slip stream of gas is channeled into the gas sampling valve and injected into the chromatograph at 4 min intervals.

Assemble the sampling system as shown in Figure 1. Adjust the needle valves to yield a flow rate of 1 L/min to the manifold and 100 mL/min to the GC gas sampling valve. Leak check the assembly to prevent sample dilution and to protect personnel from fugitive EO emissions.

Place the probe at the centroid of the stack. Start the vacuum pumps and heat the sample transfer lines to prevent condensation.

When evacuation of the chamber begins, record the vane anemometer reading and the temperature of the vent gas at 2 min intervals. During the first and second evacuations measure oxygen content at 1 min intervals during the first 7 min of the evacuation. Measure oxygen content at least once during any subsequent evacuations. Take at least one wet bulb reading during each evacuation.

Analytical Procedure

A slipstream of the sample stream is drawn through a gas sampling loop and injected into a GC at 4 min intervals.

Gas Chromatographic Conditions--

The chromatographic conditions listed in Table 1 will resolve EO from CFC-12 and other interferences common to EO sterilization chamber vents. It may be necessary to change these conditions to resolve other interferences that are present in samples collected from different EO sources.

Calibration--

Calibrate the GC before the start and at the end of the test using the gas standards. A minimum of four points (four different standard concentrations) are needed to construct a calibration curve. For analysis of samples from an uncontrolled chamber, the GC needs to be calibrated with 400 ppmv to 30% (v) EO standards. For analysis of samples from a controlled chamber, the GC requires calibration with 0.5 ppmv to 400 ppmv EO standards. Use the same injection method and the same volume of sample for the calibration standards and the samples.

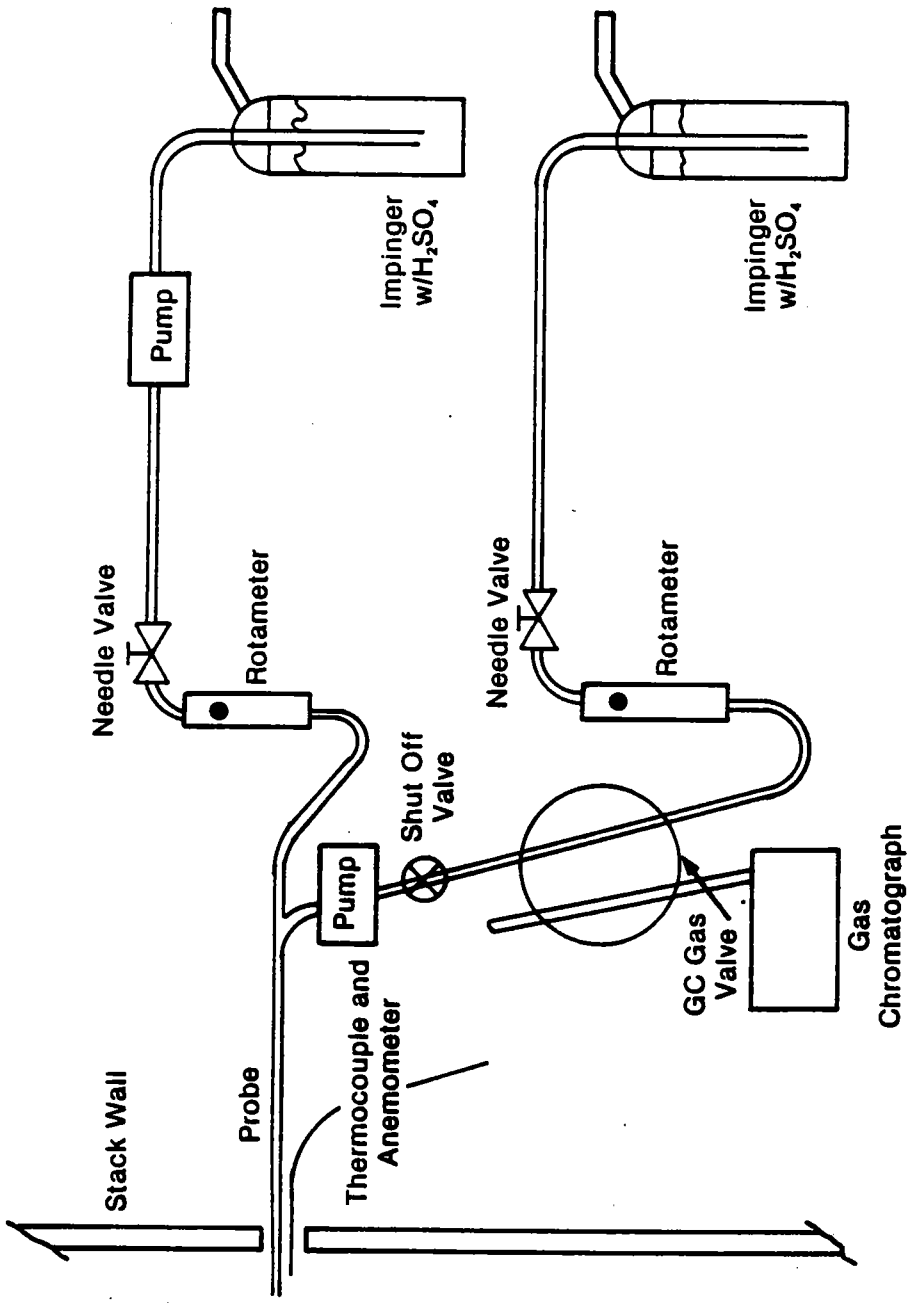

Figure 1. Semi-Continuous Direct Sampling System Assembly

TABLE 1. GAS CHROMATOGRAPHIC CONDITIONS

Parameter	Recommendation
Column	5 percent Fluorcol on 60/80 Mesh Carbopack B, 10 ft (3 m) x 1/8 in (3 mm), stainless steel
Column Temperature	55°C, isothermal for percent level analyses; 65°C, isothermal for ppmv level analyses
Injector Temperature	200°C
Detector Temperature	250°C
Gas Flow Rates	Follow manufacturer's recommendations
Valve	6-port heated to 150°C
Sample Loop Size	0.5 or 1 mL

Sample Analysis--

After the chamber evacuation begins, prepare to acquire the first sample. Before making the initial injection, allow sufficient time (3-4 min) for the residual air to purge from the line and for the sample to reach the manifold. (The time required will vary depending upon the amount of line used and the distance between the sampling port and the chromatograph. Determine sample line residence time prior to the test period.) Purge the sample loop for a minimum of 20 sec, simultaneously close the sampling valve and disconnect the vacuum pump, allow the sample loop to reach atmospheric pressure and make the initial injection. After the initial injection, make subsequent injections at 4 min intervals until the chamber evacuation ends.

Documentation--

Document each chromatogram by listing the sample location, injection volume, and injection time.

Audit Analysis

Immediately after the preparation of the calibration curve and prior to the sample analyses, perform the analysis audit described in Appendix C, Procedure 2: "Procedure for Field Auditing GC Analysis." 40 CFR, Part 61.

CALIBRATION

Rotameter

Calibrate the rotameter at three different flows before and after each test.

Probe Temperature Gauge and Thermocouple

Calibrate using ice water and boiling water (ASTM-E1 #63C or 63F specifications) before the test.

Restricted Orifice Plates and Pressure Transducers

The restricted orifice plates should be purchased calibrated in the range of expected use. The pressure transducers should be calibrated for the expected range before use in the field.

Vane Anemometer

Provide factory calibration (or equivalent) of the vane anemometer in the range of expected use.

Gas Chromatograph

Calibrate the GC at the start and at the end of each test day using prepared or purchased gas standards. Follow the calibration procedure described earlier. Use the chromatographic data (peak height or area) and standard concentration to prepare a least squares calibration curve.

Certified Standard Cylinders

Verify the certified concentrations of the purchased standard cylinders using an independent standard (one purchased from a second supplier or prepared in the laboratory using pure EO and CFC-12 diluted with nitrogen). Using the independent standard, prepare four-point calibration curves. From the calibration curves, calculate the measured concentrations of the certified standards. If the measured concentrations differ from the certified concentrations by more than ±10%, do not use the standards.

CALCULATIONS

Perform the following calculations, retaining at least one figure more than the required number of significant figures. Round off to the correct number of significant figures after making the final calculation.

Ethylene Oxide Concentration

Determine the EO concentration at each measured point by comparing the peak area obtained for each sample with those derived from the least squares calibration curve obtained as described earlier. Plot EO concentration versus elapsed time.

Inert Gas Concentration

Determine the inert gas concentration at each measured point based on GC data. If no CFC-12 is present in the sample, assume the gas which is not EO is air. Plot the inert gas concentration versus elapsed time.

Moisture Content

Calculate the moisture content (C_a) in the exhaust gas using the following formula:

$$C_a = (VP \times RH)/P_{bar} \qquad \text{(Equation 1)}$$

where:

C_a = Water vapor in the gas stream, mole fraction

P_{bar} = Barometric pressure, mm (inches) Hg

VP = Saturated vapor pressure of water at stack temperature, mm (inches) Hg

RH = Relative humidity determined by wet bulb/dry bulb method

The relative humidity using the wet bulb/dry bulb method and the saturated vapor pressure of water at stack temperature can be obtained from standard tables.[15, 16]

Molecular Weight of the Gas

Determine the molecular weight of the gas at each measured point using the following formula:

$$MW_{av} = P_{EO} \times 44.05 + P_F \times 120.91 + P_A \times 28.975 + P_W \times 18.02 \qquad \text{(Equation 2)}$$

where:

MW_{av} = Average molecular weight, g/g-mole (lb/lb-mole)

P_{EO} = Volume Percent EO

P_F = Volume Percent CFC-12

P_A = Volume Percent air

P_W = Volume Percent water

Total Gas Flow Rate

Calculate the total flow of gas emitted in terms of pounds per second (lb/sec [kilograms per second (kg/sec)]) at each measured point using the following equation:[17]

$$w = KYA \ (2g_c(p_1-p_2)\rho)^{1/2} \qquad \text{(Equation 3)}$$

where:

A = cross-sectional area of the orifice throat, ft^2,

w = mass rate of flow, lb/sec,

K = $C/(1-B^4)^{1/2}$, dimensionless,

C = coefficient of discharge, dimensionless,

B = ratio of throat diameter to pipe diameter, D_2/D_1, dimensionless,

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D_2 = orifice throat diameter, in,

D_1 = pipe diameter, in,

Y = expansion factor, dimensionless,

g_c = dimensional constant = 32.174 (lb ft)/(lb force sec^2),

p_1, p_2 = pressure at upstream and downstream static pressure taps respectively, lb/ft^2, and

ρ = density at upstream pressure and temperature, lb/ft^3.

Values for C may be obtained from Reference 17. Determine the expansion factor, Y using the equation:[17]

$$Y = \{r^{2k}[k/(k-1)][(1-r^{(k-1)/k})/(1-r)][(1-B^4)/(1-B^4 r^{2/k})]\} \qquad \text{(Equation 4)}$$

where:

$r = p_2/p_1$,

k = specific heat ratio, C_p/C_v.

Values for k may be obtained from the appropriate figures in Reference 18. Plot a graph of total gas flow rate versus elapsed time.

Ethylene Oxide Mass Flow Rate

Select a number of points at equal time intervals during the evacuation. At each selected point combine total gas flow rate, vent gas molecular weight, and EO concentration at that point using the following equation:

$$m = 60 \times w \times (P_{EO} \times MW_{EO})/MW_{av} \qquad \text{(Equation 5)}$$

where:

m = mass flow rate of EO, lb/min,

w = total gas flow rate, lb/s,

P_{EO} = EO concentration, percent by volume = $ppmv/10^6$,

MW_{av} = molecular weight of the vent gas, and

MW_{EO} = molecular weight of EO.

Plot a graph of EO mass flow rate versus elapsed time.

Total Mass of Ethylene Oxide

Integrate the curve obtained above to determine the total weight of EO exhausted to the atmosphere during the post-sterilization period. Add the weights determined for the individual evacuations to obtain the total weight

of EO emitted over the entire exhaust cycle using the following equation:

$$\sum_{i=1}^{k} \overline{M_i} \; t = \text{total mass} \qquad \text{(Equation 6)}$$

where:

i = The equally spaced time interval

k = Number of time intervals

$\overline{M_i} = (M_{i-1} + M_i)/2$

M_i = Mass flow rate, lb/min

t = Time interval, min

SECTION 5

LABORATORY METHOD EVALUATION AND OTHER EXPERIMENTS

SUMMARY OF LABORATORY STUDIES

The following tasks were performed in the laboratory and are reported below:

- A semi-continuous direct sampling method and a canister sampling method were tested on an artificially generated vent stream;
- The stability of EO standards in Summa® canisters was determined and a method of removing residual EO from the canisters was evaluated;
- A sample of vent gas taken during the pretest survey at the chosen facility was analyzed in the laboratory;
- Different packed columns were evaluated to determine their suitability to separate EO and CFC-12;
- Adsorption of EO on the sample loop and other surfaces was determined;
- The retention time shift of the EO peak on the column of choice was studied; and
- A sample of vent gas was analyzed by gas chromatography with mass spectral detection (GC/MS) and with flame ionization detection (GC/FID).

VENT STREAM TESTING

A pseudo-EO chamber vent stream was produced and the necessary sampling equipment was assembled in the laboratory. The testing system performance was checked for reproducibility. A semi-continuous direct and a canister sampling method were tested for accuracy using the assembled system.

The semi-continuous direct sampling method with on-line gas chromatographic analysis was tested because of its rigor. This method should provide accurate emissions data regardless of the EO concentration profile of the exhaust stream. However, this method has several disadvantages. First, it requires on-site analysis. Second, each sample can only be analyzed one

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time since sampling and analysis are performed on-line. Finally, the number of samples acquired is limited by the analysis time of the sample on the column.

Using grab sampling or integrated grab sampling eliminates some of these disadvantages. The collection of integrated grab samples in canisters has the advantages that collected samples can be shipped to a laboratory for later analysis and that multiple injections can be obtained for each sample. The major problem with canister sampling is that it is a time-integrated method and will only provide accurate emission measurements if the EO concentration profile of the exhaust stream is static.

Canisters were chosen instead of Tedlar® bags as the collection container for integrated samples because canisters are sturdy containers which have a lower potential for leaking. Ethylene oxide has the potential to cause chromosomal damage at levels of 50 ppmv and to increase the risk of leukemia at levels of 20-30 ppmv.[5] Using canisters would help to minimize worker exposure to EO.

Description of the Testing System and Sampling Setup

Several simulated EO chamber vent and sampling configurations were tested. The final configuration is shown in Figure 2. The dry gas meter was placed after the sampling port so that it would not interfere with concentration determinations. The EO chamber vent was simulated using a cylinder of 50 ppmv EO standard in nitrogen, a nitrogen cylinder, and calibrated Tylan flow controllers. The sampling system consisted of a needle valve, Thomas pump, and either a gas sampling loop or a Summa canister.

Both the flow rate and concentration of the vent stream were adjusted to simulate a reduced, yet similar, flow and concentration pattern which would occur from a large (1000 ft^3 [28 m^3]) sterilizer. Two different flow and concentration patterns were used, one to simulate an initial chamber evacuation and the other to simulate a subsequent evacuation.

Testing System Reproducibility

The EO and nitrogen flow rates were varied at 30-second (sec) intervals. The set flow rates were recorded after every adjustment or 30-sec interval. Using the recorded set flow rates, the total weight of EO emitted from the simulated vent was calculated. The relative standard deviation in total

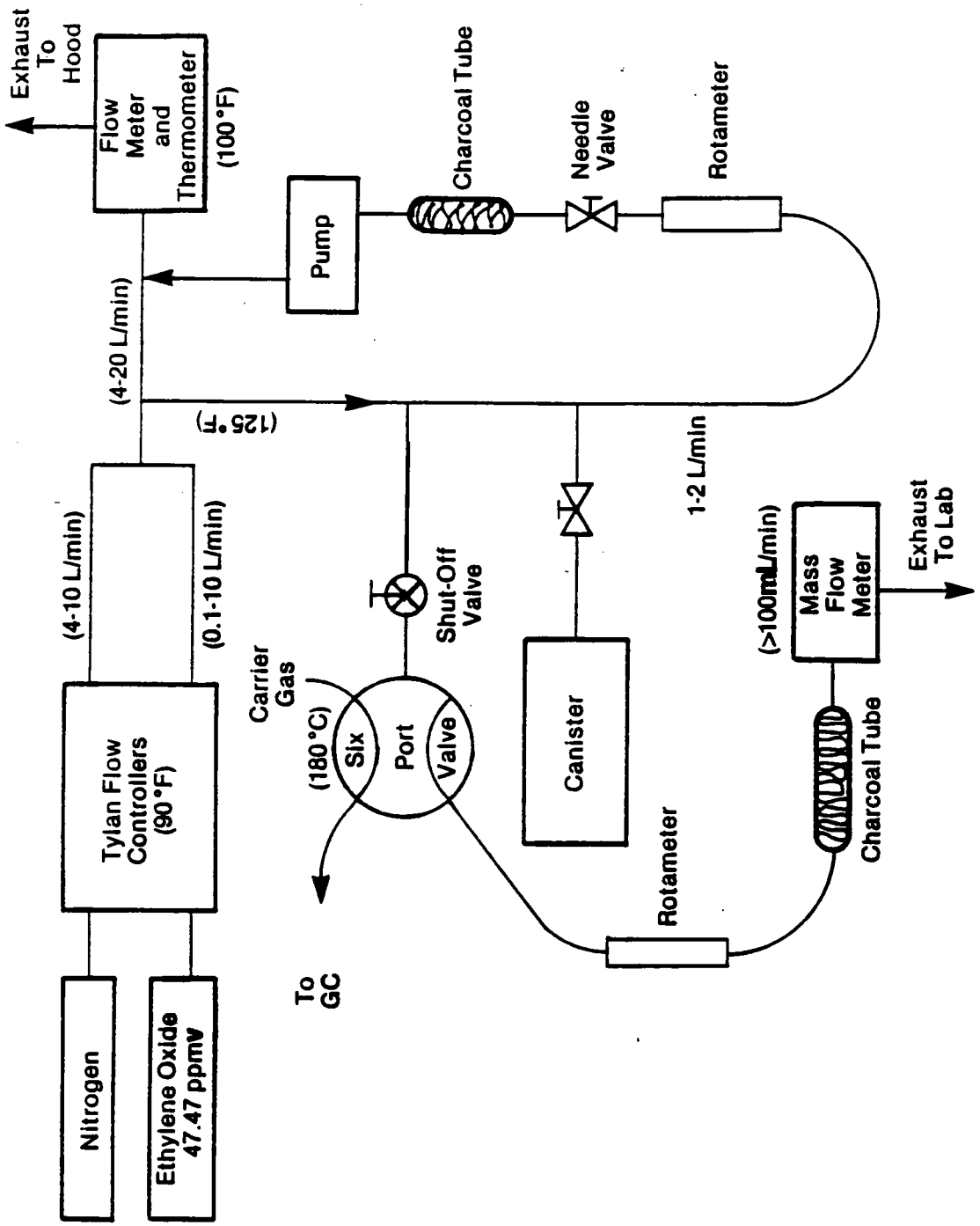

Figure 2. Laboratory Test System

milligrams of EO emitted between simulations was <1 percent. Thus, the vent simulator generated reproducible variable flow and variable concentration patterns for evaluating both sampling methods.

Results of the Semi-continuous Direct Sampling Method

Semi-continuous direct sampling was evaluated in the laboratory as a method of measuring EO emissions from a variable flow and variable concentration vent. The vent flow rate was recorded every 30 sec. Initially, the gas sampling valve was flushed for a minimum of 30 sec. Samples were injected into the gas chromatograph when the pressure within the loop reached atmospheric pressure. After the initial sample injection, samples were taken every 1.5 to 2 min by closing the gas sampling shut-off valve.

Three trials using semi-continuous direct sampling were conducted. Each trial consisted of an initial evacuation and an air wash simulation. In all three trials the measured emitted mass of EO was within 11% of the expected value. The between-trial precision, as measured by relative standard deviation, was 5 percent.

Results of the Canister Sampling Method

Canister sampling was evaluated in the laboratory as another method of measuring EO emissions from a variable flow and variable concentration vent. The vent flow rate was recorded every 30 sec. The canisters were filled at a constant rate of 500 mL/min (0.0018 cfm). The canister samples were injected into the gas chromatograph at the completion of the vent simulation.

Two trials using canister sampling were conducted. No additional trials were performed because the results of the method were reproducible. Each trial consisted of an initial evacuation and an air wash simulation. In both trials the total measured emitted mass of EO was within 15% of the expected value. The relative difference (given by the difference in the two values divided by the mean) between the two trials was <5 percent.

CANISTER STUDIES

In order to propose a viable canister field sampling method in the future, both the stability of EO in the canisters and a method of removing residual EO from the canisters were determined.

Stability Studies of EO in Summa Canisters

The stability of EO in nitrogen in 6 liter (L) [0.2 ft^3] Summa canisters was studied over a two-month period. Two canisters were used for the study. One canister was filled with a 98.05 ppmv EO standard in nitrogen and the other canister was filled with a 4.454 ppmv EO standard in nitrogen. Both EO standards were certified to within ± 2 percent.

The standards in the two canisters were analyzed throughout a two month period using GC/FID. The response of the standards in the canisters was compared to the response of the standards in the original aluminum cylinders. The results are shown graphically in Figure 3. The graph was prepared by taking the difference between the response of the sample in the canister and the response of the standard, dividing it by the response of the standard and multiplying it by 100. Numbers closer to zero indicate greater stability.

No degradation or loss of EO was observed during the first 24 hours. After three days (72 hours), the 4.454 ppmv EO standard showed a loss of approximately 7 percent. A maximum loss of 40% occurred within a one month (29 day) period. No additional loss in the low concentration standard was observed after one month (between 29 and 65 days). The 98.05 ppmv EO standard showed a 2.5% loss over the two-month (65 day) period.

The loss of EO in the Summa canisters was attributed to adsorption of the EO onto the surface of the canisters. The amount of EO adsorbed on the surface of the canisters was equivalent to approximately 2.5 ppmv. This value was obtained from the loss of approximately 50% of the 4.454 ppmv standard and approximately 2.5% of the 98.05 ppmv standard. A 0.5 ppmv EO standard was prepared in a canister that had been previously exposed to EO. Its response on the GC/FID was compared to the response of the certified 4.454 ppmv standard. After one week, the response ratio of the two standards had not changed. From this limited study of three canister samples, the following recommendations can be made:

- If possible, all EO samples collected in Summa canisters should be analyzed within one week of collection.
- Summa canisters, used to collect EO samples which are expected to be 2.5 ppmv or less, should be pre-exposed to EO before sampling.
- Additional studies regarding the stability of EO samples from actual sources in Summa canisters should be conducted.

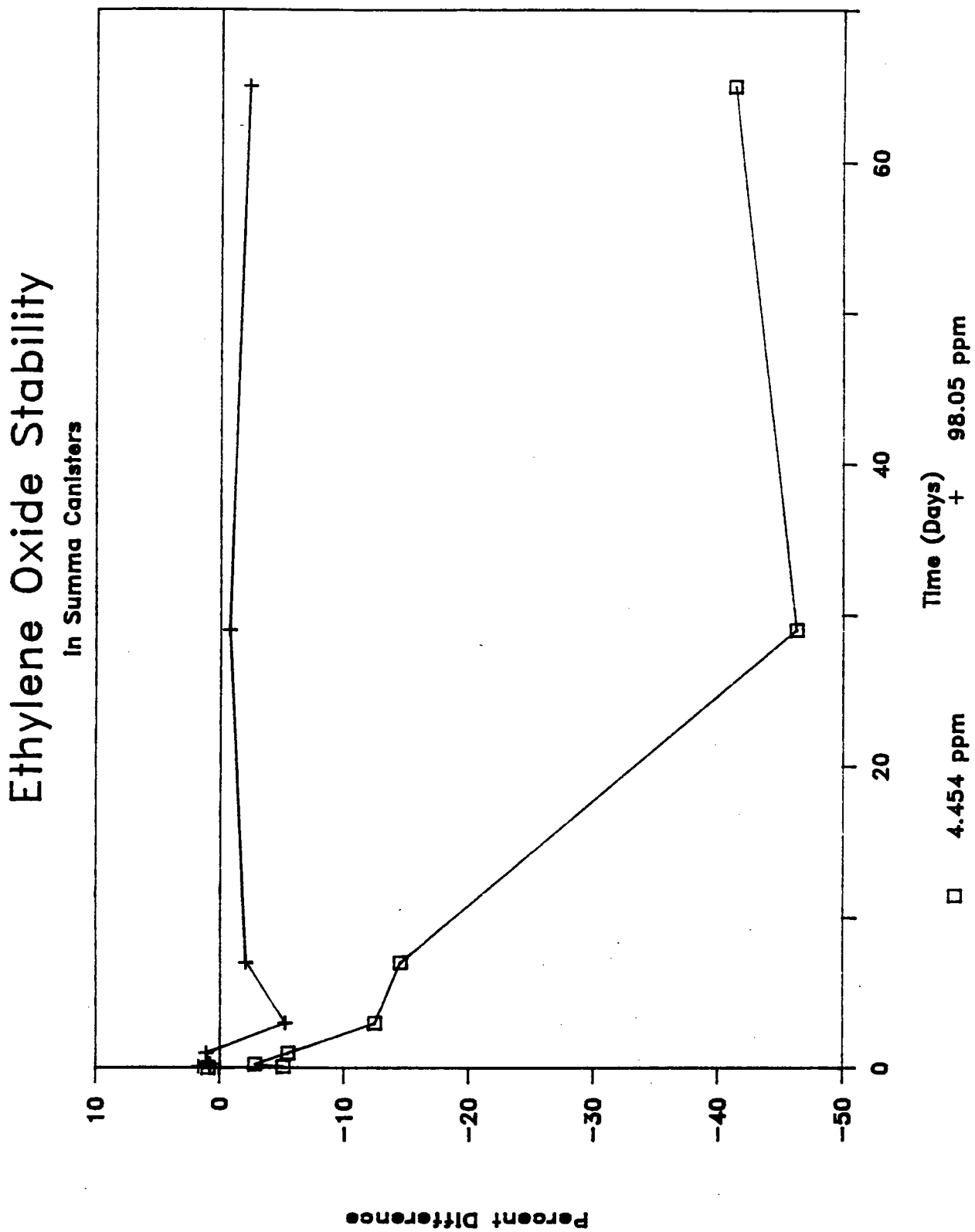

Figure 3. Ethylene Oxide Stability In Canisters

Residual Canister Cleanup

A method for cleaning the canisters in the field was developed and tested in the laboratory. Filling the canisters with clean nitrogen three times was found to be inadequate to remove the residual EO. As much as a third of the original EO remained in the canister. However, when the canister was evacuated with a vacuum pump between each of the three nitrogen purges, all of the residual EO was removed.

ANALYSIS OF PRESURVEY SAMPLE

In September 1986, Burron Medical in Allentown, Pennsylvania was selected as a field test site for evaluation of the semi-continuous direct sampling and analytical method. A pretest site survey was performed to verify the suitability of the site for the method evaluation.

During the survey, eight grab samples were obtained from the control unit stack, six in Vacusampler® cans and two in stainless steel bombs. Five of the samples (three cans and both bombs) were returned to Radian for analysis and three were analyzed by the facility. The samples were obtained during the first chamber evacuation of a normal product sterilization cycle.

The samples returned to Radian were analyzed by GC/FID using both a Porapak® R column and a 1% SP-1000 on Carbopack B column. Both were 6 ft (3 m) by 1/8 in (3 mm) O.D. stainless steel columns. On the Porapak R column the EO eluted after 4 min and the CFC-12 eluted at 2.7 min at a column temperature of 100°C. On the SP-1000 column the EO eluted at 1 min and the CFC-12 eluted at 1.9 min at a column temperature of 60°C.

The EO on the Porapak R column was well resolved from the CFC-12 when moderate amounts of CFC-12 were present; however, when the sample consisted of primarily CFC-12, the EO was lost in the CFC-12 tail. Quantitation of the EO in any of the samples was difficult on the Porapak R column.

The SP-1000 column easily resolved the EO from the CFC-12 and the EO was easily quantitated for all of the samples. The measured EO concentration in the five samples ranged from 0.2 ppmv to 2.3 ppmv.

The plant analyzed their three samples on a glass column packed with 0.8% Tetrahydroxyethylenediamine (THEED) on Carbopack C. The samples were found to contain from 1.6 to 220 ppmv EO.[19]

Analysis of the presurvey samples indicated that replicate samples analyzed using different analytical systems in different laboratories may vary greatly in analyzed concentration. Also, the presurvey sample analysis indicated that a column that eluted EO before CFC-12 would be preferable in the analysis of ppmv levels of EO in the presence of percent levels of CFC-12.

COLUMN EVALUATION

Several columns were evaluated by the EPA Project Officer in order to find a column on which EO eluted before CFC-12.

Columns Evaluated

The columns evaluated by the EPA Project Officer may be divided into three categories, those that did not resolve EO and CFC-12, those in which the CFC-12 eluted before the EO, and those in which the EO eluted before the CFC-12. The columns which failed to resolve EO and CFC-12 included a 6 ft (1.8 m) by 1/8 inch (0.3 cm) stainless steel column containing 10% SP-1000 on 80/100 mesh Supelcoport tested at 50°C and 100°C, a 5 ft (1.5 m) by 1/8 inch (0.3 cm) stainless steel column containing 3.8% OV®-1 on Chromosorb® W HP tested at 70°C, a 10 ft (3 m) by 1/8 inch (0.3 cm) stainless steel 10% Dibutyl maleate on 60/80 mesh Chromosorb P and a 6 ft (1.8 m) by 1/8 inch (0.3 cm) column containing 7% Squalene on Chromosorb 750 tested at 40°C and 70°C.[20]

The columns which eluted CFC-12 before EO can be divided into two categories, those with a liquid phase and those without. The columns without a liquid phase included a 6 ft (1.8 m) by 1/8 inch (0.3 cm) stainless steel column containing 100/120 mesh Porapak R tested at 100°C, a 6 ft (1.8 m) by 1/8 inch (0.3 cm) stainless steel column containing 60/80 mesh Chromosorb 101 tested at 40°C and 100°C, a 6 ft (1.8 m) by 1/8 inch (0.3 cm) stainless steel column containing 60/80 mesh Chromosorb 102 tested at 100°C, and a 10 ft (3 m) by 1/8 inch (0.3 cm) stainless steel column containing 80/100 mesh Porapak QS tested at 100°C.[20] Resolution data of EO from CFC-12 for most of these columns are presented in Table 2.

Columns which contained a liquid phase and in which CFC-12 eluted before EO included a 10 ft (3 m) by 1/8 inch (0.3 cm) stainless steel 10% SP-2401 on 100/120 mesh Supelcoport tested at 30 and 50°C and a 2 ft (0.6 m) by 1/8 inch (0.3 cm) stainless steel column containing 20% Dibutyl maleate on 40/60 mesh

TABLE 2. RESOLUTION OF EO FROM CFC-12[20]

Column[a] Description	Length (ft) [m]	Temperature (°C)	Resolution (R)	Retention Time (min) EO	Retention Time (min) CFC-12
Porapak R	6 [1.8]	100	2.5	4.5	
Chromosorb 101	6 [1.8]	100	1.8	2.7	
Chromosorb 101	6 [1.8]	40	1.8	26	
Chromosorb 102	6 [1.8]	100	3.2	4.4	
Porapak QS	10 [3]	100		7.9	4.6
10% SP-2401	10 [3]	50		1.6	1.0
10% SP-2401	10 [3]	30		2.3	1.0
C_4 Maleate	2 [0.6]			2.1	0.4
Carbopack B HT	6 [1.8]	60	0.5[b]	2.3	
Carbopack B HT	10 [3]	70	c	3.6	4.5
Carbopack B HT	16 [4.8]			5.6	9.6
5% Fluorcol	10 [3]	30	3.1	3.3	6.8
5% Fluorcol	10 [3]	40	2.4	2.6	4.9

[a]All columns were of premium grade stainless steel with outer diameters of 1/8 inch (0.3 cm).

[b]Almost baseline resolution. The R value is misleading because of the large width of the CFC-12 peak.

[c]Baseline resolution.

Chromosorb P.[20] Retention times for EO and CFC-12 on these columns are reported in Table 2.

Columns which resolved the EO from the CFC-12 and eluted EO before CFC-12 included 6 ft (1.8 m), 10 ft (3 m) and 16 ft (4.8 m), by 1/8 inch (0.3 cm) O.D. stainless steel columns containing 60/80 mesh Carbopack B HT and a 10 ft (3 m) by 1.8 inch (0.3 cm) O.D. stainless steel column containing 5% Fluorcol on 60/80 mesh Carbopack B.[20] Resolution and retention data for these columns is presented in Table 2. The Fluorcol column was determined to be the best of these four columns because the linear range of the EO calibration curve spanned the greatest magnitude and the Fluorcol column had the larger number of plates, 2560 plates compared to 1940 plates for the Carbopack B HT columns.[20]

Further Evaluation of the Column of Choice

The 10 ft (3 m) by 1/8 inch (3 mm) O.D. 5% Fluorcol on 60/80 Carbopack B stainless steel column was further evaluated by the EPA Project Officer to determine the optimal GC/FID conditions for the separation of EO from CFC-12 and the limit of detection (LOD) for EO.

Optimization of Instrumental Conditions--

A column temperature of 55°C was required for baseline resolution of percent level mixtures of EO (4-30% [v]) and CFC-12 (96-70% [v]).[14] For ppmv level EO concentrations baseline resolution was achieved at a column temperature of 65°C.[14] A van Deemter plot indicated an optimum flow rate of 30 mL/min.[14]

Sample loops of 0.5 and 1.0 mL and samples of EO/CFC-12 mixtures with no air present were used to determine the linearity of the FID response. Ethylene oxide response was linear up to 30% (v) EO at both sample volumes.[14] The CFC-12 response was linear from 70-100% (v) with the 0.5 mL sample loop, but with the 1.0 mL loop nonlinearity occurred above 90% (v) CFC-12.[14]

Detection Limit Determination--

The LOD was estimated using a procedure developed by Knoll[21] and by taking twice the noise level. Using the optimum conditions determined above for low levels of EO, the LODs were 0.03 and 0.07 ppmv for 1.0 and 0.5 mL sample loops, respectively.[14] Both methods of determinating LOD gave the same results.

Retention Time Shifts--

The EO retention time was observed to be a function of the EO concentration. With a nitrogen carrier gas flow rate of 30 mL/min and a column oven temperature of 65°C, the retention time was 1.7 min for percent level samples versus 2.1 min for a 1.1 ppmv sample.[14]

ADSORPTION STUDIES

During the column evaluation performed by the EPA Project Officer, some of the EO adsorbed onto the sample loop. Also, a study reported in the literature,[22] indicated that adsorption of EO was greatly reduced by replacing stainless steel sampling loops with Teflon sampling loops. Since heated stainless steel sampling loops would be used in the field, laboratory studies were performed to determine if EO adsorption occurred on heated stainless steel loops. Additional studies were also conducted to determine if adsorption occurred in the heated Teflon lines that would be used as sampling lines to transport sample from the sampling ports to the GC.

Procedure

The heated gas sampling valve was flushed for 0.5 min with nitrogen or standard flowing at 100 mL/min. Samples were injected when the rotameter indicated that there was no flow through the loop.

Initially, the system was blanked with ultra high purity nitrogen. Then the standard was injected until three peaks with reproducible area (within 10%) were obtained. Next nitrogen was injected either until the peak was very small or had totally disappeared.

Three system configurations were tested. In the first system, the shut-off valve and metering valve were connected before the sampling valve by a length of stainless steel tubing. The cylinder regulator was connected to the shut-off valve by a length of 1/4 inch O.D. Teflon tubing. To switch from nitrogen to standard to nitrogen, the Teflon tubing was switched between the nitrogen regulator and the standard regulator.

In the second configuration, the shut-off valve and metering valve were connected after the sampling valve. The cylinder regulator was connected directly to the sampling valve using a length of 1/8 inch O.D. Teflon tubing.

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Again, to switch from nitrogen to standard to nitrogen, the Teflon tubing was switched between the nitrogen regulator and the standard regulator.

The third configuration was the same as the second configuration except that two 1/8 inch O.D. lengths of Teflon tubing were used, one between the nitrogen regulator and sampling valve and the other between the standard regulator and sampling valve.

A 5.005% (v) EO standard was used in all three configurations. In the third configuration, a 4.454 ppmv EO standard was also tested.

A 100 ft (30 m) heat-traced line heated to >100°C was tested for adsorption of EO by purging the line with 4.454 ppmv EO standard and comparing the peak area measured to the peak area measured when the same standard was analyzed directly.

Calculations

The amount of adsorption occurring in the system was calculated by the ratio of the area of the EO peak for the first nitrogen injection to the average area of the three standard peaks.

Results

The results of the sample loop adsorption studies are reported in Table 3. In Configuration 3 the adsorption measured was the adsorption occurring on the loop only. The amount of this adsorption was small compared to the adsorption measured in the other two configurations. For the high EO standard, the amount of adsorption was equivalent to 4.24 ppmv and for the low EO standard the amount of adsorption was equivalent to 0.1112 ppmv.

The amount of adsorption occurring on the Teflon line and in the loop was measured using Configuration 2. Approximately 4% of this adsorption could be attributed to the loop, so the amount of adsorption occurring on the surface of the Teflon line was equivalent to 99.4 ppmv.

The EO adsorption study on the heat-traced line was repeated twice. The absolute difference between the EO peak area obtained when standard was purged through the heat-traced line and the EO peak area when standard was analyzed directly ranged from -8.9 to 7.1 percent.

TABLE 3. RESULTS OF ETHYLENE OXIDE SAMPLE LOOP ADSORPTION STUDIES

Configuration	Standard Concentration	Amount of Ethylene Oxide Adsorbed (In Terms of % of Average Standard Injection)		
		1 Purge	2 Purges	3 Purges
1	5.005% (v)	2.046%	0.569%	0.257%
2	5.005% (v)	0.207%	0.059%	0.032%
3	5.005% (v)	0.00847%	0.00428%	NA
3	4.454 ppmv	2.497%	1.411%	0%

Conclusions

The amount of adsorption occurring on the loop will not significantly affect concentration values for high concentration (>100 ppmv) EO samples. The effect of EO adsorbing on the loop will have a minimal effect on EO samples with concentrations between 10 and 100 ppmv. Sample loop adsorption effects will not become significant unless samples have concentrations below 1 ppmv; therefore, such designs are applicable for streams containing EO concentrations from 1 ppmv to 30 volume percent.

Some adsorption occurs in the Teflon lines between the standard cylinders and the sampling valve. To minimize any effect from EO adsorption on these surfaces, specific Teflon lines should be assigned to each regulator for use with that regulator only. Preferably each standard should have its own regulator or regulators should be used only on standards within a similar concentration range. Also, if possible, no metering valve or shut-off valve should be placed between the regulator and the sampling valve.

Adsorption losses of EO do not occur in the heat-traced sampling lines used to transport the sample from the sampling ports to the GC; therefore, such designs are applicable for streams containing EO concentrations from 1 ppmv to 30 volume percent.

RETENTION SHIFT STUDIES

In the initial study of the column, the EO retention time was observed to vary with the EO concentration. In the field, using a dual column instrument with one column dedicated for analyzing inlet samples and the other for outlet samples, the retention time was observed to shift on one of the columns but not on the other. Retention time shifts occurred when the carrier gas flow rate was less than 30 mL/min and the sample size was 2 mL. A carrier gas flow rate of about 60 mL/min and a 0.25 mL sample size caused minimal retention time shifts. To determine if the retention time shifts were a function of sample size or carrier gas flow rate, additional laboratory studies were performed.

Procedure

Ten standard samples, prepared gravimetrically in aluminum cylinders, were analyzed on the two 5% Fluorcol columns. Standard concentrations ranged

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from less than 1 ppmv to 12.5% (v). The carrier gas flow rates were maintained at less than 30 mL/min on one column (Column B) and about 60 mL/min on the other column (Column A). Two sample volumes, 2 mL and 0.25 mL, were injected on both of the columns. The column oven temperature was maintained at 100°C throughout the experiment.

Results

Each standard was injected twice under the four test conditions. Standard deviations from the two injections are reported in parentheses. At a high carrier flow rate and large sample volume the EO retention time shifted from 1.4 min (0.01) for a 4.5 ppmv standard to 0.9 min (.003) for a 12.5% (v) standard and the CFC-12 retention time shifted from 1.36 min (0) for a 1,200 ppmv standard to 1.14 min (0.004) for a 62.5% (v) standard. When the sample volume was decreased, the EO retention time shifted from 1.2 min (0.007) for a 9.1 ppmv standard to 0.8 min (0.01) for a 12.5% (v) standard and the CFC-12 retention time shifted from 1.21 min (0.02) for a 1,200 ppmv standard to 1.14 min for a 62.5% (v) standard.

A low carrier flow rate and large sample volume resulted in EO retention time shifts of from 2.6 min (0.04) for a 0.9 ppmv standard to 1.3 min (0.01) for a 12.5% (v) standard and CFC-12 retention time shifts of from 2.0 min (0.01) for a 1,200 ppmv to 1.6 min (0.01) for a 62.5% (v) standard. A decreased sample volume yielded EO retention time shifts of from 2.4 min (one injection only) for the 0.9 ppmv standard to 1.3 min (0.002) for the 12.5% (v) standard and CFC-12 retention time shifts of from 2.0 min (0.001) for the 1,200 ppmv standard to 1.8 min (0.003) for the 62.5% (v) standard.

For both compounds and both sample sizes the magnitude of the retention time shift is greater when the lower flow rate is used. There is no noticeable effect on the EO retention time shift due to sample size; however, the magnitude of the retention time shift increases with sample volume for CFC-12.

Retention Order Change and Coelution Possibilities

The shifting retention times raises a question regarding the conditions required for the compounds to coelute or change their relative retention characteristics. Figure 4 shows the EO and CFC-12 data plotted on the same

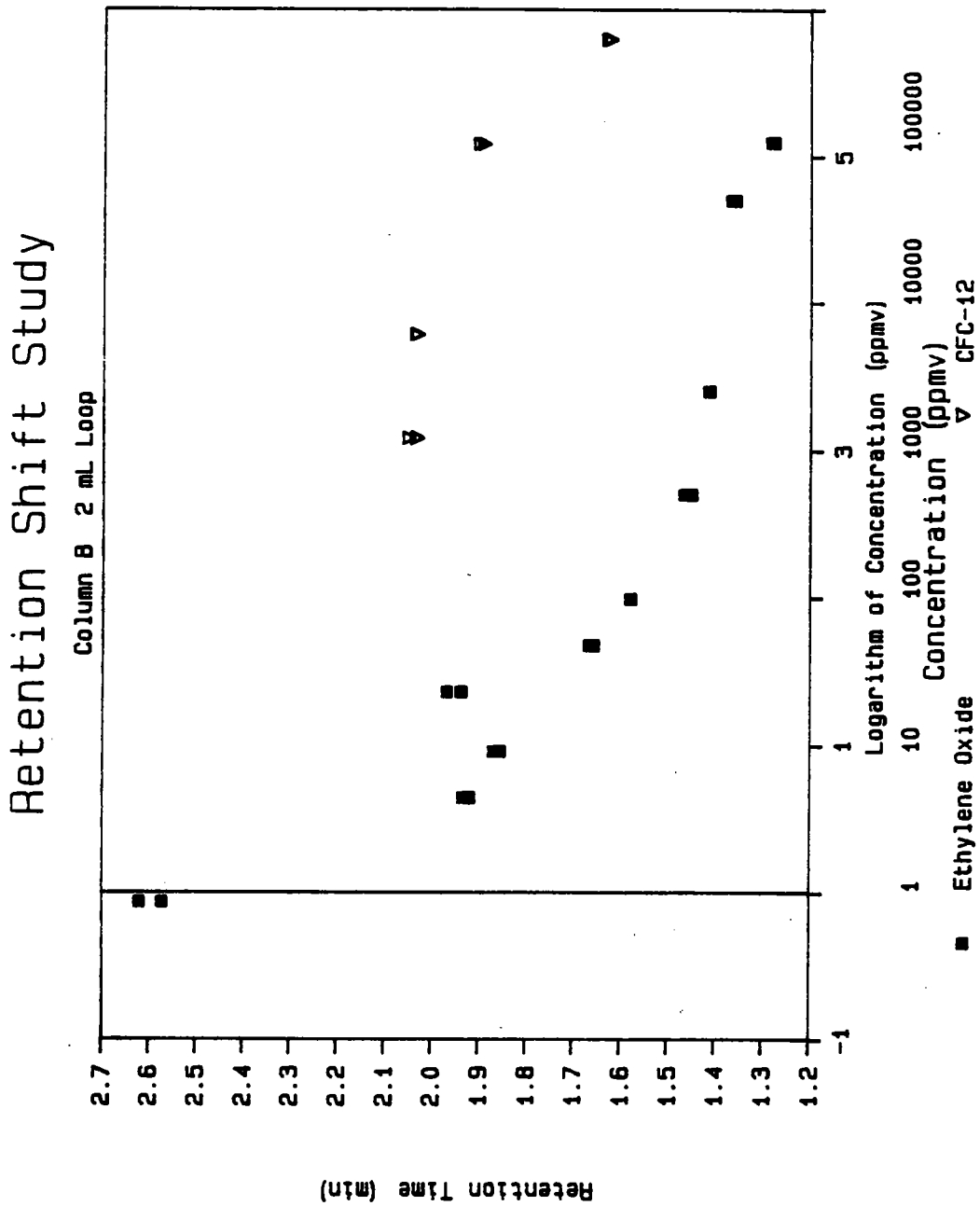

Figure 4. Retention Time Versus Logarithm of Concentration

graph at low carrier gas flow and with a large sample volume. The natural logarithm of the concentration was used for plotting to allow all of the data to be plotted legibly on one graph. From this figure it is apparent that the CFC-12 retention time remains constant until the column is overloaded with sample. The EO retention time changes continually with concentration.

The plot also shows that there are many conditions under which the compounds would be expected to coelute. For example, in samples containing less than 10 ppmv of EO and less than 1% (v) of CFC-12, it is likely that the two components would coelute. Also, in a sample containing less than 100 ppmv of EO and more than 1% (v) CFC-12, it is possible that the order of elution would be reversed. These predictions are derived from the experimental data and need to be substantiated by experimentation to verify that there are no other parameters, such as column temperature or compound interactions, that affect the elution time and order.

Conclusions

The CFC-12 retention time probably remains constant until column overload begins at a concentration of approximately 1 volume percent. The EO retention time continually decreases with increasing concentration. For both compounds, the retention time shift with changing concentration is greater when the carrier gas flow rate is slower. A larger sample size does not increase the magnitude of the EO retention time shift but does increase the magnitude of the CFC-12 retention time shift.

The larger shift in EO retention times compared with the shift in CFC-12 retention times was due to the larger range in EO concentrations which were sampled. Also, the retention time shift was exacerbated relative for the laboratory results because of the higher column temperature used to obtain the needed number of samples.

ANALYSIS OF A VENT GAS SAMPLE IN THE LABORATORY

To verify the presence of EO in the scrubber outlet vent gas and to determine what other compounds are present in the scrubber outlet vent gas, a sample taken during Test 12, Evacuation 6, was analyzed by GC/MS and by GC/FID.

Analysis of Vent Gas Sample by GC/MS

The vent gas sample was analyzed by GC/MS to verify that EO was present in the vent gas during the later evacuations and to identify the other compounds in the vent gas which were interfering with the analysis.

Procedure--

One coil of a 30 meter (m) wide-bore fused silica capillary column (DB-5) was frozen with liquid nitrogen. A 1 mL gas sample was injected through the GC injection port which was heated to 50 degrees Celsius (^{o}C). Injection was made with the GC column oven door open. The door was closed, and the column oven was heated to $35^{o}C$. After a two minute hold at $35^{o}C$, the column oven was heated to $150^{o}C$ at $8^{o}C$ per minute. Both a 5 ppmv EO standard and the sample were analyzed.

Results--

Analysis of the 5 ppmv EO standard showed that the EO elutes at 2.47 min and yields a mass spectrum with a parent peak at mass 44 and a major peak at 29 due to the loss of a methyl group.

The sample chromatogram is shown in Figure 5. There are three peaks: a large one at 2.39 min, a small one at 3.12 min, and a medium one at 3.56 min. The mass spectra identify the first peak as CFC-12, the second peak as carbon disulfide (CS_2), and the third peak as 1,2-epoxybutane (ethyloxirane).

No EO was identified by this analysis. This was not unexpected, however. The estimated detection limit for the method was 1-2 ppmv, and the estimated concentration expected in the sample was 0.5-1 ppmv.

There is no explanation for the presence of the CS_2. The 1,2-epoxybutane may be a reasonable reaction product of the EO although its presence was not expected. At this time it is not known whether these products were materials actually present in the stack or whether they are artifacts formed when the sample contacted the sample container.

Conclusion--

By the sixth evacuation, the major component of the stack gas, other than air, is CFC-12. The concentration of EO has decreased to less than 2 ppmv. Other components present in the stack gas may include CS_2 and 1,2-epoxybutane (ethyloxirane).

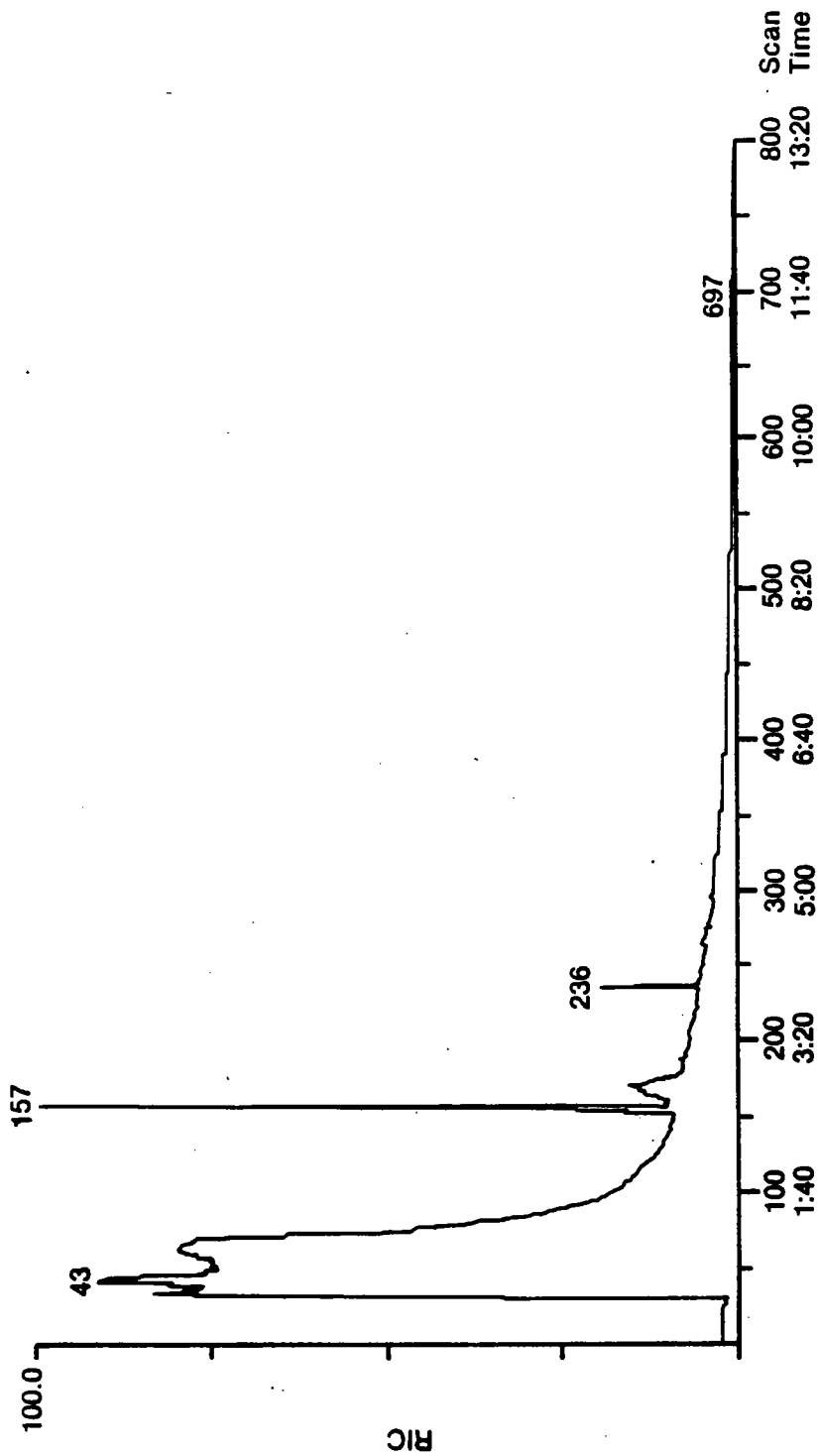

Figure 5. Total Ion Chromatogram of Vent Sample

Vent Gas Analysis by GC/FID

The vent gas sample taken during Test 12, Evacuation 6, was analyzed by GC/FID using conditions similar to field conditions. Quantitative and qualitative comparisons were made to a standard containing EO, CFC-12, CS_2, and 1,2-epoxybutane.

Procedure--

A 2-L static dilution bulb was purged with 4.454 ppmv EO standard for 2 min. Using a syringe, 0.1 mL of CFC-12, 31.66 mg of CS_2 and 20.94 mg of 1,2-epoxybutane were added to the purged bulb. The bulb was stored in an oven at 60°C. This resulted in concentrations of 4.454 ppmv EO, 50 ppmv CFC-12, 5,000 ppmv CS_2, and 3,600 ppmv 1,2-epoxybutane.

The sample prepared in the static dilution bulb, the 4.454 ppmv EO standard, and headspace samples of CS_2 and 1,2-epoxybutane were injected using a 0.5 mL gas-tight syringe on a 10 ft (3 m) by 1/8 in (3 mm) O.D. column containing 5% Fluorcol on 60/80 mesh Carbopack B. A Varian 3400 GC with a Vista 401 Data System was used. The column temperature was maintained isothermally at 100°C; the injector block was heated to 175°C, and the detector oven was maintained at 225°C. A nitrogen carrier gas flow rate of 30 mL/min was used. Support gas flow rates were set at the manufacturer's recommendations of 30 mL/min for hydrogen and 300 mL/min for air.

Results--

Analysis of the individual components yielded retention times of 1.9 min for CFC-12, 2.2 min for EO, 4.8 min for CS_2, and 5.3 min for 1,2-epoxybutane. Using the sample prepared in the static dilution bulb, the limits of quantitation (LOQs) were estimated to be 1 ppmv for CFC-12, 1.5 ppmv for EO, and 10 ppmv for 1,2-epoxybutane. No LOQ was estimated for CS_2 because the 5,000 ppmv CS_2 in the static dilution bulb was not detected by the FID. No effort was made to determine a CS_2 detection limit.

Analysis of the vent gas sample yielded a chromatogram with one peak at 1.9 min. This peak was identified as CFC-12 and was estimated to be present at a concentration of approximately 500 ppmv. The presence of EO and CS_2

could not be determined. Epoxybutane was estimated to be present at levels below the estimated LOQ of 0.01 ppmv.

Conclusions--

In a mixture containing 50 ppmv of CFC-12 and 5 ppmv of EO, the relative retention times of the two materials were reversed. Figures 6 and 7 show chromatograms taken during the field test at the inlet and outlet of the control unit, respectively. For the analysis of the inlet samples the carrier gas flow rate was faster and the sample volume was smaller. The late eluting component of the vent gas observed in the field at the scrubber outlet was probably 1,2-epoxybutane. This vent gas component required the analysis time to be lengthened on the outlet channel and decreased the number of samples which could be analyzed during each evacuation. Other unidentified components of the outlet vent stream elute before the CFC-12, possibly interfering with the EO analysis.

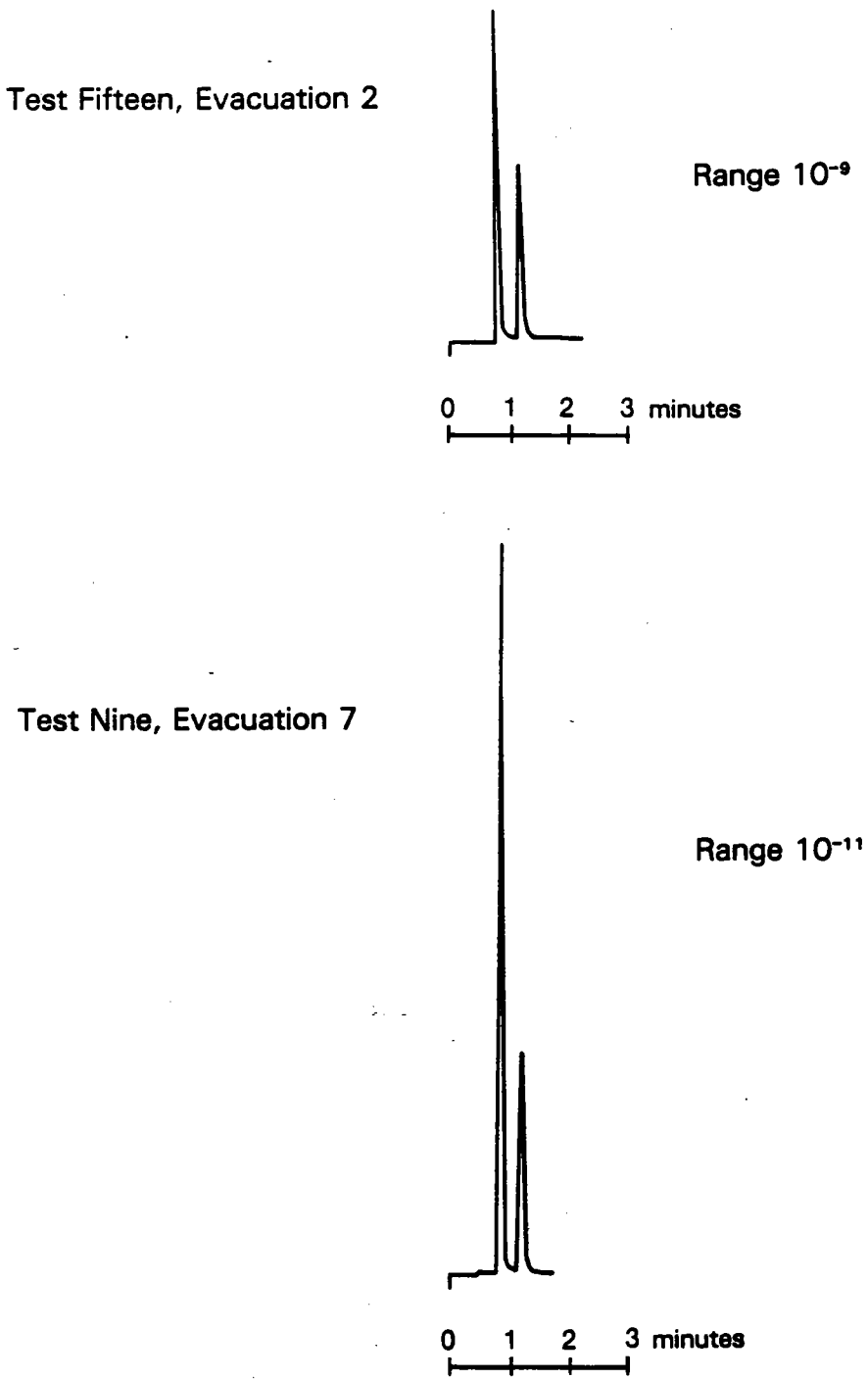

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Figure 6. Chromatograms of Vent Gas at Scrubber Inlet

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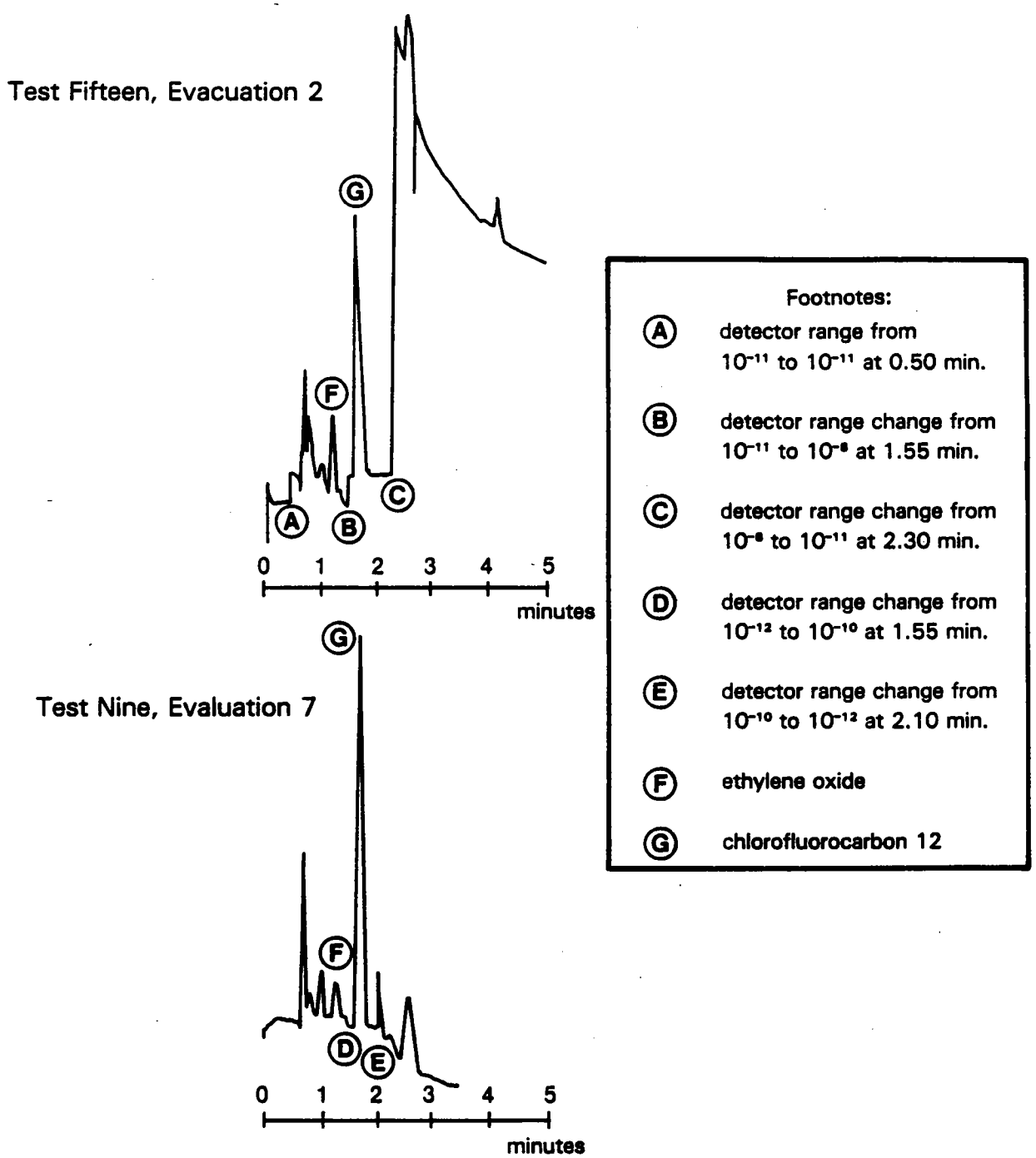

Figure 7. Chromatograms of Vent Gas at Scrubber Outlet

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SECTION 6

FIELD EVALUATION

FACILITY DESCRIPTION

The field evaluation was conducted at Burron Medical, a medical supply sterilization facility, located in Allentown, Pennsylvania. The facility has three 1000 ft^3 (28 m^3) sterilizers which use a 12/88 (w/w) EO and CFC-12 gas mixture. The gas is supplied from a common header serving all four units and is controlled by a liquid flow meter.

A sterilization cycle typically uses 38 gallons (140 L) of 12/88 gas mixture. On a weight basis, a sterilization charge consumes 368 lbs (167 Kg) of gas, of which approximately 44 lbs (20 Kg) are EO. The initial charge of EO to the chamber was calculated using the weight of the supply cylinders before and after charging the chamber. The scale measured the supply cylinders to ± 1 lb (0.5 Kg).

The exhaust from the sterilizers is controlled by a DEOXX™ system. The DEOXX system is a dilute acid scrubber manufactured by Chemrox, which hydrolyzes the EO to ethylene glycol. At the time of the test the scrubber contained a mixture of dilute phosphoric and sulfuric acid. The control system has a reported control efficiency of 99.99% based on tests conducted at the facility in April 1986 by the vendor.[12]

Each chamber is equipped with a total recirculating pump manufactured by either CIHI or Intervac. The pumps are equipped with gas/liquid separators which emit the gas to the DEOXX system and recirculate the liquid to the pump inlet. Chambers #1 and #2 are equipped with oil-sealed pumps. Chamber #3 is equipped with a water-sealed pump. All of the tests were conducted using the chambers (#1 and #2) equipped with oil-sealed pumps for the following reasons:

- The use of water-sealed pumps is more likely to affect EO emissions and efficiency calculations because of the infinite solubility of EO in water; and

- The anticipated regulatory development will most likely require the use of oil-sealed pumps.

The sterilization cycle is automatically controlled by a programmable microprocessor system. The control system has the capability to control and record the parameters of the sterilization cycle including chamber temperature, chamber pressure, and elapsed time from the start of the cycle.

The sterilization process begins with a humidification step which takes place in a separate room. After the humidification step, each load to be sterilized is transferred to the sterilization chamber. The sterilization cycle is a batch process which takes 4-6 hr. A sterilizer load begun during the morning shift exhausts at about 2:00 p.m. In a typical plant operating mode seven post-sterilization evacuations occur over a 3 hr period. After the chamber repressurizes following the seventh evacuation, the product is removed from the chamber and allowed to off-gas. Because the control system is designed to handle the exhaust from two sterilizers venting simultaneously, the tested sterilization cycles were scheduled so that only one sterilizer vented at a time.

Three different sterilization programs were used for testing, one for the empty chamber tests, one for the full chamber tests, and one for the last full chamber test (Test 13). Before the start of every test (except Test 13), the chamber was evacuated to 2 pounds per square inch absolute (psia) and then pressurized to 3.1 psia with steam. The humidity dwell at 3.1 psia was maintained for 1 hr for the loaded chamber tests, but was shortened to 5 min for the empty chamber tests. At the completion of the humidity dwell the chamber was charged to 23.9 psia with 12/88 gas. The exposure at 23.9 psia was maintained for 4 hrs for the loaded chamber tests, but was shortened to 5 min for the empty chamber tests. During the last full chamber test (Test 13), the chamber was evacuated to 7 psia and pressurized to 32.9 psia.

Each program contained seven post-sterilization evacuations, the initial chamber evacuation and pump down and six air in-bleeds and subsequent evacuations, followed by a final air in-bleed. Except in Test 13, the chamber was evacuated to 2 psia and pressurized with air to 13.9 psia during each evacuation and air in-bleed cycle. The initial chamber evacuation and pump down lasted 26-27 min. The subsequent evacuations lasted 12-14 min and

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the air in-bleeds required 12-14 min. During Test 13 the chamber was evacuated to 7.0 psia, which reduced each evacuation and air in-bleed time by 7 min.

Seventeen tests were performed, five with product in the chamber and 12 without product. Data from ten of these tests were reduced and used to prepare this report. Table 4 summarizes the 10 tests that were used.

SAMPLING LOCATIONS

Samples were acquired at two locations, before and after the control unit. At the scrubber inlet the EO and CFC-12 concentrations were at percent levels and the sample temperatures were 40-50°C (100-120°F). At the scrubber outlet the EO concentrations were at the low ppmv level, CFC-12 concentrations were at the percent levels, and sample temperatures ranged from 30-70°F (0-20°C) depending on the ambient temperature at the time of the test.

Scrubber Inlet Sampling Location

The scrubber inlet sampling location, shown schematically in Figure 8, was used to obtain a continuous sample of sterilizer chamber exhaust. The exhaust was transferred from the chamber outlet to the scrubber inlet via a 6-inch diameter polyvinyl chloride (PVC) duct. Samples were taken from the midpoint between the sterilizer outlet and the scrubber inlet. Sample, acquired with a 3/16-inch Teflon probe, was transported to the GC through 50 ft 0.5 m) of 1/4-inch O.D. heated Teflon sample line. No direct flow measurements were made at this location because the installation of orifice plates in the existing PVC pipe was not considered to be cost-effective.

Scrubber Outlet Sampling Location

A continuous sample of scrubber exhaust was obtained and volumetric flow measurements were made at the scrubber outlet sampling location. Exhaust exited the scrubber vertically through a 6-inch diameter PVC ductwork that exhausted 5 ft (1.5 m) above roof level. To measure volumetric flow, the stack was modified by the installation of:

- additional 6-inch diameter PVC ductwork to allow for diversion of the scrubber exhaust through one of two parallel ducts,

TABLE 4. TEST SUMMARY

Test Number	Product Present	Chamber Number	Weight 12/88 Used	Test Date	Test Start Time	Test End Time
6[a]	Yes	2	368 lb	87/10/06	21:39	00:38
7[b]	No	1	365 lb	87/10/07	10:19	14:04
8[a]	Yes	2	388 lb	87/10/07	15:10	18:11
9[b]	No	1	346 lb	87/10/08	09:25	12:42
10[b]	No	1	353 lb	87/10/08	14:41	17:48
11[a]	Yes	2	392 lb	87/10/08	18:00	21:01
12[b]	No	1	346 lb	87/10/09	12:44	15:53
13[c]	Yes	2	442 lb	87/10/09	16:16	18:03
14[b]	No	1	350 lb	87/10/10	08:54	12:01
15[b]	No	1	343 lb	87/10/10	13:35	16:43

[a]The chamber was evacuated to 2 psia before being pressurized with steam to 3.1 psia. Humidity dwell lasted 1 hr and then the chamber was charged to 23.9 psia with 12/88. Exposure lasted 4 hr. Post-sterilization chamber pressure cycled between 2 psia and 13.9 psia.

[b]The chamber was evacuated to 2 psia before being pressurized with steam to 3.1 psia. Humidity dwell lasted 5 min and then the chamber was charged to 23.9 psia with 12/88. Exposure lasted 5 min. Post-sterilization chamber pressure cycled between 2 psia and 13.9 psia.

[c]The chamber was evacuated to 7 psia before being pressurized with steam to 8 psia. Humidity dwell lasted 1 hr and then the chamber was charged to 32.9 psia with 12/88. Exposure lasted 5 hr. Post-sterilization chamber pressure cycled between 7 psia and 13.5 psia.

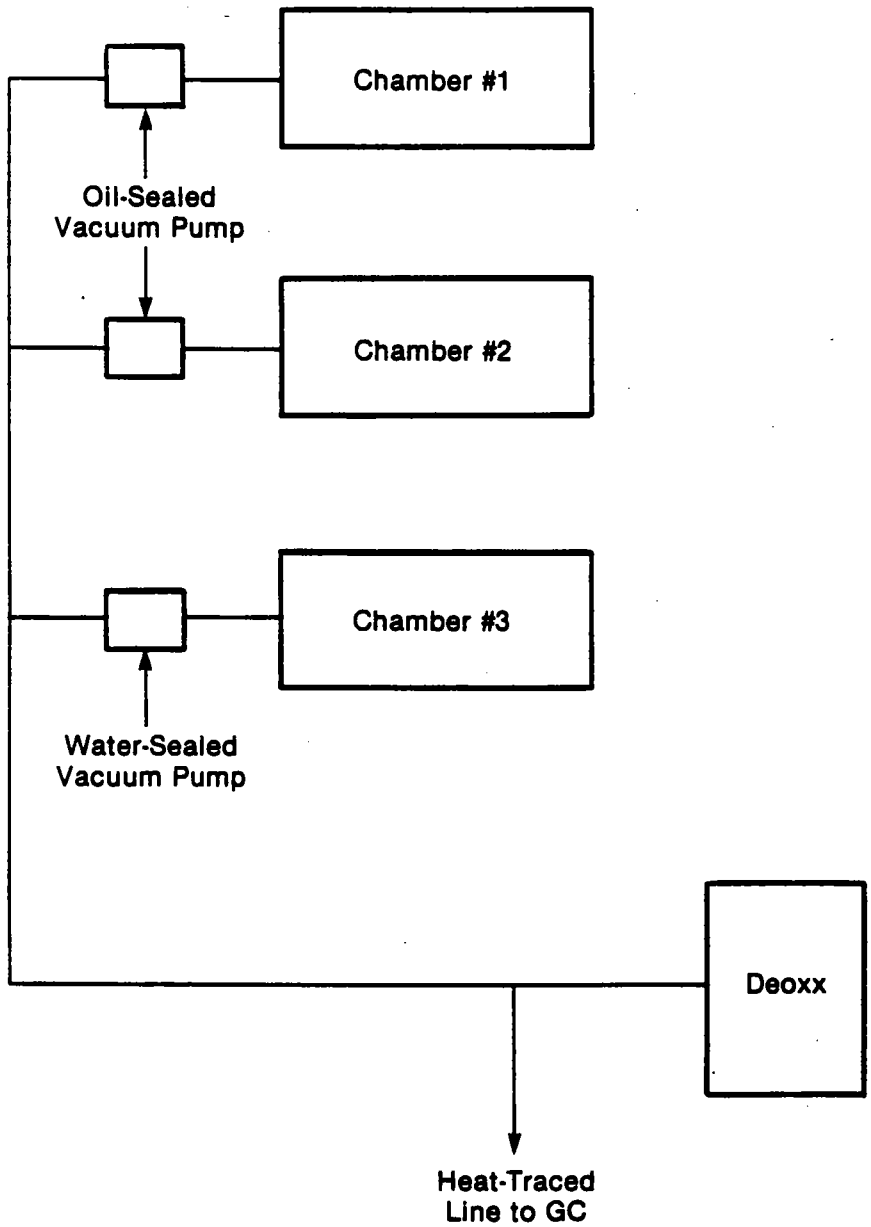

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Figure 8. Inlet Sample Location

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- a vane anemometer in the center of the duct 26 ft (7.9 m [52 duct diameters]) downstream of the the scrubber outlet and 1.3 ft (40 cm [2.7 duct diameters]) upstream of the first 90 degree (^{0}) bend in the stack addition,
- a 3/16-inch (48-mm) sampling probe,
- two butterfly valves to divert the scrubber exhaust through one of the two parallel ducts,
- two orifice plates in parallel, 6.3 ft (1.9 m [12.7 duct diameters]) downstream of their respective butterfly valves, and 1.3 ft (40 cm [2.7 duct diameters]) upstream of their respective 90^{0} bends, and
- wet and dry bulb temperature probes.

These modifications are diagrammed in Figure 9 and can be seen in the photographs shown in Figures 10-13. Descriptions and operational procedures are contained in the Sampling Procedures Subsection.

SAMPLING PROCEDURES

The semi-continuous direct sampling method was used at both sampling locations. The method is described in detail in Section 4.

Ethylene Oxide Sampling

The EO sampling equipment is shown in Figure 14. Samples were taken simultaneously from both sampling locations using the equipment and procedures described below.

Ethylene Oxide Sampling Equipment--

Sample was withdrawn into heated, 1/4-inch (64-mm), Teflon lines using Teflon-lined diaphragm pumps. A 50-ft (15-m) line was used on the inlet port and a 100-ft (30-m) line was used on the outlet port. Stainless steel, 1/4-inch (64-mm) tees were used prior to the pumps to remove slipstreams from the main sampling lines. The slipstreams were routed through heated, 6-port, gas sampling valves that were used to introduce the samples onto the GC columns. Prior to the 6-port valves were pumps with Teflon-lined diaphragms and stainless steel, 1/4-inch (64-mm), toggle operated shut-off valves. Stainless steel fine metering valves and rotameters were used after the 6-port valves to control the flow rates of the slipstreams. Before

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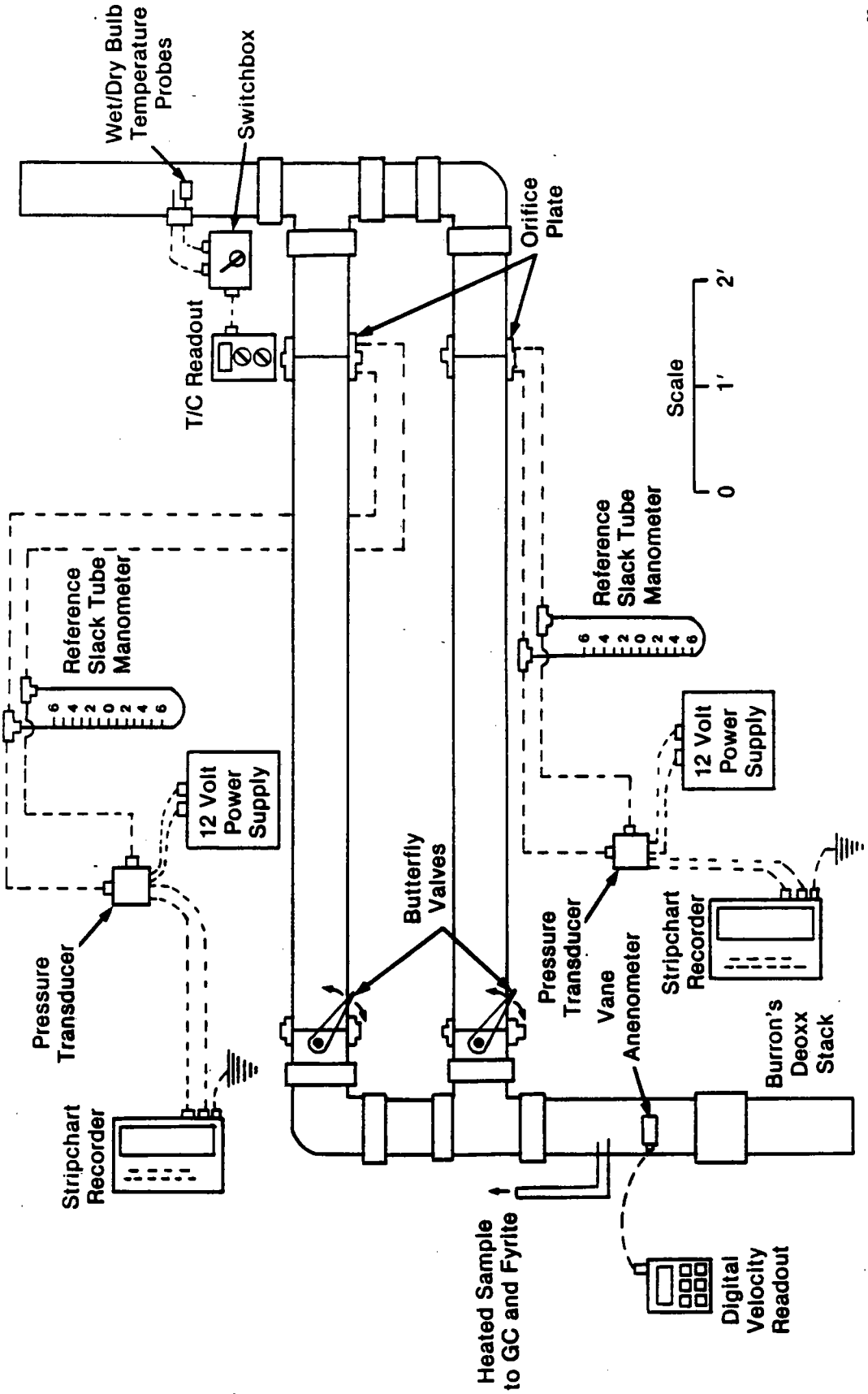

Figure 9. Outlet Vent Modifications

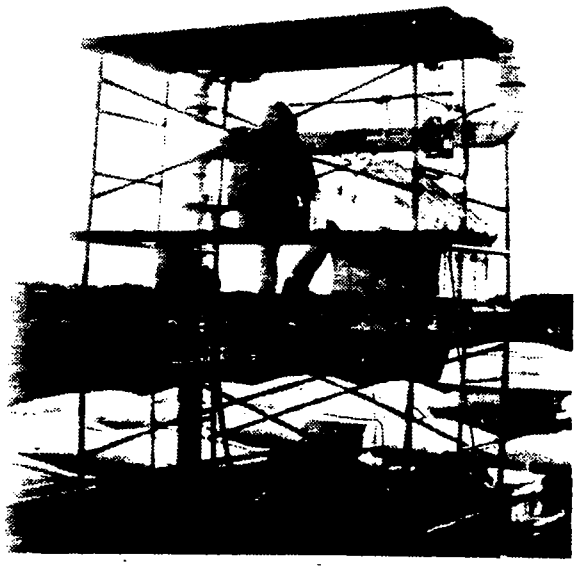

Figure 10. View of Vent Modification From Northeast Side

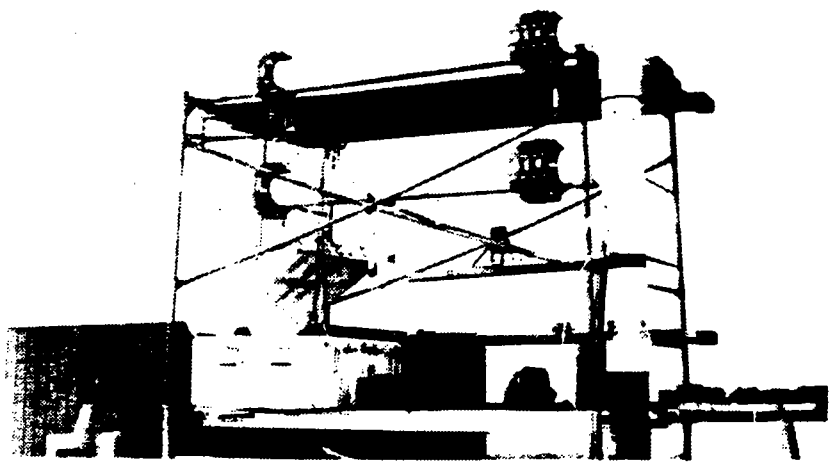

Figure 11. View of Vent Modification From Southwest Side

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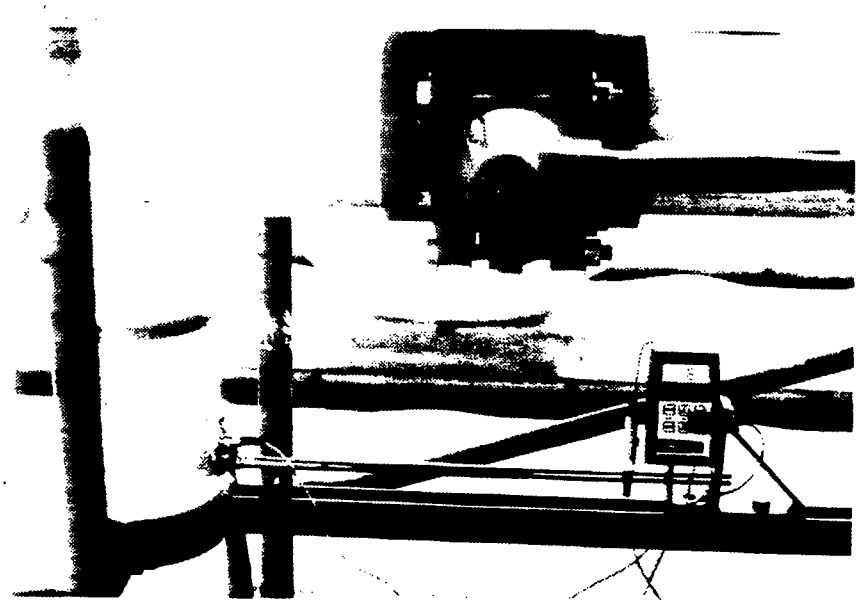

Figure 12. Close-Up of Butterfly Valve and Vane Anemometer Installation

Figure 13. Close-Up of Orifice Flange and Pressure Taps

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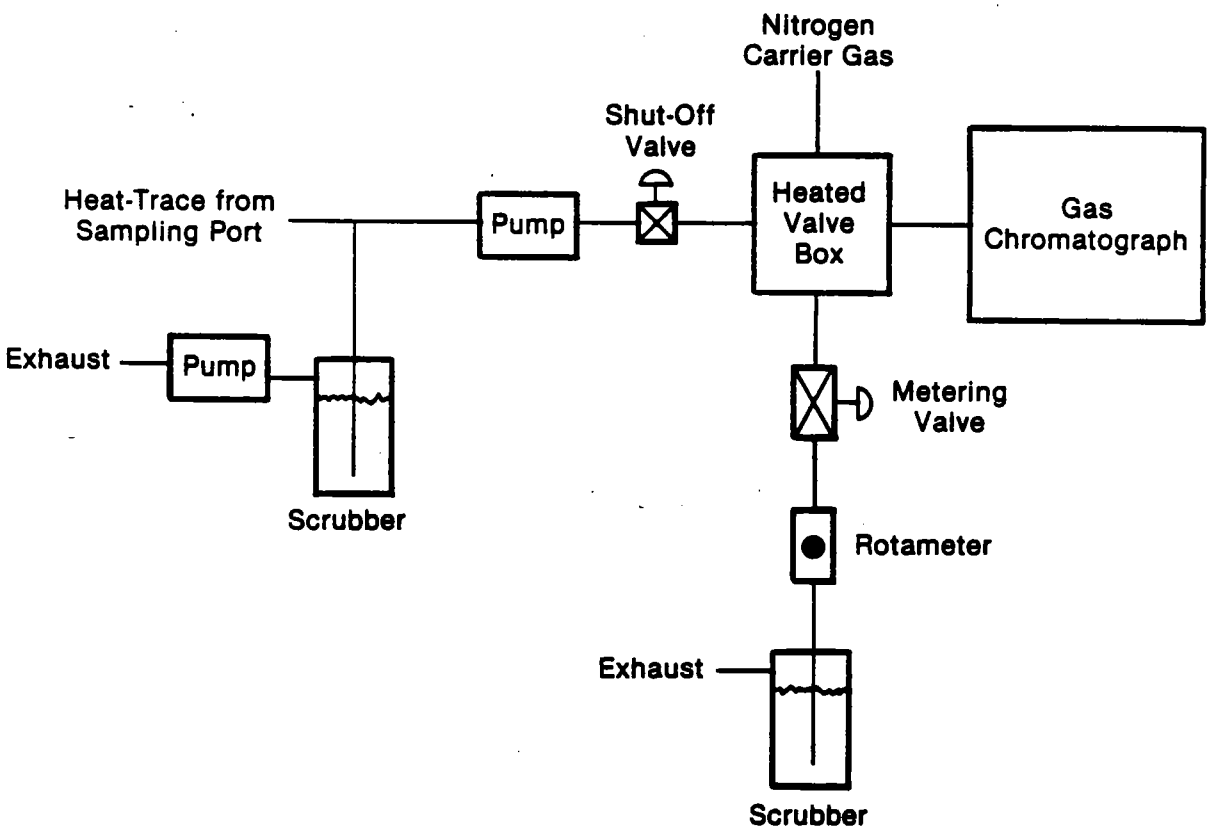

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Figure 14. Sampling/Analytical Interface

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exhausting to the atmosphere, the slipstreams and main sample streams were routed through dilute acid (1 N H_2SO_4) scrubbers to remove the EO.

Ethylene Oxide Sampling Operation--

Testing began when the DEOXX scrubber started to exhaust in preparation for the initial chamber evacuation. Each test consisted of seven evacuations, the initial chamber evacuation and pump down and six air in-bleeds and subsequent evacuations. Testing stopped at the start of the seventh air in-bleed. The start time and end time of the evacuations were identified by flow or lack of flow across the orifice plates.

The sampling lines were continually flushed with sample throughout the test day. Flow rates through the slipstreams which flushed the gas sampling loops were maintained at 100 mL/min (0.0035 cfm). Samples were isolated in the 6-port valves by closing the shut-off valves simultaneously. When the rotameters indicated no flow, the sample loops were at atmospheric pressure, and the samples were injected into the GC.

Table 5 compares the EO sampling parameters for each evacuation of each test. For most of the tests, the first sample was acquired at either one, two, three or four minutes after the start of the first evacuation. After the first sample, samples were acquired at three or four minute intervals until the end of the first evacuation. For the second through the seventh evacuations the first sample was acquired at either one, two or three minutes after the start of the evacuation. Again, samples were acquired at three to four minute intervals. The first evacuation was always longer because the initial chamber pressure was higher so a total of five or six samples were acquired during the first evacuation. For the second through seventh evacuations, a total of three or four samples were acquired during each evacuation. In test 13, the chamber was not evacuated to as low a pressure as in the other tests, so only four samples were acquired during the first evacuation and one sample during each of the subsequent six evacuations.

Volumetric Flow Rate Measurement

Volumetric flow rate measurements of scrubber exhaust were performed at the scrubber outlet location. A vane anemometer followed by two orifice plates in parallel was used to measure velocity. Two orifice plates were used to cover the range of expected flow rates and composition of the vent

TABLE 5. COMPARISON OF ETHYLENE OXIDE SAMPLING OPERATION PARAMETERS WITH TEST CONDITIONS

	Test 6-12,14,15		Test 13	
	Evacuation		Evacuation	
Parameter	1	2-7	1	2-7
Time from start of evacuation to first sample	1,2,3 or 4 minutes	1,2, or 3 minutes	3 minutes	3 or 4 minutes
Sampling Interval	3 or 4 minutes	3 or 4 minutes	4 or 5 minutes	
Total Samples Acquired	5 or 6	3 or 4	4	1
Chamber Pressure at start of evac.	23 psia	13.9 psia	33 psia	13.9 psia
at end of evac.	2 psia	2 psia	7.5 psia	7.5 psia

gas. Temperatures were measured using a bimetallic temperature probe and a pyrometer.

Vane Anemometer--

A PACER INDUSTRIES Model AD4000 vane anemometer was used to measure exhaust flows of <300 feet per minute (ft/min [90 m/min]). The vane anemometer probe head is factory calibrated using a Laser anemometer as reference in a 6-inch (15-cm) diameter wind tunnel. The reference calibration, performed in air, is contained in an internal microprocessor chip. Placement of the anemometer was upstream of the orifice plates as shown in Figure 9. A close-up of the vane anemometer placement in the stack extension is shown in Figure 12. Linear velocities were recorded manually every 2 min.

Orifice Plates--

Two standard, squared-edged orifice plates with standard pipe taps were mounted in parallel ducts as shown in Figures 9-11 to allow the determination of scrubber exhaust flow rate. The orifice diameters used were 1.763-inch (4.48-cm) and 2.591-inch (6.58-cm). The 1.763-inch (4.48-cm) diameter orifice plate was used to ensure accurate velocity head measurement during the latter part of the evacuations and when the low molecular weight of the vent stream resulted in velocities as low as 300 ft/min (90 m/min). The 2.591-inch (6.58-cm) diameter orifice was used during the initial portion of the evacuations and when the high molecular weight of the vent stream resulted in velocities approaching 1000 ft/min (300 m/min). Butterfly valves, as shown in Figure 12, were used to isolate the two orifice plates. The standard pressure taps on the orifice flanges were connected to Setra pressure transducers that were calibrated from 0-10 inches of water (inches H_2O [0-254 kg/m^2]). Output from the pressure transducers was recorded on stripchart recorders. A close-up of the orifice flanges and pressure taps is shown in Figure 13.

Stack Temperature--

Exit gas temperatures were measured at the scrubber outlet location. A bimetallic temperature sensor was placed in the duct as shown in Figure 9. Stack temperatures were digitized by a calibrated pyrometer and recorded every 2 min.

Sampling Operation--

The two parallel orifice plates in series with the vane anemometer were used to measure velocity. As previously mentioned, vane anemometer and stack temperature readings were recorded every 2 min during the initial exhaust and subsequent air wash periods. The differential pressure measurement from the orifice plates was continuously recorded with stripchart recorders.

The initial sterilizer exhaust velocity was determined using the large (2.591-inch [6.58 cm] diameter) orifice through the depressurization and most of the pump down phase. When the flow registered less than 3 inches H_2O (76 kg/m^2) of differential pressure for the large orifice, the flow was diverted through the smaller (1.763-inches [4.48-cm]) diameter orifice. Figure 15 shows an example of the differential pressures measured using the large orifice during a typical initial exhaust.

Velocity measurements taken during the second to seventh evacuations used the same orifice plate procedures. Due to the reduced molecular weight of the exhaust gas during these evacuations, the duration of flow requiring use of the larger diameter orifice was usually shorter. However, during the second evacuation some of the heavier molecular weight gas from the first evacuation remained in the system. The exhaust of this heavier molecular weight gas lengthened the time the larger orifice plate was used to measure the pressure differential. Similarly, the first few minutes of the first evacuation contained gas from a previous evacuation.

Moisture Determination

The percent moisture of the stack gas was determined by the wet bulb/dry bulb method. The procedure measured relative humidity which was converted to percent moisture. Wet and dry bulb temperature measurements used to determine relative humidity were recorded at least once during each exhaust episode.

Molecular Weight Determination

The molecular weight of the exhaust stream, which changed with time due to EO removal, was needed to calculate the flow rate. Nitrogen, oxygen, carbon dioxide, water, EO, and CFC-12 were considered the main components of the sterilizer exhaust gas. The emissions of EO and CFC-12 were continuously

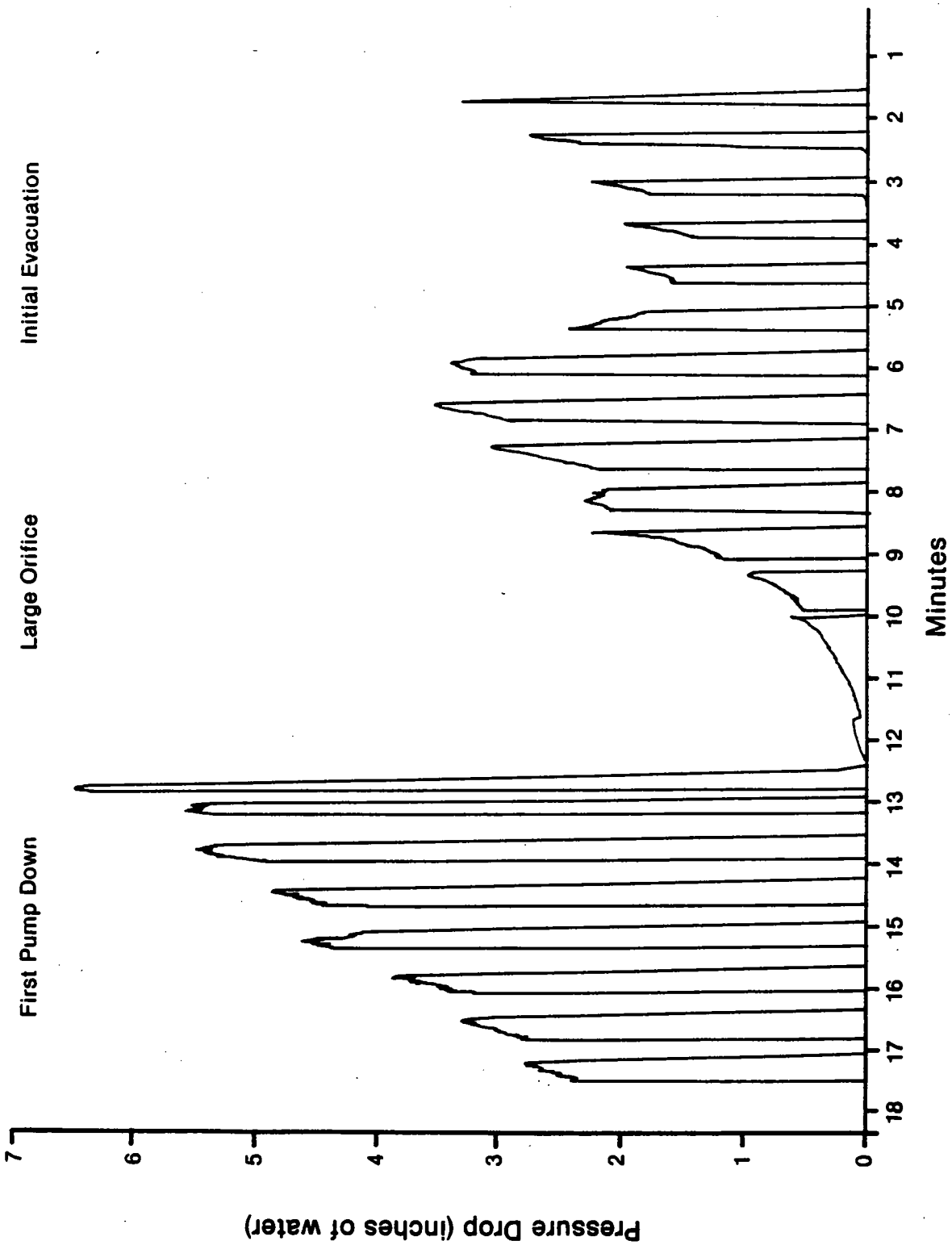

Figure 15. Measured Differential Pressures During First Evacuation

monitored by GC/FID. Emissions of oxygen and carbon dioxide were measured with Fyrite oxygen and carbon dioxide indicators. The nitrogen concentration was determined by difference.

Fyrite Oxygen And Carbon Dioxide Indicators--

BACHARACH Fyrite oxygen and carbon dioxide indicators were used to determine percent levels of oxygen and carbon dioxide in the sterilizer exhaust at the outlet sampling location. Fyrite indicators use volumetric displacement involving chemical absorption of oxygen or carbon dioxide from the sample. The reagent used to absorb carbon dioxide was potassium hydroxide, and chromous chloride was the absorbent for oxygen. Accuracy of analysis was ±0.5%.

Sampling Operation--

Percent levels of oxygen and carbon dioxide were usually measured once during each evacuation. For several of the runs oxygen was measured at 1- or 2-min intervals. These measurements were used to determine the dead volume of the scrubber system. Measurements of carbon dioxide in the exhausts were numerically negative, indicating an interference with the potassium hydroxide absorption solution. Because carbon dioxide levels were expected to be low (<1% [v]) an alternate method of determining carbon dioxide was not pursued. Sample was removed from the stack downstream of the vane anemometer. An aspirator bulb was used to pull the sample from the stack.

ANALYTICAL PROCEDURES

The analytical method used for the measurement of the EO and CFC-12 was gas chromatography with flame ionization detection (GC/FID). The CFC-12 concentration was needed for the determination of the gas stream molecular weight. The equipment and procedures used are described below.

Analytical Equipment Description

Some of the analytical equipment was shown in Figure 14. The dual FID Varian 3400 GC was equipped with a Nutech heated valve box containing two 6-port valves. An 0.25 mL loop was used on the inlet sample line and a loop of 2 mL was used on the outlet sample line. The analytical columns were 10 ft (3 m) x 1/8 inch (3 mm) O.D. stainless steel columns containing 5% Fluorcol on 60/80 Carbopack B. The FID electrometers were connected to Shimadzu CR1-A integrators.

Operating Conditions

The GC column oven was operated isothermally at 100°C, the injector oven at 175°C, and the detector oven at 200°C. Nitrogen carrier gas flow rates were 30 mL/min on the outlet channel and 60 mL/min on the inlet channel. The FID support gas flow rates recommended by the GC manufacturer were used.

The same FID electrometer range was used for the EO and CFC-12 on the inlet channel but the range used varied from 10^{-9} to 10^{-11} depending on the inlet sample concentration. The FID electrometer range was programmed on the outlet channel. A range of 10^{-10} to 10^{-12} was used for the EO and 10^{-8} to 10^{-10} was used for the CFC-12. The electrometer range was programmed to switch at 1.1 min during the first evacuations and at 1.55 min during the second through seventh evacuations.

Analytical Sampling Procedures

The sample loops were purged with sample flowing at 100 mL/min for a minimum of 20 s. Samples were taken simultaneously at the inlet and at the outlet by closing toggle valves in-line previous to the sample loops. The pressure in the loops was allowed to equilibrate to atmospheric pressure, as indicated by lack of flow through the rotameters, before the injections were made. Data collection on the inlet channel was stopped after the elution of the CFC-12 peak. On the outlet channel, although the last peak did not elute until after 3 min, data collection was stopped after about 2.5 min to allow the integrator time to print out its report before the next injection.

The first sample was injected from 1-4 min after the start of the initial exhaust and additional samples at 3-4 min thereafter. For subsequent exhausts, sampling was started 1-3 min after the first indication of flow through the stack. Five to six samples were acquired during the first evacuation and three to four during the subsequent evacuations except during Test 13 when four samples were acquired during the initial evacuation and one sample during the subsequent evacuations.

Gas Chromatograph Calibration

Both channels of the chromatograph were calibrated for EO and CFC-12 at the beginning and end of the day. At least one standard was also analyzed between tests. Standards were purchased from Scott Specialty Gases, Scientific Gas Products, and MG Industries and ranged in EO concentration

from less than 1 ppmv to 20% (v) and in CFC-12 concentration from 1200 ppmv to 62.5% (v). In addition, lecture bottles containing 99.9% EO and CFC-12 were used to verify response at the upper levels of concentrations observed in the vent streams. Calibration curves consisted of a minimum of three standards which bracketed the sample concentrations.

CALCULATIONS

The data were reduced using LOTUS® 1-2-3 software. Rounding was performed at the completion of the calculations.

Ethylene Oxide and CFC-12 Concentration

Calibration curves were prepared by taking the logarithm of the peak area and plotting that logarithm versus the logarithm of the concentration. Although the use of logarithm-logarithm plots is a departure from normal practice, the logarithm procedure weighted each point of the calibration curve more equally than the use of a straight calibration curve. Equal weighting was important because the calibration curve covered six orders of magnitude. Under those conditions, the highest standard (100% [v]) received the greatest weight when using a straight response versus concentration curve. Essentially, the highest standard by being so much larger than the other standards determined the calibration curve. Unfortunately, the highest standard was also the standard most likely to be inaccurate due to possible curvature in the response curve at high concentrations and irregularites in response due to possible column overloading. With a logarithm-logarithm plot the high point that was most likely to be in error received less weight and the middle points that were most likely to be correct received more weight. Table 6 shows a comparison of data calculated using the logarithm calibration to data calculated using a standard curve.

The slope (M) and the y-intercept (B) were obtained from the least squares fit of the data points to the curve using Equations 7 and 8:

$$M=[n(\Sigma XY) - (\Sigma X)(\Sigma Y)/[n(\Sigma X^2) - (\Sigma X)^2] \quad \text{(Equation 7)}$$

$$B = (\Sigma Y)/n - M(\Sigma X)/n \quad \text{(Equation 8)}$$

where n is the number of standard concentrations used, X is the logarithm of the standard concentration, and Y is the logarithm of the peak area.

The calibration curves are shown in Figures 16-19. The EO inlet calibration curve is shown in Figure 16, the CFC-12 inlet calibration curve

TABLE 6. COMPARISON OF ETHYLENE OXIDE CONCENTRATIONS CALCULATED USING LOGARITHM-LOGARITHM AND STANDARD CALIBRATION CURVES FOR DATA FROM THE SCRUBBER OUTLET DURING TEST 14

Elapsed Time (min)	Concentration in ppmv	
	Logarithm Method[a]	Standard Method[b]
5	17.69	19.52
8	35.52	37.36
12	57.43	59.12
16	59.21	60.87
20	63.49	65.11
24	61.89	63.53
44	20.90	22.74
48	56.78	58.47
52	41.58	43.39
71	32.69	34.54
75	30.07	31.92
79	33.05	34.89
97	17.05	18.88
101	15.58	17.39
105	10.93	12.70
124	9.28	11.03
128	6.54	8.24
132	7.36	9.08
150	5.49	7.17
154	4.41	6.06
158	2.47	4.07
177	2.11	3.70
181	2.35	3.94
185	3.60	5.23

[a] Calibration from 1 ppmv to 12.5% (v).

[b] Calibration from 1 ppmv to 502.4 ppmv.

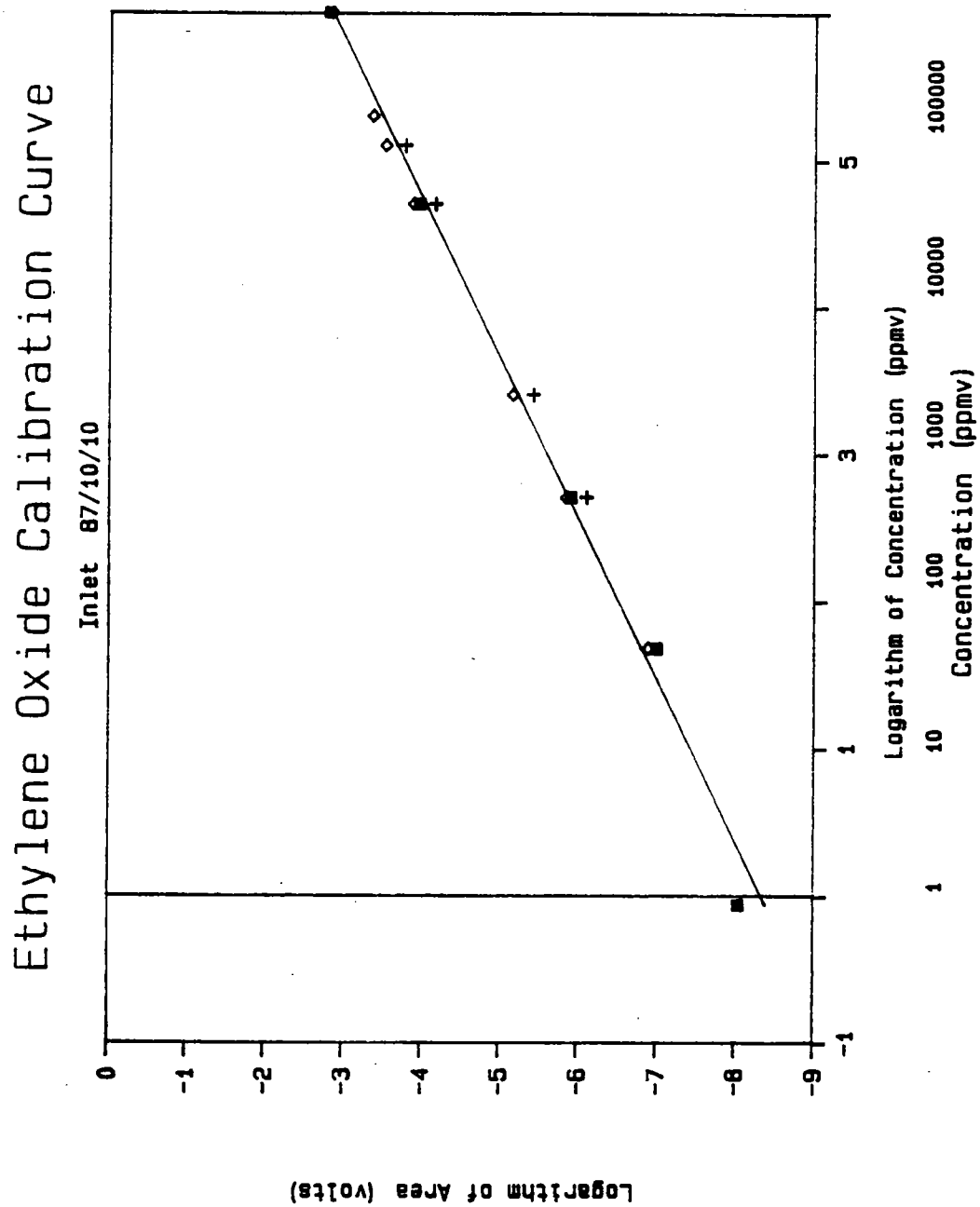

Figure 16. Ethylene Oxide Calibration Curve Used for Quantitation of Scrubber Inlet Samples

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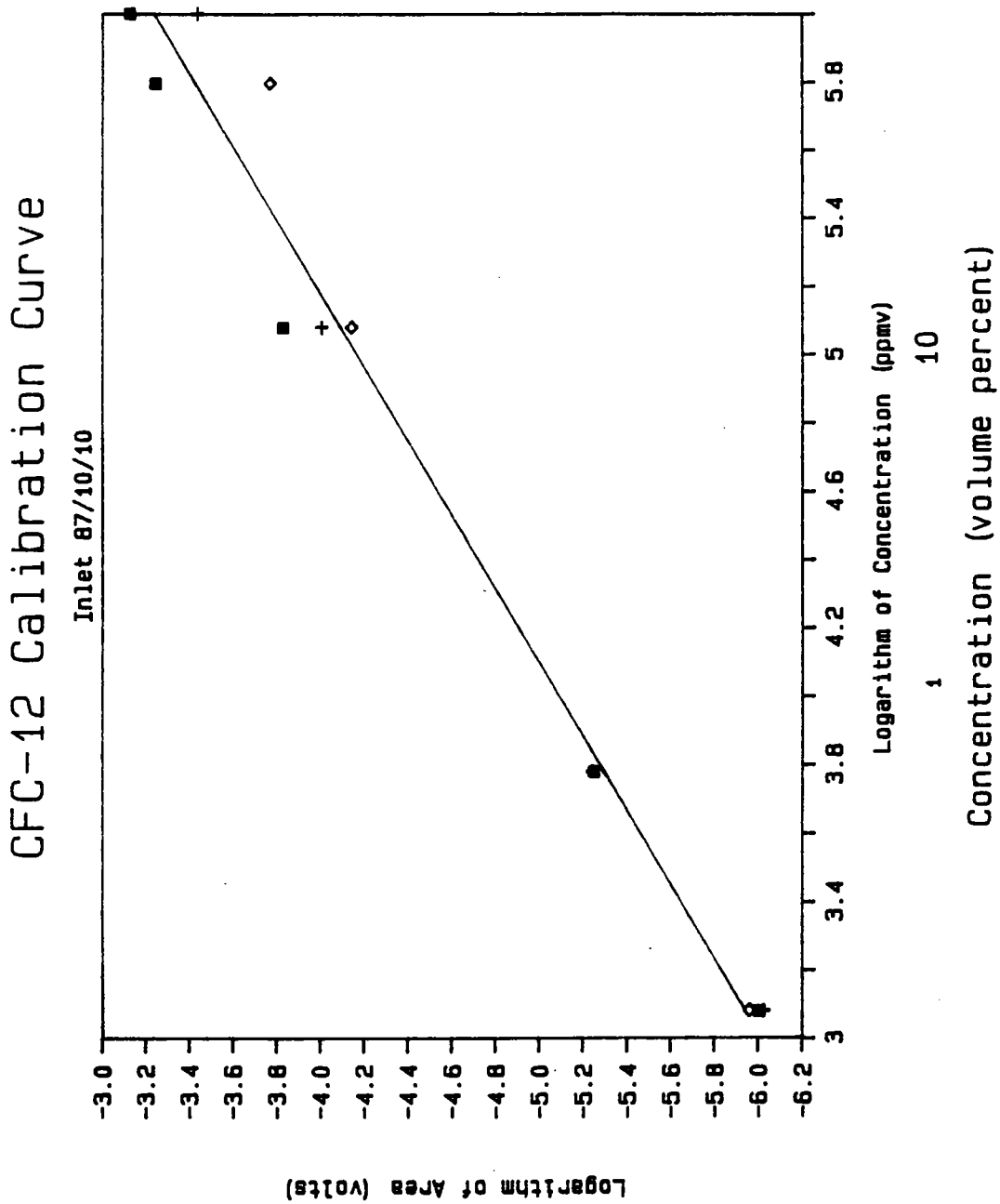

Figure 17. Chlorofluorocarbon-12 Calibration Curve Used for Quantitation of Scrubber Inlet Samples

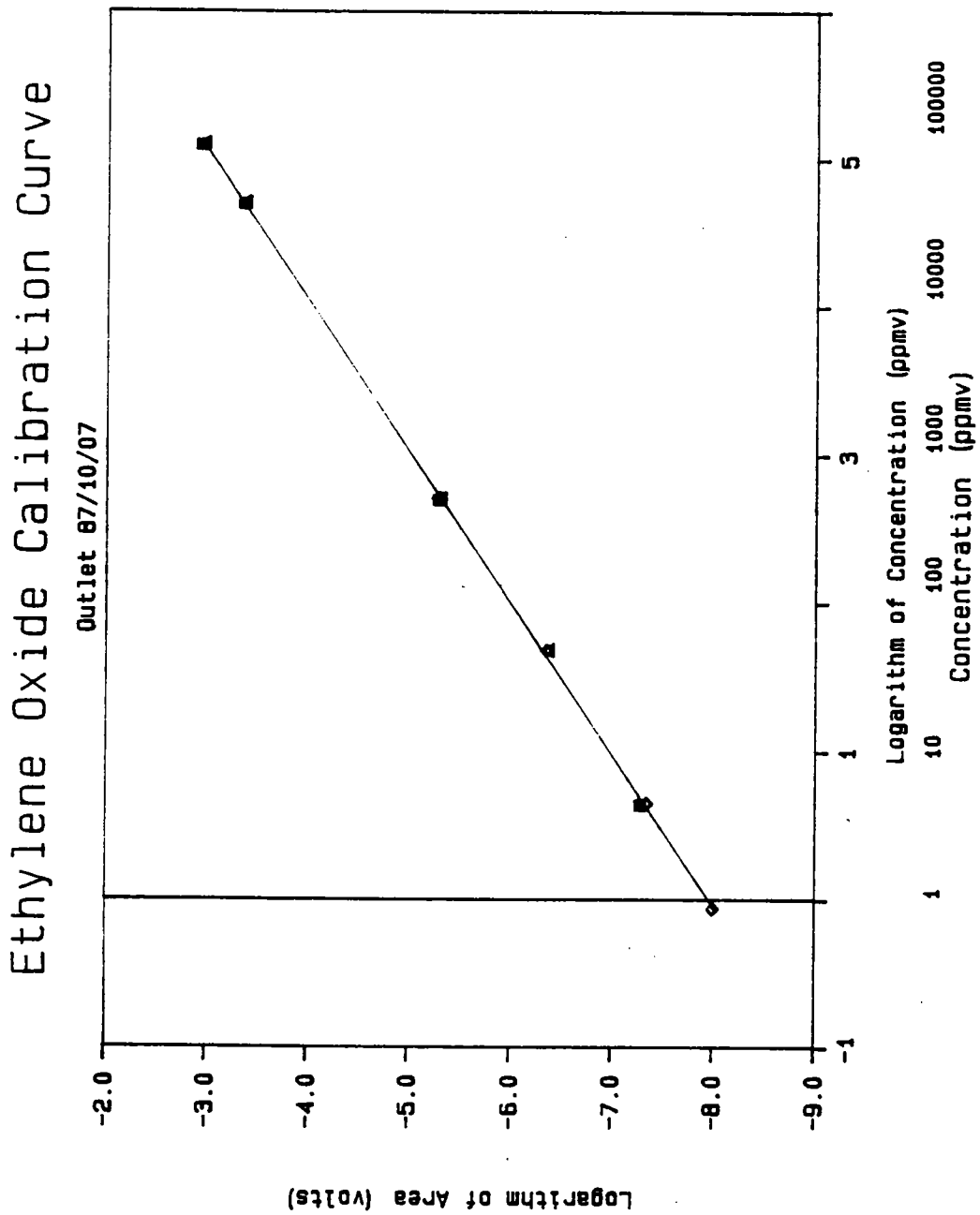

Figure 18. Ethylene Oxide Calibration Curve Used for Quantitation of Scrubber Outlet Samples

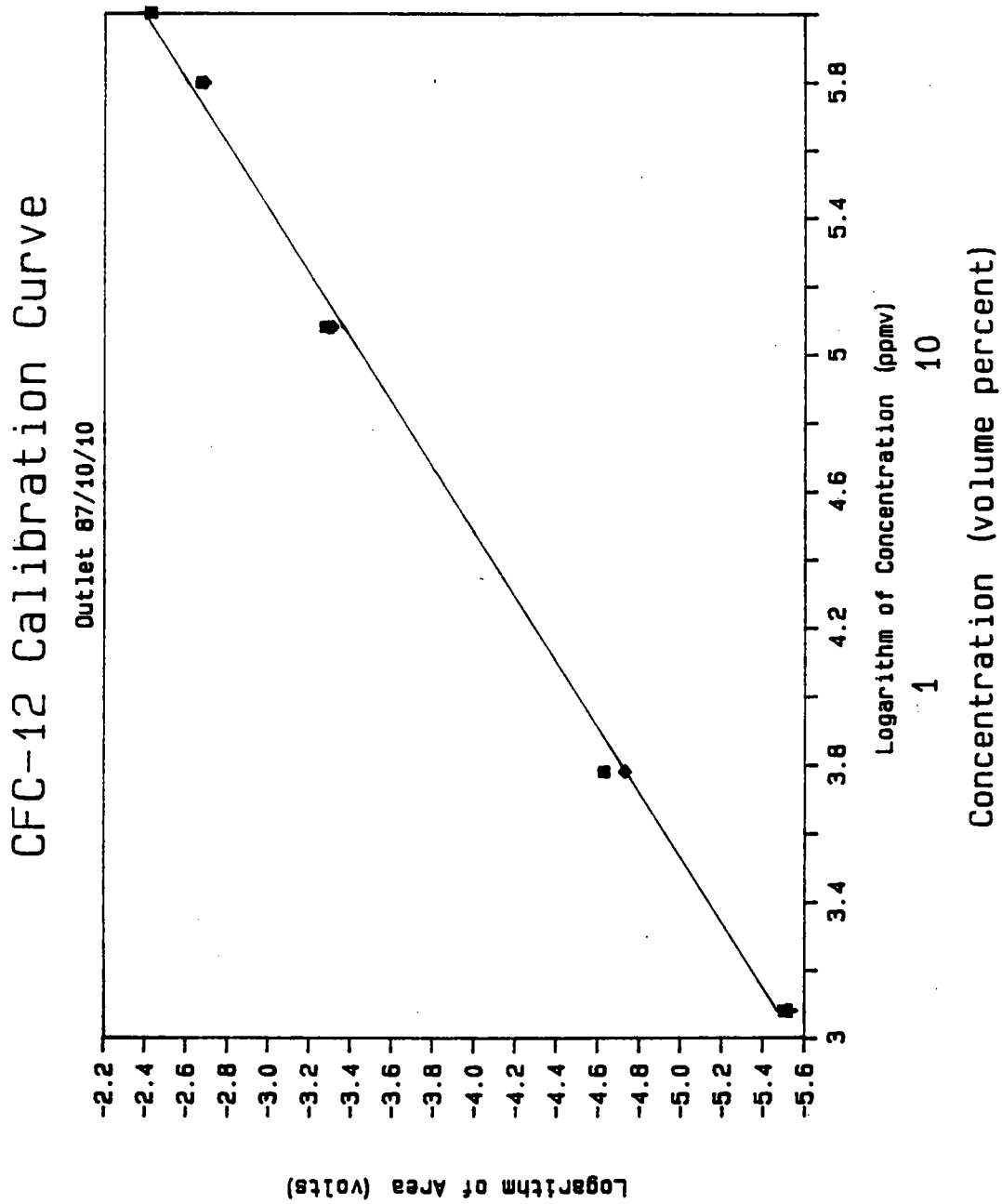

Figure 19. Chlorofluorocarbon-12 Calibration Curve Used for Quantitation of Scrubber Outlet Samples

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in Figure 17, the EO outlet calibration curve in Figure 18, and the CFC-12 outlet calibration curve in Figure 19. Many of the standards were injected several times during the day as indicated by the various symbols on the graphs. The lines represent the least squares best fit using all of the data points. In general, for the inlet analyses the system was calibrated from 1 ppmv to 100% (v) for EO and from 500 ppmv to 100% (v) CFC-12 and for the outlet analyses from 1 ppmv to 12.5% (v) for EO and from 500 ppmv to 100% (v) for CFC-12.

As shown in Figures 20 and 21, at the scrubber outlet the EO and CFC-12 concentrations were interpolated at 10-sec intervals for the first evacuations. Usually, the concentrations were assumed to increase linearly, plateauing at a maximum determined by an average of the data points after the concentration versus time curve leveled off. In some cases the concentration was assumed to decrease linearly after reaching a maximum and in other cases the concentration was assumed to be constant throughout the evacuation.

For the second evacuations the concentrations were assumed to decrease linearly where enough data were present to validate that assumption. In most cases an average concentration was used. Examples of the concentration interpolations for the second evacuations are shown in Figures 22 and 23. In all cases for the third through seventh evacuations average concentrations were used.

At the scrubber inlet the EO and CFC-12 concentrations were interpolated at two-minute intervals for the first evacuations as shown in Figures 24 and 25. The same interpolation procedures were used at the scrubber inlet as at the scrubber outlet. Examples of the concentration interpolations at the scrubber inlet for the second evacuations are shown in Figures 26 and 27.

Vent Stream Molecular Weight

The molecular weight of the vent stream (MW_{vs}) is the sum of the molecular weight (MW) of each component multiplied by the mole fraction (C) of that component in the vent stream:

$$MW_{vs} = C_a MW_a + C_b MW_b + \ldots + C_z MW_z \qquad \text{(Equation 9)}$$

The components in the vent stream that were considered to contribute to the molecular weight were EO, CFC-12, oxygen, nitrogen, and water. Carbon dioxide was not included because it was present at low levels (<1 volume percent).

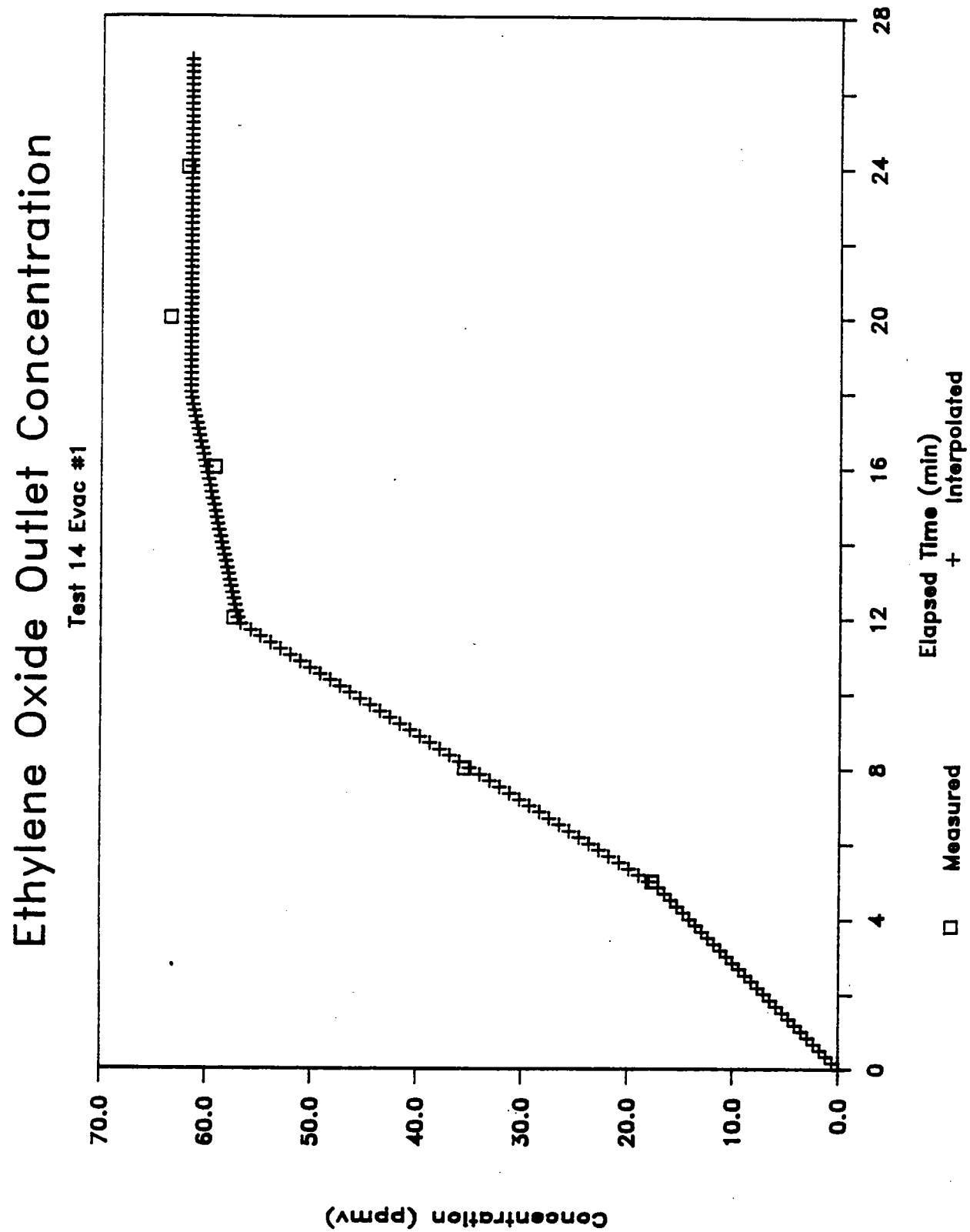

Figure 20. Interpolated EO Scrubber Outlet Concentrations for for Test 14 Evacuation 1

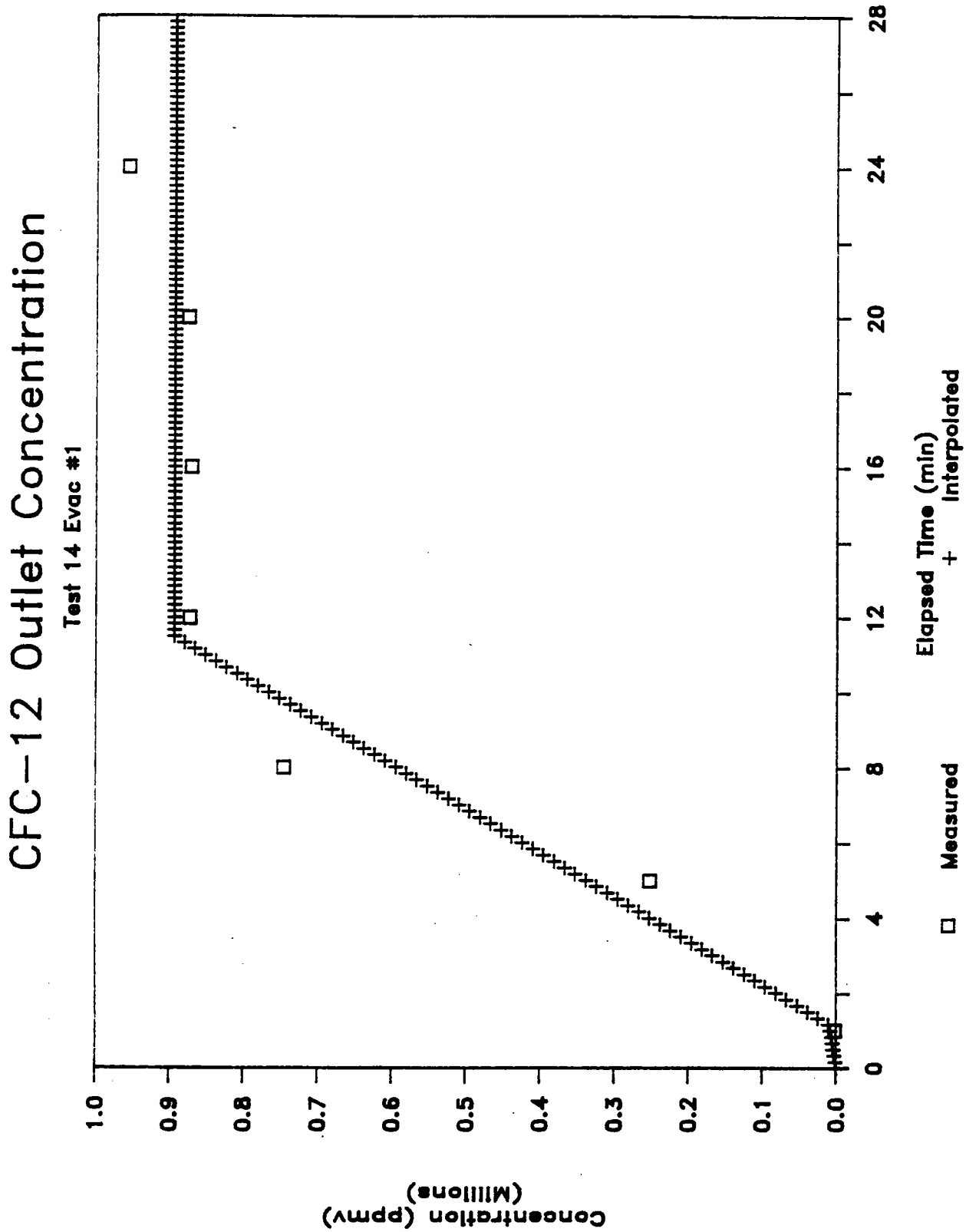

Figure 21. Interpolated CFC-12 Scrubber Outlet Concentrations for Test 14 Evacuation 2

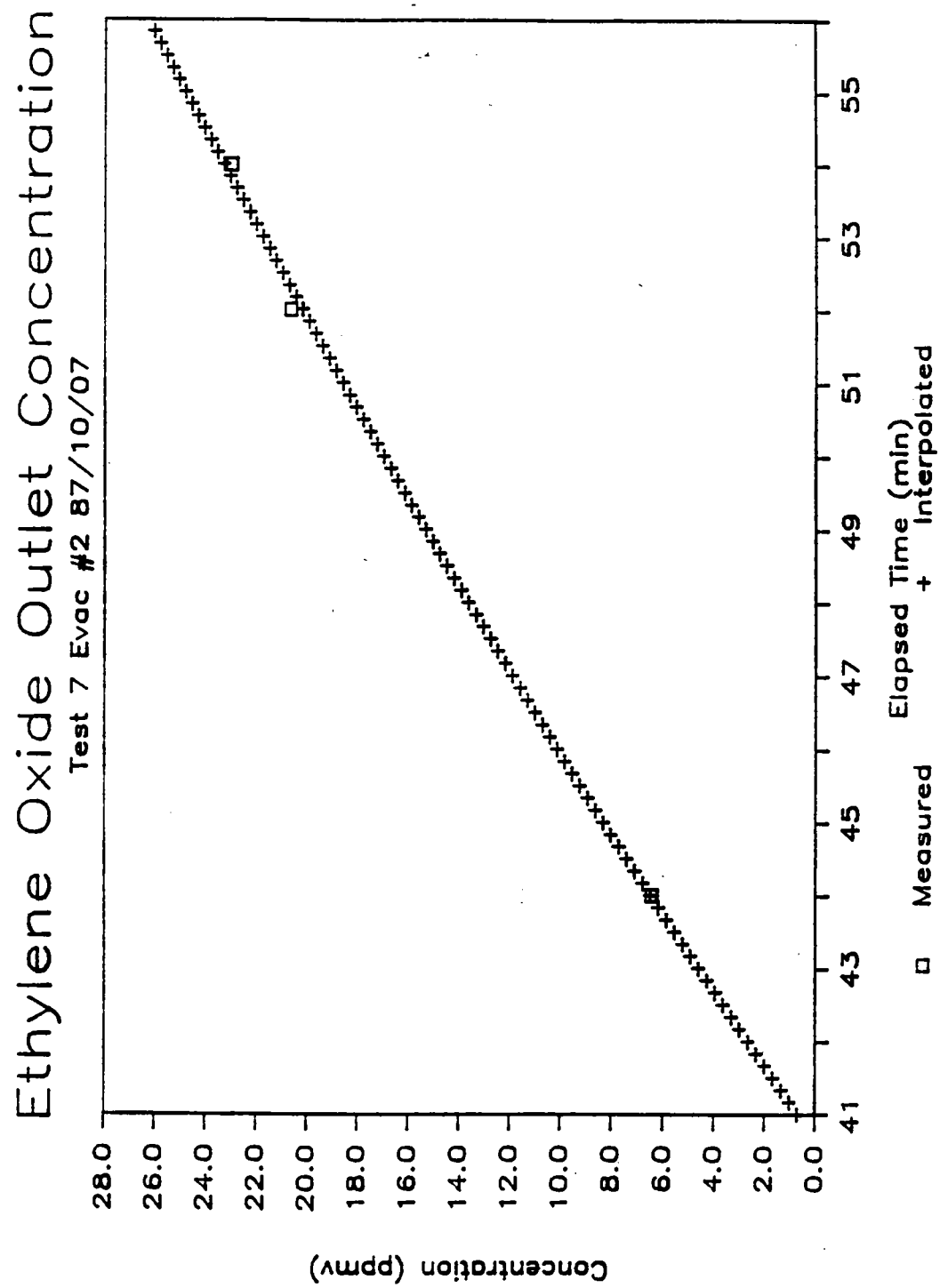

Figure 22. Interpolated EO Scrubber Outlet Concentrations for Test 7 Evacuation 2.

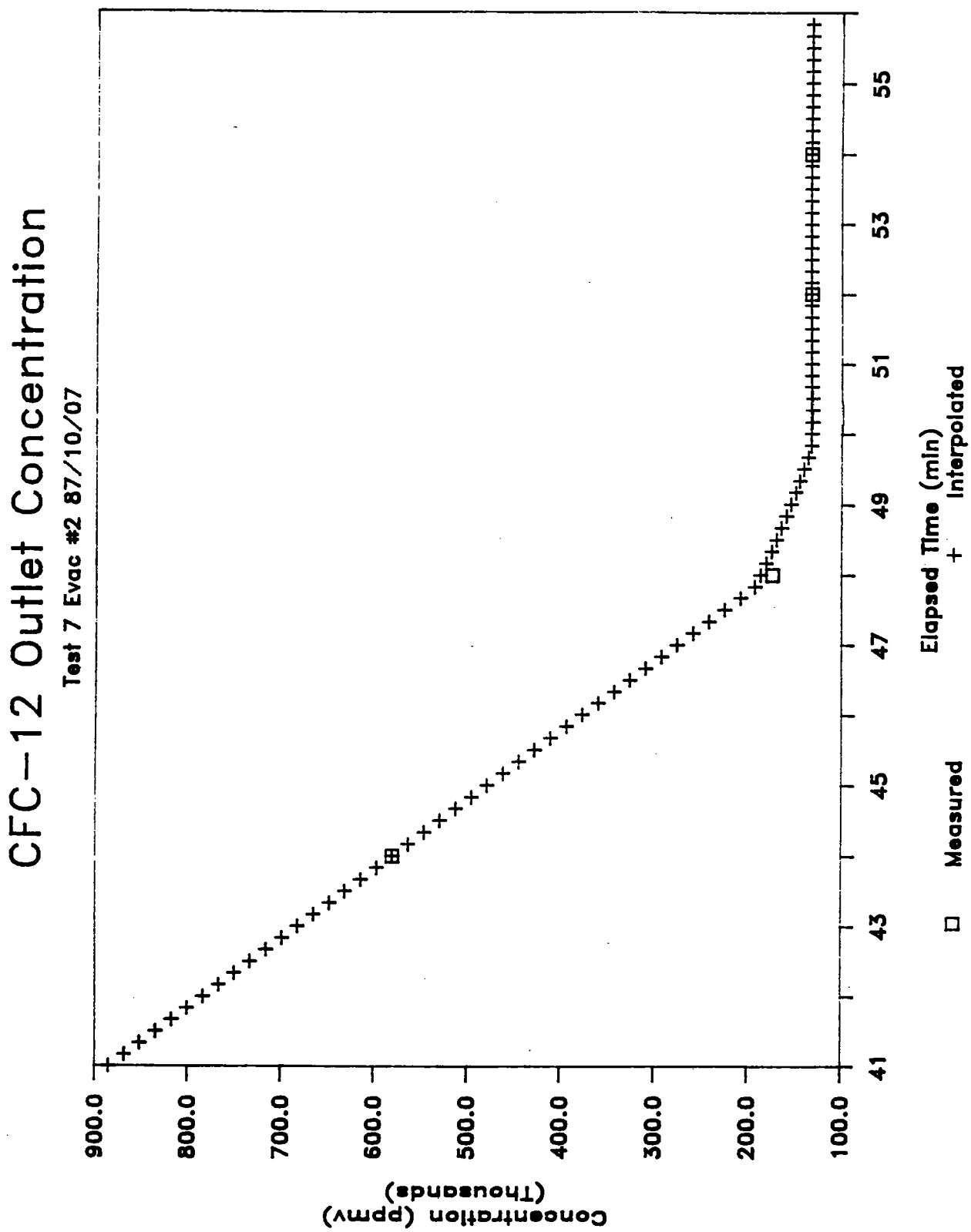

Figure 23. Interpolated CFC-12 Scrubber Outlet Concentrations for Test 7 Evacuation 2

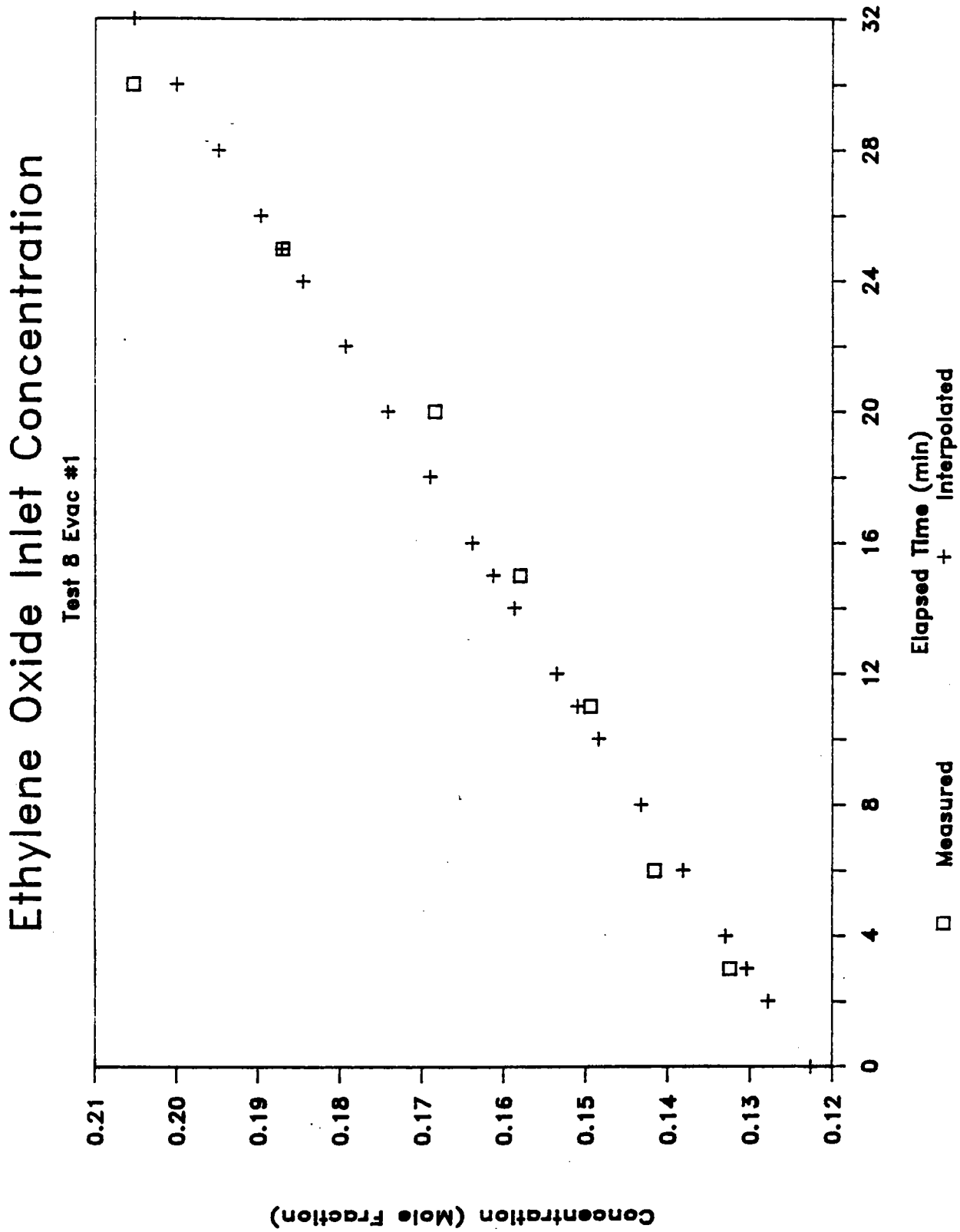

Figure 24. Interpolated EO Scrubber Inlet Concentrations for Test 8 Evacuation 1

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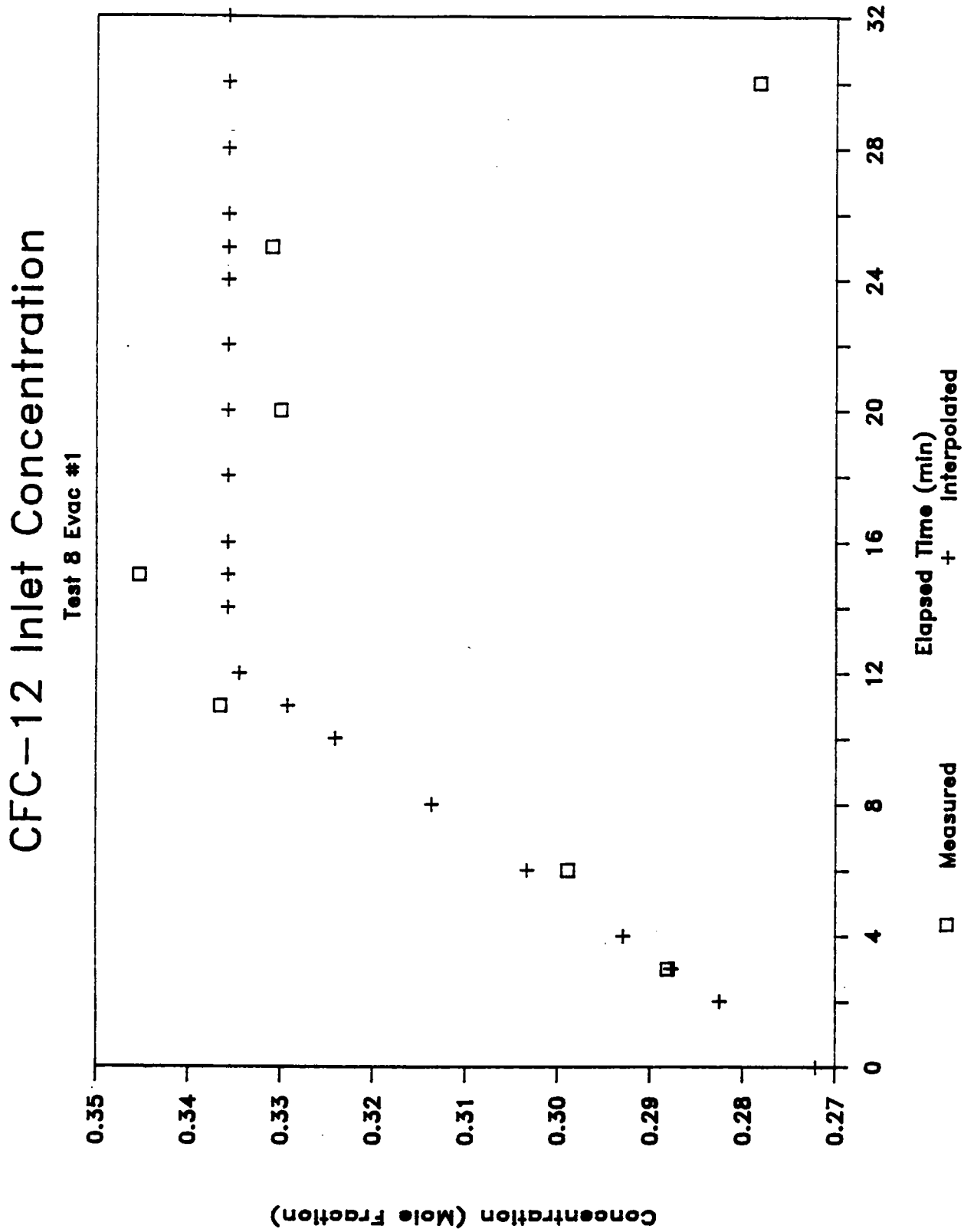

Figure 25. Interpolated CFC-12 Scrubber Inlet Concentrations for Test 8 Evacuation 1

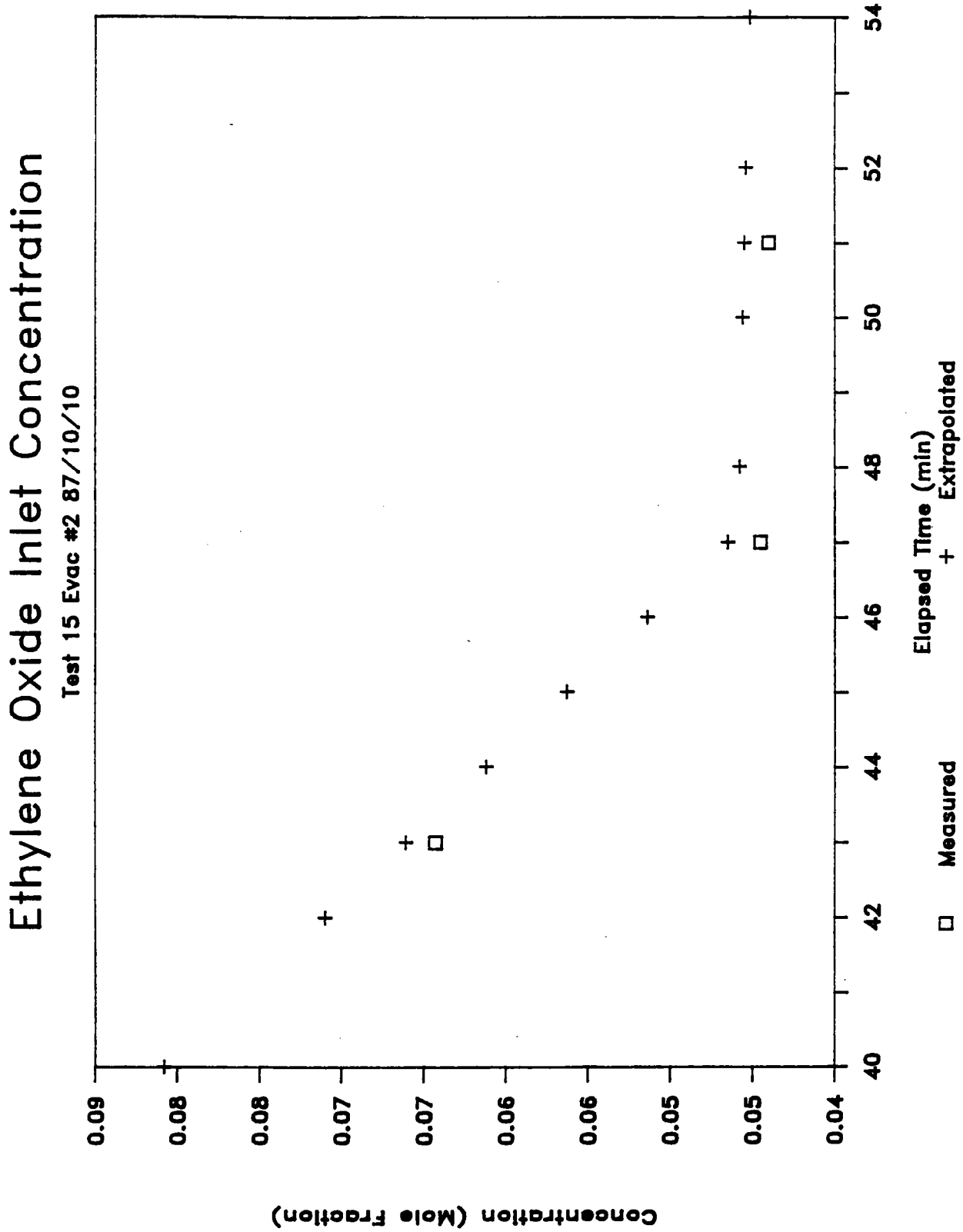

Figure 26. Interpolated EO Scrubber Inlet Concentrations for Test 15 Evacuation 1

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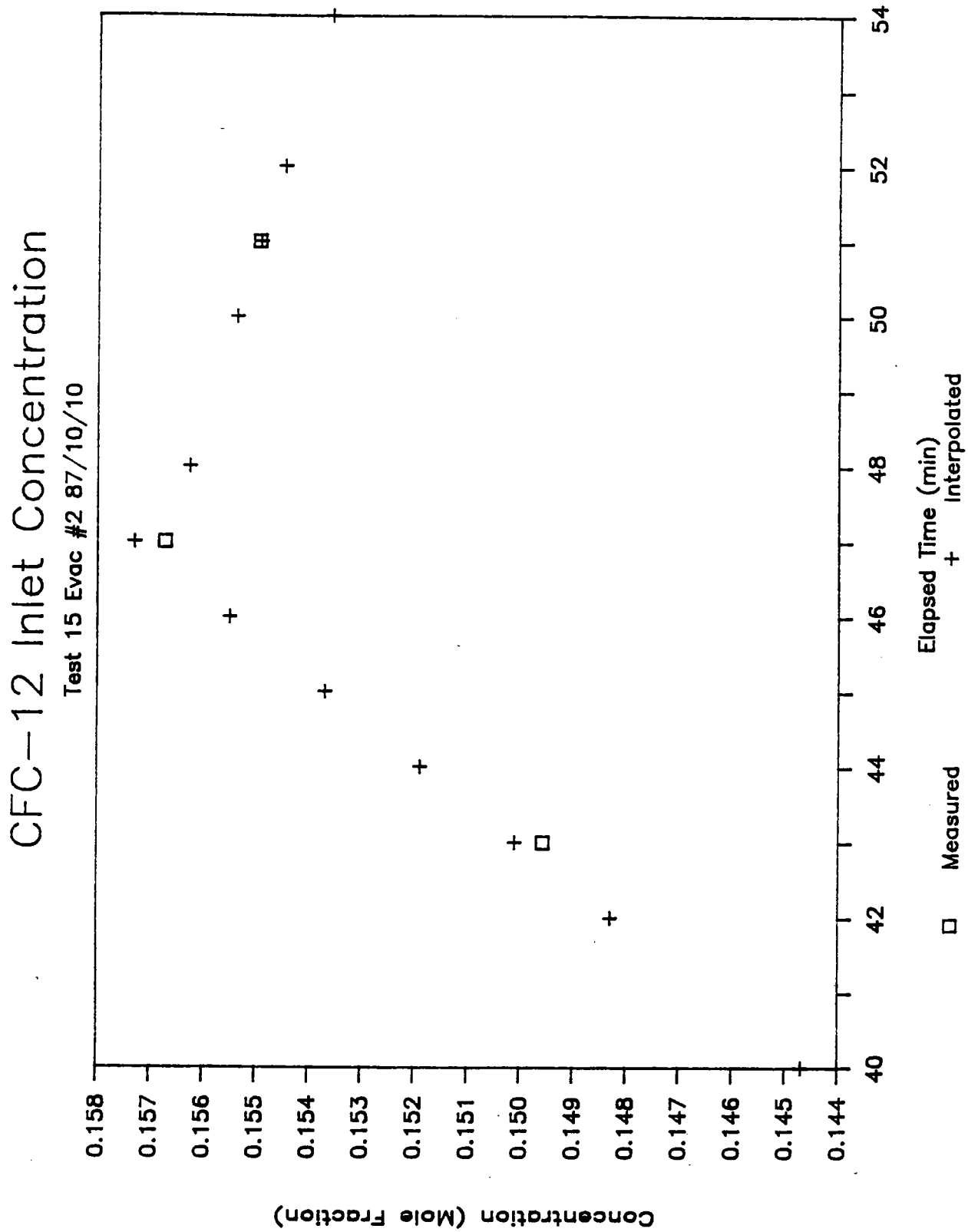

Figure 27. Interpolated CFC-12 Scrubber Inlet Concentrations for Test 15 Evacuation 2

The EO and CFC-12 concentrations were calculated as described above. The oxygen concentration was measured using Fyrite. For the first evacuations the oxygen was assumed to decrease exponentially from 20% to 0% by volume as shown in Figure 28. In several cases for the second evacuations the oxygen was assumed to increase as shown in Figure 29; however, in most cases either the average of all measurements was used or a value of 19% (v) was assumed. For the third through seventh evacuations the measured value was used or, if no measurements were taken, a value of 20% (v) was assumed.

Vent gas water content was measured using wet bulb/dry bulb measurements. Using the temperature differential and the dry bulb temperature, relative humidity was obtained from a table.[15] Another table was used to obtain the vapor pressure of water at the dry bulb temperature.[16] The mole fraction of water in the vent stream was calculated using Equation 1 presented in Section 4. The fraction of vent gas which was not attributed to EO, CFC-12, oxygen, or water was assumed to be nitrogen.

Ethylene Oxide Emission Rates

Both EO emission rates into and out of the control unit were calculated. The calculational procedures differed for the two locations because of the different procedures used to measure the flow rates.

Mass Flow Rate into the Control Unit--

The EO mass flow rate into the control unit was calculated based on the number of moles of gas exiting the chamber during each 2-min interval. Table 7 provides an example of the data used and the mass flow rates calculated during Test 6, Evacuation 1.

Assuming the chamber gas behaved as an ideal gas and using the chamber pressure (P, psia) and jacket temperature (T, K) provided on the chamber parameter printout sheet, the moles (mol) of gas leaving the chamber were given by:

$$mol = PV/RT \qquad \text{(Equation 10)}$$

where V was the chamber volume (1065 ft^3) and R was the gas constant (19.31 psia ft^3/[mol K]). Although the chamber gas probably deviated from ideal behavior, the assumption that it was ideal was a reasonable approximation at the chamber conditions used.

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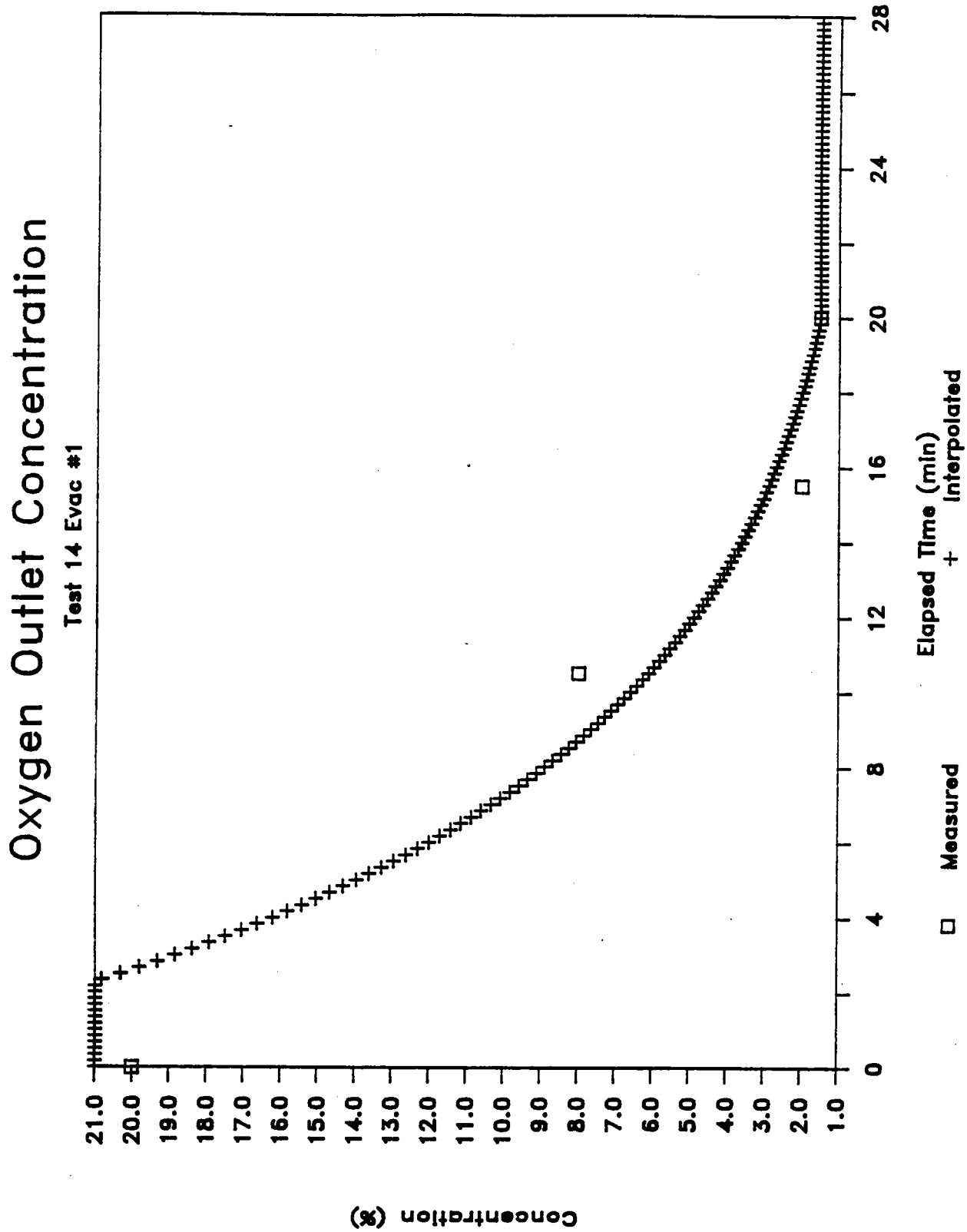

Figure 28. Interpolation of O_2 Scrubber Outlet Concentrations for Test 14 Evacuation 1

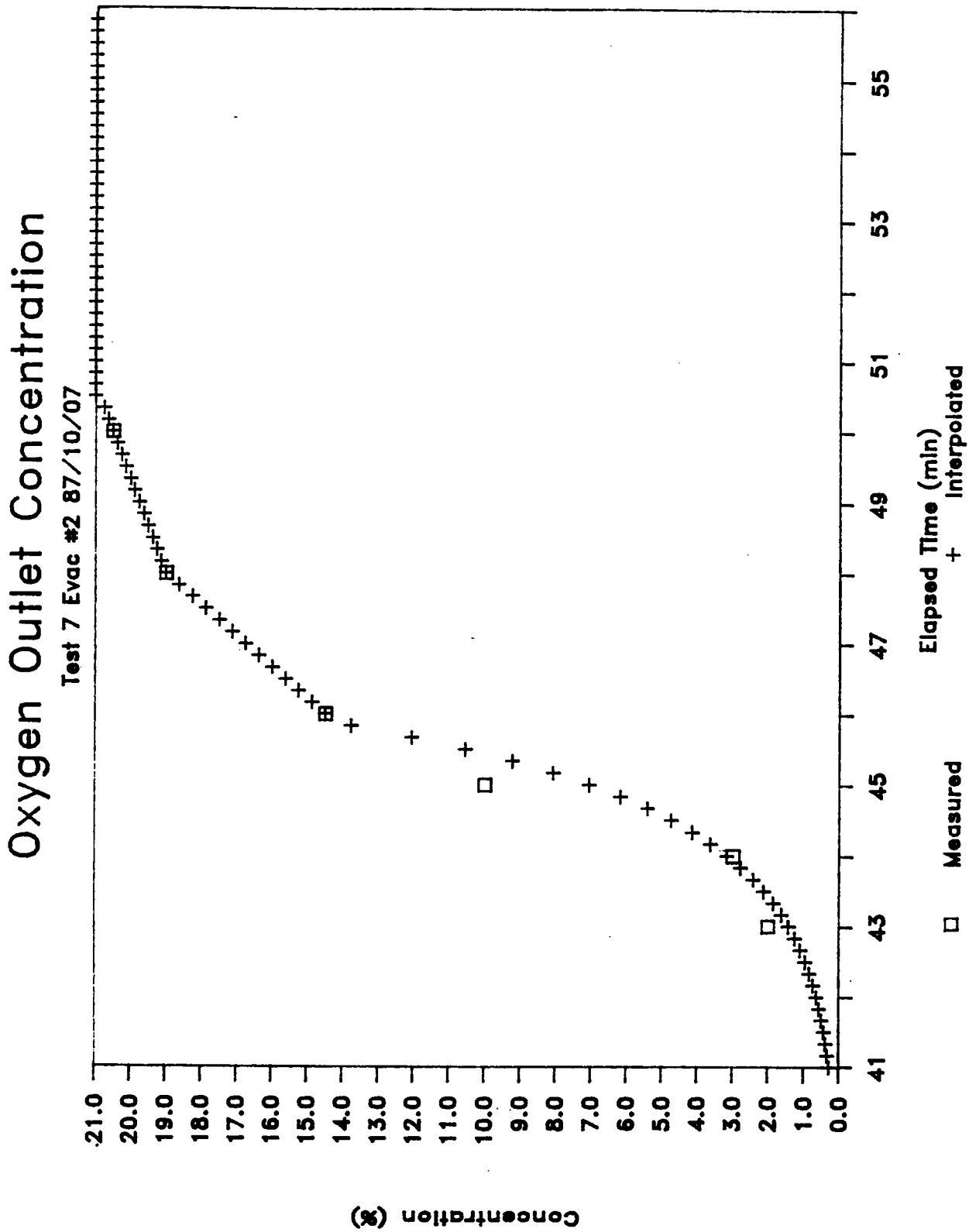

Figure 29. Interpolation of O_2 Scrubber Outlet Concentrations for Test 7 Evacuation 2

TABLE 7. ETHYLENE OXIDE MASS FLOW RATE INTO SCRUBBER DURING TEST 6, EVACUATION 1

Elapsed Time (min)	Clock Time	EO Conc. (% [v])	Molecular Weight (lb/mole)	Chamber Temp. (deg. C)	Chamber Pressure (psia)	Flow Rate (lb mol/min)	EtO Emission (lb/min)
2.00	21:41	19.79	83.03	53.1	21.4	0.18	1.57
4.00	21:43	20.43	84.04	52.2	19.2	0.18	1.63
6.00	21:45	21.07	85.56	52.7	17.2	0.17	1.59
8.00	21:47	21.71	87.16	52.7	15.6	0.14	1.29
10.00	21:49	22.35	87.22	52.6	13.5	0.18	1.74
12.00	21:51	22.99	87.29	52.0	11.3	0.18	1.87
14.00	21:53	23.63	87.36	51.9	9.5	0.15	1.58
16.00	21:55	24.26	87.45	51.9	7.5	0.17	1.81
18.00	21:57	24.90	85.66	51.8	5.6	0.16	1.76
20.00	21:59	25.54	83.87	51.5	4.2	0.12	1.33
22.00	22:01	26.18	82.08	51.3	3.3	0.08	0.88
24.00	22:03	26.82	80.30	51.1	2.6	0.06	0.70
26.00	22:05	27.46	78.51	51.6	2.2	0.03	0.41
						total lbs =	36.37

The EO mass flow rate (R_{in}, lb/min) for EO into the control unit was given by:

$$R_{in} = MW_b C_b mol/t \qquad \text{(Equation 11)}$$

where MW_b was the molecular weight of EO (44 lb mol), C_b was the mole fraction of EO in the gas, and t was the time interval (2 min). The total weight (W_{in}, lbs) of EO entering the control unit was then given by:

$$W_{in} = \Sigma R_{in} \times t \qquad \text{(Equation 12)}$$

Emission out of the Control Unit--

The EO emission out of the control unit was calculated based on the pounds of gas exiting the control unit during each 10-sec interval. The total weight (W_{out}, lbs) of EO leaving the control unit was then given by:

$$W_{out} = \Sigma m \times t \qquad \text{(Equation 13)}$$

where m was the mass flow rate in lb/min and t was the time interval (0.16 min).

To calculate the flow rate of EO from the pressure drop across standard orifices Equations 3 and 4 from Section 4 were used. A Houston Instrument Digitizer was used to convert the stripchart lines representing continuous pressure readings across the orifice plates into numerical values. A BASIC program was used to interpret the electronic signals from the digitizer and generate a LOTUS 1-2-3 print file of the data. These data were imported into LOTUS. LOTUS spreadsheets were made for the 10 test runs, the seven evacuation sequences, and the two plate sizes.

Input parameters required by the program are:

- Chart speed = 28.3 inches/hr (0.2 mm/s),
- Baseline = 0 inches H_2O (0 kg/m^2),
- Full scale = 10 inches H_2O (254 kg/m^2),
- Standards = 2,
- Start time = varies according to test times, and
- Time intervals = 10 sec (interval between data readings).

The values for the input parameters were based on information from the stripcharts. Values listed above were used for each test run and both large and small orifice plates.

The mass rate of EO flow out of the control unit was then given by Equation 5 in Section 4.

Efficiency Calculations

Efficiency was calculated in terms of a throughput efficiency and a recovery efficiency.

Throughput Efficiency--

A throughput efficiency was calculated using the emissions into and out of the control unit. The throughput efficiency (E_T) is given by Equation 14.

$$E_T = 100 \times (W_{in}-W_{out})/W_{in} \qquad \text{(Equation 14)}$$

Recovery Efficiency--

A recovery efficiency was calculated using the weight of the original EO charge and the measured EO emissions at the outlet of the control unit. The weight of EO originally charged to the chamber was obtained by multiplying the weight of 12/88 gas by 0.12. No analysis was performed on the sterilant gas to verify the EO concentration. A correction was made for the EO remaining in the chamber (W_R) which was determined by Equation 15.

$$W_R = (MW_b C_b PV)/(RT) \qquad \text{(Equation 15)}$$

The mole fraction of EO left in the chamber was obtained from samples taken after Evacuation 7 either before or after the chamber had been refilled. The recovery efficiency (E_R) is then given by:

$$E_R = 100 \times (W_c-W_R-W_{out})/(W_c-W_R) \qquad \text{(Equation 16)}$$

where W_c is the weight of EO originally charged to the chamber.

RESULTS

The sampling and analytical method for EO emissions from sterilizers ultimately must be capable of determining whether a sterilizer EO control unit is operating efficiently. To do that the method must be capable of measuring the EO emissions accurately enough to provide consistent efficiency measurements. The sampling method must deliver unbiased sample and the analytical method must accurately identify and quantitate the components of interest.

In addition the test data was used to compare several options which exist in defining the method. A comparison was made between calculating efficiency by the Throughput Method and the Recovery Method and by using a chamber with product and without. The utility of the orifice plates was evaluated by comparing emission and efficiency results obtained using the orifice plates to

results which would have been obtained if the flow rate had been estimated using the data from the chamber control monitor.

Sampling Method Evaluation

The sampling method was evaluated using a gas cylinder containing known concentrations of EO and CFC-12. The gas cylinder was first analyzed on the GC. Then the gas cylinder was treated as a sample by installing a tee between the cylinder and the sampling line. The flow rate of the gas out of the cylinder was adjusted so that there was always excess flow past the tee during sampling. Response of the cylinder sample through the sample line was compared to the response of the cylinder sample analyzed directly.

Evaluation of Inlet Sampling--

The inlet sampling bias was measured twice using a 2,508 ppmv EO and 6,022 ppmv CFC-12 standard. The total sampling and analytical bias in the EO measurement ranged from 0-7% with an average of 3.5%. The sampling bias in the EO measurement ranged from 0.2 to 11.9% with an average of 6%. In both cases the sampling was biased positively for EO indicating that the method would tend to overestimate EO emissions.

The total sampling and analytical bias in the CFC-12 measurement ranged from 4.3 to 12.5% with an average of 8.4%. The sampling bias in the CFC-12 measurement ranged from 0 to 15.2% with an average of 7.6%.

Evaluation of Outlet Sampling--

The outlet sampling bias was measured three times using a 502.4 ppmv EO and 1,200 ppmv CFC-12 standard. The total sampling and analytical bias in the EO measurement ranged from 1.9 to 12.9% with an average of 7.4%. The sampling bias in the EO measurement ranged from -7.5 to 7.1% with an average of +1.3%.

The total sampling and analytical bias in the CFC-12 measurement ranged from -9.5 to 4.8% with an average of -2.4%. The sampling bias in the CFC-12 measurement averaged 11%.

Analytical Method Evaluation

The analytical method was evaluated using a gas cylinder containing concentrations of EO and CFC-12 that were certified to ±2 percent. The gas cylinder was analyzed on the GC using the same procedure as for the standard cylinders. Using the response of the cylinder sample and the prepared

calibration curve, a measured concentration of the cylinder sample was calculated. The measured concentration was compared to the expected or known concentration of the gas cylinder.

Evaluation of Inlet Analysis--

The inlet analysis bias was measured twice using a 2508 ppmv EO and 6022 ppmv CFC-12 standard. The analytical bias in the EO measurement ranged from -0.2 to -4.4% with an average of -2.3%. In both cases the analytical bias was negative. The analytical bias in the CFC-12 measurement ranged from -2.4% to 4.3% with an average of 1%.

Evaluation of Outlet Analysis--

The outlet analysis bias was measured three times using a 502.4 ppmv EO and 1200 ppmv CFC-12 standard. The analytical bias in the EO measurement ranged from 0.3 to 10.1% with an average of 6.2 percent. In all cases the analytical bias in the EO measurement was positive.

The analytical bias in the CFC-12 measurement ranged from -5.6 to -18.5% with an average of -12 percent. In all cases the analytical bias in the CFC-12 measurement was negative, indicating that the column may be overload by the combination of the 2-mL sample size and the high CFC-12 concentration.

Method Utility in Emissions Determination

The utility of the method in determining emissions was evaluated by comparing the measured EO emissions for the six empty chamber tests on the assumption that the control device efficiency did not change with time. Emissions data are presented in Table 8.

Emissions from Uncontrolled Sterilizers--

The expected quantity of EO entering the control unit during the six empty chamber tests ranged from 41 to 44 lb and averaged 42 lb. These values were based on 12% of the total weight of the 12/88 charge. The measured quantity of EO entering the control unit during these same six tests ranged from 24 to 62 lb and averaged 47 lb. In Test 7 where the measured mass of EO entering the scrubber was low, the inlet sampling pump leaked during the first 10 minutes of the evacuation and the FID flame was extinguished during portions of the third and fourth evacuations. Test 9 and 10 were performed on a day when the EO standard calibration curve for inlet samples was lower than on other test days.

TABLE 8. CONTROL UNIT INLET AND OUTLET EO MASS FLOW RATE FOR THE EMPTY CHAMBER TESTS

Test Number	Initial EO Charged to Chamber (lb)	EO Left in Chamber ~~(10^3 lb)~~	EO Entering Control Unit Measured (lb)	EO Exiting Control Unit Measured (lb)
7	43.8	0.42×10^{-3}	24.19[a]	0.043
9	41.5	1.5	60.59[b]	0.011
10	42.4	0.22	62.12[b]	0.029
12	41.5	0.16	44.00	0.011
14	42.0	0.16	48.80	0.021
15	41.2	0.07	52.82	0.014

[a]During Test 7 there was a leak in the inlet sampling pump during the first 10 minutes of the evacuation and the FID flame was extinguished during portions of the third and fourth evacuations. Loss of these samples may explain the lower mass of EO entering the control unit during this test.

[b]The EO standard calibration curve for inlet samples on October 8, 1987 was lower than on the other test days. This would have raised the measured EO concentrations, and caused the EO mass flow into the control unit to be over estimated.

The absolute difference between measured emissions and expected emissions was >40% for three tests and was <10% for only one test. In five of the six tests the measured emissions were larger than the expected emissions.

Emissions from Controlled Sterilizers--

The measured quantity of EO emitted to the atmosphere from the control unit during the six empty chamber tests ranged from 0.011 to 0.043 lb and averaged 0.022 lb. The relative standard deviation (RSD) in these six measurements was twice the RSD for the inlet measurements indicating that more variation is associated with the scrubbing process than with the sterilization chamber.

Conclusions--

Most of the error in the EO mass flow rate and emission measurements probably resulted from errors in the interpolation of the flow rate/concentration profile. Ethylene oxide emissions were measured with greater precision at the scrubber inlet than at the scrubber outlet as was expected because of the higher concentrations at the inlet. Part of this loss of precision in EO emission measurement may be due to difficulty in identifying the EO peak in the chromatogram because of EO retention times that shifted as the EO concentration decreased.

Method Utility in Control Unit Efficiency Determination

The utility of the method in determining control unit efficiency was evaluated by comparing the measured throughput efficiencies obtained from the six empty chamber tests on the assumption that the control device efficiency did not change with time. All of the empty chamber tests were performed on the same chamber. Efficiency data for the empty chamber tests is presented in Table 9. The measured efficiency using the throughput method with the data from the six empty chamber tests ranged from 99.82 to 99.98% and averaged 99.94 percent. The median efficiency was 99.96 percent. Efficiency values were above 99.95% in five of the six tests. The one test in which the efficiency was below 99.9% was Test 7 where sampling and analytical problems were encountered as footnoted in Table 9.

TABLE 9. EFFICIENCY FROM EMPTY CHAMBER TESTS

Test Number	Throughput Efficiency	Recovery Efficiency
7[a]	99.82%	99.90%
9	99.98%	99.97%
10	99.95%	99.93%
12	99.98%	99.97%
14	99.96%	99.95%
15	99.97%	99.97%

[a]During Test 7 there was a leak in the inlet sampling pump during the first 10 minutes of the first evacuation and the FID flame was extinguished during portions of the third and fourth evacuations. The test was halted at these times until the problems were solved. This may explain the lower efficiencies measured during Test 7.

Effect of Calculational Method on Efficiency Determination

Comparisons of the groupings shown in Table 9 were done by a one-way analysis of variance (ANOVA) with sampling-calculational procedures as a fixed factor. The model was:

$$Y_{ijk} = \mu + M_i + e_{k(ij)} \qquad \text{(Equation 17)}$$

where

Y_{ijk} = the efficiency results,

μ = overall mean efficiency,

M_i = the calculational procedures, i=1 or 2, for Throughput and Recovery Procedures, respectively,

$e_{k(ij)}$ = the error term.

The M_i interaction term was tested to determine if there was a significant effect on efficiency results based on the calculational procedure used.

Basically, the error in the means of the efficiencies (the dependent variable) calculated using the Throughput and Recovery Methods are compared to the error in all the individual measurements using a F-Ratio. From the F-Ratio a probability (P) that the independent variable (the method used) has no effect can be calculated. If $P \leq 0.05$, then the effect is taken to be significant. If $P \leq 0.01$, then the effect is taken to be highly significant. A one-way ANOVA resulted in a P of 0.86 for the tests using chambers which did not contain product and 0.32 for the tests using chambers which did contain product; therefore, the procedure used to calculate the efficiency does not significantly affect the efficiency determined.

Effect of Product Presence on Efficiency Determination

The efficiency results from the tests where product was present in the chamber were compared with the efficiency results from the tests were product was not present in the chamber using a fixed factor ANOVA. The model was

$$Y_{ijk} = \mu + M_i + F_j + MF_{ij} + e_{k(ij)} \qquad \text{(Equation 18)}$$

where

Y_{ijk} = the efficiency results,

μ = the overall mean efficiency,

M_i = the procedure, i = 1 or 2, for Throughput or Recovery Procedure, respectively,

F_j = the chamber condition, j = 1 or 2, for chamber without and with product, respectively,

MF_{ij} = the MF_{ij} interaction term, and

$e_{k(ij)}$ = the error term.

A fixed factor ANOVA was used because the interaction terms, M_i and F_j, represented parameters that were fixed, i.e. the chamber either did or did not contain product. The M_i interaction term represented the effect of calculational procedure on the efficiency measurement. The F_j interaction term represented the effect of the presence of product on the efficiency measurement. The MF_{ij} interaction term represented the combined effect of the calculational procedure and the chamber condition on the efficiency measurement. The error term represented the random error of the method. The variances in calculating the efficiencies by the various methods were compared using an F-Ratio. From the F-Ratio, a probability that the independent variable does not effect the efficiency was calculated. If $P \leq 0.05$, then the effect is taken to be significant. The results of the ANOVA calculations are reported in Table 10.

None of the dependent variables tested had a $P \leq 0.05$. Therefore, there was no significant effect on the efficiency measurement due to the presence of product in the chamber. Furthermore, there was no interaction between the calculational method used and the presence or absence of product in the chamber. Thus, the efficiency results were within random error of the overall mean efficiency.

Orifice Plate Measurements Compared to Use of Monitor Data

Several outlet EO emissions were calculated using the chamber pressure and temperature data used to calculate inlet flow rates. Results are reported in Table 11. No correction was made for the change in the gas composition which occurred while the gas was in the scrubber. The largest change in gas composition occurs during the first evacuation when the gas composition changes from 30/70 % (v) EO/CFC-12 entering the scrubber to <1/>99 % (v) EO/CFC-12 exiting the scrubber. This meant that during the first evacuation approximately 30% of the moles of gas entering the control unit did not exit the control unit. Thus, the actual flow rate of the gas coming out of the control unit was probably less than the flow rate calculated by this method. This method should over-estimate EO emissions, resulting in an under-estimation of the control unit efficiency.

TABLE 10. FIXED FACTOR ANALYSIS OF VARIANCE RESULTS

Source	Sum of Squares	Degrees of Freedom	Mean Square	F-Ratio	P
M_i	0.00048	1	0.00048	0.3034	0.59
F_j	0.00133	1	0.00133	0.8427	0.37
MF_{ij}	0.00012	1	0.00012	0.0758	0.79
$e_{k(ij)}$	0.02532	16	0.00158		

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TABLE 11. EMISSIONS AND EFFICIENCIES CALCULATED USING ESTIMATED FLOWS

Test Number	Weight EO Emitted (lb)	Throughput Efficiency	Recovery Efficiency
6	0.006	99.99%	99.99%
7	0.036	99.85%	99.92%
8	0.012	99.95%	99.98%
9	0.010	99.98%	99.98%
10	0.006	99.99%	99.99%
15	0.014	99.97%	99.97%

Statistical comparisons of data in Table 11 with data in Tables 8 and 9 using a one-way ANOVA with flow-calculational procedures as a fixed factor showed that the EO emissions from the scrubber calculated using orifice plate data were not significantly different from the EO emissions estimated using chamber temperatures and pressures. The probability that there was no difference in the calculated EO emissions was 0.35; in the calculated throughput efficiencies, 0.59; and in the calculated recovery efficiencies, 0.25. A probability of 0.05 indicated a significant difference. The calculated efficiencies were not significantly different due to the high efficiency of the EO control unit. Therefore, in tests performed on units that are closed systems, flow estimation may be a possible alternative to orifice plate installation.

Vane Anemometer Data Compared to Orifice Plate Data

Several outlet EO emissions were calculated using the vane anemometer data. Results are reported in Table 12. The vane anemometer velocity readings were multiplied by the square root of the ratio of the molecular weight of air to the molecular weight of the vent gas stream. The corrected velocity readings were converted to volumetric flow rates by multiplying by the cross sectional area of the stack. The volumetric flow rates were corrected to standard conditions and converted to molar flow rates. Multiplying the molar flow rates by the vent gas molecular weight gave the mass flow rates. A correction was made for the time no flow was observed by multiplying the mass flow rate by 0.375. (Actual flow out of the stack occurs during only 37.5% of the total time required to evacuate the chamber.)

Comparison of data in Table 12 with data in Tables 8 and 9 show that the calculated EO emissions are much greater and the efficiencies lower using the vane anemometer data. This is because the vane anemometer data tends to overestimate the flow rate. Figure 15 shows the cyclical nature of the flow emitted from the scrubber. The vane anemometer was read at two minute intervals, providing a velocity reading based on the flow during the proceding 16-second interval. Thus, the vane anemometer provides grab samples of the flow rate versus the orifice plates which provide a continuous pressure differential readout. The quality of the vane anemometer data may be improved by taking more frequent velocity readings but could never surpass the quality of the orifice plate data due to the mechanics of the anemometer measurements.

TABLE 12. EMISSIONS AND EFFICIENCIES CALCULATED USING VANE ANEMOMETER DATA

Test Number	Weight EO Emitted (lb)	Throughput Efficiency	Recovery Efficiency
9	0.232	99.62%	99.44%
10	0.175	99.72%	99.59%
12	0.235	99.47%	99.43%

DISCUSSION

During the test several interesting problems arose and observations were made regarding the operation of the EO control device, the sterilization exhaust process, and the analytical system. These problems and observations will be discussed in this section as well as some possible modifications to the method.

Ethylene Oxide Control Device Operation

The system is designed so that the sterilization chambers can not exhaust until the control device is ready. At the end of the exposure cycle, the scrubber receives a signal from the sterilizer control panel that the chamber is ready to exhaust. The scrubber system starts up and requires a two-minute period before chamber evacuation can begin. During this two-minute period the gas from the previous chamber exhaust is emitted from the stack. At the end of the two-minute period, evacuation of the current chamber gas begins. An additional five to seven minutes is required before the chamber gas reaches equilibrium measured by the oxygen content taken during the 10 minutes of the first and second chamber exhausts.

Thus, during the first two minutes of the evacuation the concentrations of EO and CFC-12 should be the same as they were at the end of the previous exhaust and should be fairly constant. During the next five to seven minutes the EO and CFC-12 concentrations should change rapidly as the old chamber gas is swept out of the stack and the remaining chamber gas is diluted by the new chamber gas entering the scrubber. After 10 minutes the measured concentrations should level off to lower values than in the previous evacuation.

With this process cycle, a minimum of three samples would be required to characterize each evacuation, one during the first two minutes, one between two and seven minutes, and one after 10 minutes. The tested sampling/analytical method allows only three samples to be taken during each evacuation. With careful planning the exhaust could be sampled at one minute, five minutes, and 11 minutes. It is recommended that a minimum of six samples be taken. Two samples could be taken during each of the three predicted phases of the evacuation. This criterion would require either an analytical system capable of acquiring samples at 1-min intervals, a dual analytical

system for each sampling port, or the collection of samples in a suitable container for later analysis.

Chamber Evacuation Process

The chamber is evacuated in pulses generated by a solenoid valve opening and closing to prevent the chamber from evacuating too rapidly. At the facility tested, the solenoid was open for 15 sec and closed for 25 sec. Operating with relay control, the gas flow out of the chamber and control unit is not continuous; however, the sampling system is a continuous process. The sampling system is composed of pumps which constantly are pulling sample out of the stack. Since, the chamber is not constantly exhausting, it could be possible for the sampling system to pull ambient air back through the stack, diluting the sample.

To maintain sample integrity, the sampling system must not pull more sample out of the stack than what is contained in the stack during the time period when the solenoid valve is closed. This can be accomplished by controlling the rate at which the sampling pumps pump and by increasing the size of the stack extension. The stack extension used for this test contained approximately 2.6 ft^3 and the main sample pump pulled a maximum of 10-15 L/min. So during the 25 sec period when the solenoid valve was closed, the pump pulled a maximum of 10 L of sample which is <10% of the stack extension volume. Thus, under the test conditions dilution of the sample when the solenoid valve was closed should not have occurred.

Analytical Method

The analytical method is deficient in several areas. Some are due to the characteristics of the vent gas and others to the characteristics of the analytical column.

Problems Due to Vent Gas Characteristics--

Three characteristics of the vent gas which pose problems for the on-line analysis of EO and CFC-12 are the relative concentrations of the EO and CFC-12, the high CFC-12 concentrations present in the first evacuation, and the presence of other interfering materials in the vent gas. The quantitation of CFC-12 is required for determining the molecular weight of the vent gas. The molecular weight is only needed if an orifice plate or a vane anemometer is used to measure the flow rate.

At the scrubber outlet, the EO is present at low ppmv levels and the CFC-12 is present at levels ranging anywhere from 500 ppmv to 99 volume percent. This wide difference in concentration makes the analysis of the two components on the same analytical column very difficult, but it can be done by programming the detector range. A sensitive range can be used for the EO and a less sensitive range for the CFC-12. To program the detector range successfully, near baseline separation of the two compounds must be obtained. Although this is possible with the analytical column chosen, baseline separation extends the time required for analysis and reduces the number of samples which can be collected and analyzed during an evacuation. Also, programming the detector range is further complicated when using the Fluorcol column due to the dependence of retention time on sample concentrations.

The high concentration of CFC-12 (90-99% [v]) in the first evacuation complicates the quantitation of the CFC-12 for two reasons, the calibration curve tends to be nonlinear over the entire concentration range and 99.9% (v) CFC-12 is necessary for the high point on the calibration curve. Accuracy of the CFC-12 quantitation may be improved by dilution of the sample. Sample dilution will introduce errors caused by sample handling and may be difficult, but not impossible, to do with on-line analysis. Alternately, the CFC-12 injected on the column could be reduced by using small sample loops (0.1 mL), but this would increase the difficulty of detecting the EO if both compounds were analyzed on the same analytical column.

The presence of other components in the vent gas creates two problems. First, components eluting near the EO peak may create confusion in correctly identifying and quantitating the EO peak. Second, components which elute after the EO and CFC-12 extend the analysis time and decrease the number of on-line samples that can be collected and analyzed during an evacuation. Although these compounds are present at low concentrations, they create analytical difficulties because of the low EO concentrations (ppmv) which must be measured.

Problems Due to the Analytical Column--

With the current analytical column the retention times of EO and CFC-12 shift with concentration. Increases in EO concentration decreases EO retention time. Interaction of EO with the column coating and packing seems to be minimal and totally dependent upon EO concentration at the temperature

tested (100°C). A column temperature higher than the optimum phase temperature was necessary to maximimize the number of samples obtained during each evacuation; however, the increased sample throughput at the higher temperature compromised the efficiency of the column. The magnitude of the EO retention time shifts may be reduced by operating at lower column temperatures but the required analysis time would increase and the number of samples analyzed during an evacuation would decrease.

The CFC-12 retention time shift with increasing concentrations occurs at concentrations above 12 percent. Thus, the CFC-12 retention time shift is only a problem during the first two evacuations. The use of small loops (0.1 mL) or the dilution of the samples should eliminate this problem.

The time required for complete analysis of a vent sample limits the number of samples that can be analyzed. Over 3 min are needed to elute the major components of the vent gas. This limits the number of samples which can be analyzed during an evacuation to three. A minimum of six samples per evacuations is recommended.

Recommended Method Modifications

First, the field test data indicate that a minimum of six samples should be acquired from the scrubber outlet during each evacuation, two samples during the first 2 min, two samples between 2 and 9 min, and 2 samples after 10 min. This could best be accomplished off-line by taking grab samples in syringes or small gas sampling bags or cans and analyzing them later. However, this technique requires sample containers of the appropriate material of construction and proper storage procedures.

Second, the acquistion of off-line grab samples, allows the analysis to be performed under optimal conditions. That is, the column can be operated at lower temperatures, reducing the magnitude of the retention time shifts.

Third, the CFC-12 and EO should each be analyzed on a separate analytical system to optimize linearity. The CFC-12 should be analyzed on a system with a small gas sample loop (0.1 mL) and the EO on a system with a large loop (2 mL).

Conclusions

The sampling/analytical method adequately determined EO mass flow rate into and emissions out of the control unit; however, shifting EO retention

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times caused difficulty in measuring EO concentrations in the scrubber outlet emissions. Scrubber EO emissions based on orifice plate data gave similar efficiencies as efficiencies calculated from scrubber EO emissions estimated from chamber temperatures and pressures. The test data indicate that sampling at the control unit inlet and measuring control unit outlet flow rates with orifice plates, may not be necessary to obtain reasonable estimates of control unit efficiencies. Analytical bias of the method at the control unit outlet may be decreased by quantitating EO and CFC-12 on separate columns. Error in interpolation of the flow/concentration profile may be decreased by taking a minimum of six samples during each evacuation. Off-line sampling may improve both the quantitative ability of the analytical method and reduce the error in EO mass flow rate by optimizing analytical conditions and maximizing the number of samples that can be acquired. Also, the sampling/analytical method measured efficiencies precisely, and the efficiencies calculated were independent of the calculational procedure used, and the presence of product in the chamber.

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FINAL REPORT

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FINAL REPORT

ANALYTICAL METHOD EVALUATION FOR MEASURING ETHYLENE OXIDE EMISSIONS FROM COMMERCIAL DILUTE-ACID HYDROLYTIC CONTROL UNITS

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DISCLAIMER

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ABSTRACT

The Source Branch of the Environmental Protection Agency's (EPA) Environmental Monitoring Systems Laboratory (EMSL) at Research Triangle Park, North Carolina, has a program to develop stationary source test methods of known precision and accuracy for determining compliance with EPA standards. While participating in this program, Radian Corporation performed a field evaluation of a method for sampling and analyzing ethylene oxide (EO) in the vent stream from a dilute acid scrubber of a commercial sterilizer. The purposes of the test were to evaluate the ability of the analytical method to quantitate EO in scrubber emissions, to determine EO stability in sample containers, and to measure the EO concentration profile and EO-to-oxygen and EO-to-dichlorodifluoromethane (CFC-12) ratios during the initial sterilizer evacuation.

The test method acquired three-second grab samples that were analyzed by gas chromatography with flame ionization detection. Samples were acquired at one-minute, three-minute, four-minute or six-minute intervals. All samples were analyzed in the field and a portion of the samples were reanalyzed in the laboratory.

The analytical method was evaluated on three 1/8-inch (3 millimeter) OD stainless steel columns packed with a liquid phase coated on 60/80 mesh Carbopack B. The 5% Fluorcol column was 10 feet (3 meters) long; the 3% SP-1000 column was 8 feet long (2.4 m); and the 1% SP-1000 column was 6 feet (1.8 m) long. Evaluations based on column efficiency, resolution, linearity, retention time stability, and limits of detection and quantitation showed that a 5% Fluorocol column at 65°C was best for measuring percent level EO and CFC-12 concentrations and a 1% SP-1000 column at 45°C was best for measuring part-per-million EO levels. Under these conditions, baseline resolution of EO from CFC-12 was obtained. The 1% SP-1000 column showed good

retention time stability and can be used for both scrubber inlet and outlet monitoring.

Sample stability was evaluated in one-liter Tedlar bags, five-milliliter gas-tight syringes, and Vacu-Samplers. Results indicated that grab samples in gas-tight syringes should be analyzed within several hours, samples in bags within 48 hours and samples in Vacu-Samplers within four days of collection. Samples were not stable long in 1-L bags because of the high surface-to-volume ratio.

The EO concentration profile was measured by taking samples at one-minute intervals during Test 1 Evacuation 1. This test used 12 wt% EO and 88 wt% CFC-12 as the sterilizing gas. The EO concentration ranged from 400 ppmv to 1,500 ppmv and plateaued between 13 and 20 minutes after beginning evacuation. For 12/88 exhausts, EO concentrations decreased to 80 ppmv during Evacuation 6. During Test 3 Evacuation 1, using 100% EO, the EO concentration ranged from 500 ppmv to 3,000 ppmv. For 100% EO exhausts, EO concentrations decreased to 300 ppmv during the post-sterilization cycle. Exhaust EO concentrations decreased between 20 and 70% between Evacuations 1 and 2 and between 55 and 85% between Evacuations 1 and 3. The EO concentration decreased most rapidly in the 100% EO exhaust.

This report contains conclusions and recommendations based on the field test results, a description of the field test site, the grab sampling and analytical method used, results of the field evaluation, test data, and references used to prepare this report.

This report was submitted in partial fulfillment of EPA Contract No. 68-02-4119 by Radian Corporation under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period from March to August of 1988.

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SECTION 1

INTRODUCTION

The Source Branch of the Environmental Protection Agency's (EPA) Environmental Monitoring Systems Laboratory (EMSL) at Research Triangle Park, North Carolina, has a program to develop stationary source test methods of known precision and accuracy for use in determining compliance with EPA standards. While participating in this program, Radian Corporation performed two field evaluations of methods for sampling and analyzing ethylene oxide (EO) in the vent stream from a dilute acid scrubber of a commercial sterilizer. The first test was reported earlier.[1] The second test is reported here. The purpose of the second test was to evaluate the ability of the analytical method for quantitating EO in the scrubber emissions. A second purpose was to determine the stability of the EO in the sample containers, and a third purpose was to measure the EO concentration profile and EO-to-oxygen and EO-to-dichlorodifluoromethane (CFC-12) ratios during the initial sterilizer evacuation.

Because EPA has listed EO as a possible hazardous air pollutant, a standardized analytical method is needed to measure EO levels in a vent stream and for determining control equipment performance. In the first field test, reported earlier,[1] the efficiency of the scrubber was measured by taking samples at the scrubber inlet and outlet. The samples were pumped through heated Teflon® lines directly into gas sampling valves of a gas chromatograph. Scrubber outlet gas flow rates were measured using two orifice plates installed in parallel stack extensions. This first test showed that the technology to measure the vent gas flow rate and acquire samples existed but that additional testing of the analytical method was needed.

For the second test, two recommended changes in the analytical method were made:

- off line analysis was used, and
- the analytical column (5% Fluorcol on Carbopack B) temperature was lowered.

Also, two other analytical columns, 1% and 3% SP-1000 on Carbopack B, were evaluated. Evaluation of the 1% SP-1000 column was proposed in the test plan because this column successfully analyzed samples taken from hospital sterilizers, aerators and drains.[2] The 3% SP-1000 column was evaluated to determine if a higher percentage of liquid phase would improve the column performance.

To evaluate the columns, grab samples were taken in either one-liter Tedlar bags, five-milliliter gas-tight syringes or Vacu-Samplers, and analyzed by gas chromatography with flame ionization detection (GC/FID). The grab samples were also used to determine the stability of the vent gas in the sample containers by analyzing the samples in the field and reanalyzing them in the Radian Perimeter Park (PPK) Laboratory. Also, during the first test, the EO concentration profile and EO-to-oxygen and EO-to-CFC-12 ratios were measured during the initial chamber evacuation. The EO concentration profile and ratios may provide useful information in developing a regulation based on maximum EO concentration emitted normalized to a fixed percent oxygen or CFC-12.

Grab sampling with off-line gas chromatographic analysis was used because this technology provided a large number of samples for evaluating the analytical method and for determining the EO concentration profile of the exhaust stream. The analytical method was tested at the outlet of the control unit, where the vent gas EO concentrations were in the parts per million by volume range and the vent gas was at ambient temperatures.

The purposes of the field evaluation were:

- To evaluate the analytical method using field samples from an operating commercial sterilizer with a dilute acid scrubber;
- To evaluate the stability of the EO in the sample containers as a function of storage time; and
- To determine the EO concentration profile and the EO-to-oxygen and EO-to-CFC-12 ratios during the initial sterilizer evacuation.

Section 2 reports the conclusions and recommendations based on the test results. Section 3 describes the properties of EO and provides a basic description of the sterilization process, the sterilization industry, and previously used sampling and analytical methods for EO in scrubber emissions. Section 4 describes the test site and the sampling and analytical methods used. Section 5 contains the test results. Section 6 lists references. The Appendices contain a detailed description of the method, a description of the Vacu-Samplers, and the test data.

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The following conclusions were based on the field test results and the laboratory reanalysis of the samples and are applicable to three distinct categories: the analytical column, the sampling container, and the determination of the EO concentration profile.

Analytical Column

All of the tested columns were 1/8-inch (3 millimeter) stainless steel columns packed with a liquid phase coated on 60/80 mesh Carbopack B. The 5% Fluorcol column was 10 feet (3 meters) long; the 3% SP-1000 column was 8 feet long (2.4 m); and the 1% SP-1000 column was 6 feet (1.8 m) long.

Linearity--

Based on a one milliliter injection volume, the FID response using these three columns was linear between 31.25 and 100 vol% for CFC-12. Below 31.25 vol% CFC-12 linearity was not evaluated. Using a one-milliliter injection volume, the FID response when using the 3% SP-1000 column had the largest linear range (0.5 to 100 vol% and 2.281 to 1,254 ppmv) for EO at the percent level and at the part-per-million level. At the part-per-thousand level, the FID response when using the 1% SP-1000 column had the largest linear range (22.81 to 5,016 ppmv) for EO. Therefore, the FID response when using the 1% SP-1000 column provides the best linear range for determining the maximum EO concentration emitted from a dilute-acid hydrolytic control unit.

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Efficiency--

Of the three columns evaluated, the 5% Fluorcol column operated at 65°C provided the best efficiency for analyzing percent levels of EO. For part-per-million levels of EO the 1% SP-1000 column was the most efficient. At part-per-thousand levels of EO the 5% Fluorcol and the 1% SP-1000 columns were comparable. The 3% SP-1000 column was clearly the least efficient column at all tested temperatures and concentrations. Therefore, the Fluorcol column provides the best efficiency for percent level EO analyses and the 1% SP-1000 column provides the best efficiency for part-per-million level EO analyses.

Resolution--

The 1% SP-1000 and the 5% Fluorcol columns provided comparable resolution of the EO from the CFC-12 at the percent and parts-per-thousand levels. At column temperatures of 45 and 55°C baseline resolution of EO from CFC-12 was obtained on both columns. Both of these columns provided significantly better resolution of the two compounds than did the 3% SP-1000 column. Therefore, the 3% SP-1000 column is not recommended for analyzing samples of 12/88 gas. Resolution was not evaluated at the parts-per-million level.

Retention Time Stability--

The EO retention times were most stable on the 1% SP-1000 column where they varied from 1.38 to 1.46 minutes (± 6%) at 55°C and were least stable on the 5% Fluorcol column where they varied from 2.21 to 5.43 minutes (± 150%) at 55°C. In general the EO retention times varied least at column temperatures of 65°C. The CFC-12 retention times were most stable on the 3% SP-1000 column where they varied from 1.46 to 1.56 minutes (± 7%) at 65°C and were least stable on the 5% Fluorcol column where they varied from 4.72 to 5.57 minutes (± 18%) at 45°C. Therefore, the Fluorcol column should be used only to analyze for EO at the percent levels in situations where the concentration is not expected to change by more than two orders of magnitude.

Limits of Detection and Quantitation--

The 3% SP-1000 column provided the lowest detection and quantitation limits; therefore, it would be the best column for low-level and trace analyses. The limits of detection and quantitation were comparable for the 1% SP-1000 and 5% Fluorcol columns; therefore, the performance of these two columns may not be distinguished by these criteria.

Sample Container

Evaluations were made of the stability of EO in samples collected in one-liter Tedlar bags, five-milliliter gas-tight syringes, and Vacu-Samplers. After four days in an unpunctured Vacu-Sampler, the EO concentrations in four out of seven duplicate samples (57%) were within ± 8% of the EO concentrations in the original samples. The seven duplicate samples in the unpunctured Vacu-Samplers lost an average of 15% of the EO. Therefore, EO samples in unpunctured Vacu-Samplers remained stable for up to four days, with stability defined as over 50% of the samples being within ± 10% of the original concentrations and the average of all EO concentration changes being less than ± 15 percent.

After four or five days in gas-tight syringes, the EO concentrations in only two out of 12 duplicate samples (17%) were within ± 9% of the EO concentrations in the original samples. The twelve duplicate syringe samples lost an average of 20% of the EO. Therefore, EO samples are not stable in syringes for four or five days.

In leak-free bags the EO in 12/88 exhaust at EO concentrations above 1,000 ppmv varied by an averaged relative difference of + 9% after 48 hours. After five to six days the bags with concentrations of EO greater than 1,000 ppmv showed an average EO loss of 22 percent. In the same time period, bags with concentrations of EO less than 500 ppmv showed an average EO loss of 36 percent. After 17 to 18 days the bags with EO concentrations greater than 1,000 ppmv showed an average EO loss of 41 percent. Therefore, samples of 12/88 exhaust containing EO at concentrations above 1,000 ppmv are stable in Tedlar bags for up to 48 hours.

Leak-free bags containing 100% EO exhaust at EO concentrations above 1,000 ppmv varied by an averaged relative difference of + 3% after four days. After eight days these bags averaged a 20% loss and after twelve days an average of 33% of the EO was lost. In leak-free bags of 100% EO exhaust at concentrations below 500 ppmv an average of approximately 20% of the EO was lost after four days. No additional loss was observed in these bags between Day 4 and Day 12. Therefore, samples of 100% EO exhaust containing EO at concentrations above 1,000 ppmv are stable in Tedlar bags for at least four days.

Since the EO loss in the bags is concentration dependent and more EO is lost at lower concentrations, the EO loss is expected to be caused by adsorption of the EO onto the bag walls. The short sample stability observed in the 1-L bags results from the high surface-to-volume ratio.

Ethylene Oxide Concentration Profile

During the first evacuation of the first test using 12/88 gas, the EO concentration ranged from 400 ppmv to 1,500 ppmv and reached a maximum plateau between 13 and 20 minutes. Concentrations of EO during 12/88 exhausts were approximately 1,200 ppmv during the second evacuation, 600 ppmv during the third evacuation, 300 ppmv during the fourth evacuation, 100 ppmv during the fifth evacuation, and 80 ppmv during the sixth evacuation. During the first evacuation of the third test using 100% EO, the EO concentration ranged from 500 ppmv to 3,000 ppmv. Concentrations of EO during 100% EO exhausts were approximately 600 ppmv during the second exhaust, and 300 ppmv during the third exhaust. Therefore, to measure the maximum EO concentration emitted from a dilute acid hydrolytic scrubber, samples should be acquired between 13 and 20 minutes after the start of the first chamber evacuation when 12/88 is used.

Ratios of the EO-to-CFC-12 concentration were calculated in 12/88 exhaust and a plot of the ratios versus time was similar to a plot of EO concentration versus time due to the high and relatively constant CFC-12 concentration. Oxygen concentrations in the 12/88 exhaust were monitored using Fyrite and

indicated that after five minutes the exhaust contained minimal air. Therefore, EO-to-CFC-12 ratios could be established for determining the maximum EO concentration emitted from chambers using 12/88. The EO-to-CFC-12 ratios would only be useful during the first evacuation when the expected CFC-12 concentration is 99.9 percent.

RECOMMENDATIONS

Based on the test results, Radian makes the following seven recommendations. First, a 5% Fluorocol column at 65°C is recommended for measuring percent level EO and CFC-12 concentrations, levels expected at the scrubber inlet or in the exhaust of uncontrolled sterilizers. The FID response when using a 5% Fluorcol column is linear, as indicated by a F-test for linearity, from 0.5 to 50 vol% EO. The 5% Fluorcol column is the most efficient column tested for percent levels of EO, and provides baseline resolution of the CFC-12 and EO at column temperatures of 45 and 55°C and near baseline resolution at 65°C. Also, the retention time instability on the Fluorcol column is less pronounced at percent concentrations.

Second, a 1% SP-1000 column at 45°C is recommended for measuring part-per-million levels of EO, levels expected at the scrubber outlet. The FID response when using the 1% SP-1000 column is linear, as indicated from a F-test for linearity, from 22.81 to 5,016 ppmv EO. The 1% SP-1000 column is the most efficient column tested for parts-per-million levels of EO, and provides baseline resolution of the CFC-12 and EO at 45°C.

Third, it is recommended that a 3% SP-1000 column at 45°C be investigated for quantitating sub-part-per-million levels of EO, levels expected in ambient air at sterilization facilities. The 3% SP-1000 column provided limits of detection and quantitation almost three times lower than the other two tested columns.

Fourth, it is recommended that grab samples collected in gas-tight syringes be analyzed within several hours of collection, samples collected in bags within 48 hours of collection and samples collected in Vacu-Samplers

within four days of collection. Syringe samples lost an average of 20% of the EO after four days. In leak-free bags, EO remained stable for at least 48 hours and may be stable for up to four days. After five or six days bag samples lost an average of one-third of the EO. In unpunctured Vacu-Samplers, 57% of the samples were within ± 8% of the expected concentration after four days and the average EO loss for all samples was 15 percent.

Fifth, sampling at least three times between 13 and 20 minutes after the first indication of flow through the stack is recommended for determining maximum EO concentration emitted from a dilute acid hydrolytic scrubber during the first evacuation. The EO concentration in the exhaust increased linearly between five and 13 minutes, plateaued between 13 and 20 minutes, and dropped off after 20 minutes. This time frame corresponds to chamber pressures between 16 and 10 pounds per square inch actual and may need to be adjusted when using a different sterilization program.

Sixth, if the second and following evacuations are monitored, sampling between five and 10 minutes during these evacuations is recommended. During the first five minutes, the gas coming out of the stack is a mixture of gas from the chamber and residual gas from the scrubber so samples taken during this time may be biased high or low.

Seventh, for determining EO-to-CFC-12 ratios during the first evacuation, a 0.1 mL sample volume is recommended for CFC-12 quantitation. A 1 mL sample of percent levels of CFC-12 overloads the analytical column, decreasing the column performance.

SECTION 3

BACKGROUND

PROPERTIES OF ETHYLENE OXIDE

The chemical and physical properties of EO are discussed in References 3, 4 and 5. Only a brief summary is included here. Ethylene oxide, an epoxide, is also called oxirane (the International Union of Pure and Applied Chemistry name).[3] Other synonyms include: dihydrooxirene, dimethylene oxide, 1,2-epoxylethane, oxacyclopropane, oxane, oxidoethane, and α, β-oxidoethane.[3]

It is usually handled as a liquid under pressure. At room temperature and pressure, EO is a gas that has a pungent, irritating, ether-like odor.[3] At 10 degrees Celsius (^{o}C) [50 degrees Fahrenheit (^{o}F)] it condenses to a colorless liquid.[3,4,5] It is completely miscible with water and with organic solvents.[3,4] Ethylene oxide penetrates cardboard, shrink-wrap, paperboard, and product wrappings such as cellophane. Also, EO adsorbs on surfaces and will polymerize or isomerize during storage.

The reactive and volatile properties of EO make it highly flammable and potentially explosive.[3,4] It has a flash point of <-18°C (0.4^{o}F) and is flammable in air at concentrations ranging from 3 to 100 volume percent (vol%).[3,4] It is currently regulated by the Occupational Safety and Health Administration (OSHA) for occupational exposure of 1 part per million (ppm) over 8 hours (hr).[6] EO is a known reproductive hazard[4,7] and a suspected carcinogen.[7] These last considerations, coupled with the fact that there is no upper explosive limit, require that special safety precautions be taken when handling and storing EO.

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GENERAL DESCRIPTION OF THE BULK STERILIZATION PROCESS

Detailed descriptions of the sterilization process are contained in References 3 and 8. The bulk sterilization process, used by the majority of the commercial sterilization industry, is described here in general terms. Hospital and medical products to be sterilized are preconditioned with steam in a separate chamber prior to sterilization. An air-tight sterilization chamber is loaded with the preconditioned products. Air inside the chamber is evacuated using steam ejectors to decrease the chamber pressure. If 100 wt% EO is used, the chamber may be purged several times with nitrogen.

Once the desired vacuum level is achieved, the air inside the chamber is humidified to a predetermined value by adding steam. The sterilant is pressurized into the chamber to a predetermined level. The chamber is held at a constant pressure for a specified period, while the products are sterilized by EO. When sterilization is complete, the sterilizer gas mixture is exhausted from the chamber until the chamber pressure is decreased to a predetermined level. Filtered air is introduced into the chamber to flush the sterilant gases from the chamber and product. If 100 wt% EO is used, the chamber is flushed with nitrogen prior to introducing the filtered air. These air washes may be repeated several times. After the last air wash, the door is opened and the chamber unloaded.

The gas in an EO sterilization chamber does not vent at a constant rate for two reasons. First the initial maximum venting rate is determined by the size of the chamber vacuum pump. As the chamber empties, the vacuum is increased, less and less volume of gas is available for removal, and the vent gas flow rate decreases. Second, the evacuation of the chamber is controlled by a solenoid valve that opens and closes at regular intervals to prevent the chamber from evacuating too rapidly and damaging the products. This changing and pulsing flow rate makes measuring the EO mass flow rate in the gas stream more difficult. First, calculating the total flow through the vent is an integration rather than a multiplication process and requires continuous monitoring of the flow. Second, calculating the total emissions requires taking many grab samples over the sampling period or collecting a representative sample using special techniques.

There are two models for the EO concentration profile in the chamber exhaust. In one model the chamber is considered to be a closed system at equilibrium. For this model, the EO concentration in the exhaust gas remains constant and only the vent stream flow rate varies. In the other model, the chamber is considered to be a dynamic system. For this model, both the EO concentration and flow rate of the exhaust gas change with time.

If the sterilization chamber does not contain product, the exhaust stream will be characterized best by the first (static) model because equilibrium will occur quickly between evacuations. However, other than for measuring scrubber efficiency and developing sampling and analytical methods, most chambers are operated with product. Any product present in the chamber will offgas, releasing EO during chamber evacuations and air washes. With a product-containing chamber, the exhaust stream will be characterized best by the second (dynamic) model. From this second, more realistic model, performance factors may be developed and used to study the whole system.

HOSPITAL SUPPLY STERILIZATION INDUSTRY

Throughout the United States and Puerto Rico approximately two hundred facilities use EO for sterilizing heat- or moisture-sensitive products or for fumigating microorganisms and insects.[8,9] Chambers range in volume from less than 2 cubic meters (m^3) [60 cubic feet (ft^3)] to 170 m^3 (6000 ft^3).[9] Most of the chambers in the industry (76%) are charged with a mixture of 12 weight percent (wt%) EO and 88 wt% of dichlorodifluoromethane (CFC-12).[9] The 12/88 gas mixture is used because it is nonflammable. Pure EO is used in 68% of the chambers and mixtures of carbon dioxide and EO are used in 10 percent.[9] Carbon dioxide mixtures are used because the carbon dioxide increases the effectiveness of the EO and prevents it from being flammable. (Some chambers are used with more than one type of sterilant gas.) Some of the 12/88 gas users are converting to 100 wt% EO in anticipation of CFC-12 emission regulations.

The vent streams from 17% of the EO sterilization facilities have some type of control unit, ranging from a neutral-water scrubber to an incinerator.[9] Forty-four percent of the control units chemically hydrolize

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the EO to ethylene glycol using dilute acid solutions, 3% use catalytic oxidation to convert the EO to carbon dioxide and water, and 19% of the control units are condensation/reclamation systems.[9] Commercial vendors of EO control units include Chemrox Incorporated, Damas Corporation, Donaldson Company (purchasers of Mine Safety Appliances' EO control division), and Croll Reynolds. A segment of the industry (approximately five to 15%) has custom-designed control units. Control units have been tested by the manufacturers and the industry. Ethylene oxide removal efficiencies greater than 99% have been measured.[1,10,11,12,13] Condensation/reclamation and catalytic oxidation systems have lower EO removal efficiencies than the dilute-acid hydrolytic systems.

ETHYLENE OXIDE EMISSION MEASUREMENTS

Several methods are currently being used in the EO sterilization industry to measure the emissions from EO control units.[10,11,12,13] In general, the emissions from an EO control unit are determined on a weight basis over the entire post-sterilization cycle. The post-sterilization cycle includes the initial chamber evacuation and all subsequent air washes. The control units tested and reported include:

- A Chemrox unit in Pennsylvania tested by the manufacturer under contract to the user,[10]
- A Chemrox unit in New York tested by the manufacturer,[11]
- A Damas unit,[12] and
- An MSA unit (now manufactured by Donaldson Company).[13]

The Chemrox unit in Pennsylvania was tested by taking grab samples of the vent gas in Vacu-Samplers every five minutes. The samples were analyzed in the laboratory using standard EO methods. The amount of EO emitted from the control unit was calculated from the concentration of EO in the outlet grab samples, the exhaust temperature, and outlet flow rate of the vent gas. The volumetric gas flow rate was calculated using chamber temperature and pressure data and assuming all components other that EO pass through the scrubber unaffected.

The Chemrox unit in New York was tested using direct semi-continuous sampling at the outlet of the control unit. Samples were directed through heat-traced lines into the gas sampling valve of a gas chromatograph (GC) at one-minute intervals. The weights of EO at the outlet of the control unit were calculated from the concentration of EO measured by the GC and the measured temperature and flow rate of the vent gas.

The Damas unit was tested by taking outlet samples collected on charcoal tubes. A series of outlet samples were collected at a constant sampling rate over five-minute intervals during the entire post-evacuation cycle. The charcoal tubes were desorbed using carbon disulfide and the extracts were analyzed by GC. The weights of EO at the outlet of the control unit were calculated from the measured EO concentrations, vent gas temperature, and vent gas flow rate during each sampling period.

The MSA unit was tested using 10-milliliter (mL) syringes to collect outlet samples at one-minute intervals. Stream flow rates and temperatures were recorded at the time of sample collection. The entire sample in the syringe was injected directly onto a GC column for analysis. The amounts of EO at the outlet of the control system were calculated from the measured EO concentrations and stream flow rates.

SECTION 4

SAMPLING AND ANALYTICAL PROCEDURES

FACILITY DESCRIPTION

The field evaluation was conducted at Burron Medical, a medical supply sterilization facility, located in Allentown, Pennsylvania. The facility has three 1000-ft^3 (28-m^3) sterilizers: one uses a 12/88 (wt%/wt%) EO and CFC-12 gas mixture and two use 100% EO. A 12/88 sterilization cycle typically uses 38 gallons (140 L) of 12/88 gas mixture. On a weight basis, a 12/88 sterilization charge consumes 368 lbs (167 Kg) of gas, of which approximately 44 lbs (20 Kg) are EO. A 100% EO charge typically uses 44 lbs (20 Kg) of gas.

The exhaust from the sterilizers is controlled by a DEOXX™ system. The DEOXX system is a dilute acid scrubber manufactured by Chemrox, which hydrolyzes the EO to ethylene glycol. At the time of the test the scrubber contained dilute sulfuric acid and approximately 10 wt% of ethylene glycol. The control system has reported control efficiencies of 99.99%, based on tests conducted at the facility in April 1986 by the vendor,[10] and 99.94%, based on tests performed in October 1987 by Radian.[1]

Each chamber is equipped with a total recirculating oil-sealed pump. The pumps are equipped with gas/liquid separators that emit the gas to the DEOXX system and recirculate the liquid to the pump inlet. The sterilization cycle is automatically controlled by a programmable microprocessor system. The microprocessor system has the capability to control and record the parameters of the sterilization cycle including chamber temperature, chamber pressure, and elapsed time from the start of the cycle. Because the scrubber is designed to handle the exhaust from two sterilizers venting simultaneously,

the tested sterilization cycles were scheduled so that only one sterilizer vented at a time.

Two different sterilization programs plotted in Figures 1 and 2 were used for testing, one for the 12/88 tests (Figure 1) and one for the 100% EO test (Figure 2). Before the start of the tests using 12/88 gas, the chamber was evacuated to 2 pounds per square inch absolute (psia) and then pressurized to 3.1 psia with steam. The steam pressure was maintained for 15 minutes at 3.1 psia and the time period was called a "humidity dwell." At the completion of the humidity dwell the chamber was charged to 23.7 psia with 12/88 gas. The exposure at 23.7 psia was maintained for 15 minutes. The program contained six post-sterilization evacuations, the initial chamber evacuation and pump down and five air in-bleeds and subsequent evacuations, followed by a final air in-bleed. The chamber was evacuated to 2 psia and pressurized with air to 10 psia during each evacuation and air in-bleed cycle. For the sixth air in-bleed the chamber pressure was returned to atmospheric.

Before the start of the test using 100% EO, the chamber was evacuated to 1.5 psia, pressurized to 13 psia with nitrogen, and re-evacuated to 1.5 psia. Then the chamber was pressurized to 2.6 psia with steam. The humidity dwell lasted for 30 minutes. Then the chamber was first pressurized to 6.7 psia with nitrogen, followed by pressurization to 12.1 psia with EO, and capped by pressurizing to 13 psia with nitrogen. The sterilization dwell was maintained for 125 minutes. The program contained five post-sterilization evacuations: the initial chamber pump down, a nitrogen purge and pump down, and three air in-bleeds and subsequent pump downs, followed by a final air in-bleed. For the nitrogen purge the chamber was evacuated to 1.5 psia and pressurized to 13 psia with nitrogen. For the air washes the chamber was evacuated to 1.5 psia and pressurized to 10 psia. For the fourth air in-bleed the chamber pressure was returned to atmospheric.

Three tests were performed, one with product in the chamber using 100% EO and two without product using 12/88 gas. Data from all of these tests were reduced and used to prepare this report. Table 1 summarizes the three tests that were used.

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DISCLAIMER

The information in this document has been funded wholly or in part by the United States Environmental Protection Agency under contract number 68-02-4119 to Radian Corporation. It has been subject to the Agency's peer and administrative review, and has been approved for publication as an EPA document.

Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

ABSTRACT

The Source Branch of the Environmental Protection Agency's (EPA) Environmental Monitoring Systems Laboratory (EMSL) at Research Triangle Park, North Carolina, has a program to develop stationary source test methods of known precision and accuracy for determining compliance with EPA standards. While participating in this program, Radian Corporation performed a field evaluation of a method for sampling and analyzing ethylene oxide (EO) in the vent stream from a dilute acid scrubber of a commercial sterilizer. The purposes of the test were to evaluate the ability of the analytical method to quantitate EO in scrubber emissions, to determine EO stability in sample containers, and to measure the EO concentration profile and EO-to-oxygen and EO-to-dichlorodifluoromethane (CFC-12) ratios during the initial sterilizer evacuation.

The test method acquired three-second grab samples that were analyzed by gas chromatography with flame ionization detection. Samples were acquired at one-minute, three-minute, four-minute or six-minute intervals. All samples were analyzed in the field and a portion of the samples were reanalyzed in the laboratory.

The analytical method was evaluated on three 1/8-inch (3 millimeter) OD stainless steel columns packed with a liquid phase coated on 60/80 mesh Carbopack B. The 5% Fluorcol column was 10 feet (3 meters) long; the 3% SP-1000 column was 8 feet long (2.4 m); and the 1% SP-1000 column was 6 feet (1.8 m) long. Evaluations based on column efficiency, resolution, linearity, retention time stability, and limits of detection and quantitation showed that a 5% Fluorocol column at 65°C was best for measuring percent level EO and CFC-12 concentrations and a 1% SP-1000 column at 45°C was best for measuring part-per-million EO levels. Under these conditions, baseline resolution of EO from CFC-12 was obtained. The 1% SP-1000 column showed good

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retention time stability and can be used for both scrubber inlet and outlet monitoring.

Sample stability was evaluated in one-liter Tedlar bags, five-milliliter gas-tight syringes, and Vacu-Samplers. Results indicated that grab samples in gas-tight syringes should be analyzed within several hours, samples in bags within 48 hours and samples in Vacu-Samplers within four days of collection.

The EO concentration profile was measured by taking samples at one-minute intervals during Test 1 Evacuation 1. This test used 12 wt% EO and 88 wt% CFC-12 as the sterilizing gas. The EO concentration ranged from 400 ppmv to 1,500 ppmv and plateaued between 13 and 20 minutes after beginning evacuation. For 12/88 exhausts, EO concentrations decreased to 80 ppmv during Evacuation 6. During Test 3 Evacuation 1, using 100% EO, the EO concentration ranged from 500 ppmv to 3,000 ppmv. For 100% EO exhausts, EO concentrations decreased to 300 ppmv during the post-sterilization cycle. Exhaust EO concentrations decreased between 20 and 70% between Evacuations 1 and 2 and between 55 and 85% between Evacuations 1 and 3. The EO concentration decreased most rapidly in the 100% EO exhaust.

This report contains conclusions and recommendations based on the field test results, a description of the field test site, the grab sampling and analytical method used, results of the field evaluation, test data, and references used to prepare this report.

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SECTION 1

INTRODUCTION

The Source Branch of the Environmental Protection Agency's (EPA) Environmental Monitoring Systems Laboratory (EMSL) at Research Triangle Park, North Carolina, has a program to develop stationary source test methods of known precision and accuracy for use in determining compliance with EPA standards. While participating in this program, Radian Corporation performed two field evaluations of methods for sampling and analyzing ethylene oxide (EO) in the vent stream from a dilute acid scrubber of a commercial sterilizer. The first test was reported earlier.[1] The second test is reported here. The purpose of the second test was to evaluate the ability of the analytical method for quantitating EO in the scrubber emissions. A second purpose was to determine the stability of the EO in the sample containers, and a third purpose was to measure the EO concentration profile and EO-to-oxygen and EO-to-dichlorodifluoromethane (CFC-12) ratios during the initial sterilizer evacuation.

Because EPA has listed EO as a possible hazardous air pollutant, a standardized analytical method is needed to measure EO levels in a vent stream and for determining control equipment performance. In the first field test, reported earlier,[1] the efficiency of the scrubber was measured by taking samples at the scrubber inlet and outlet. The samples were pumped through heated Teflon® lines directly into gas sampling valves of a gas chromatograph. Scrubber outlet gas flow rates were measured using two orifice plates installed in parallel stack extensions. This first test showed that the technology to measure the vent gas flow rate and acquire samples existed but that additional testing of the analytical method was needed.

For the second test, two recommended changes in the analytical method were made:

- off line analysis was used, and
- the analytical column (5% Fluorcol on Carbopack B) temperature was lowered.

Also, two other analytical columns, 1% and 3% SP-1000 on Carbopack B, were evaluated. Evaluation of the 1% SP-1000 column was proposed in the test plan because this column successfully analyzed samples taken from hospital sterilizers, aerators and drains.[2] The 3% SP-1000 column was evaluated to determine if a higher percentage of liquid phase would improve the column performance.

To evaluate the columns, grab samples were taken in either one-liter Tedlar bags, five-milliliter gas-tight syringes or Vacu-Samplers, and analyzed by gas chromatography with flame ionization detection (GC/FID). The grab samples were also used to determine the stability of the vent gas in the sample containers by analyzing the samples in the field and reanalyzing them in the Radian Perimeter Park (PPK) Laboratory. Also, during the first test, the EO concentration profile and EO-to-oxygen and EO-to-CFC-12 ratios were measured during the initial chamber evacuation. The EO concentration profile and ratios may provide useful information in developing a regulation based on maximum EO concentration emitted normalized to a fixed percent oxygen or CFC-12.

Grab sampling with off-line gas chromatographic analysis was used because this technology provided a large number of samples for evaluating the analytical method and for determining the EO concentration profile of the exhaust stream. The analytical method was tested at the outlet of the control unit, where the vent gas EO concentrations were in the parts per million by volume range and the vent gas was at ambient temperatures.

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The purposes of the field evaluation were:

- To evaluate the analytical method using field samples from an operating commercial sterilizer with a dilute acid scrubber;
- To evaluate the stability of the EO in the sample containers as a function of storage time; and
- To determine the EO concentration profile and the EO-to-oxygen and EO-to-CFC-12 ratios during the initial sterilizer evacuation.

Section 2 reports the conclusions and recommendations based on the test results. Section 3 describes the properties of EO and provides a basic description of the sterilization process, the sterilization industry, and previously used sampling and analytical methods for EO in scrubber emissions. Section 4 describes the test site and the sampling and analytical methods used. Section 5 contains the test results. Section 6 lists references. The Appendices contain a detailed description of the method, a description of the Vacu-Samplers, and the test data.

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The following conclusions were based on the field test results and the laboratory reanalysis of the samples and are applicable to three distinct categories: the analytical column, the sampling container, and the determination of the EO concentration profile.

Analytical Column

All of the tested columns were 1/8-inch (3 millimeter) stainless steel columns packed with a liquid phase coated on 60/80 mesh Carbopack B. The 5% Fluorcol column was 10 feet (3 meters) long; the 3% SP-1000 column was 8 feet long (2.4 m); and the 1% SP-1000 column was 6 feet (1.8 m) long.

Linearity--

Based on a one milliliter injection volume, the FID response using these three columns was linear between 31.25 and 100 vol% for CFC-12. Below 31.25 vol% CFC-12 linearity was not evaluated. Using a one-milliliter injection volume, the FID response when using the 3% SP-1000 column had the largest linear range (0.5 to 100 vol% and 2.281 to 1,254 ppmv) for EO at the percent level and at the part-per-million level. At the part-per-thousand level, the FID response when using the 1% SP-1000 column had the largest linear range (22.81 to 5,016 ppmv) for EO. Therefore, the FID response when using the 1% SP-1000 column provides the best linear range for determining the maximum EO concentration emitted from a dilute-acid hydrolytic control unit.

Efficiency--

Of the three columns evaluated, the 5% Fluorcol column operated at 65°C provided the best efficiency for analyzing percent levels of EO. For part-per-million levels of EO the 1% SP-1000 column was the most efficient. At part-per-thousand levels of EO the 5% Fluorcol and the 1% SP-1000 columns were comparable. The 3% SP-1000 column was clearly the least efficient column at all tested temperatures and concentrations. Therefore, the Fluorcol column provides the best efficiency for percent level EO analyses and the 1% SP-1000 column provides the best efficiency for part-per-million level EO analyses.

Resolution--

The 1% SP-1000 and the 5% Fluorcol columns provided comparable resolution of the EO from the CFC-12 at the percent and parts-per-thousand levels. At column temperatures of 45 and 55°C baseline resolution of EO from CFC-12 was obtained on both columns. Both of these columns provided significantly better resolution of the two compounds than did the 3% SP-1000 column. Therefore, the 3% SP-1000 column is not recommended for analyzing samples of 12/88 gas. Resolution was not evaluated at the parts-per-million level.

Retention Time Stability--

The EO retention times were most stable on the 1% SP-1000 column where they varied from 1.38 to 1.46 minutes (± 6%) at 55°C and were least stable on the 5% Fluorcol column where they varied from 2.21 to 5.43 minutes (± 150%) at 55°C. In general the EO retention times varied least at column temperatures of 65°C. The CFC-12 retention times were most stable on the 3% SP-1000 column where they varied from 1.46 to 1.56 minutes (± 7%) at 65°C and were least stable on the 5% Fluorcol column where they varied from 4.72 to 5.57 minutes (± 18%) at 45°C. Therefore, the Fluorcol column should be used only to analyze for EO at the percent levels in situations where the concentration is not expected to change by more than two orders of magnitude.

Limits of Detection and Quantitation--

The 3% SP-1000 column provided the lowest detection and quantitation limits; therefore, it would be the best column for low-level and trace analyses. The limits of detection and quantitation were comparable for the 1% SP-1000 and 5% Fluorcol columns; therefore, the performance of these two columns may not be distinguished by these criteria.

Sample Container

Evaluations were made of the stability of EO in samples collected in one-liter Tedlar bags, five-milliliter gas-tight syringes, and Vacu-Samplers. After four days in an unpunctured Vacu-Sampler, the EO concentrations in four out of seven duplicate samples (57%) were within ± 8% of the EO concentrations in the original samples. The seven duplicate samples in the unpunctured Vacu-Samplers lost an average of 15% of the EO. Therefore, EO samples in unpunctured Vacu-Samplers remained stable for up to four days, with stability defined as over 50% of the samples being within ± 10% of the original concentrations and the average of all EO concentration changes being less than ± 15 percent.

After four or five days in gas-tight syringes, the EO concentrations in only two out of 12 duplicate samples (17%) were within ± 9% of the EO concentrations in the original samples. The twelve duplicate syringe samples lost an average of 20% of the EO. Therefore, EO samples are not stable in syringes for four or five days.

In leak-free bags the EO in 12/88 exhaust at EO concentrations above 1,000 ppmv varied by an averaged relative difference of + 9% after 48 hours. After five to six days the bags with concentrations of EO greater than 1,000 ppmv showed an average EO loss of 22 percent. In the same time period, bags with concentrations of EO less than 500 ppmv showed an average EO loss of 36 percent. After 17 to 18 days the bags with EO concentrations greater than 1,000 ppmv showed an average EO loss of 41 percent. Therefore, samples of 12/88 exhaust containing EO at concentrations above 1,000 ppmv are stable in Tedlar bags for up to 48 hours.

Leak-free bags containing 100% EO exhaust at EO concentrations above 1,000 ppmv varied by an averaged relative difference of + 3% after four days. After eight days these bags averaged a 20% loss and after twelve days an average of 33% of the EO was lost. In leak-free bags of 100% EO exhaust at concentrations below 500 ppmv an average of approximately 20% of the EO was lost after four days. No additional loss was observed in these bags between Day 4 and Day 12. Therefore, samples of 100% EO exhaust containing EO at concentrations above 1,000 ppmv are stable in Tedlar bags for at least four days.

Ethylene Oxide Concentration Profile

During the first evacuation of the first test using 12/88 gas, the EO concentration ranged from 400 ppmv to 1,500 ppmv and reached a maximum plateau between 13 and 20 minutes. Concentrations of EO during 12/88 exhausts were approximately 1,200 ppmv during the second evacuation, 600 ppmv during the third evacuation, 300 ppmv during the fourth evacuation, 100 ppmv during the fifth evacuation, and 80 ppmv during the sixth evacuation. During the first evacuation of the third test using 100% EO, the EO concentration ranged from 500 ppmv to 3,000 ppmv. Concentrations of EO during 100% EO exhausts were approximately 600 ppmv during the second exhaust, and 300 ppmv during the third exhaust. Therefore, to measure the maximum EO concentration emitted from a dilute acid hydrolytic scrubber, samples should be acquired between 13 and 20 minutes after the start of the first chamber evacuation when 12/88 is used.

Ratios of the EO-to-CFC-12 concentration were calculated in 12/88 exhaust and a plot of the ratios versus time was similar to a plot of EO concentration versus time due to the high and relatively constant CFC-12 concentration. Oxygen concentrations in the 12/88 exhaust were monitored using Fyrite and indicated that after five minutes the exhaust contained minimal air. Therefore, EO-to-CFC-12 ratios could be established for determining the maximum EO concentration emitted from chambers using 12/88. The EO-to-CFC-12 ratios would only be useful during the first evacuation when the expected CFC-12 concentration is 99.9 percent.

RECOMMENDATIONS

Based on the test results, Radian makes the following seven recommendations. First, a 5% Fluorocol column at 65°C is recommended for measuring percent level EO and CFC-12 concentrations, levels expected at the scrubber inlet or in the exhaust of uncontrolled sterilizers. The FID response when using a 5% Fluorcol column is linear, as indicated by a F-test for linearity, from 0.5 to 50 vol% EO. The 5% Fluorcol column is the most efficient column tested for percent levels of EO, and provides baseline resolution of the CFC-12 and EO at column temperatures of 45 and 55°C and near baseline resolution at 65°C. Also, the retention time instability on the Fluorcol column is less pronounced at percent concentrations.

Second, a 1% SP-1000 column at 45°C is recommended for measuring part-per-million levels of EO, levels expected at the scrubber outlet. The FID response when using the 1% SP-1000 column is linear, as indicated from a F-test for linearity, from 22.81 to 5,016 ppmv EO. The 1% SP-1000 column is the most efficient column tested for parts-per-million levels of EO, and provides baseline resolution of the CFC-12 and EO at 45°C.

Third, it is recommended that a 3% SP-1000 column at 45°C be investigated for quantitating sub-part-per-million levels of EO, levels expected in ambient air at sterilization facilities. The 3% SP-1000 column provided limits of detection and quantitation almost three times lower than the other two tested columns.

Fourth, it is recommended that grab samples collected in gas-tight syringes be analyzed within several hours of collection, samples collected in bags within 48 hours of collection and samples collected in Vacu-Samplers within four days of collection. Syringe samples lost an average of 20% of the EO after four days. In leak-free bags, EO remained stable for at least 48 hours and may be stable for up to four days. After five or six days bag samples lost an average of one-third of the EO. In unpunctured Vacu-Samplers, 57% of the samples were within ± 8% of the expected concentration after four days and the average EO loss for all samples was 15 percent.

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Fifth, sampling at least three times between 13 and 20 minutes after the first indication of flow through the stack is recommended for determining maximum EO concentration emitted from a dilute acid hydrolytic scrubber during the first evacuation. The EO concentration in the exhaust increased linearly between five and 13 minutes, plateaued between 13 and 20 minutes, and dropped off after 20 minutes. This time frame corresponds to chamber pressures between 16 and 10 pounds per square inch actual and may need to be adjusted when using a different sterilization program.

Sixth, if the second and following evacuations are monitored, sampling between five and 10 minutes during these evacuations is recommended. During the first five minutes, the gas coming out of the stack is a mixture of gas from the chamber and residual gas from the scrubber so samples taken during this time may be biased high or low.

Seventh, for determining EO-to-CFC-12 ratios during the first evacuation, a 0.1 mL sample volume is recommended for CFC-12 quantitation. A 1 mL sample of percent levels of CFC-12 overloads the analytical column, decreasing the column performance.

SECTION 3

BACKGROUND

PROPERTIES OF ETHYLENE OXIDE

The chemical and physical properties of EO are discussed in References 3, 4 and 5. Only a brief summary is included here. Ethylene oxide, an epoxide, is also called oxirane (the International Union of Pure and Applied Chemistry name).[3] Other synonyms include: dihydrooxirene, dimethylene oxide, 1,2-epoxylethane, oxacyclopropane, oxane, oxidoethane, and α, β-oxidoethane.[3]

It is usually handled as a liquid under pressure. At room temperature and pressure, EO is a gas that has a pungent, irritating, ether-like odor.[3] At 10 degrees Celsius (^{o}C) [50 degrees Fahrenheit (^{o}F)] it condenses to a colorless liquid.[3,4,5] It is completely miscible with water and with organic solvents.[3,4] Ethylene oxide penetrates cardboard, shrink-wrap, paperboard, and product wrappings such as cellophane. Also, EO adsorbs on surfaces and will polymerize or isomerize during storage.

The reactive and volatile properties of EO make it highly flammable and potentially explosive.[3,4] It has a flash point of <-18°C (0.4^{o}F) and is flammable in air at concentrations ranging from 3 to 100 volume percent (vol%).[3,4] It is currently regulated by the Occupational Safety and Health Administration (OSHA) for occupational exposure of 1 part per million (ppm) over 8 hours (hr).[6] EO is a known reproductive hazard[4,7] and a suspected carcinogen.[7] These last considerations, coupled with the fact that there is no upper explosive limit, require that special safety precautions be taken when handling and storing EO.

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GENERAL DESCRIPTION OF THE BULK STERILIZATION PROCESS

Detailed descriptions of the sterilization process are contained in References 3 and 8. The bulk sterilization process, used by the majority of the commercial sterilization industry, is described here in general terms. Hospital and medical products to be sterilized are preconditioned with steam in a separate chamber prior to sterilization. An air-tight sterilization chamber is loaded with the preconditioned products. Air inside the chamber is evacuated using steam ejectors to decrease the chamber pressure. If 100 wt% EO is used, the chamber may be purged several times with nitrogen.

Once the desired vacuum level is achieved, the air inside the chamber is humidified to a predetermined value by adding steam. The sterilant is pressurized into the chamber to a predetermined level. The chamber is held at a constant pressure for a specified period, while the products are sterilized by EO. When sterilization is complete, the sterilizer gas mixture is exhausted from the chamber until the chamber pressure is decreased to a predetermined level. Filtered air is introduced into the chamber to flush the sterilant gases from the chamber and product. If 100 wt% EO is used, the chamber is flushed with nitrogen prior to introducing the filtered air. These air washes may be repeated several times. After the last air wash, the door is opened and the chamber unloaded.

The gas in an EO sterilization chamber does not vent at a constant rate for two reasons. First the initial maximum venting rate is determined by the size of the chamber vacuum pump. As the chamber empties, the vacuum is increased, less and less volume of gas is available for removal, and the vent gas flow rate decreases. Second, the evacuation of the chamber is controlled by a solenoid valve that opens and closes at regular intervals to prevent the chamber from evacuating too rapidly and damaging the products. This changing and pulsing flow rate makes measuring the EO mass flow rate in the gas stream more difficult. First, calculating the total flow through the vent is an integration rather than a multiplication process and requires continuous monitoring of the flow. Second, calculating the total emissions requires taking many grab samples over the sampling period or collecting a representative sample using special techniques.

There are two models for the EO concentration profile in the chamber exhaust. In one model the chamber is considered to be a closed system at equilibrium. For this model, the EO concentration in the exhaust gas remains constant and only the vent stream flow rate varies. In the other model, the chamber is considered to be a dynamic system. For this model, both the EO concentration and flow rate of the exhaust gas change with time.

If the sterilization chamber does not contain product, the exhaust stream will be characterized best by the first (static) model because equilibrium will occur quickly between evacuations. However, other than for measuring scrubber efficiency and developing sampling and analytical methods, most chambers are operated with product. Any product present in the chamber will offgas, releasing EO during chamber evacuations and air washes. With a product-containing chamber, the exhaust stream will be characterized best by the second (dynamic) model. From this second, more realistic model, performance factors may be developed and used to study the whole system.

HOSPITAL SUPPLY STERILIZATION INDUSTRY

Throughout the United States and Puerto Rico approximately two hundred facilities use EO for sterilizing heat- or moisture-sensitive products or for fumigating microorganisms and insects.[8,9] Chambers range in volume from less than 2 cubic meters (m^3) [60 cubic feet (ft^3)] to 170 m^3 (6000 ft^3).[9] Most of the chambers in the industry (76%) are charged with a mixture of 12 weight percent (wt%) EO and 88 wt% of dichlorodifluoromethane (CFC-12).[9] The 12/88 gas mixture is used because it is nonflammable. Pure EO is used in 68% of the chambers and mixtures of carbon dioxide and EO are used in 10 percent.[9] Carbon dioxide mixtures are used because the carbon dioxide increases the effectiveness of the EO and prevents it from being flammable. (Some chambers are used with more than one type of sterilant gas.) Some of the 12/88 gas users are converting to 100 wt% EO in anticipation of CFC-12 emission regulations.

The vent streams from 17% of the EO sterilization facilities have some type of control unit, ranging from a neutral-water scrubber to an incinerator.[9] Forty-four percent of the control units chemically hydrolize

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the EO to ethylene glycol using dilute acid solutions, 3% use catalytic oxidation to convert the EO to carbon dioxide and water, and 19% of the control units are condensation/reclamation systems.[9] Commercial vendors of EO control units include Chemrox Incorporated, Damas Corporation, Donaldson Company (purchasers of Mine Safety Appliances' EO control division), and Croll Reynolds. A segment of the industry (approximately five to 15%) has custom-designed control units. Control units have been tested by the manufacturers and the industry. Ethylene oxide removal efficiencies greater than 99% have been measured.[1,10,11,12,13] Condensation/reclamation and catalytic oxidation systems have lower EO removal efficiencies than the dilute-acid hydrolytic systems.

ETHYLENE OXIDE EMISSION MEASUREMENTS

Several methods are currently being used in the EO sterilization industry to measure the emissions from EO control units.[10,11,12,13] In general, the emissions from an EO control unit are determined on a weight basis over the entire post-sterilization cycle. The post-sterilization cycle includes the initial chamber evacuation and all subsequent air washes. The control units tested and reported include:

- A Chemrox unit in Pennsylvania tested by the manufacturer under contract to the user,[10]
- A Chemrox unit in New York tested by the manufacturer,[11]
- A Damas unit,[12] and
- An MSA unit (now manufactured by Donaldson Company).[13]

The Chemrox unit in Pennsylvania was tested by taking grab samples of the vent gas in Vacu-Samplers every five minutes. The samples were analyzed in the laboratory using standard EO methods. The amount of EO emitted from the control unit was calculated from the concentration of EO in the outlet grab samples, the exhaust temperature, and outlet flow rate of the vent gas. The volumetric gas flow rate was calculated using chamber temperature and pressure data and assuming all components other that EO pass through the scrubber unaffected.

The Chemrox unit in New York was tested using direct semi-continuous sampling at the outlet of the control unit. Samples were directed through heat-traced lines into the gas sampling valve of a gas chromatograph (GC) at one-minute intervals. The weights of EO at the outlet of the control unit were calculated from the concentration of EO measured by the GC and the measured temperature and flow rate of the vent gas.

The Damas unit was tested by taking outlet samples collected on charcoal tubes. A series of outlet samples were collected at a constant sampling rate over five-minute intervals during the entire post-evacuation cycle. The charcoal tubes were desorbed using carbon disulfide and the extracts were analyzed by GC. The weights of EO at the outlet of the control unit were calculated from the measured EO concentrations, vent gas temperature, and vent gas flow rate during each sampling period.

The MSA unit was tested using 10-milliliter (mL) syringes to collect outlet samples at one-minute intervals. Stream flow rates and temperatures were recorded at the time of sample collection. The entire sample in the syringe was injected directly onto a GC column for analysis. The amounts of EO at the outlet of the control system were calculated from the measured EO concentrations and stream flow rates.

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SECTION 4

SAMPLING AND ANALYTICAL PROCEDURES

FACILITY DESCRIPTION

The field evaluation was conducted at Burron Medical, a medical supply sterilization facility, located in Allentown, Pennsylvania. The facility has three 1000-ft^3 (28-m^3) sterilizers: one uses a 12/88 (wt%/wt%) EO and CFC-12 gas mixture and two use 100% EO. A 12/88 sterilization cycle typically uses 38 gallons (140 L) of 12/88 gas mixture. On a weight basis, a 12/88 sterilization charge consumes 368 lbs (167 Kg) of gas, of which approximately 44 lbs (20 Kg) are EO. A 100% EO charge typically uses 44 lbs (20 Kg) of gas.

The exhaust from the sterilizers is controlled by a DEOXX™ system. The DEOXX system is a dilute acid scrubber manufactured by Chemrox, which hydrolyzes the EO to ethylene glycol. At the time of the test the scrubber contained dilute sulfuric acid and approximately 10 wt% of ethylene glycol. The control system has reported control efficiencies of 99.99%, based on tests conducted at the facility in April 1986 by the vendor,[10] and 99.94%, based on tests performed in October 1987 by Radian.[1]

Each chamber is equipped with a total recirculating oil-sealed pump. The pumps are equipped with gas/liquid separators that emit the gas to the DEOXX system and recirculate the liquid to the pump inlet. The sterilization cycle is automatically controlled by a programmable microprocessor system. The microprocessor system has the capability to control and record the parameters of the sterilization cycle including chamber temperature, chamber pressure, and elapsed time from the start of the cycle. Because the scrubber is designed to handle the exhaust from two sterilizers venting simultaneously,

the tested sterilization cycles were scheduled so that only one sterilizer vented at a time.

Two different sterilization programs plotted in Figures 1 and 2 were used for testing, one for the 12/88 tests (Figure 1) and one for the 100% EO test (Figure 2). Before the start of the tests using 12/88 gas, the chamber was evacuated to 2 pounds per square inch absolute (psia) and then pressurized to 3.1 psia with steam. The steam pressure was maintained for 15 minutes at 3.1 psia and the time period was called a "humidity dwell." At the completion of the humidity dwell the chamber was charged to 23.7 psia with 12/88 gas. The exposure at 23.7 psia was maintained for 15 minutes. The program contained six post-sterilization evacuations, the initial chamber evacuation and pump down and five air in-bleeds and subsequent evacuations, followed by a final air in-bleed. The chamber was evacuated to 2 psia and pressurized with air to 10 psia during each evacuation and air in-bleed cycle. For the sixth air in-bleed the chamber pressure was returned to atmospheric.

Before the start of the test using 100% EO, the chamber was evacuated to 1.5 psia, pressurized to 13 psia with nitrogen, and re-evacuated to 1.5 psia. Then the chamber was pressurized to 2.6 psia with steam. The humidity dwell lasted for 30 minutes. Then the chamber was first pressurized to 6.7 psia with nitrogen, followed by pressurization to 12.1 psia with EO, and capped by pressurizing to 13 psia with nitrogen. The sterilization dwell was maintained for 125 minutes. The program contained five post-sterilization evacuations: the initial chamber pump down, a nitrogen purge and pump down, and three air in-bleeds and subsequent pump downs, followed by a final air in-bleed. For the nitrogen purge the chamber was evacuated to 1.5 psia and pressurized to 13 psia with nitrogen. For the air washes the chamber was evacuated to 1.5 psia and pressurized to 10 psia. For the fourth air in-bleed the chamber pressure was returned to atmospheric.

Three tests were performed, one with product in the chamber using 100% EO and two without product using 12/88 gas. Data from all of these tests were reduced and used to prepare this report. Table 1 summarizes the three tests that were used.

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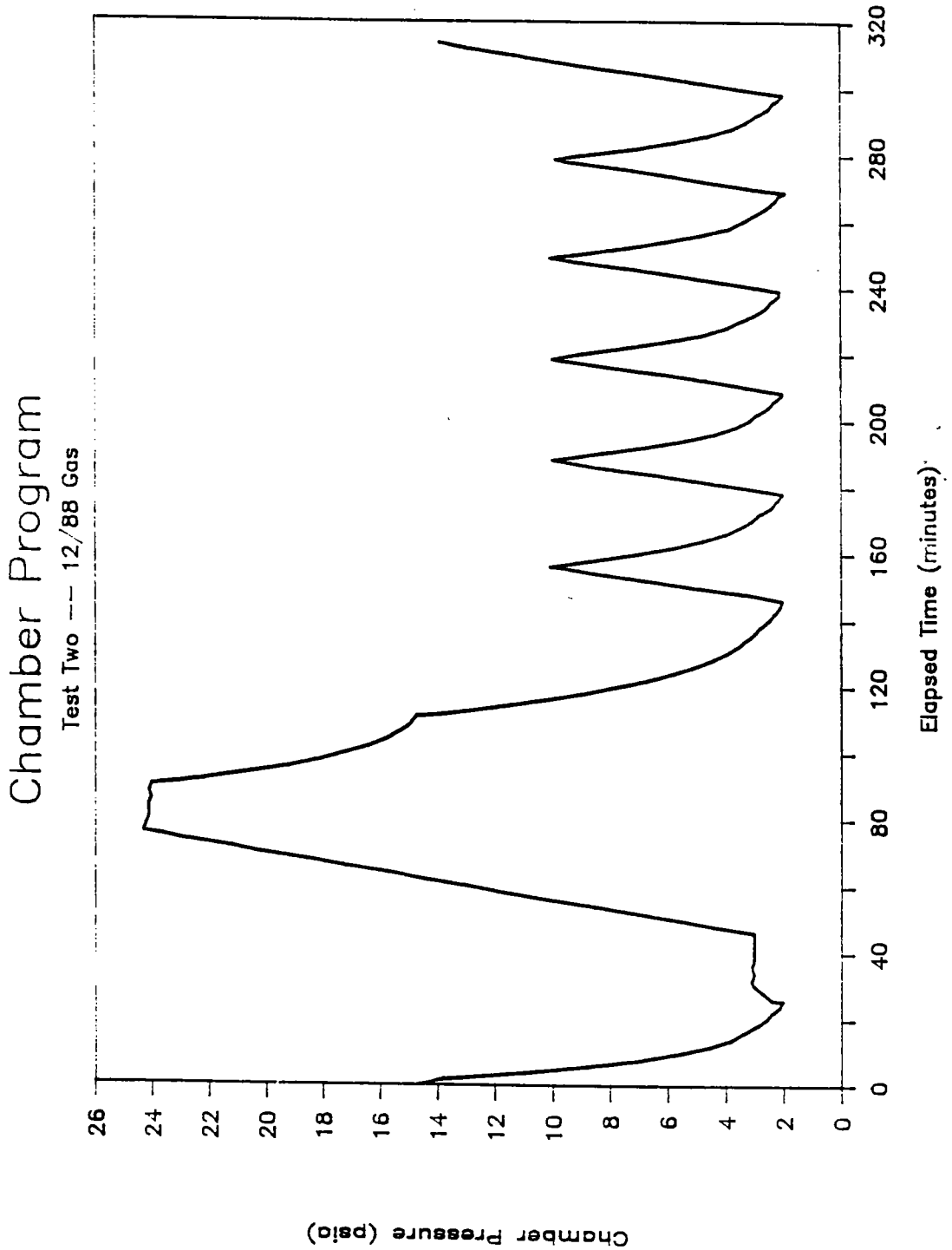

Figure 1. Chamber pressure during tests using 12/88 gas.

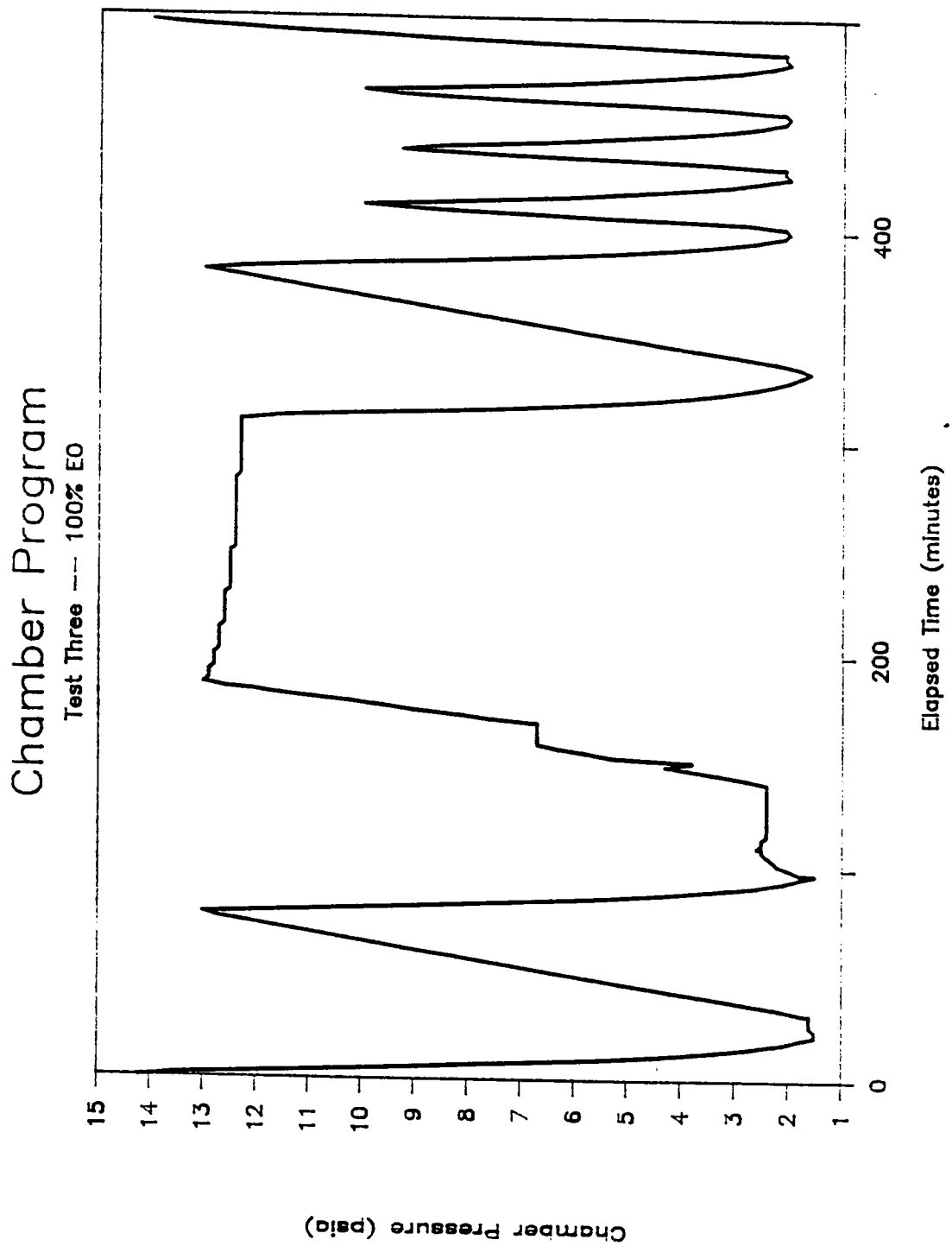

Figure 2. Chamber pressure during tests using 100% ethylene oxide.

TABLE 1. TEST SUMMARY

Test Number	Product Present	Chamber Number	Sterilant Gas Used	Test Date	Test Start Time	Test End Time
1[a]	No	3	12/88	88/06/21	13:03	16:19
2[a]	No	3	12/88	88/06/22	10:00	13:26
3[b]	Yes	1	100% EO	88/06/23	11:45	14:35

[a]The chamber was evacuated to 2 psia before being pressurized with steam to 3.1 psia. Humidity dwell lasted 15 minutes and then the chamber was charged to 23.7 psia with 12/88 gas. Exposure lasted 15 minutes. Post-sterilization chamber pressure cycled between 2 psia and 10 psia.

[b]The chamber was evacuated to 1.5 psia before being filled with nitrogen to 13 psia. After evacuation to 1.5 psia, the chamber was pressurized with steam to 2.6 psia. Humidity dwell lasted 30 minutes and then the chamber was pressurized to 6.7 psia with nitrogen, then to 12.1 psia with EO, and capped at 13 psia with nitrogen. Exposure lasted 125 minutes. The chamber pressure was reduced to 1.5 psia and then pressurized to 13 psia with nitrogen. Post-nitrogen purge chamber pressure cycled between 1.5 psia and 10 psia.

SAMPLING LOCATION

Samples were acquired after the scrubber. At the scrubber outlet the EO concentrations ranged from 80 to 3,000 ppmv, CFC-12 concentrations were at the percent levels, and sample temperatures ranged from 77 to 122°F (25 to 50°C) depending on the ambient temperature at the time of the test.

The stack was modified as shown in Figure 3 to remove exhaust gases from the sampling area and to provide a small amount of back pressure to facilitate sampling and eliminate the possibility of diluting the sample with ambient air. Sample was withdrawn at a point as close to the end of the plant's stack as was feasible.

SAMPLING PROCEDURES

Grab sampling was used for determining EO, CFC-12, and oxygen concentrations. The method used is described in detail in Appendix A.

Ethylene Oxide and Dichlorodifluoromethane Sampling

The EO and CFC-12 sampling equipment is shown in Figure 4. Grab samples were taken using the equipment and procedures described below.

Ethylene Oxide and Dichlorodifluoromethane Sampling Equipment--

Sample was withdrawn into a heated, 1/4-inch (6.4-mm), Teflon® line using a Teflon-lined diaphragm pump. A stainless steel, 1/4-inch (6.4-mm) tee was used after the pump to provide a continuous purge of the vent gas through the sampling system. After the tee, on one branch, the sample stream was routed through tygon tubing and exhausted downwind from the sampling area. There was a pinch clamp on the tygon tubing to block the exhaust line during sample collection. On the other branch of the tee, a stainless steel, 1/4-inch (6.4-mm), toggle-operated shut-off valve was placed prior to the sample container.

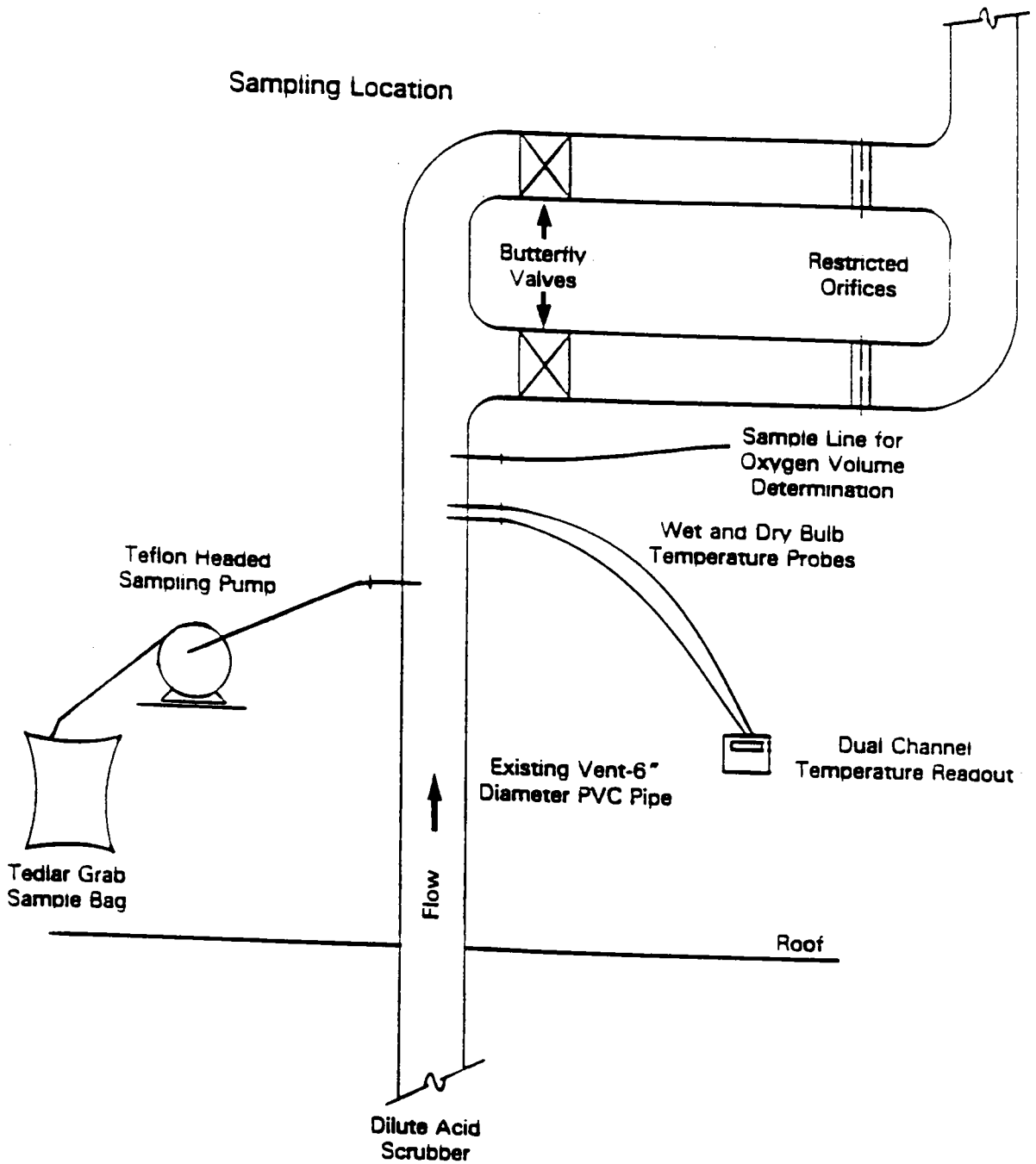

Figure 3. Stack modification for grab sampling.

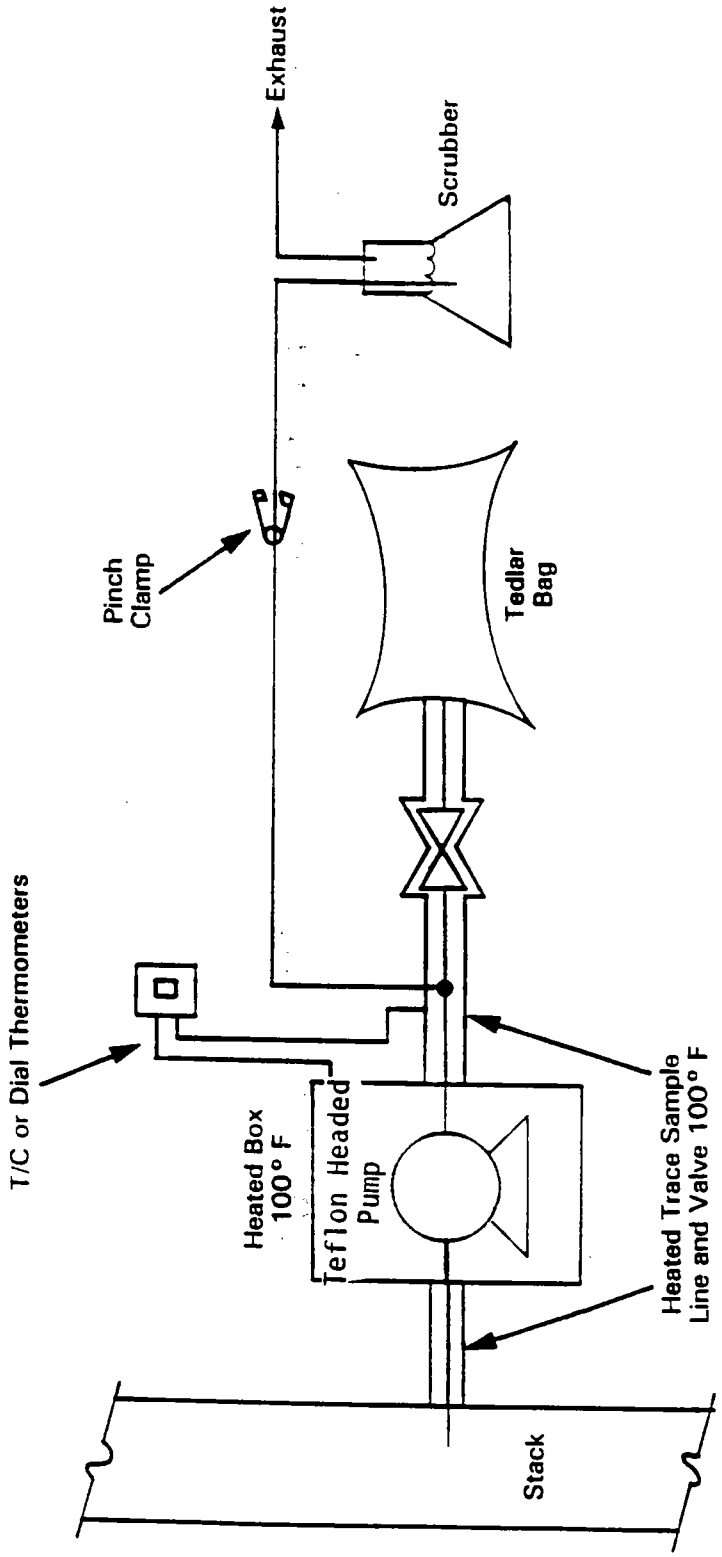

Figure 4. Ethylene oxide sampling equipment.

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Ethylene Oxide and Dichlorodifluoromethane Sampling Operation--

The sampling line was continually flushed with sample throughout the test. Prior to attaching the sample container, the line was flushed with sample by closing the pinch clamp on the tygon exhaust line and opening the toggle valve on the sample line. The same procedure was used to fill the sample container.

Table 2 compares the EO and CFC-12 sampling parameters for each evacuation of each test. For the first test, sampling began one minute after the DEOXX scrubber started to exhaust in preparation for the initial chamber evacuation. The test consisted of six evacuations: the initial chamber evacuation and pump down and five air in-bleeds and subsequent evacuations. Sampling stopped eleven minutes after the start of the sixth evacuation. The start time and end time of the evacuations were identified by the chamber control panel.

For the second and third tests, the first sample was acquired five minutes after the start of the first evacuation. After the first sample, bag samples were acquired at six-minute intervals during the first evacuation and at four-minute intervals during the following evacuations.

Oxygen Sampling

The sampling location for oxygen determinations was shown in Figure 3. Grab samples were taken using the materials and procedures described below.

Fyrite Oxygen Indicator--

BACHARACH Fyrite oxygen indicator was used to determine percent levels of oxygen in the sterilizer exhaust at the sampling location. Fyrite indicators use volumetric displacement involving chemical absorption of oxygen from the sample. The reagent used to absorb oxygen was chromous chloride. Accuracy of analysis was ± 0.5 percent.

TABLE 2. COMPARISON OF ETHYLENE OXIDE SAMPLING OPERATION PARAMETERS WITH TEST CONDITIONS

	Test 1		Test 2		Test 3		
	Evacuation		Evacuation		Evacuation		
Parameter	1	2-6	1	2-6	1	2	3-5
Time from start of evacuation to first sample (minutes)	1	5 or 6	5	5	5	5	5
Sampling Interval (minutes)	1	3	6	3 or 4	6	4	3 or 4
Total Samples Acquired							
Bag	24	3	3	3	3	3	3
Syringe	0	0	2	2	1	1	1
Vacu-Sampler	0	0	1	1	2	2	2
Chamber Pressure at start of evac. (psia)	23.7	10	23.7	10	13	13	10
at end of evac. (psia)	2	2	2	2	1.5	1.5	1.5

Sampling Operation--

Percent levels of oxygen were measured when bag samples were taken. The measurements were used to indicate the scrubber dead volume and to determine EO-to-oxygen ratios. Sample was removed from the stack downstream of the EO sampling port. An aspirator bulb was used to pull the sample from the stack.

Stack Temperature

Exit gas temperatures were measured at the scrubber outlet location using a bimetallic temperature probe and a pyrometer. The bimetallic temperature sensor was placed in the duct as shown in Figure 3. Stack temperatures were digitized by a calibrated pyrometer and recorded every time a bag sample was taken.

Moisture Determination

The percent moisture of the stack gas was determined by the wet bulb/dry bulb method. Relative humidity was converted to percent moisture. Wet and dry bulb temperature measurements used to determine relative humidity were recorded every time a bag sample was taken.

ANALYTICAL PROCEDURES

The analytical method used for the measurement of the EO and CFC-12 was gas chromatography with flame ionization detection (GC/FID). The CFC-12 concentration was needed for the determination of the EO-to-CFC-12 ratios. The equipment and procedures used are described below.

Analytical Equipment Description

A dual FID Varian 3400 GC was equipped with a 10 ft (3 m) x 1/8 inch (3 mm) OD stainless steel column containing 5% Fluorcol on 60/80 Carbopack B and a 6 ft (2 m) x 1/8 inch (3 mm) OD stainless steel column containing

1% SP-1000 on 60/80 mesh Carbopack B. On July 9, the 1% SP-1000 column was replaced with an 8 ft (2.4 m) x 1/8 inch (3 mm) OD stainless steel column containing 3% SP-1000 on 60/80 mesh Carbopack B. The FID electrometers were connected to Shimadzu CR1-A integrators.

Operating Conditions

The GC column oven was operated isothermally at 45°, 55° or 65°C on June 21, 22 and 23, respectively. Laboratory reanalyses were performed with an isothermal column temperature of 65°C except on July 9 when the 3% SP-1000 column was used at 55°C. The injector oven was heated to 175°C, and the detector oven to 200°C. Nitrogen carrier gas flow rates were 30 mL/min. The FID support gas flow rates recommended by the GC manufacturer were used.

During the first evacuation of the first test when both EO and CFC-12 were quantitated, the FID electrometers were programmed so that the range would shift from 10^{-10} or 10^{-11} amperes to 10^{-9} amperes.

Analytical Sampling Procedures

One-milliliter samples were injected using a 5-mL gas-tight syringe with an on/off valve.

Gas Chromatograph Calibration

Both channels of the chromatograph were calibrated for EO at the beginning and end of the day. On the first test day, the GC/FID was also calibrated for CFC-12 to determine the EO-to-CFC-12 ratios. At least one standard was analyzed after every twentieth sample. Standards were purchased from Scott Specialty Gases and MG Industries and ranged in EO concentration from less than 5 ppmv to 12.5 vol% and in CFC-12 concentration from 1200 ppmv to 62.5 volume percent. In addition, a lecture bottle containing 99.9% CFC-12 was used to verify response at the upper level of CFC-12 concentration observed in the vent stream. Calibration curves consisted of a minimum of three standards that bracketed the sample concentrations.

SECTION 5

TEST RESULTS

The purpose of this field test was to evaluate the performance of the analytical column. Three columns were evaluated in terms of linearity, efficiency, resolution, retention time stability, and limits of detection and quantitation. A second purpose of the field test was to evalute EO stability in samples collected in Tedlar bags, gas-tight syringes and Vacu-Samplers. A third purpose of the field test was to determine EO-to-oxygen and EO-to-CFC-12 ratios and to measure the EO concentration profile for means of establishing a standard based on maximum EO concentration emitted.

COLUMN EVALUATION

The linearity, efficiency, resolution, retention time stability, and limits of detection and quantitation were evaluated for the following three columns:

- 5% Fluorcol on 60/80 mesh Carbopack B (10 ft x 1/8 inches, stainless steel);
- 1% SP-1000 on 60/80 mesh Carbopack B (6 ft x 1/8 inches, stainless steel); and
- 3% SP-1000 on 60/80 mesh Carbopack B (8 ft x 1/8 inches, stainless steel).

The Fluorcol column and the 1% SP-1000 column were used to analyze samples in the field. All three columns were used to analyze samples in the laboratory. The three columns were evaluated at 45°, 55° and 65°C using a nitrogen carrier gas flowing at 30 mL/min. The results are reported below.

Linearity

The linearity of the EO and CFC-12 response on the FID detector when using the three columns was evaluated using the F-test given in Equation 1:

$$F^* = MSLF/MSPE \qquad \text{(Equation 1)}$$

where:

F^* = the F-test statistic,
MSLF = the lack of fit mean square = SSLF/(c-2),
MSPE = the pure error mean square = SSPE/(n-c),
n = the total number of injections, and
c = the total number of concentrations.

The lack of fit sum of squares (SSLF) is a weighted sum of squares of the deviations between the mean area at each concentration and the fitted area at that concentration. The weights are the number of injections at each concentration. The degree of freedom (c-2) associated with SSLF is two less than the number of concentrations evaluated. Thus the lack of fit mean square (MSLF) provides a variance of the sample points about the fitted line and a smaller MSLF increases the probability that the regression function is linear.

The pure error sum of squares (SSPE) is a sum of squares of the deviations between the area measured for each injection at a concentration and the mean area measured at that concentration. The degree of freedom (n-c) associated with SSPE is the total number of injections less the total number of concentrations evaluated. Thus the MSPE provides an unbiased estimator of the error variance regardless of the nature of the regression function.

The F-statistic, F^*, is compared to a critical F-statistic, $F_{1-\alpha/2,c-2,n-c}$, obtained from tables that provide points for the distribution of F^*. If $F^* > F_{1-\alpha/2,c-2,n-c}$, then the data indicate lack of fit, or non-linear behavior.

The EO concentration may vary over several orders of magnitude depending upon the test situation. Although the FID response for EO is linear from the part-per-million by volume to the volume percent level, a calibration curve prepared over six orders of magnitude must be properly weighted to prevent the volume percent levels from dominating the fitted results. Because proper weighting can complicate calibration curve calculations, the EO concentration range was divided into three fractions with a span limited to 2 or 3 orders of magnitude. No effort was made to determine where non-linearity begins.

Table 3 provides F-test data at the three EO concentration levels and at one CFC-12 concentration level for the FID when using the three columns. At the 0.01 level of significance (99% probability level), FID response for all columns was linear for CFC-12 concentrations between 30 and 100 vol%. For a one milliliter injection volume, CFC-12 concentrations at 30 vol% and higher saturate the FID as indicated by the humped-shaped peaks. Thus, for quantitation of high percent levels of CFC-12, a 0.1 mL sample volume would provide better chromatography. In this study, CFC-12 linearity was not evaluated below 31 vol%.

At a 0.01 level of significance (99% probability level), the FID response using the 3% SP-1000 column had the largest linear range at both the high and low EO levels. Three linear ranges determined for FID response using the 3% SP-1000 column were 2.28 to 1,250 ppmv, 22.8 to 2,510 ppmv, and 0.5 to 100 vol%. The FID response using the 1% SP-1000 column had the largest linear range for intermediate EO concentrations. Linear ranges determined for the FID when using the 1% SP-1000 column were 2.28 to 251 ppmv, 22.8 to 5,020 ppmv and 0.5 to 20 vol%. On the 5% Fluorcol column the FID linear ranges were 2.28 to 502 ppmv, 49 to 2,500 ppmv, and 0.1 to 50 vol%.

Thus, the FID response using the 1% SP-1000 column provided the best linear range for analyses of EO at the outlet of dilute acid hydrolytic scrubbers when 12/88 or 100 wt% EO was used. The FID response using the 5% Fluorcol column provided the best linear range for EO analyses at the scrubber inlet when 12/88 or 100 wt% EO was used. Plots of the calibration curves are provided in Appendix B.

TABLE 3. F-TEST DATA USED TO DETERMINE LINEARITY OF RESPONSE

Concentration	Calculated F-statistic	Degrees of Freedom	Critical[a] F-Statistic	Analytical[b] Column
31 to 100 vol% CFC-12	0.10	2, 10	7.56	5% Fluorcol
2.28 to 502 ppmv EO	1.31	9, 55	2.75	5% Fluorcol
49 to 2,500 ppmv EO	0.67	7, 97	2.82	5% Fluorcol
0.1 to 50 vol% EO	2.13	6, 14	4.46	5% Fluorcol
31 to 100 vol% CFC-12	0.12	2, 14	6.51	1% SP-1000
2.28 to 251 ppmv EO	1.40	4, 6	9.15	1% SP-1000
23 to 5,000 ppmv EO	3.87	5, 7	7.46	1% SP-1000
0.5 to 20 vol% EO	9.81	3, 5	12.06	1% SP-1000
31 to 100 vol% CFC-12	1.73	2, 24	5.61	3% SP-1000
2.28 to 1,250 ppmv EO	0.02	5, 50	3.41	3% SP-1000
23 to 2,500 ppmv EO	2.82	4, 26	4.14	3% SP-1000
0.5 to 100 vol% EO	1.97	5, 34	3.61	3% SP-1000

[a] F-statistics reported at 0.01 level of significance (99% probability level).

[b] All columns were made of 3 mm OD stainless steel and contained the liquid phase coated on Carbopack B (60/80 mesh). All measurements were made using a nitrogen carrier gas flowing at 30 mL/min. Samples were injected via syringe.

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Efficiency

Column efficiency in terms of the height-equivalent-to-a-theoretical plate (HETP) was evaluated by injecting one milliliter of samples containing three different EO levels:

- 12.5 vol%,
- 2,508 ppmv, and
- 98.05 ppmv.

The EO retention time and full width at half height were used to calculate the plate number from Equation 2:

$$N = 5.54\ (t_r/W_{0.5})^2 \qquad \text{(Equation 2)}$$

where:

N = the number of plates,
t_r = the retention time of EO in seconds, and
$W_{0.5}$ = the full width at half height of the EO peak in seconds.

The full width at half height was either obtained directly from the integrator or was measured mechanically by running the chart paper at 50 cm/min. To obtain the HETP, the column length in millimeters was divided by the number of plates. The columns were evaluated at three temperatures and the HETP results are shown in Tables 4 through 6. Smaller HETP values indicate greater efficiency. Values are reported as means with 95% confidence intervals.

For the 12.5 vol% EO sample, the most efficient column was the 5% Fluorcol at 65°C. Surprisingly, for the percent level sample, the efficiency of the columns decreased with decreasing column temperature. For the 2,508 ppmv EO sample, the most efficient columns were the 1% SP-1000 and the 5% Fluorcol operated at 45°C. At this concentration level, the column efficiencies increased with decreasing temperature. For the 98.05 ppmv EO sample, the most efficient column (1% SP-1000) was equally efficient at all three tested temperatures.

TABLE 4. COLUMN EFFICIENCY AT 45°C

Column I.D.[a]	HETP (mm)[b,c] 12.5%	2.508 ppmv	98.05 ppmv
1% SP-1000 (1.8 m)	1.58 ± 0.10	1.10 ± 0.05	0.933 ± 0.057
3% SP-1000 (2.4 m)	2.62 ± 0.17	1.94 ± 0.03	1.88 ± 0.07
5% Fluorcol (3.0 m)	1.44 ± 0.05	1.12 ± 0.02	2.16 ± 0.12

[a] All columns were made of 3 mm OD stainless steel and contained the liquid phase coated on Carbopack B (60/80 mesh). All measurements were made using a nitrogen carrier gas flowing at 30 mL/min. A 1-mL sample was injected via syringe. Full widths at half height were measured mechanically for the 3% SP-1000 column, and at the 12.5% EO level at 45°C for the other two columns and at 65°C for the 1% SP-1000 column. All other full widths at half height were measured electronically.

[b] $HETP = 0.18 \times L \times (W_{0.5}/t_r)^2$

HETP = Height Equivalent to a Theoretical Plate, mm
L = column length, mm
t_r = retention time, EO peak, seconds
$W_{0.5}$ = full-width at half-height, EO peak, seconds

[c] Data are reported as means with 95% confidence intervals

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TABLE 5. COLUMN EFFICIENCY AT 55°C

Column I.D.[a]	HETP (mm)[b,c]		
	12.5%	2.508 ppmv	98.05 ppmv
1% SP-1000 (1.8 m)	0.999 ± 0.011	1.22 ± 0.11	0.888 ± 0.069
3% SP-1000 (2.4 m)	3.87 ± 0.12	2.08 ± 0.18	2.26 ± 0.02
5% Fluorcol (3.0 m)	0.883 ± 0.013	1.33 ± 0.03	1.71 ± 0.04

[a] All columns were made of 3 mm OD stainless steel and contained the liquid phase coated on Carbopack B (60/80 mesh). All measurements were made using a nitrogen carrier gas flowing at 30 mL/min. A 1-mL sample was injected via syringe. Full widths at half height were measured mechanically for the 3% SP-1000 column, and at the 12.5% EO level at 45°C for the other two columns and at 65°C for the 1% SP-1000 column. All other full widths at half height were measured electronically.

[b] $HETP = 0.18 \times L \times (w_{0.5}/t_r)^2$

HETP = height equivalent to a theoretical plate, mm
L = column length, mm
t_r = retention time, EO peak, seconds
$W_{0.5}$ = full-width at half-height, EO peak, seconds

[c] Data are reported as means with 95% confidence intervals.

TABLE 6. COLUMN EFFICIENCY AT 65°C

Column I.D.[a]	HETP (mm)[b,c] 12.5%	2,508 ppmv	98.05 ppmv
1% SP-1000 (1.8 m)	0.994 ± 0.092	1.69 ± 0.09	0.948 ± 0.093
3% SP-1000 (2.4 m)	2.30 ± 0.02	1.92 ± 0.02	2.02 ± 0.15
5% Fluorcol (3.0 m)	0.792 ± 0.004	1.78 ± 0.05	1.72 ± 0.05

[a] All columns were made of 3 mm OD stainless steel and contained the liquid phase coated on Carbopack B (60/80 mesh). All measurements were made using a nitrogen carrier gas flowing at 30 mL/min. A 1-mL sample was injected via syringe. Full widths at half height were measured mechanically for the 3% SP-1000 column, and at the 12.5% EO level at 45°C for the other two columns and at 65°C for the 1% SP-1000 column. All other full widths at half height were measured electronically.

[b] $HETP = 0.18 \times L \times (W_{0.5}/t_r)^2$

HETP = height equivalent to a theoretical plate, mm
L = column length, mm
t_r = retention time, EO peak, seconds
$W_{0.5}$ = full-width at half-height, EO peak, seconds

[c] Data are reported as means with 95% confidence intervals

Thus, the 5% Fluorcol column at 65°C was most efficient for percent level EO analyses and the 1% SP-1000 column was most efficient for part-per-million level EO analyses. Both columns at 45°C were comparable in efficiency for part-per-thousand level analyses of EO. The 3% SP-1000 column was clearly the least efficient column at all tested temperatures and concentrations.

Resolution

The column resolution of EO from CFC-12 was evaluated by injecting one milliliter samples at two concentration levels:

- 12.5 vol% EO and 62.5 vol% CFC-12, and
- 2,508 ppmv EO and 6,022 ppmv CFC-12.

The EO and CFC-12 retention times and full widths at the baseline were used to calculate the resolution from Equation 3:

$$R = [2 \times (t_r - t_{r'})]/(W_b + W_{b'}) \qquad \text{(Equation 3)}$$

where:

R = the column resolution,
t_r = the retention time of EO in seconds,
$t_{r'}$ = the retention time of CFC-12 in seconds,
W_b = the full width at the baseline for the EO peak in seconds, and
$W_{b'}$ = the full width at the baseline for the CFC-12 peak in seconds.

The full width at the baseline was obtained mechanically using a chart speed of either 20 or 50 cm/min. The columns were tested at three temperatures and the results are given in Tables 7 and 8. The higher the column resolution, the better the column separates the two peaks. Baseline resolution is given by a column resolution of 1.5 or greater. Values are reported as means with 95% confidence intervals. Examples of the chromatograms are provided in Appendix C.

TABLE 7. COLUMN RESOLUTION FOR VOLUME PERCENT CONCENTRATIONS

	Resolution[b,c] 12.5 vol% Ethylene Oxide and 62.5 vol% Chlorofluorocarbon 12		
Column I.D.[a]	Column @ 45°C	Column @ 55°C	Column @ 65°C
1% SP-1000 (1.8 m)	2.28 ± 0.32	1.70 ± 0.01	0.90 ± 0.21
3% SP-1000 (2.4 m)	1.24 ± 0.18	1.06 ± 0.14	0.64 ± 0.05
5% Fluorcol (3.0 m)	2.04 ± 0.30	1.78 ± 0.24	0.84 ± 0.10

[a] All columns were made of 3 mm OD stainless steel and contained the liquid phase coated on Carbopack B (60/80 mesh). All measurements were made using a nitrogen carrier gas flowing at 30 mL/min. A 1-mL sample was injected via syringe. Full widths at baseline were measured mechanically. Retention times were measured electronically.

[b] $R = [2 \times t_r - t_{r'})]/(W_b + W_{b'})$

R = column resolution
t_r = retention time of EO, seconds
$t_{r'}$ = retention time of CFC-12, seconds
W_b = full width at baseline for EO, seconds
$W_{b'}$ = full width at baseline for CFC-12, seconds

[c] Data are reported as means with 95% confidence intervals

TABLE 8. COLUMN RESOLUTION FOR PARTS-PER-THOUSAND CONCENTRATIONS

	Resolution[b] 2.508 ppmv Ethylene Oxide and 6.022 ppmv Chlorofluorocarbon 12		
Column I.D.[a]	Column @ 45°C	Column @ 55°C	Column @ 65°C
1% SP-1000 (1.8 m)	2.72 ± 0.86	1.72 ± 0.61	0.88 ± 0.30
3% SP-1000 (2.4 m)	1.92 ± 1.28	1.58 ± 0.03	1.38 ± 0.13
5% Fluorcol (3.0 m)	2.08 ± 0.25	1.72 ± 0.13	1.40 ± 0.07

[a] All columns were made of 3 mm OD stainless steel and contained the liquid phase coated on Carbopack B (60/80 mesh). All measurements were made using a nitrogen carrier gas flowing at 30 mL/min. A 1-mL sample was injected via syringe. Full widths at baseline were measured mechanically. Retention times were measured electronically.

[b] $R = [2 \times (t_r - t_{r'})]/(W_b + W_{b'})$

R = column resolution
t_r = retention time of EO, seconds
$t_{r'}$ = retention time of CFC-12, seconds
W_b = full width at baseline for EO, seconds
$W_{b'}$ = full width at baseline for CFC-12, seconds

[c] Data are reported as means with 95% confidence intervals.

The highest column resolutions at both concentration levels were obtained at 45°C on the 1% SP-1000 and 5% Fluorcol columns. As expected, the resolution decreased significantly as the column temperature increased.

Thus, the 1% SP-1000 and 5% Fluorcol columns provided comparable (baseline) resolution of the EO from the CFC-12 at the percent and parts-per-thousand levels. Both of these columns provided significantly better resolution of the two compounds than did the 3% SP-1000 column. Resolution was not evaluated at the part-per-million levels.

Retention Time Stability

The retention time stability was evaluated by injecting one milliliter samples at various EO and CFC-12 concentrations. The percent relative difference between the earliest retention time and the latest retention time was calculated and used to compare the column performance at different temperatures and to compare the columns to each other.

Ethylene oxide and CFC-12 retention times at several concentrations and three column temperatures are reported in Tables 9 through 11. Values are reported as means with 95% confidence intervals. Retention times varied by ± 10% or less on the two SP-1000 columns. Figure 5 graphically shows the retention time stability for the 1% SP-1000 column.

On the Fluorcol column the retention times increased with decreasing concentration as depicted in Figure 6. At 45°C the EO retention time shifted from 2.64 to 5.98 minutes (126%) when going from a concentration of 12.5 vol% to 4.454 ppmv. When going from a concentration of 12.5 vol% to 22.81 ppmv the EO retention time shifted from 2.21 to 5.43 minutes (146%) at 55°C and from 1.82 to 2.59 minutes (42%) at 65°C. For changes in CFC-12 concentrations of 62.5 vol% to 6,022 ppmv, the CFC-12 retention time shifted from 4.72 to 5.57 minutes (18%) at 45°C. The CFC-12 retention time shifted from 3.70 to 4.22 minutes (11%) at 55°C and from 2.91 to 3.36 minutes (15%) at 65°C.

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Table 9 here

TABLE 9. ETHYLENE OXIDE AND DICHLORODIFLUOROMETHANE RETENTION TIMES ON 1% SP-1000[a]

Ethylene Oxide			
Concentration (ppmv)	Retention Times (minutes)[b]		
	Column @ 45°C	Column @ 55°C	Column @ 65°C
125,000	1.76 ± 0.05	1.46 ± 0.09	1.15 ± 0.01
2,508	1.73 ± 0.02	1.41 ± 0.03	1.15 ± 0.02
502.4	1.71 ± 0.03	NA	NA
98.05	1.77 ± 0.36	1.46 ± 0.03	1.17 ± 0.02
22.81	1.78 ± 0.08	1.45 ± 0.10	1.19 ± 0.02
4.451	1.75 ± 0.01	1.38 ± 0.03	NA

Chlorofluorocarbon-12			
Concentration (ppmv)	Retention Times (minutes)[b]		
	Column @ 45°C	Column @ 55°C	Column @ 65°C
625,000	3.16 ± 0.06	2.39 ± 0.18	1.83 ± 0.04
6,022	3.30 ± 0.03	2.57 ± 0.04	2.02 ± 0.02
1,200	3.22 ± 0.05	NA	NA

[a] The column was made of 3 mm OD stainless steel and contained the liquid phase coated on Carbopack B (60/80 mesh). All measurements were made using a nitrogen carrier gas flowing at 30 mL/min. A 1-mL sample was injected via syringe. Retention times were measured electronically.

[b] Data are reported as means with 95% confidence intervals.

NA = Not analyzed

TABLE 10. ETHYLENE OXIDE AND DICHLORODIFLUOROMETHANE RETENTION TIMES ON 5% FLUORCOL[a]

Ethylene Oxide				Chlorofluorocarbon-12			
Concentration (ppmv)	Retention Times (minutes)[b] Column @ 45°C	Column @ 55°C	Column @ 65°C	Concentration (ppmv)	Retention Times (minutes)[b] Column @ 45°C	Column @ 55°C	Column @ 65°C
125,000	2.64 ± 0.08	2.21 ± 0.01	1.82 ± 0.03	625,000	4.72 ± 0.08	3.70 ± 0.03	2.91 ± 0.03
2,508	2.81 ± 0.05	2.27 ± 0.02	1.89 ± 0.03	6,022	5.57 ± 0.07	4.22 ± 0.11	3.36 ± 0.05
502.4	3.20 ± 0.34	NA	NA	1,200	5.38 ± 0.11	NA	NA
98.05	3.48 ± 0.14	2.79 ± 0.18	2.41 ± 0.15				
22.81	4.69 ± 3.54	5.43 ± 1.45	2.59 ± 0.08				
4.451	5.98 ± 1.55	NA	NA				

[a] The column was made of 3 mm OD stainless steel and contained the liquid phase coated on Carbopack B (60/80 mesh). All measurements were made using a nitrogen carrier gas flowing at 30 mL/min. A 1-mL sample was injected via syringe. Retention times were measured electronically.

[b] Data are reported as means with 95% confidence intervals.

NA = Not analyzed

TABLE 11. ETHYLENE OXIDE AND DICHLORODOFLUOROMETHANE RETENTION TIMES ON 3% SP-1000[a]

Ethylene Oxide				Chlorofluorocarbon-12			
Concentration (ppmv)	Retention Times (minutes)[b]			Concentration (ppmv)	Retention Times (minutes)[b]		
	Column @ 45°C	Column @ 55°C	Column @ 65°C		Column @ 45°C	Column @ 55°C	Column @ 65°C
125,000	1.49 ± 0.18	1.30 ± 0.18	1.24 ± 0.03	625,000	1.98 ± 0.09	1.68 ± 0.27	1.46 ± 0.03
2,508	1.36 ± 0.27	1.24 ± 0.27	1.21 ± 0.18	6,022	2.08 ± 0.27	1.76 ± 0.18	1.56 ± 0.18
98.05	1.38 ± 0.72	1.26 ± 0.09	1.23 ± 0.05				
22.81	1.36 ± 0.00	1.23 ± 0.18	1.21 ± 0.02				

[a] The column was made of 3 mm OD stainless steel and contained the liquid phase coated on Carbopack B (60/80 mesh). All measurements were made using a nitrogen carrier gas flowing at 30 mL/min. A 1-mL sample was injected via syringe. Retention times were measured electronically.

[b] Data are reported as means with 95% confidence intervals.

NA = Not analyzed

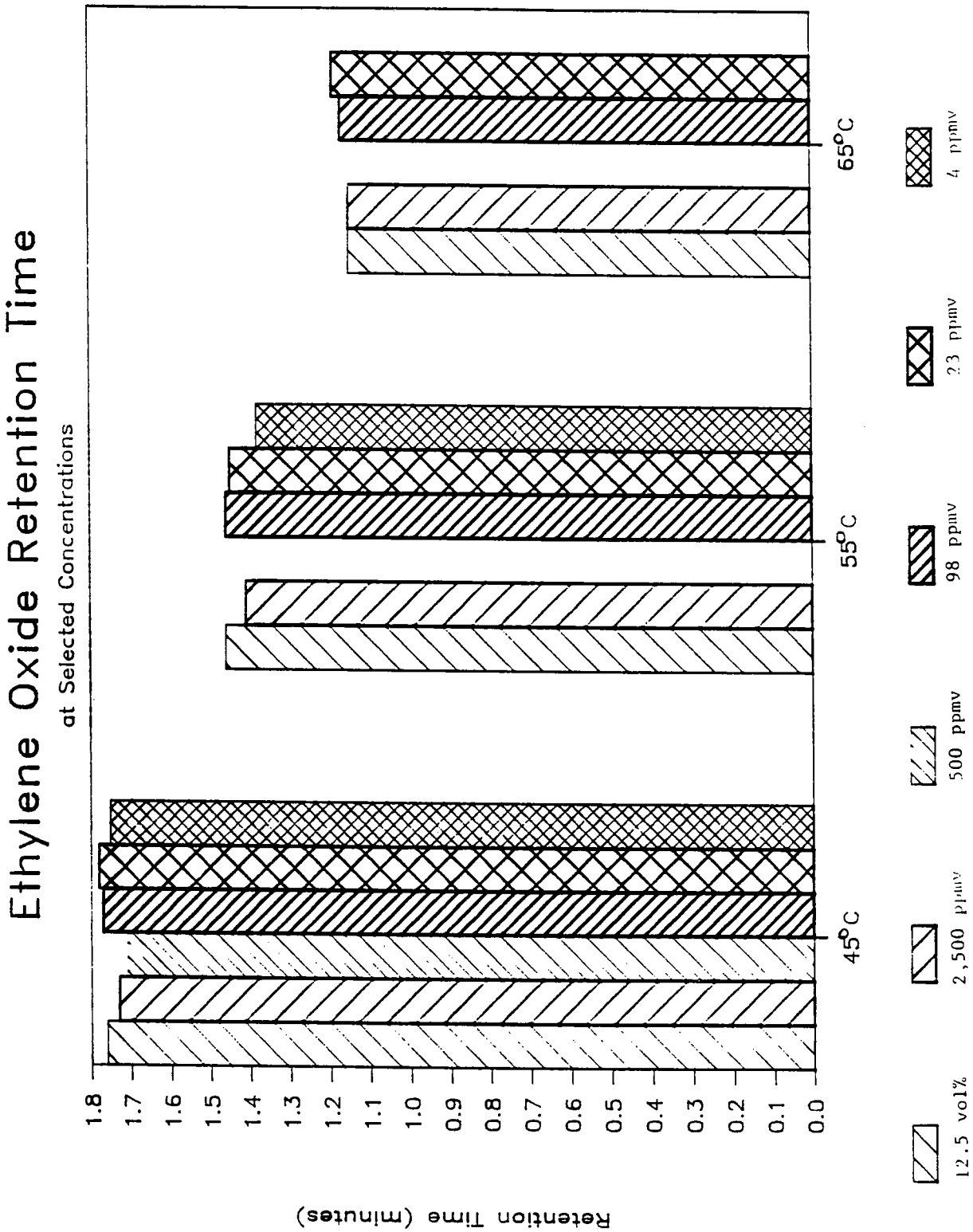

Figure 5. Ethylene oxide retention times on a 1% SP-1000 column.

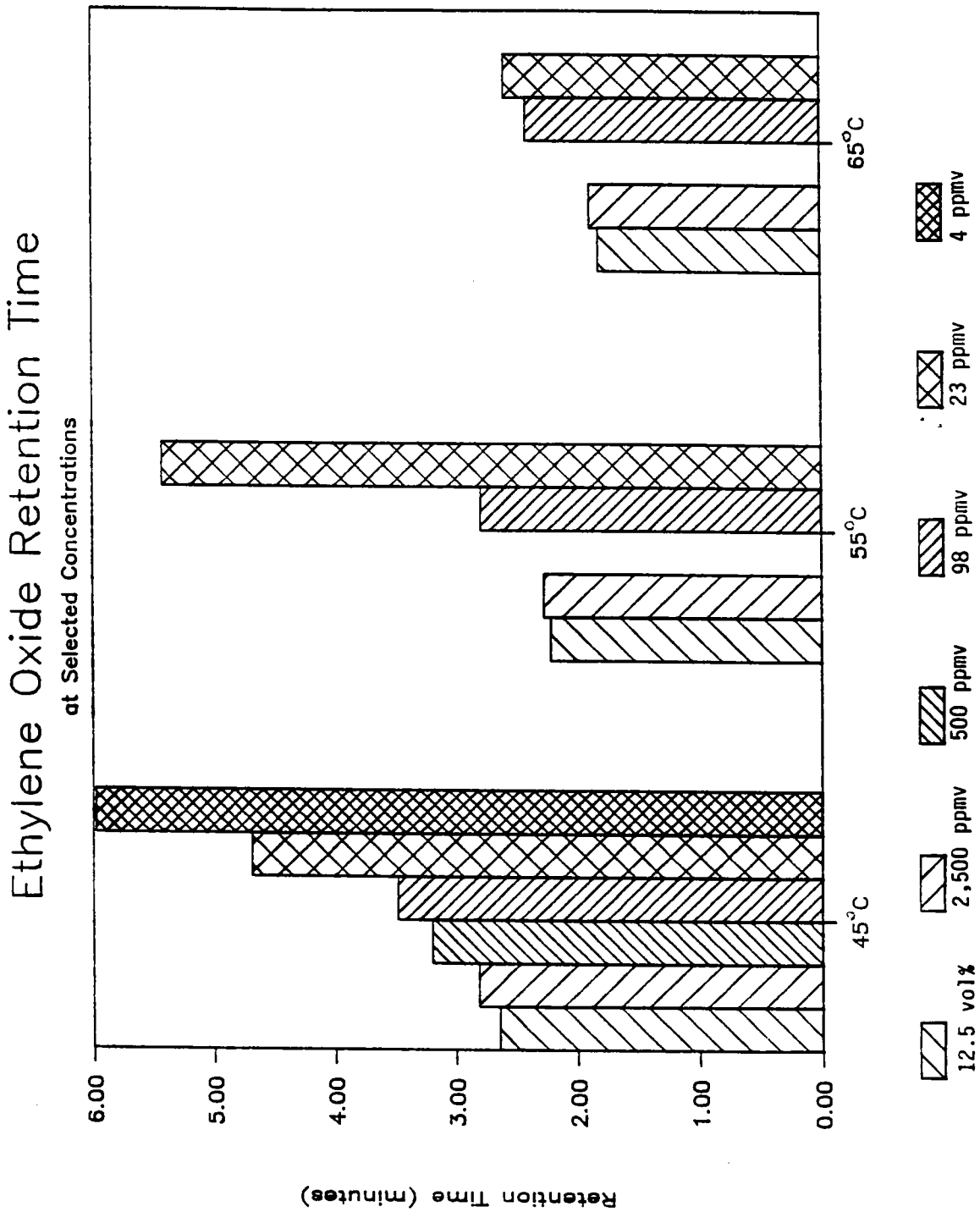

Figure 6. Ethylene oxide retention times on a 5% Fluorcol column.

Thus, the SP-1000 columns were superior for analyzing samples where the expected concentration was unknown or where the concentration was expected to vary by several magnitudes. The Fluorcol column is most useful for analyzing samples with percent level EO concentrations where the retention time shift is minimal. Because of the retention time stability, the 1% SP-1000 column can be used for both scrubber inlet and outlet analyses, whereas the Fluorcol column can not.

Limits of Detection and Quantitation

The limits of detection (LOD) and quantitation (LOQ) were determined using the method reported by Knoll.[14] The columns were evaluated at three temperatures and the results are reported in Tables 12 and 13. Lower LOD and LOQ values indicate columns better suited for trace analyses. Values are reported as means with 95% confidence intervals.

The LOD and LOQ are lowest for the 3% SP-1000 column and are independent of column temperature. For the 1% SP-1000 and 5% Fluorcol columns the LODs and LOQs are comparable and approximately a factor of three greater than for the 3% SP-1000 column.

SAMPLE CONTAINER

The stability of EO was evaluated in three sample containers:

- One-liter Tedlar bags,
- Five-milliliter gas-tight syringes, and
- Vacu-Samplers.

The one-liter Tedlar bags were purchased from NuTech Corporation and had double seams and a twist-valve tube fitting and a septum port for a syringe. Before use they were leak-checked by filling them with inert gas and allowing them to sit overnight under a blanket. Ten percent of the bags were blanked and all of the bags were evacuated prior to sample collection. The bags were not pre-conditioned with sample prior to use.

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TABLE 12. LIMIT OF DETECTION[a]

Column I.D.[b]	Concentration (ppmv)[c]		
	Column @ 45°C	Column @ 55°C	Column @ 65°C
1% SP-1000 (1.8 m)	0.17 ± 0.002	0.19 ± 0.004	0.16 ± 0.16
3% SP-1000 (2.4 m)	0.06 ± 0.003	0.07 ± 0.003	0.08 ± 0.002
5% Fluorcol (3.0 m)	0.20 ± 0.03	2.33 ± 0.17	0.14 ± 0.14

[a] Limits of detection and quantitation were determined using the method reported by Joseph E. Knoll in "Estimation of the Limit of Detection in Chromatography," Journal of Chromatographic Science, Volume 23, September, 1985, pages 422-425.

[b] All columns were made of 3 mm OD stainless steel and contained the liquid phase coated on Carbopack B (60/80 mesh). All measurements were made using a nitrogen carrier gas flowing at 30 mL/min.

[c] Data are reported as means with 95% confidence intervals.

TABLE 13. LIMIT OF QUANTITATION[a]

Column I.D.[b]	Concentration (ppmv)[c]		
	Column @ 45°C	Column @ 55°C	Column @ 65°C
1% SP-1000 (1.8 m)	0.51 ± 0.007	0.55 ± 0.01	0.46 ± 0.46
3% SP-1000 (2.4 m)	0.18 ± 0.008	0.20 ± 0.008	0.22 ± 0.007
5% Fluorcol (3.0 m)	0.58 ± 0.09	6.79 ± 0.51	0.41 ± 0.41

[a] Limits of detection and quantitation were determined using the method reported by Joseph E. Knoll in "Estimation of the Limit of Detection in Chromatography," Journal of Chromatographic Science, Volume 23, September, 1985, pages 422-425.

[b] All columns were made of 3 mm OD stainless steel and contained the liquid phase coated on Carbopack B (60/80 mesh). All measurements were made using a nitrogen carrier gas flowing at 30 mL/min.

[c] Data are reported as means with 95% confidence intervals.

The five-milliliter gas-tight syringes were Pressure-Lok® Series A-2 with push-button valves. The syringes were used with two-inch tapered needles (0.028 inches OD by 0.008 inches ID). Ten percent of the syringes were filled with inert gas and blanked prior to analysis.

The Vacu-Samplers were purchased from MDA Scientific, Incorporated, and are aerosol-type cans that have been completely evacuated and then back-filled with nitrogen to a partial vacuum of 20 inches of mercury (246.6 mL of nitrogen at standard temperature and pressure). The Vacu-Sampler will collect 123.3 mL of sample at standard temperature and pressure. Additional information on the Vacu-Sampler is contained in Appendix D.

Sample Stability

Duplicate syringe and Vacu-Sampler samples were acquired. One sample was analyzed in the field on the day of acquistion. The other sample was analyzed four or five days later in the Radian PPK laboratory. Stability was determined by calculating percent relative difference using Equation 4:

$$PRD = (C_2 - C_1)/C_1 \times 100 \qquad \text{(Equation 4)}$$

where:

PRD = percent relative difference,
C_2 = measured concentration at PPK laboratory in ppmv, and
C_1 = measured concentration at field site in ppmv.

Stability results for syringes and Vacu-Samplers are listed in Tables 14 and 15, respectively.

Twenty-four of the syringe samples provided reliable stability data. The relative percent differences between duplicate samples analyzed four or five days apart ranged from -40 to +10 and averaged -20 showing that over a four or five day period the EO concentration in the syringes dropped by an average of 20 percent. Previous studies of stability of hydrocarbons in 50-mL syringes

TABLE 14. STABILITY OF ETHYLENE OXIDE IN GAS-TIGHT SYRINGES

Concentration (ppmv) on Analysis Date			Percent[a]	Sterilizing	Analytical
June 22	June 23	June 27	Difference	Gas	Column
1,400	NA	913	-34.8	12/88	1% SP-1000
1,150	NA	1,100	-4.35	12/88	1% SP-1000
1,330	NA	999	-24.9	12/88	1% SP-1000
645	NA	517	-19.8	12/88	1% SP-1000
644	NA	492	-23.6	12/88	1% SP-1000
353	NA	273	-22.7	12/88	1% SP-1000
310	NA	219	-29.4	12/88	1% SP-1000
102	NA	75.7	-25.8	12/88	1% SP-1000
	563[b]	460	-18.3	100% EO	5% Fluorcol
	397[b]	274	-31.0	100% EO	5% Fluorcol
	561[b]	346	-38.3	100% EO	5% Fluorcol
	1,340	1,450	+8.21	100% EO	5% Fluorcol
		average =	-22.1		

[a] Percent Difference is defined as $(C_2 - C_1)/C_1 \times 100$ where C_2 is the concentration on June 27 and C_1 is the concentration on June 22 or 23.

[b] These samples were analyzed on the 1% SP-1000 column and were adjusted for the lower response obtained on the Fluorcol column on June 23 by multiplying the response by 0.77.

NA = Not available

TABLE 15. STABILITY OF ETHYLENE OXIDE IN VACU-SAMPLERS

Concentration (ppmv) on Analysis Date		Percent[a] Difference	Sterilizing Gas	Analytical Column
June 23	June 27			
2,130[b]	2,190	+2.82	100% EO	5% Fluorcol
534[b]	548	+2.62	100% EO	5% Fluorcol
781[b,c]	433	-44.6	100% EO	5% Fluorcol
460	424	-7.83	100% EO	1% SP-1000
778	557	-28.4	100% EO	1% SP-1000
1,480	1,520	+2.70	100% EO	5% Fluorcol
1,460	950	-34.9	100% EO	5% Fluorcol
	average =	-15.4		

[a] Percent Difference is defined as $(C_2 - C_1)/C_1 \times 100$ where C_2 is the concentration on June 27 and C_1 is the concentration on June 23.

[b] These samples were analyzed on the 1% SP-1000 column and were adjusted for the lower response obtained on the Fluorcol column on June 23 by multiplying the response by 0.77.

[c] Sample concentration probably biased high for an unknown reason.

showed that 20% of the hydrocarbons were lost within a four-hour period.[15] The hydrocarbon loss was attributed to diffusion from the syringe.

Only fourteen of the Vacu-Sampler samples were used to provide stability data. The three duplicate Vacu-Sampler samples that had extremely low area counts (below 60 ppmv) were taken at the very end of the evacuation and were suspected of not being true duplicate samples. The relative percent differences between duplicate samples analyzed four days apart ranged from -45 to +3 and averaged -15. Thus, over a four-day period the EO concentration in the Vacu-Samplers dropped by an average of 15 percent. If the one sample suspected of being biased high was eliminated from the data base, the relative difference ranged from -35% to +3% and averaged -10 percent.

Stability results are listed in Tables 16 and 17 for bag samples containing exhaust from 12/88 and 100% EO tests, respectively. For bags containing exhaust from tests using 12/88 gas, the EO remained stable over a 48-hour period. After five to six days, these bags showed an average EO loss of 30 percent. The bags containing EO at concentrations less than 500 ppmv lost 36% and those containing EO at concentrations higher than 1,000 ppmv lost 22 percent. The average EO loss remained at 30% after nine to 10 days and after 13 to 14 days. Only bags with EO concentrations above 1,000 ppmv were analyzed after 17 to 18 days and they showed an average EO loss of 40 percent. Figures 7 and 8 show the variation in measured EO concentration over the 18 day test period for bags containing 12/88 exhaust.

Bags containing 100% EO exhaust at concentrations above 1,000 ppmv remained stable over four days. After eight days these bags averaged a 20% EO loss that increased to 33% after twelve days. Bags with concentrations below 550 ppmv averaged a 20% EO loss that remained unchanged between the fourth and twelfth day. Figures 9 and 10 show the variation in measured EO concentration over the 14-day test period for bags containing 100% EO exhaust.

Since the EO loss in the bags is concentration dependent and more EO is lost at lower concentrations, the EO loss is expected to be caused by adsorption of the EO onto the bag walls. Initially, an equilibrium probably occurs between the bag surface and the gas within the bag accounting for the

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TABLE 16. ETHYLENE OXIDE STABILITY IN TEDLAR BAGS CONTAINING 12/88 EXHAUST

Sample	Concentration (ppmv)						
	June 21	June 22	June 23	June 27	July 1	July 5	July 9[a]
Bag #13	1230	1370	1320	995	824	716	733
Bag #20	1340	NA	NA	1010	830	1420	985
Bag #22	1200	1360	1320	956	828	790	760
Bag #25	NA	976	NA	734	562	962	536
Bag #30	NA	374	NA	NA	NA	166	NA
Bag #32	NA	133	96.5	34.2	34.4	NA	NA
Bag #36	NA	28.5	NA	NA	61.8	48.8	65.6
Bag #37	NA	36.7	NA	NA	NA	124	NA
Bag #39	NA	29.8	27.2	1.08	11.9	NA	NA
Bag #41	NA	1170	NA	NA	636	546	538
Bag #44	NA	NA	NA	1120	954	803	810
Bag #45	NA	1240	1380	958	865	690	683
Bag #48	NA	NA	NA	462	370	556	NA
Bag #50	NA	305	340	214	195	173	NA
Bag #55	NA	NA	80.6	57.4	75.2	71.0	NA
Bag #56	NA	NA	101	53.6	70.5	70.6	NA
Bag #57	NA	NA	83.5	51.8	65.8	48.4	NA

[a] Samples analyzed on a 3% SP-1000 column

NA = Not available

TABLE 17. ETHYLENE OXIDE STABILITY IN TEDLAR BAGS CONTAINING 100% EO EXHAUST

Sample	Concentration (ppmv)				
	June 23	June 27	July 1	July 5	July 9[a]
Bag #58	343	NA	270	248	212.8
Bag #60	2,840	2,410	2,030	1,660	1,408.0
Bag #63	544	470	426	430	364.8
Bag #64[b]	342	170	13.7	NA	NA
Bag #65	344	238	258	242	220.8
Bag #66	334	230	268	244	225.6
Bag #67	430	370	322	303	284.0
Bag #68	426	352	307	516	NA
Bag #69	387	282	270	226	NA
Bag #70	1,530	1,760	1,400	1,200	NA
Bag #71	1,440	1,490	1,080	902	NA
Bag #72	1,200	1,270	974	756	NA

[a] Samples analyzed on a 3% SP-1000 column

[b] Bag leaked

NA = Not available

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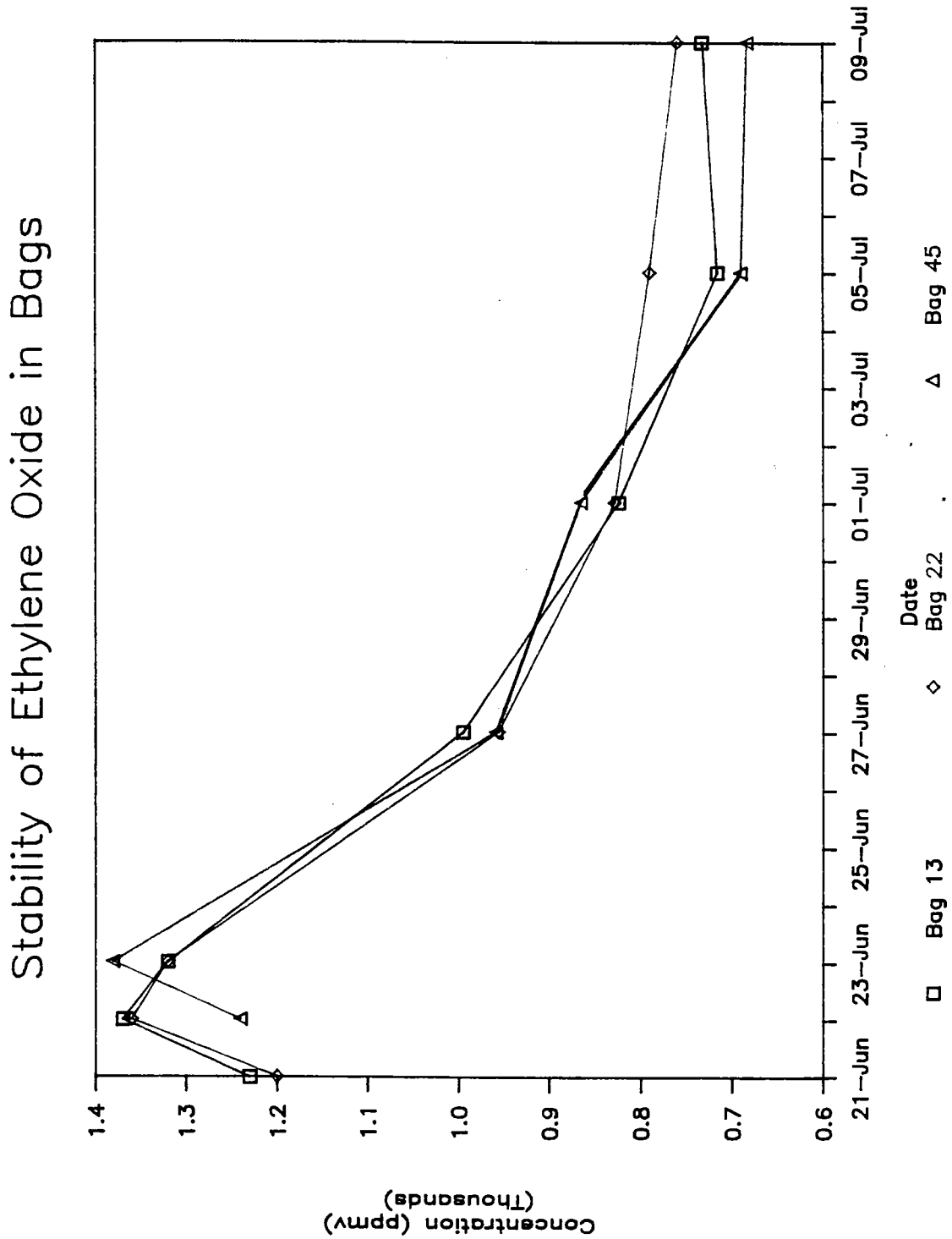

Figure 7. Ethylene oxide stability in 12/88 exhaust at > 1,000 ppmv.

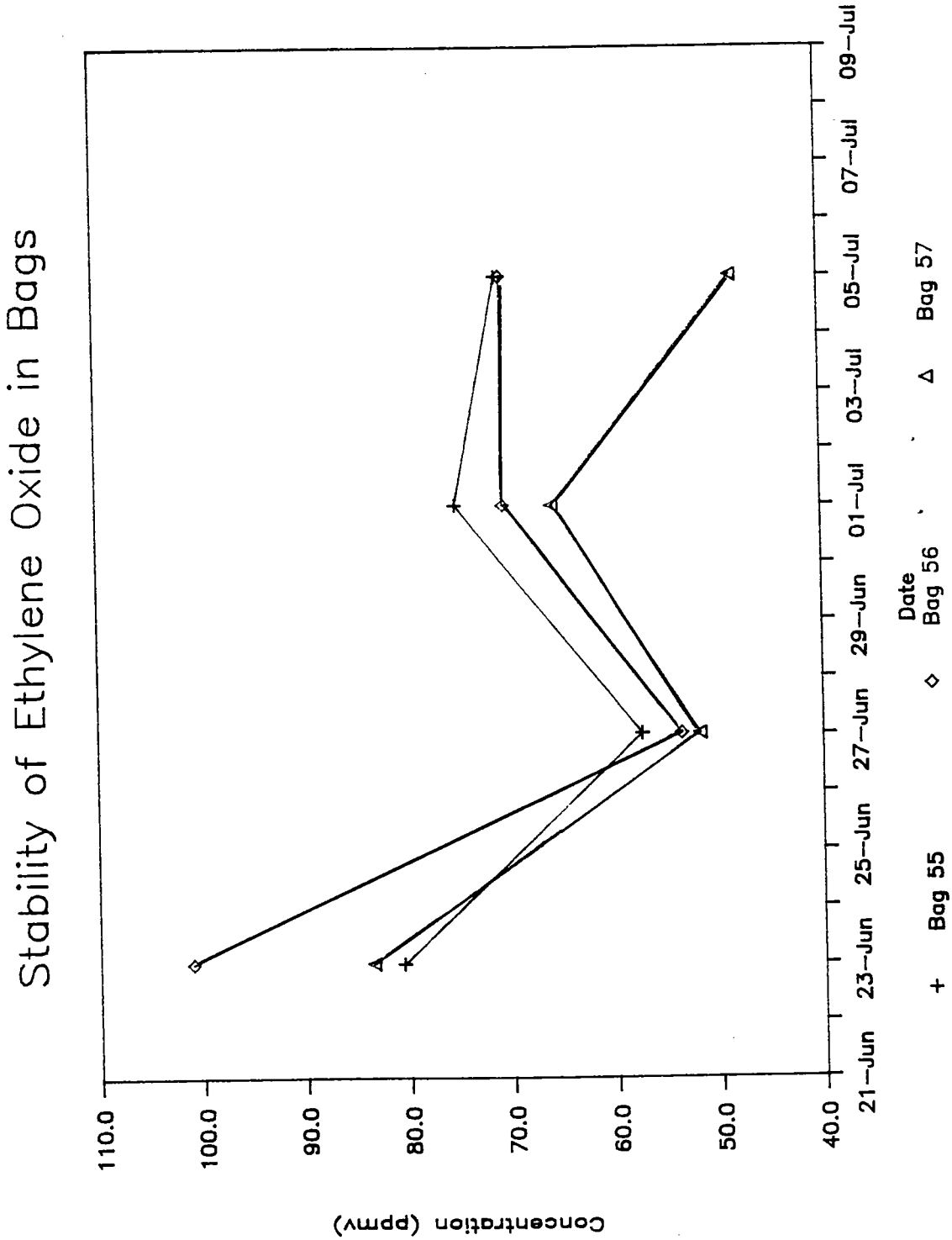

Figure 8. Ethylene oxide stability in 12/88 exhaust at < 100 ppmv.

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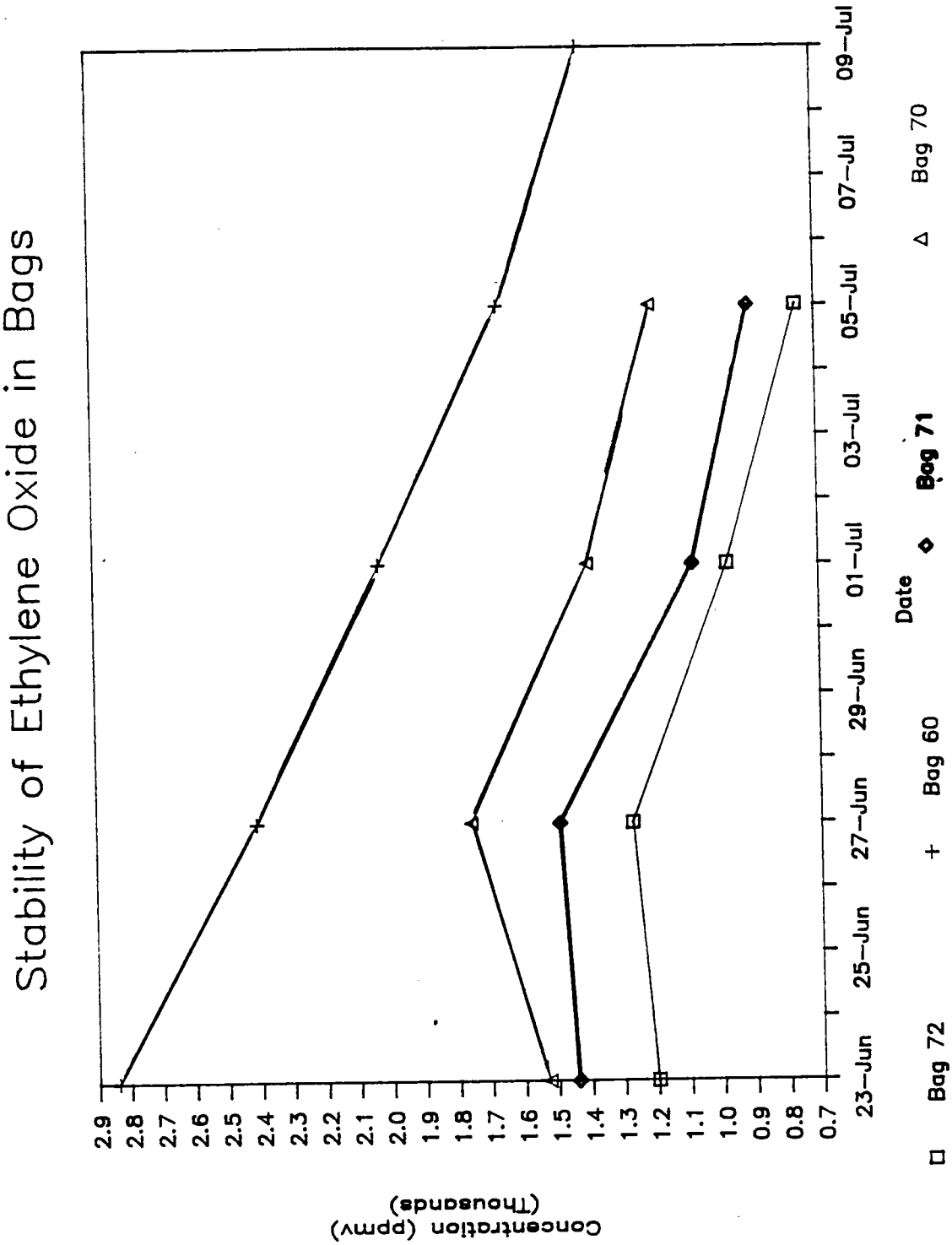

Figure 9. Ethylene oxide stability in 100% EO exhaust at >1,000 ppmv.

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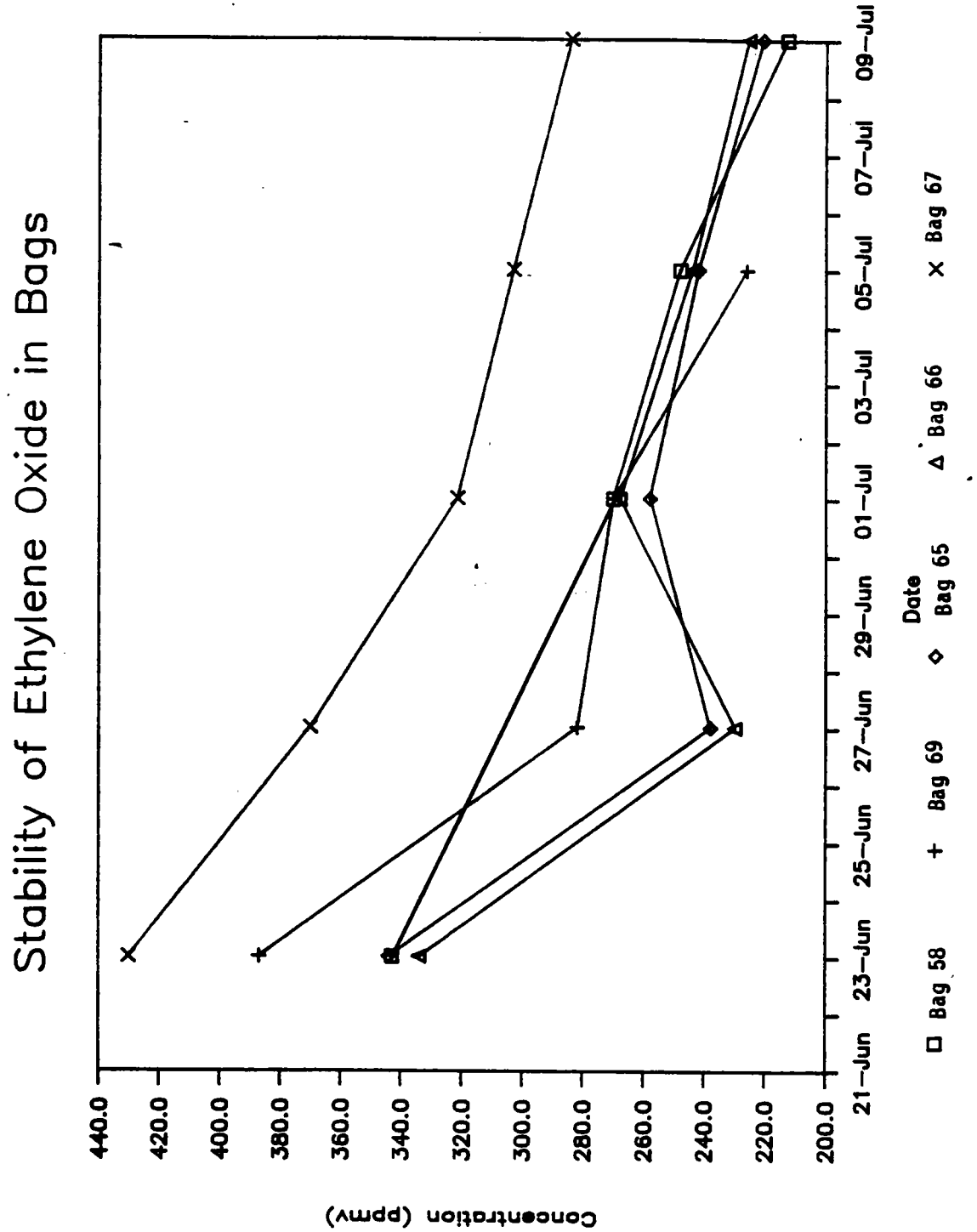

Figure 10. Ethylene oxide stability in 100% EO exhaust at < 500 ppmv.

two- to four-day period of stability observed. As the gas remains in the bag longer, the EO may be penetrating further into the bag wall, accounting for the additional EO loss. Other data[16] shows that improved EO stability can be obtained at surface-to-volume ratios of 3.6×10^{-2} and 2.0×10^{-2} m^2/L. In these bags, 10 ppmv EO samples remained stable for one week.

Sample Container Comparison

During the second and third tests samples were acquired in all three sample containers. Although samples were not acquired simultaneously, they were taken within a two- to three-minute interval so that they would be as identical in composition as possible. The containers were compared by calculating percent relative differences as defined in Equations 5 to 7:

$$PRD_{VB} = (C_V - C_B)/C_B \times 100 \qquad \text{(Equation 5)}$$

$$PRD_{VS} = (C_V - C_S)/C_S \times 100 \qquad \text{(Equation 6)}$$

$$PRD_{SB} = (C_S - C_B)/C_B \times 100 \qquad \text{(Equation 7)}$$

where:

PRD_{VB} = the percent relative difference between EO concentrations measured in Vacu-Samplers and bags,

PRD_{VS} = the percent relative difference between EO concentrations measured in Vacu-Samplers and syringes,

PRD_{SB} = the percent relative difference between EO concentrations measured in syringes and bags,

C_V = the EO concentration measured in the Vacu-Samplers,

C_B = the EO concentration measured in the bag samples, and

C_S = the EO concentration measured in the syringe samples.

The results are given in Table 18.

In general, when looking at the concentrations for comparable samples, the concentrations measured from the three tested containers are usually of similar magnitude. In two cases the syringe samples are obviously low, a

TABLE 18. COMPARISON OF ETHYLENE OXIDE SAMPLE CONTAINERS

Concentration (ppmv) Sample Container			Percent Relative Difference				
Bag	Vacu-Sampler	Syringe	Vacu-Sampler to bag	Vacu-Sampler to syringe	Syringe to bag	Sterilizing Gas	Analytical Column
1,170	Void	1,400	NA	NA	+19.7	12/88	1% SP-1000
1,540	NS	1,150	NA	NA	-25.3	12/88	1% SP-1000
1,430[d]	Void	645[a]	NA	NA	NA	12/88	1% SP-1000
1,240	NS	1,330	NA	NA	+7.26	12/88	1% SP-1000
684[d]	Void	645	NA	NA	-5.70	12/88	1% SP-1000
630[d]	NS	644	NA	NA	+2.22	12/88	1% SP-1000
305	Void	353	NA	NA	+15.7	12/88	1% SP-1000
308[d]	NS	310	NA	NA	+0.649	12/88	1% SP-1000
120	Void	NC	NA	NA	NA	12/88	1% SP-1000
145	NS	175	NA	NA	+20.7	12/88	1% SP-1000
101	Void	102	NA	NA	+0.990	12/88	1% SP-1000
83.5	NS	96.0	NA	NA	+15.0	12/88	1% SP-1000
1,117[a]	2,130[b]	248[a,b]	+90.7	NA	NA	100% EO	5% Fluorcol
2,840	2,602[b]	NS	-8.38	NA	NA	100% EO	5% Fluorcol
560	534[b]	563[b]	-4.64	-5.15	+0.536	100% EO	5% Fluorcol
544	781[b,c]	NS	+43.6	NA	NA	100% EO	5% Fluorcol
344	354[b]	397[b]	+2.91	-10.8	+15.4	100% EO	5% Fluorcol
334	71.5[a,b]	NS	-78.6	NA	NA	100% EO	5% Fluorcol
426	599[b]	561[b]	+40.6	+6.77	+31.7	100% EO	5% Fluorcol
387	465[b]	NS	+20.2	NA	NA	100% EO	5% Fluorcol
1,440	1,480	1,340	+2.78	+10.4	-6.94	100% EO	5% Fluorcol
1,200	1,460	NS	+21.7	NA	NA	100% EO	5% Fluorcol
		Average	+13.1	+0.46	+6.57		

[a] Sample concentration obviously low -- cause unknown.

[b] These samples were analyzed on the 1% SP-1000 column and were adjusted for the lower response obtained on the Fluorcol column on June 23 by multiplying the response by 0.77.

[c] Sample concentration probably biased high for unknown reason.

[d] These samples were analyzed on the 5% Fluorcol column and were adjusted for the higher response obtained on the 1% SP-1000 column on June 22 by dividing the response by 0.82.

NA = Not available

V = Vacu-Sampler pressure was greater than atmospheric.

NS = No sample taken.

NC = Syringe needle was clogged.

conclusion based on analysis of the duplicate syringe sample analyzed for stability purposes and the comparable bag and Vacu-Sampler samples. No known explanation exists for these low syringe sample values. However, possible explanations include a clogged needle, a leaky syringe valve or syringe, and poor sample injection due to a clogged needle, leaky GC septum or operator error. Since these two syringe values were suspected to be low, they were not used in sample container comparisons or in syringe stability determinations.

In one case the Vacu-Sampler data are probably biased high based on the analysis of the duplicate Vacu-Sampler sample and the comparable bag sample. In another case the measured concentration is obviously lower than what was expected based on the comparable bag sample; however, the duplicate Vacu-Sampler sample is also low indicating that the sample may have been taken at the end of the evacuation when flow through the stack was low. In fact, that sample was taken during the last minute of the evacuation when the chamber pressure was 2 psia. For the bag samples, only one sample appears to be obviously and unexplainably lower than expected based on the comparable Vacu-Sampler sample. These data have been included in the sample container comparisons but have been flagged as questionable.

In comparing the Vacu-Samplers with the bags, the percent relative difference for all 10 samples ranged from -80 to +90. The measured EO concentration of samples taken within a two-minute interval averaged 13% higher in Vacu-Samplers than in bags. These data include the questionable Vacu-Sampler data and the questionable bag data. If these data are eliminated from consideration, the percent relative difference ranged from -10 to +40 with the Vacu-Samplers having an EO concentration that averaged 11% higher than the bags.

In comparisons of the Vacu-Samplers to the syringes, the four samples showed relative differences in measured EO concentrations of ± 10 percent. The EO concentration in the Vacu-Samplers averaged 0.5% higher than in the syringes.

The percent relative difference in the EO concentrations measured when comparing bag samples to syringe samples was ± 30 percent. The average relative difference was + 7%, indicating that the EO concentration tended to be higher in the syringe samples. Because the EO concentrations in the bags were also lower than the EO concentrations in the alternate containers, some of the EO was probably lost in the bag samples by adsorption on the bag walls. The EO adsorption losses in the bags were probably increased by not pre-conditioning the bags with sample prior to sample collection.

Another way to compare the sample containers is by the number of valid samples obtained. Out of 34 syringe samples, three samples were lost due to clogged needles, one sample was lost due to a septum leak at the column inlet, and two samples appeared low for an undetermined reason; thus, 17.6% of the syringe samples were invalid. At least 50% of the invalid syringe samples were due to clogged needles, a problem that may be reduced by using sideport needles.

Out of 20 Vacu-Samplers, four samples were inordinately lower than expected and one sample was unexpectedly high; thus, 25% of the samples were questionable. However, eighty percent of the questionable samples were probably due to an inopportune sample time as these samples were taken at the end of the evacuation (chamber pressure less than 2.3 psia) when gas flow through the stack was probably too low to provide an adequate sample.

Only three out of 27 bags (11%) retained for stability analysis had obvious leaks. The three bags were flat after six days. Leaks were not detected in the other 45 bags that were retained but not reanalyzed in the laboratory.

ETHYLENE OXIDE CONCENTRATION PROFILE

Ethylene Oxide Concentration Ranges in the Exhaust Gas

During Test 1 Evacuation 1 using 12/88 gas, grab samples were collected in bags at one-minute intervals. Eighteen samples collected between five and

22 minutes were analyzed. The results are shown in Figure 11. The EO concentration increased from 500 to 1,500 ppmv, indicating that EO volatilization may be more rapid than the decrease in chamber pressure. The desorption rate may be limiting as the maximum concentration plateaued between approximately 13 and 20 minutes. After 20 minutes, the concentration gradually decreased, probably due to decreased volumetric flow.

To summarize the observed EO concentration ranges during each evacuation, the measured EO concentration was 1,200 ppmv during the second 12/88 evacuation, 500 ppmv during the third, 300 ppmv during the fourth, 100 ppmv during the fifth and 80 ppmv during Evacuation 6. When 100% EO was used as the sterilizer gas, higher EO concentrations were measured in the exhaust gas. During Evacuation 1, the EO concentration ranged from 500 to 3,000 ppmv. The measured EO concentration was 500 ppmv during the second 100% EO evacuation, 300 ppmv during the third, 400 ppmv during the fourth, and 1,400 ppmv during the fifth evacuation. The increase in EO concentrations measured during the fourth and fifth evacuations are suspected of being high because Chamber #2 finished its cycle and began exhausting before Test 3 was completed. Since the chambers were all exhausted through one scrubber, attempts were made to prevent two chambers from exhausting simultaneously. This required manual monitoring of the chamber status and was subject to operator error.

Ethylene Oxide Concentration Ratios

During 12/88 tests, both the CFC-12 concentration and oxygen concentration were monitored. Concentration ratios were calculated from these data. Such ratios may be useful in establishing a regulation based on a maximum permissable EO concentration. The Fyrite provides reliable oxygen data for the 12/88 exhausts and can be used to verify whether the plant is diluting the emissions with air. However, if the facility used nitrogen to dilute emissions the dilution would not be detected by this procedure.

The calculated EO-to-CFC-12 ratios ranged from 0.001 to 0.002. A ratio plot as a function of time showed a distribution similar to the concentration profile.

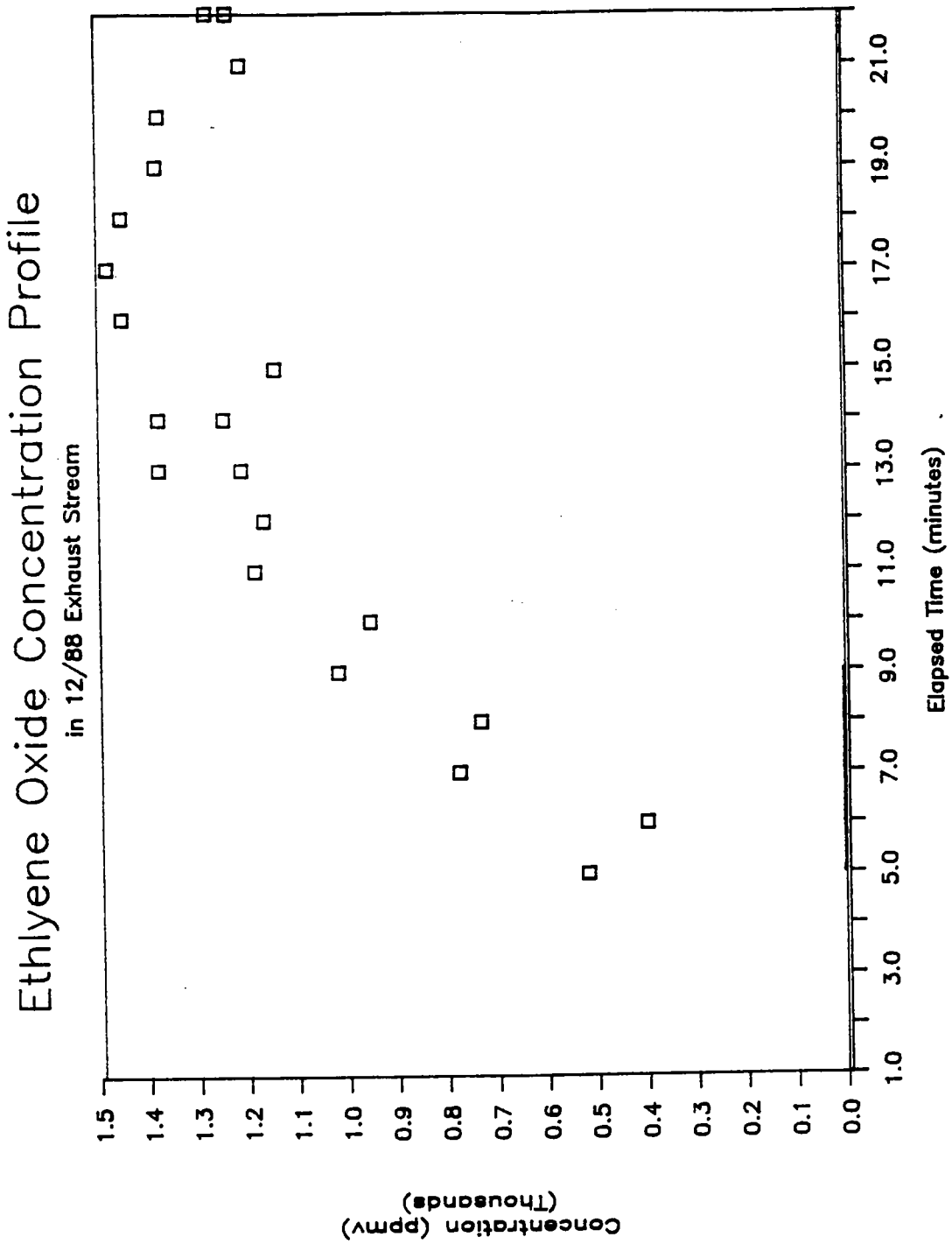

Figure 11. Ethylene oxide concentration profile during the first evacuation.

Unfortunately, Fyrite did not provide reliable oxygen data for 100% EO exhausts; thus, dilution of the exhaust by air cannot be determined. Since no other major components are expected in the 100% EO exhaust, there is no component concentration to which to ratio the EO concentration to indicate that the sample has been diluted.

SECTION 6

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APPENDIX A

GRAB SAMPLING AND ANALYTICAL METHOD DESCRIPTION

APPENDIX A

GRAB SAMPLING AND ANALYTICAL METHOD DESCRIPTION

APPLICABILITY AND PRINCIPLE

Applicability

This method applies to the measurement of the maximum EO concentration normalized to percent oxygen and CFC-12 emitted from sterilization chamber control units. It is applicable to emissions from sterilization control units that use dilute acid hydrolysis to remove the EO. The analytical method is capable of measuring from 0.5 parts per million by volume (ppmv) to 50 volume percent.

Principle

Samples are collected from the sterilization chamber control unit using a 3-second or shorter grab sampling technique and are analyzed off-line by gas chromatography with flame ionization detection (GC/FID). The maximum EO concentration emitted is determined directly from a standard calibration curve and the concentration ratios of EO-to-oxygen and EO-to-CFC-12 are calculated using the measured EO concentrations and the measured oxygen and CFC-12 concentrations.

APPARATUS

The following equipment is required for performing grab sampling with off-line GC/FID analysis.

Heat-traced Teflon® Line

A short heat-traced Teflon line is used to transport the sample from the vent stream to the sample container. The line is heated to a temperature

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slightly higher than the temperature of the vent gas in order to prevent condensation. The length of line required depends upon the proximity of the sampling container to the sampling port.

Vacuum Pumps

A vacuum pump, capable of pumping 20 liters per minute (L/min) [0.7 cubic feet per minute (cfm)] with a leak-free, Teflon-coated diaphragm, is required to continuously withdraw sample from the sampling port and to pump sample to the sample container.

Acid Scrubber

One 500 mL-Erlenmeyer flask with a two-hole stopper containing dilute sulfuric acid at a pH of 1 is used to remove EO from the sampling stream before venting it to the atmosphere. The acid scrubber may not be required when sampling controlled emissions if the exhaust line is vented in a well-ventilated area void of personnel.

Thermocouples

Two thermocouples are needed to monitor the temperature of the vent stream. One should be wrapped in moist material to measure the wet bulb temperature. The accompanying temperature readout devices should be capable of measuring from ambient temperature up to 200°F (93°C).

Gas Chromatograph with Flame Ionization Detectector(FID)

A GC with a column and FID detector is needed for the off-line analysis of the grab samples. Other detectors (Thermal Conductivity Detector or Photoionization Detector) may be substituted for the FID if they are shown to give equivalent results.

Chromatographic Column

For controlled exhausts, a stainless steel, 6 foot (ft) [1.8 meter (m)] x 1/8 inch [3 millimeter (mm)] outside diameter (OD), column

containing 1% SP-100 on 60/80 mesh Carbopack B is used to separate the EO from the CFC-12 and other materials present in the vent gas. For uncontrolled exhausts a stainless steel 10 foot (3m) x 1/8 inch (3mm) OD column containing 5% Fluorcol on 60/80 mesh carbopack B is used. Other columns (Chromosorb 102, Porapak® Q or R, Carbowax 20M) may be used, provided that the precision and accuracy of the standards analysis are not impaired. Information confirming the adequate resolution of the EO peak must be presented. Adequate resolution is defined as an area overlap of not more than 10% of the EO peak by an interferent peak.

Recorder/Integrator

A recorder/integrator is needed to record results.

Regulators

The following regulators are required for the GC support gases and the EO standards.

CGA 580--

One regulator is needed for the nitrogen carrier gas. A second regulator may be required for the standard manifold purge if the carrier gas line cannot be tapped.

CGA 590--

One regulator is needed for the air for the FID.

CGA 350--

Five regulators are needed; one regulator for the hydrogen on the FID and four regulators for the EO and CFC-12 standards. Two regulators with stainless steel diaphragms and Teflon seats and seals are required for the low concentration standards; one should be reserved for standards under 100 ppmv

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EO and the other for standards between 100 and 1000 ppmv EO. The other two standard regulators must be stainless steel; one should be reserved for standards between 1000 ppmv and 0.5 vol% and the other for standards above 0.5 volume percent.

Teflon Tubing

Teflon tubing is needed to connect the gas cylinders to the GC, the sampling line to the exhaust area, and for other miscellaneous connections. The diameter and length of the tubing depend upon the requirements of the system used. A recommended amount and diameter of tubing would be 10 to 20 ft (3 to 6 m) of 1/4-inch OD tubing. Each standard regulator should be equipped with 4 to 5 ft (1 to 2 m) of 1/8-inch OD Teflon tubing.

Fittings

An assortment of Swagelock® fittings is desirable to plumb the GC to the gas cylinders and the sample containers to ensure leak-tight fittings. The size and type of fittings needed depend upon the type of tubing used and the type of fittings required by the GC and the cylinder regulators. Some recommendations are:

Caps and Front and Back Ferrules--

Teflon caps and ferrules (1/4-inch) are needed to plumb in the glass flask. Stainless steel caps and ferrules (1/4-inch and 1/8-inch) are used on the ends of the Teflon tubing.

Unions--

Teflon (1/4-inch) and stainless steel (1/4-inch and 1/8-inch) unions are used to connect tubing to impingers, etc.

Reducing Unions--

Stainless steel reducing unions (3/8-inch to 1/4-inch and 1/4-inch to 1/8-inch) are needed to connect cylinders to the GC and the sampling line to the sample containers.

Soap Film Flow Meter

A soap film flow meter is used to measure GC carrier and support gas flow rates. It is also needed to calibrate any rotameters, dry gas meters, and mass flow meters used.

Heated Box or Large Oven

A heated box or large oven is needed for storing the sample containers prior to analysis to prevent water from condensing out of the sample. The box should be capable of being heated up to 40°C (105°F).

Sample Containers

Two dozen sample containers are needed to hold the grab samples. The containers should be clean and evacuated.

Gas-tight Syringe

A 2-mL gas tight syringe with an on-off valve is required for injection of the grab samples into the GC/FID.

Two- or Three-way Radio

A two- or three-way radio is helpful to simplify communications between personnel at the sampling port, in the analytical area, and in the sterilizer control room.

REAGENTS

Unless otherwise indicated, all reagents should conform to the specifications established by the Committee on Analytical Reagents of the American Chemical Society where such specifications are available; otherwise, the best available grade should be used.

Nitrogen Gas

A grade of nitrogen which is 99.995 percent pure is required for use as the chromatographic carrier gas and as the system blank. If lower grades of nitrogen are used, purify the gas using hydrocarbon, water, and oxygen traps.

Hydrogen Gas

A grade of hydrogen which is 99.995 percent pure is required as a support gas for the FID. If lower grades of hydrogen are used, purify the gas using a hydrocarbon trap.

Air

A grade of air which is 99.9999 percent pure is required as a support gas for the FID. If lower grades of air are used, purify the gas using a hydrocarbon trap containing activated carbon.

Ethylene Oxide Standard Cylinders

Ethylene oxide and CFC-12 standards prepared in nitrogen which are certified through direct analysis are recommended for system calibration. The following concentrations balanced in nitrogen are suggested:

- 4,000 ppmv EO and 80 vol % CFC-12,
- 1,000 ppmv EO and 20 vol % CFC-12,
- 250 ppmv EO and 5 vol % CFC-12,
- 62.5 ppmv EO and 1.25 vol % CFC-12.

Dichlorodifluoromethane Lecture Bottle

A lecture bottle of 99% CFC-12 is required for calibrating the analytical system for samples containing CFC-12 at concentrations above 80 vol%.

1 N Sulfuric Acid Solution

A scrubbing solution consisting of 1 N H_2SO_4 with a pH between 1 and 2 is required for removing EO from the sampling stream before venting to the atmosphere. To prepare add 30 mL of concentrated sulfuric acid to 1 L of distilled water. Mix well. A minimum of 500 mL of scrubbing solution is needed.

Quality Assurance Audit Samples

A minimum of one gas audit cylinder from the EPA repository, if possible, in the range of the expected EO concentration is required to verify the accuracy of the analytical system and the competence of the analyst.

PROCEDURE

Sampling Considerations

The sampling period begins four to 13 minutes after the start of the initial chamber evacuation and lasts about seven to 16 minutes, ending when the chamber has been completely evacuated or approximately 20 minutes after the start of the evacuation. The sampling line is continuously flushed with sample during the sampling period. The number of grab samples is based on the length of the evacuation interval and expected EO concentration profile.

Flow Rate Estimation--

If flow rate information in desired, molar gas flow rate may be estimated from chamber temperature and pressure provided from the chamber monitor console.

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Temperature--

Record the stack temperature using a type-K thermocouple or equivalent device every time a sample is acquired or every two minutes.

Moisture Content--

Determine the moisture content of the vent stream during each evacuation using the wet bulb/dry bulb technique.

Grab Sampling Procedure

In this procedure, sample is continuously withdrawn from the vent stream using a vacuum pump. The gas is channeled into the sample container during a three-second interval over regularly spaced intervals.

Assemble the sampling system as shown in Figure A-1. Leak check the assembly to prevent sample dilution and to protect personnel from fugitive EO emissions.

Place the probe at the centroid of the stack. Start the vacuum pumps and heat the sample transfer lines to prevent condensation.

When evacuation of the chamber begins, wait at least four minutes for the system dead volume to be flushed out. Record the temperature of the vent gas when a sample is taken or at two-minute intervals. Measure oxygen content at one-minute intervals or each time a sample is taken. Take at least one wet bulb reading during each evacuation. The sample data sheet shown in Figure A-2 should be used to record the necessary sample data.

Analytical Procedure

Grab samples are analyzed by GC/FID. Samples collected in gas-tight syringes should be analyzed within several hours of collection. Samples collected in Tedlar bags should be analyzed with 48 hours of collection and samples collected in Vacu-Samplers should be analyzed within four days.

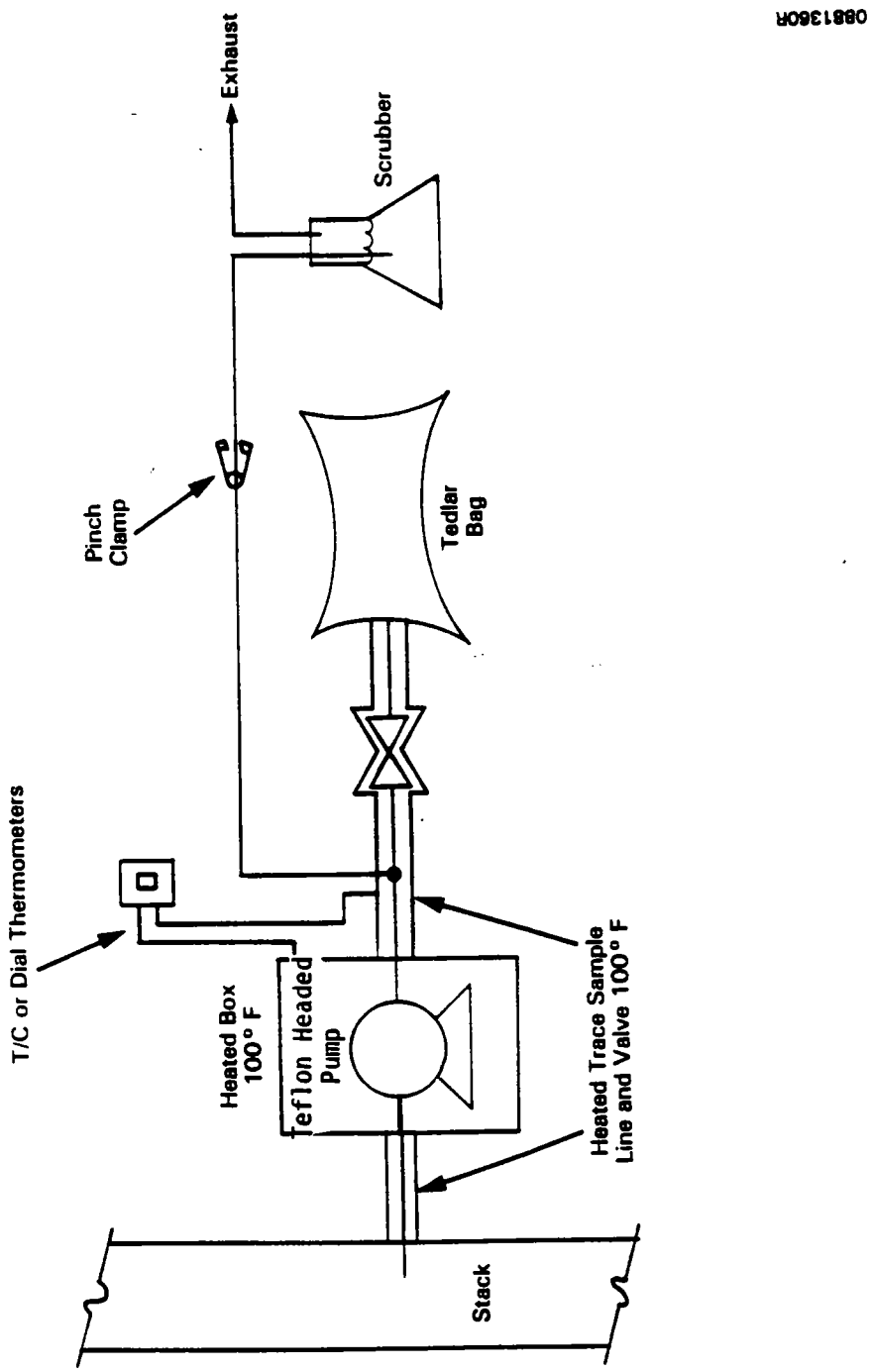

Figure A-1. Grab sampling assembly.

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ETHYLENE OXIDE SAMPLING DATA SHEET

DATE _____

RUN ID _____

SAMPLER _____

SCHEDULE:

INITIAL EXHAUST _____

AIR WASHES _____

FACILITY _____

BAROMETRIC PRESSURE _____

TIME	EXHAUST #	START	CONTAINER	ID	TEMPERATURE (F) VENT	t'	PUMP	HEAT TRACE	PERCENT OXYGEN	Ps (IN Hg)	NOTES

Figure A.2 Sample data sheet.

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Gas Chromatographic Conditions--

The chromatographic conditions listed in Table A-1 will resolve EO from CFC-12 and other interferences common to EO control unit vents. It may be necessary to change these conditions to resolve other interferences that are present in samples collected from different EO sources.

Calibration--

Calibrate the GC before the start and at the end of the test using the gas standards. A minimum of four points (four different standard concentrations) are needed to construct a calibration curve. For analysis of samples from a controlled chamber, the GC requires calibration with 60 ppmv to 4,000 ppmv EO standards. For calculation of the EO to CFC-12 concentration ratio, calibrate the GC for CFC-12 using the CFC-12 lecture bottle. Use the same injection method and the same volume of sample for the calibration standards and the samples.

Sample Analysis--

After the GC is calibrated, analyze the samples. After every tenth sample perform a replicate analysis. After every twentieth sample, inject a mid-point standard to verify detector response and stability.

Documentation--

Document each sample and chromatogram by listing the sample location, sample time, sampler initials, vent gas temperature and static pressure, injection volume and time, barometric pressure, room temperature, and analyst initials.

Audit Analysis

Immediately after the preparation of the calibration curve and prior to the sample analyses, perform the analysis audit described in Appendix C, Procedure 2: "Procedure for Field Auditing GC Analysis." 40 CFR, Part 61.

TABLE A-1. GAS CHROMATOGRAPHIC CONDITIONS

Parameter	Recommendation
Column	5% Fluorcol on 60/80 Mesh Carbopack B, 10 ft (3 m) x 1/8 inch (3 mm), stainless steel for percent level analyses; 1% SP-1000 on 60/80 Mesh Carbopack B, 6 ft (1.8 m) x 1/8 inch (3 mm), stainless steel for ppmv level analyses.
Column Temperature	65°C, isothermal for percent level analyses; 45°C, isothermal for ppmv level analyses
Injector Temperature	175°C
Detector Temperature	200°C
Gas Flow Rates	Follow manufacturer's recommendations

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CALIBRATION

Probe Temperature Gauge and Thermocouple

Calibrate using ice water and boiling water (ASTM-E1 #63C or 63F specifications) before the test.

Gas Chromatograph

Calibrate the GC at the start and at the end of each test day using prepared or purchased gas standards. Follow the calibration procedure described earlier. Use the chromatographic data (peak height or area) and standard concentration to prepare a least squares calibration curve.

Certified Standard Cylinders

Verify the certified concentrations of the purchased standard cylinders using an independent standard (one purchased from a second supplier or prepared in the laboratory using pure EO and CFC-12 diluted with nitrogen). Using the independent standard, prepare four-point calibration curves. From the calibration curves, calculate the measured concentrations of the certified standards. If the measured concentrations differ from the certified concentrations by more than ±10%, do not use the standards.

CALCULATIONS

Perform the following calculations, retaining at least one figure more than the required number of significant figures. Round off to the correct number of significant figures after making the final calculation.

Ethylene Oxide Concentration

Determine the EO concentration at each measured point by comparing the area obtained for each sample with the least squares calibration curve obtained as described earlier. Plot EO concentration versus elapsed time.

Reproducibility

Calculate the reproducibility of the analysis by comparing the response of the replicate analysis to the original analysis using the following equation:

$$R = (C_R - C_O)/C_R \times 100 \qquad \text{(Equation A-1)}$$

where:

R = percent difference between replicate analyses,
C_R = the EO concentration in the replicate analysis, and
C_O = the EO concentration in the original analysis.

If more than three replicate analyses are performed per day, report an average R value with a standard deviation.

Inert Gas Concentration

Determine the inert gas concentration at each measured point based on GC data. If no CFC-12 is present in the sample, assume the gas which is not EO is air. Plot the inert gas concentration versus elapsed time.

Moisture Content

Calculate the moisture content (C_a) in the exhaust gas using the following formula:

$$C_a = (VP \times RH)/P_{bar} \qquad \text{(Equation A-2)}$$

where:

C_a = Water vapor in the gas stream, mole fraction
P_{bar} = Barometric pressure, mm (inches) Hg
VP = Saturated vapor pressure of water at stack temperature, mm (inches) Hg
RH = Relative humidity determined by wet bulb/dry bulb method

The relative humidity using the wet bulb/dry bulb method and the saturated vapor pressure of water at stack temperature can be obtained from standard tables.

Normalized Ethylene Oxide Concentration

Calculate the normalized EO concentration by dividing the measured EO concentration in ppmv by the CFC-12 or oxygen concentration in volume percent using the following equation:

$$N_{EO} = C1/C_2 \times 10{,}000) \qquad \text{(Equation A-3)}$$

where:

N_{EO} = normalized EO concentration,
C_1 = EO concentration, ppmv,
C_2 = CFC-12 or oxygen concentration, vol%, and
10,000 = conversion factor, ppmv/volume percent.

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APPENDIX B

CALIBRATION CURVES

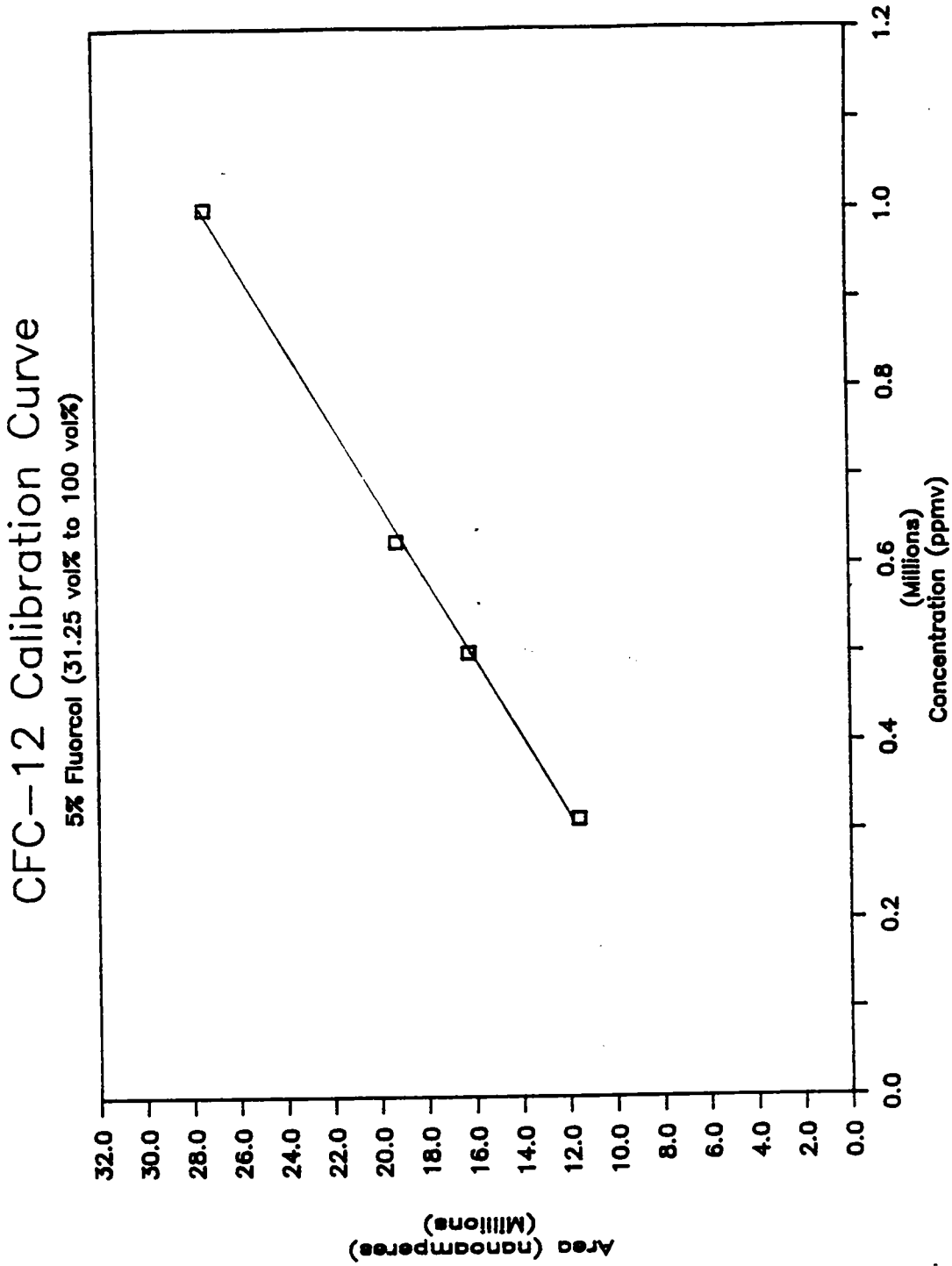

Figure B-1. Dichlorodifluoromethane calibration curve on the 5% Fluorcol column.

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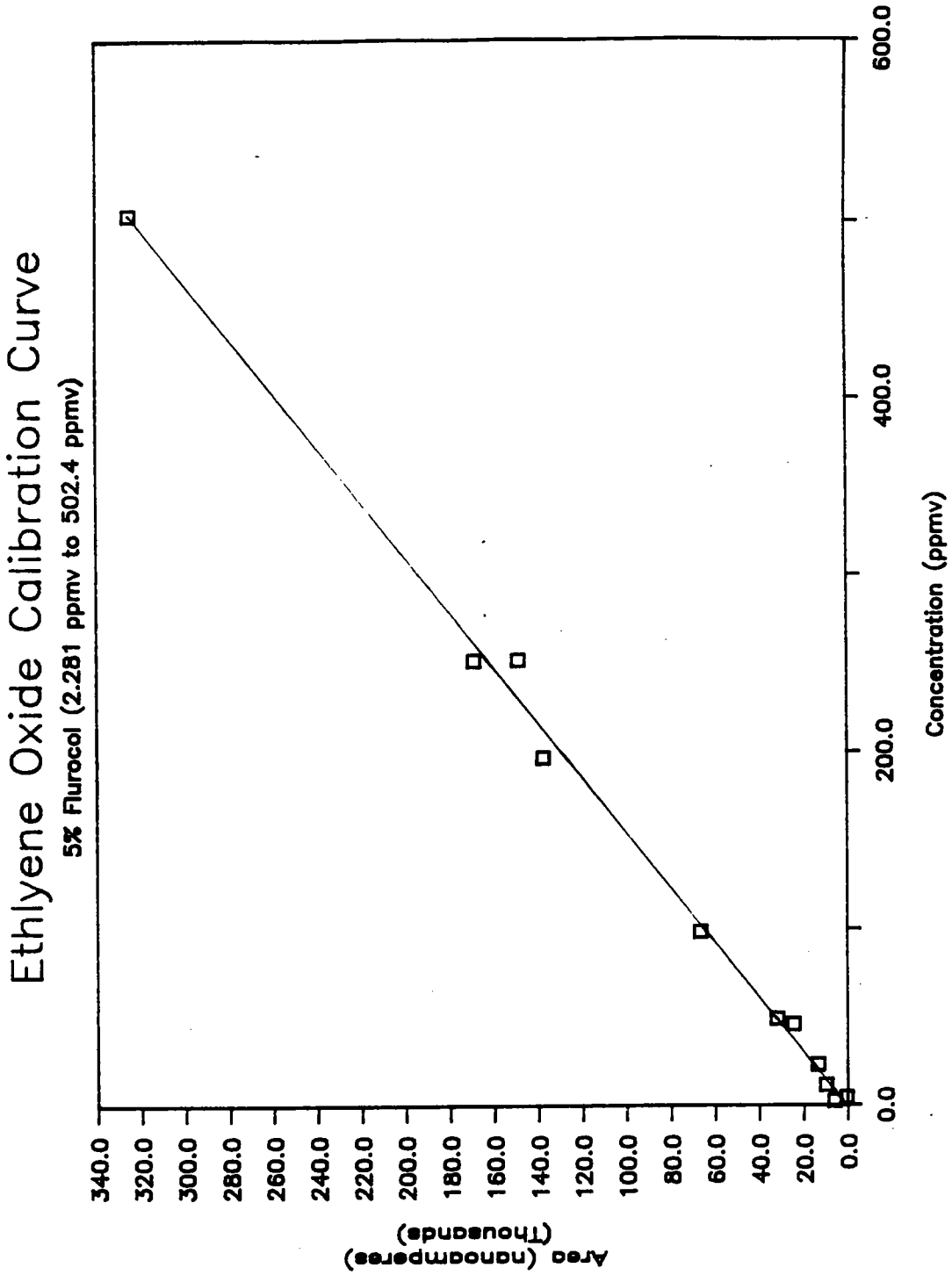

Figure B-2. Ethylene oxide calibration curve at the low part-per-million level on the 5% Fluorcol column.

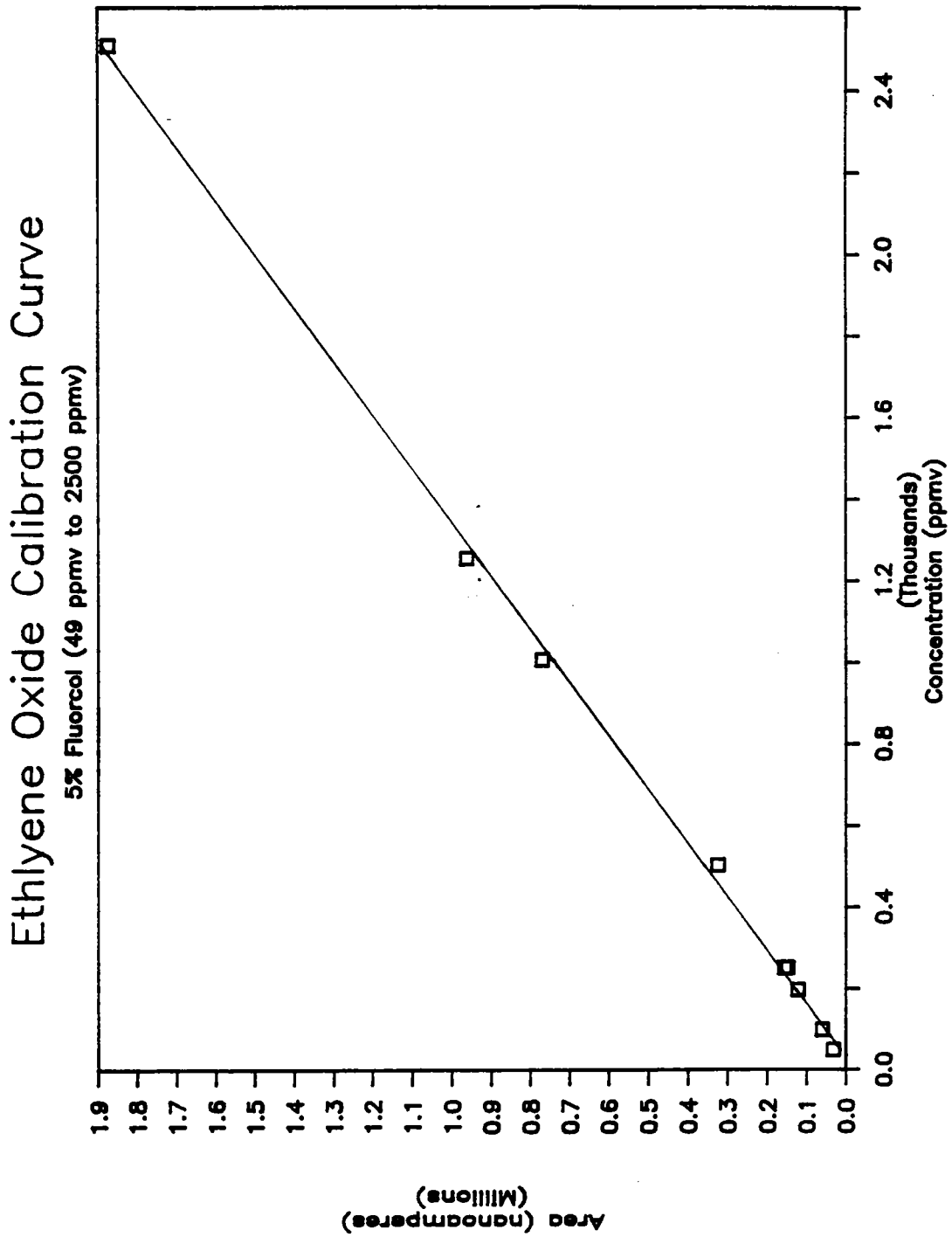

Figure B-3. Ethylene oxide calibration curve at the high part-per-million level on the 5% Fluorcol column.

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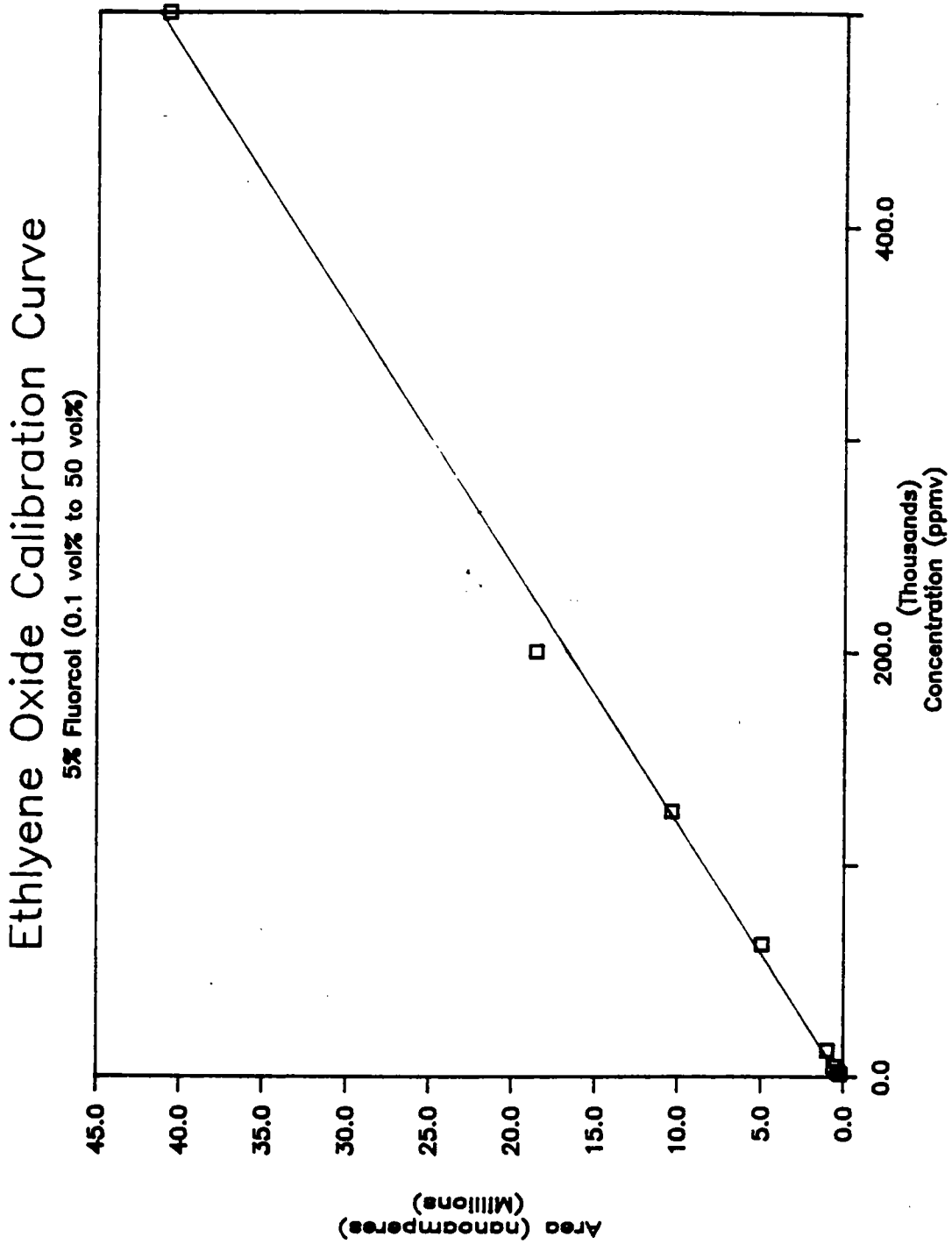

Figure B-4. Ethylene oxide calibration curve at the volume percent level on the 5% Fluorcol column.

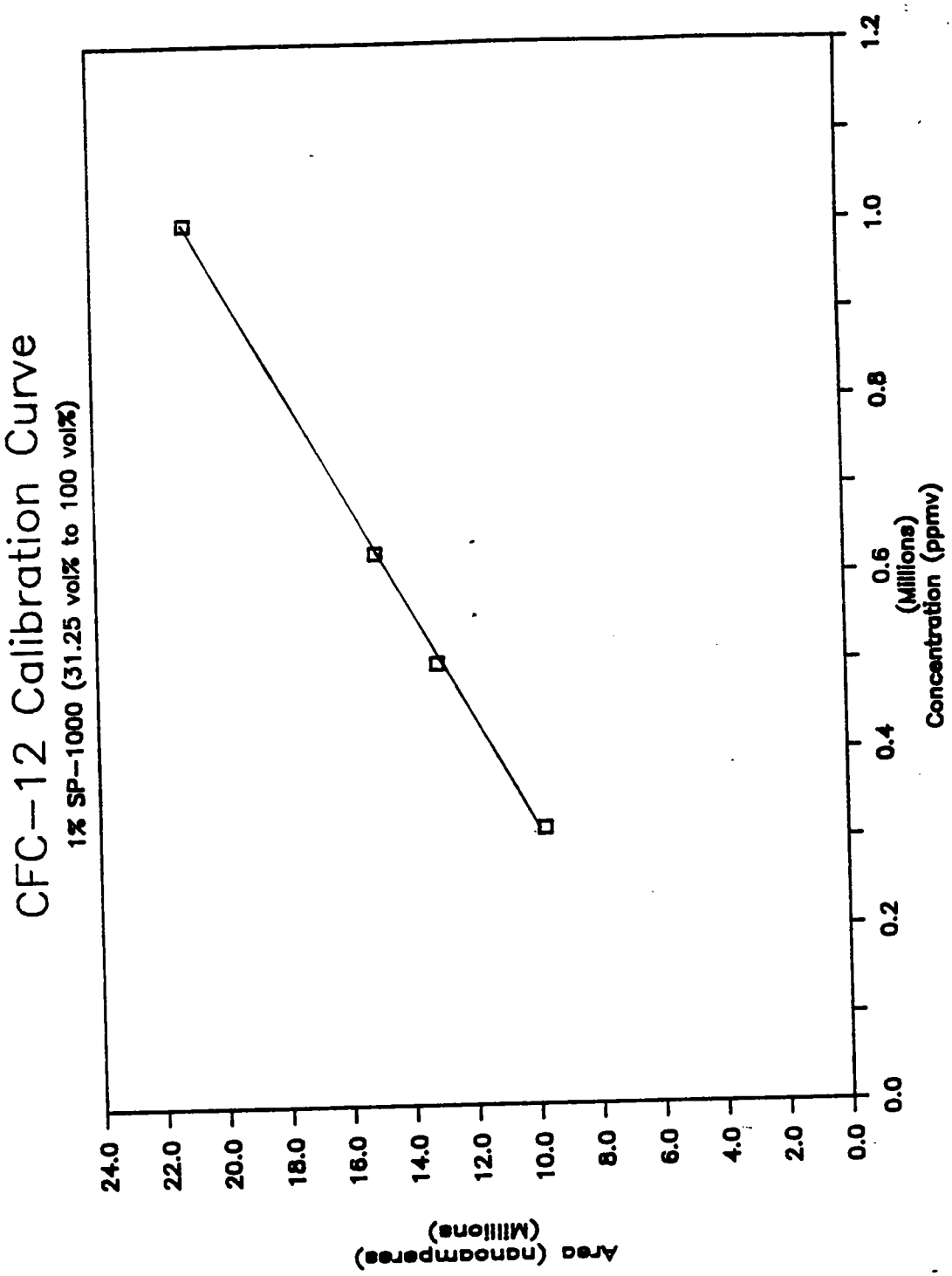

Figure B-5. Dichlorodifluoromethane calibration curve on the 1% SP-1000 column.

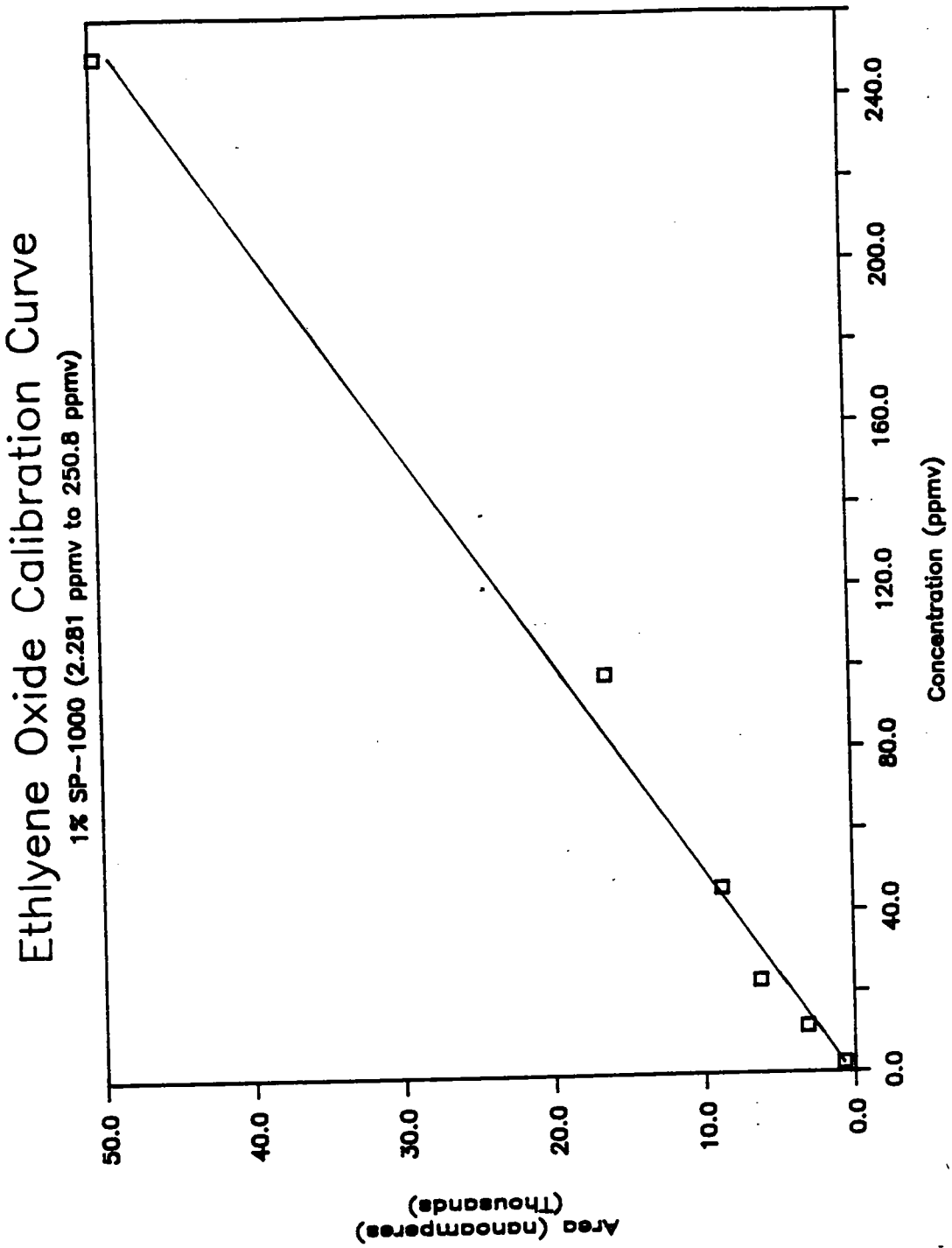

Figure B-6. Ethylene oxide calibration curve at the low part-per-million level on the 1% SP-1000 column.

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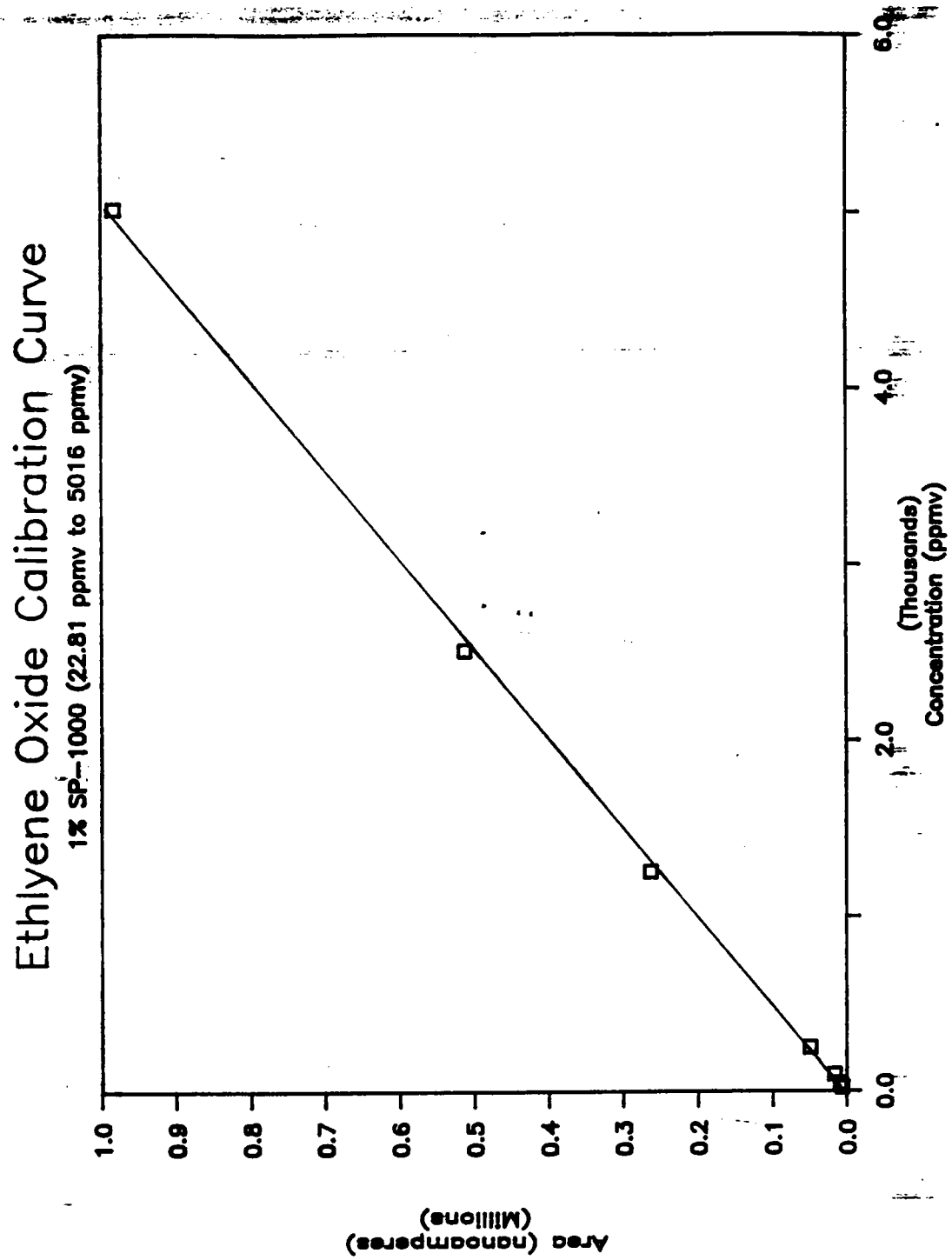

Figure B-7. Ethylene oxide calibration curve at the high part-per-million level on the 1% SP-1000 column.

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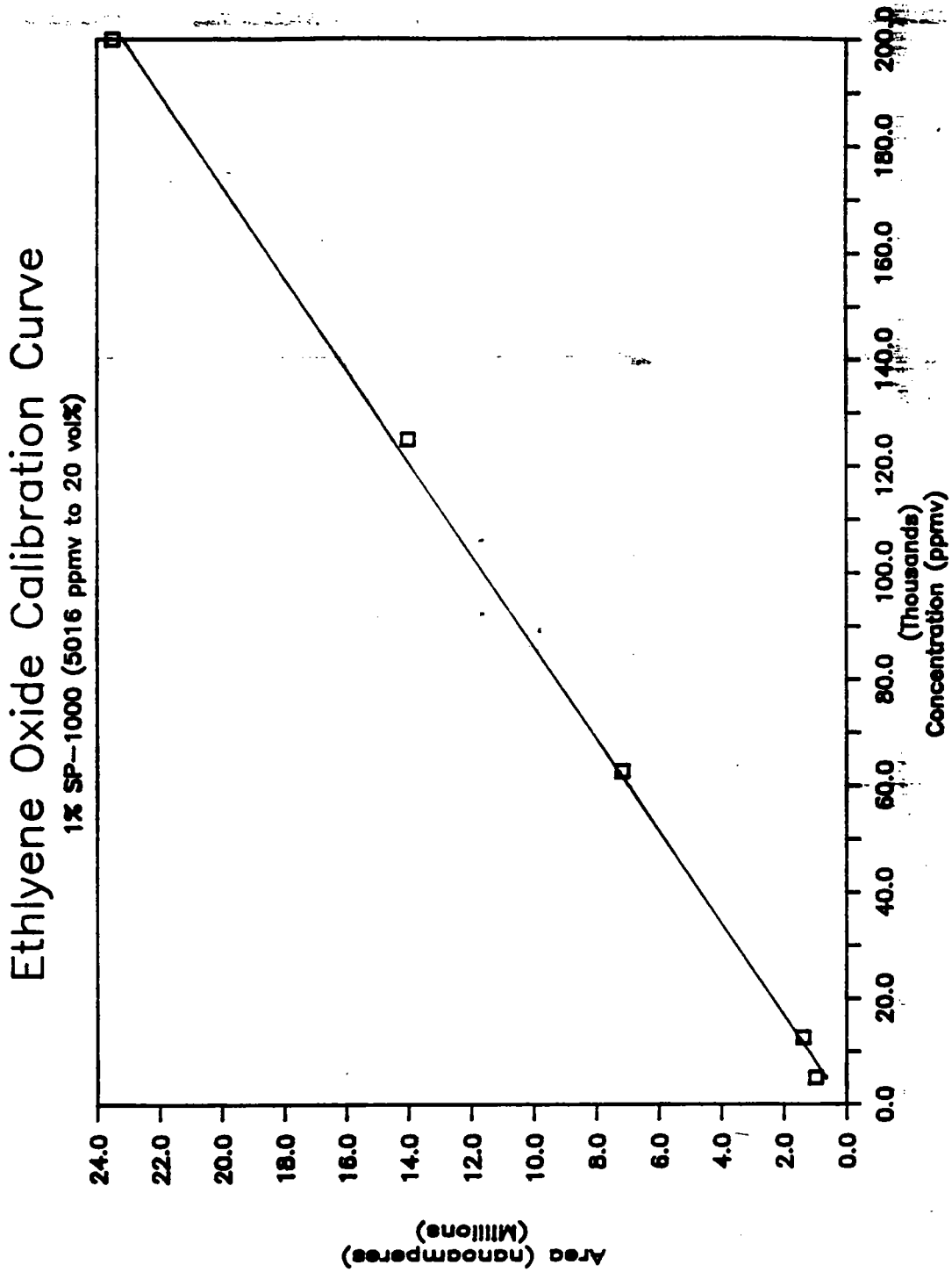

Figure B-8. Ethylene oxide calibration curve at the volume percent level on the 1% SP-1000 column.

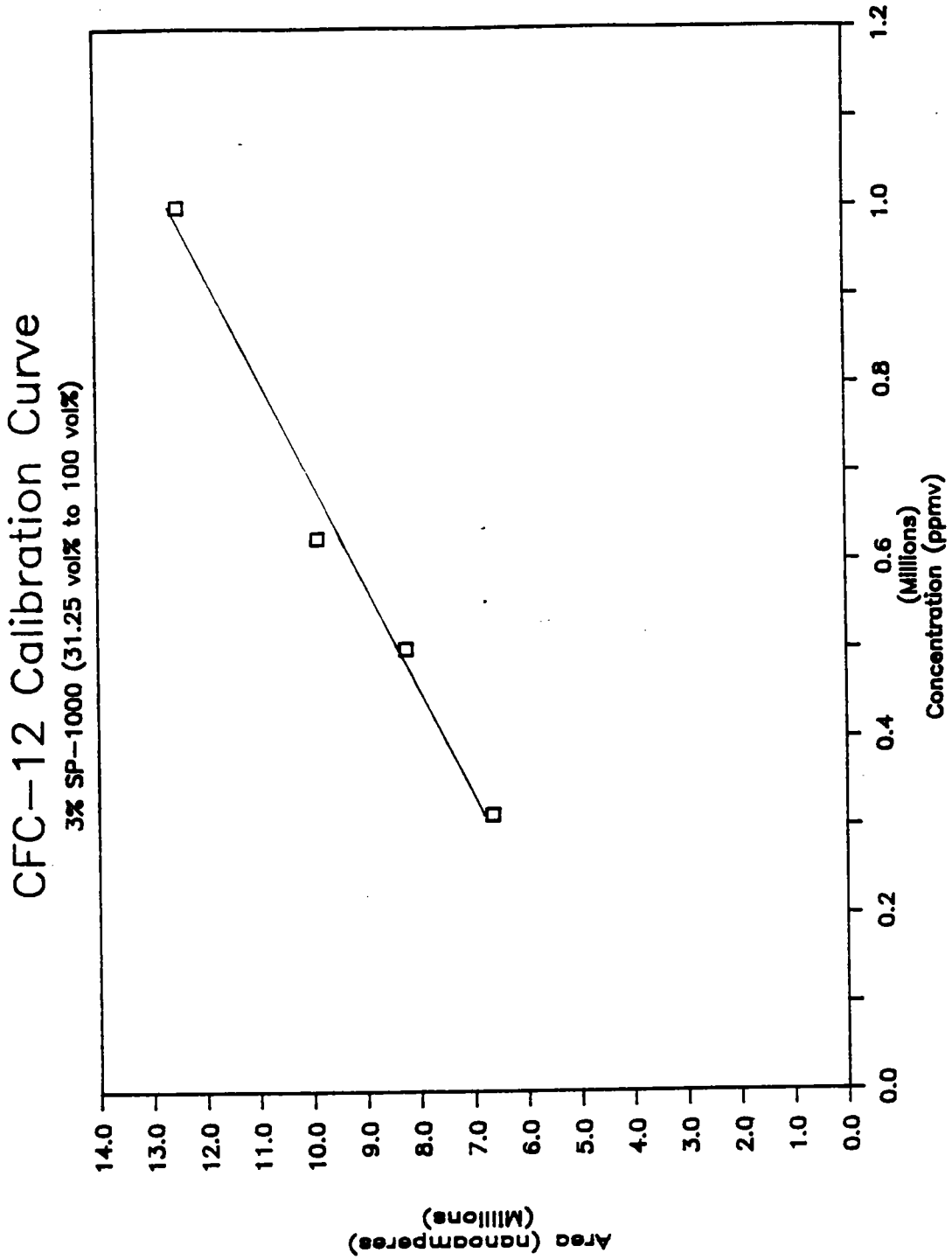

Figure B-9. Dichlorodifluoromethane calibration curve on the 3% SP-1000 column.

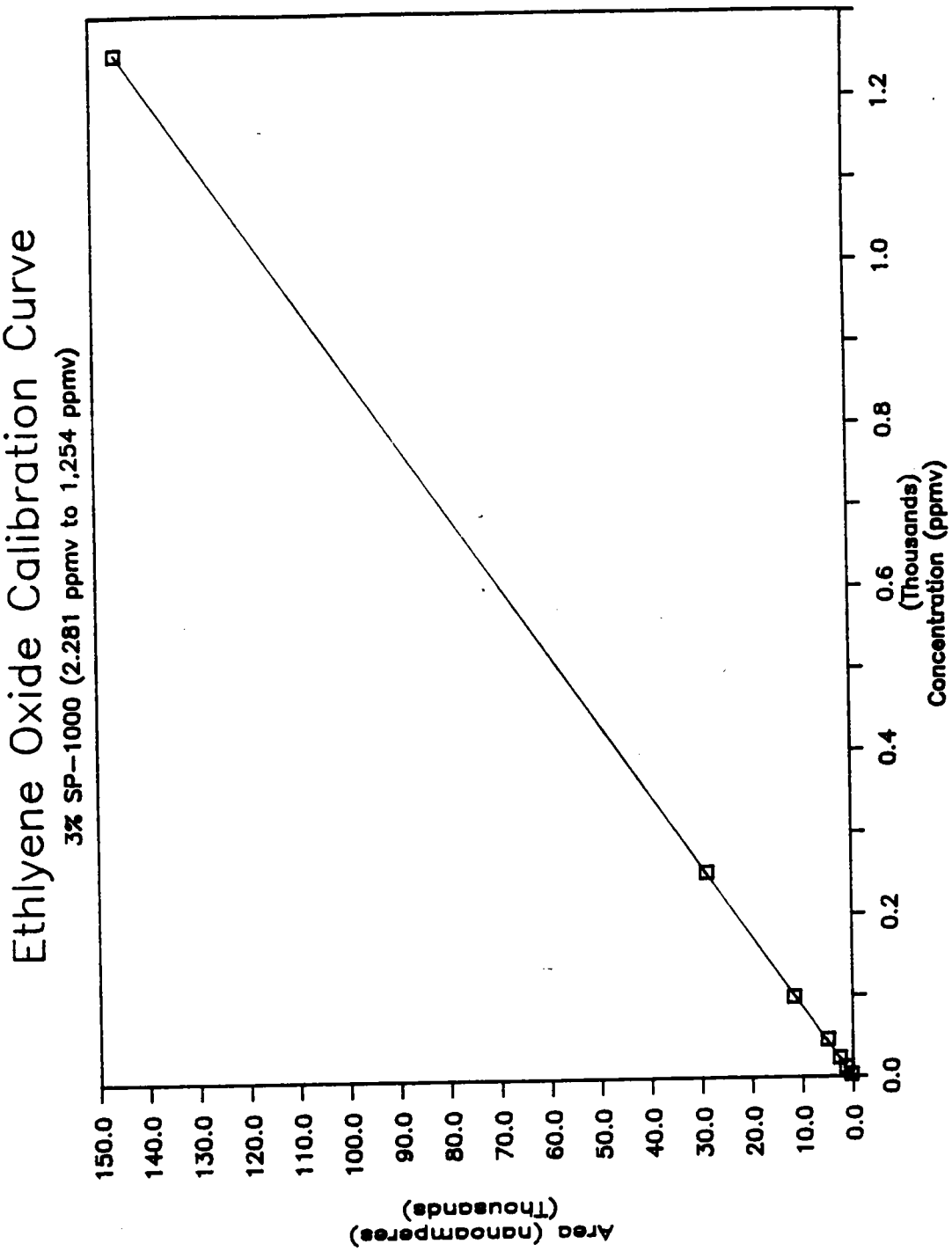

Figure B-10. Ethylene oxide calibration curve at the low part-per-million level on the 3% SP-1000 column.

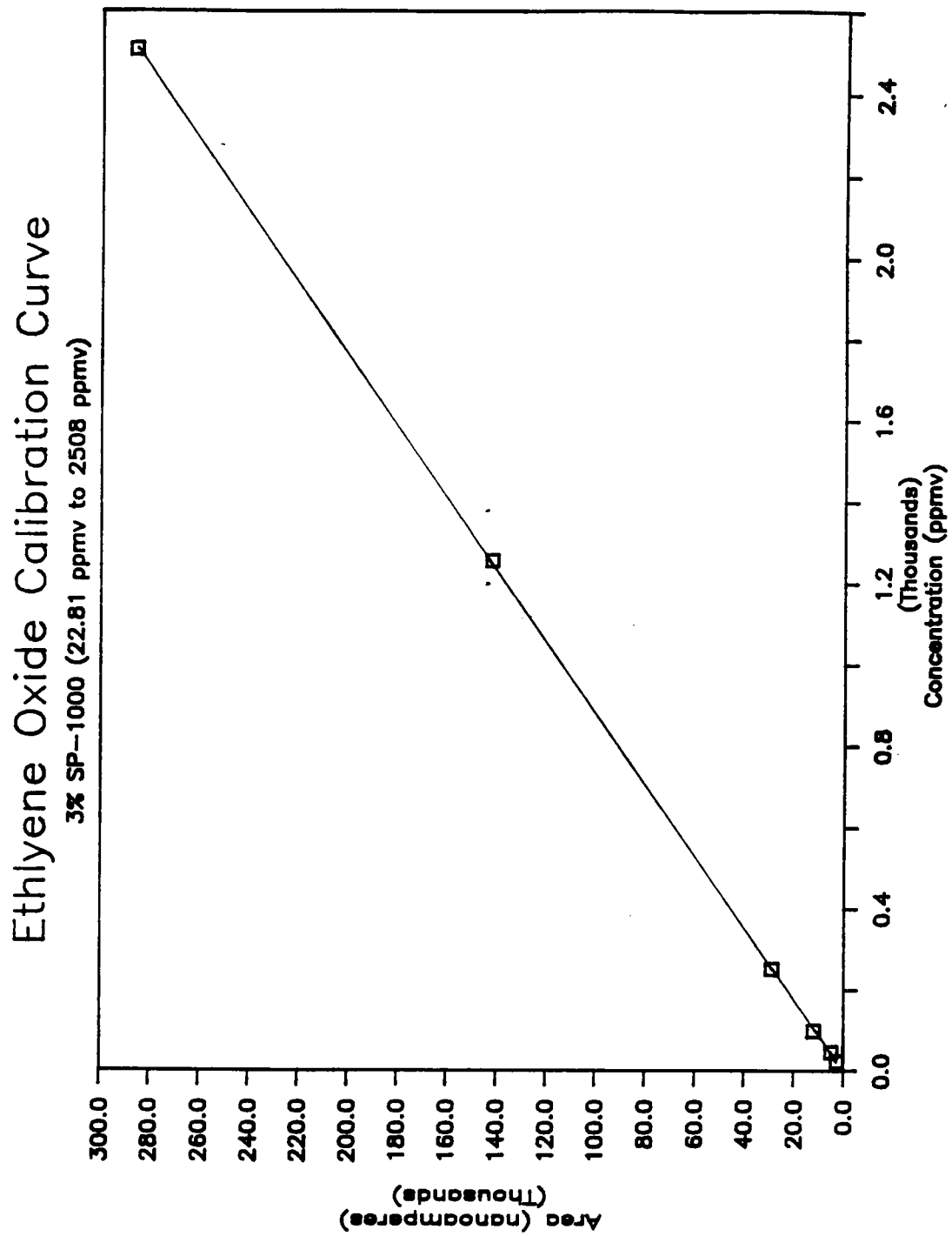

Figure B-11. Ethylene oxide calibration curve at the high part-per-million level on the 3% SP-1000 column.

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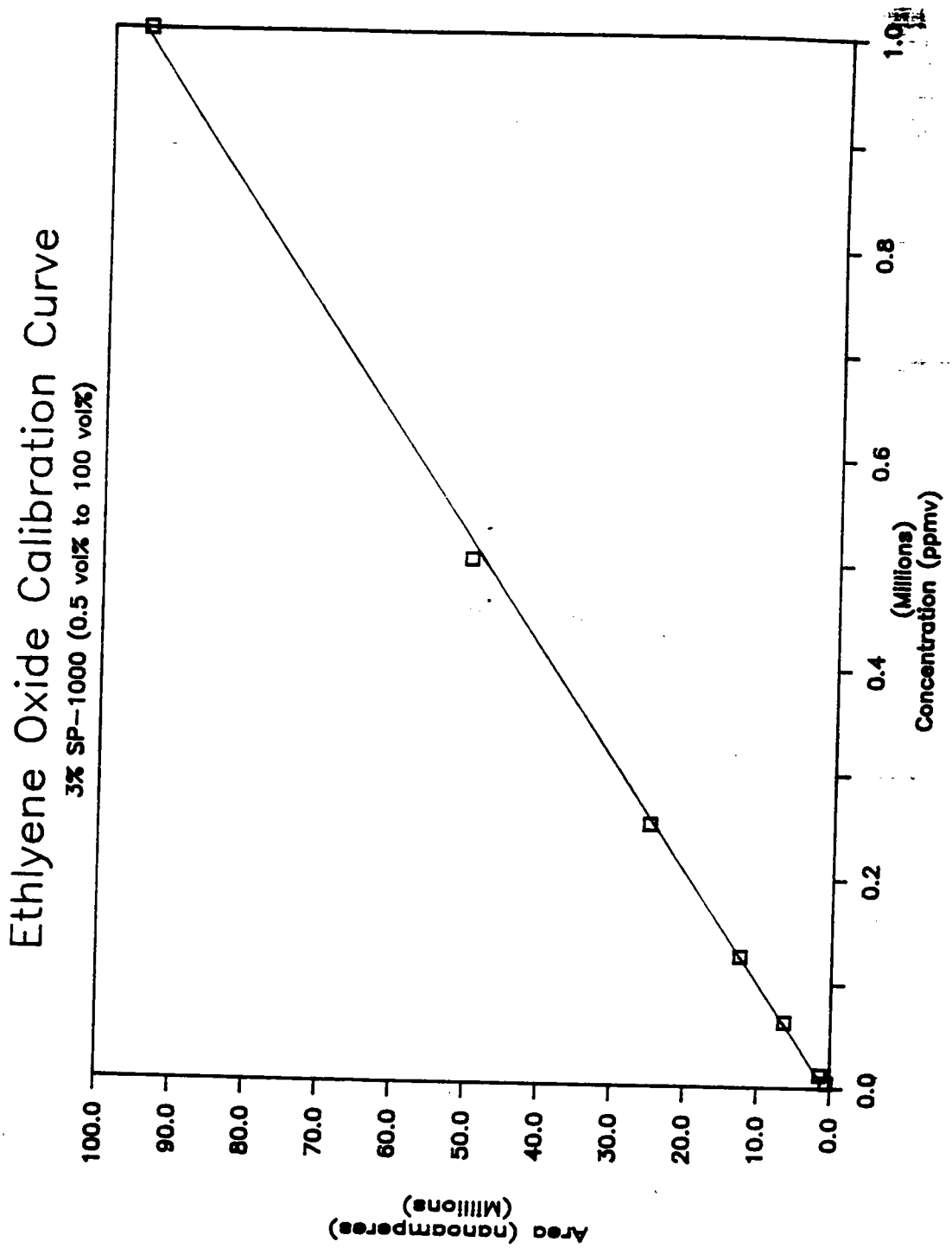

Figure B-12. Ethylene oxide calibration curve at the volume percent level on the 3% SP-1000 column.

APPENDIX C

EXAMPLE CHROMATOGRAMS

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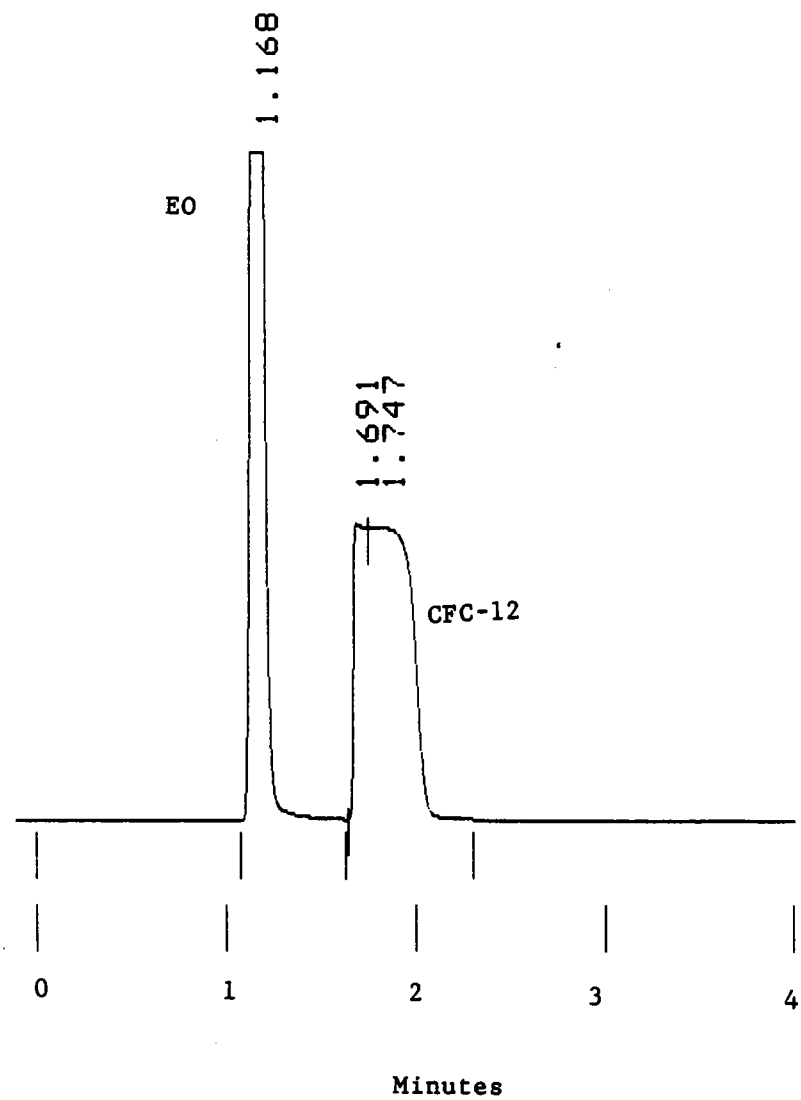

Figure C-1. Chromatogram of 62.5 vol% CFC-12 and 12.5 vol% EO on 1% SP-1000 at 65°C.

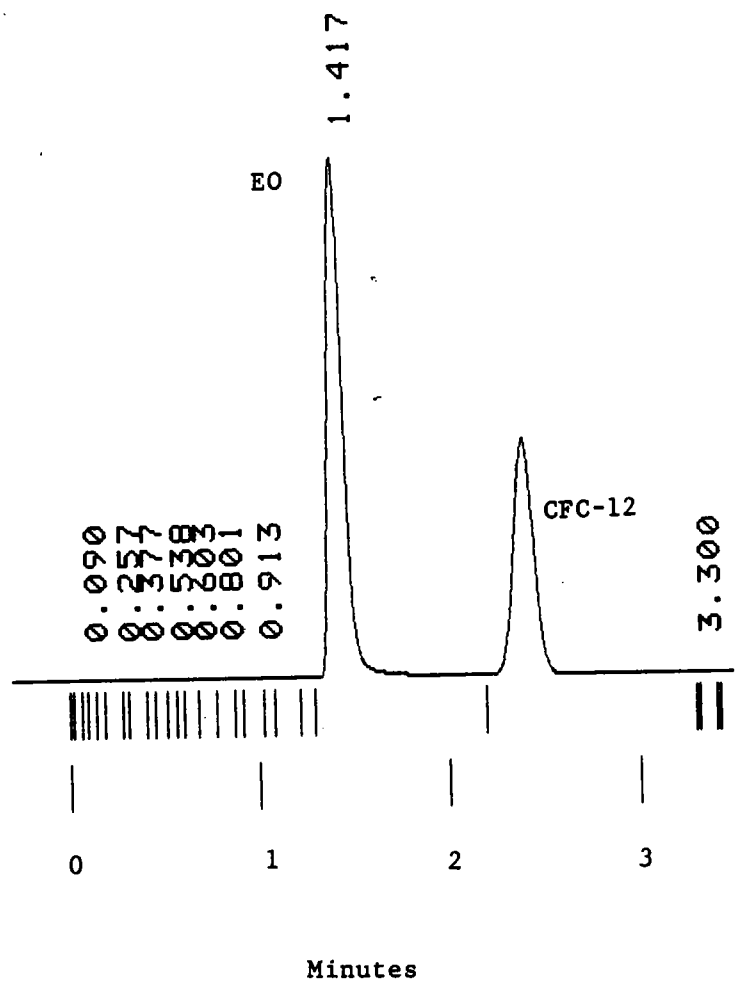

Figure C-2. Chromatogram of 6,022 ppmv CFC-12 and 2,508 ppmv EO on 1% SP-1000 at 55°C.

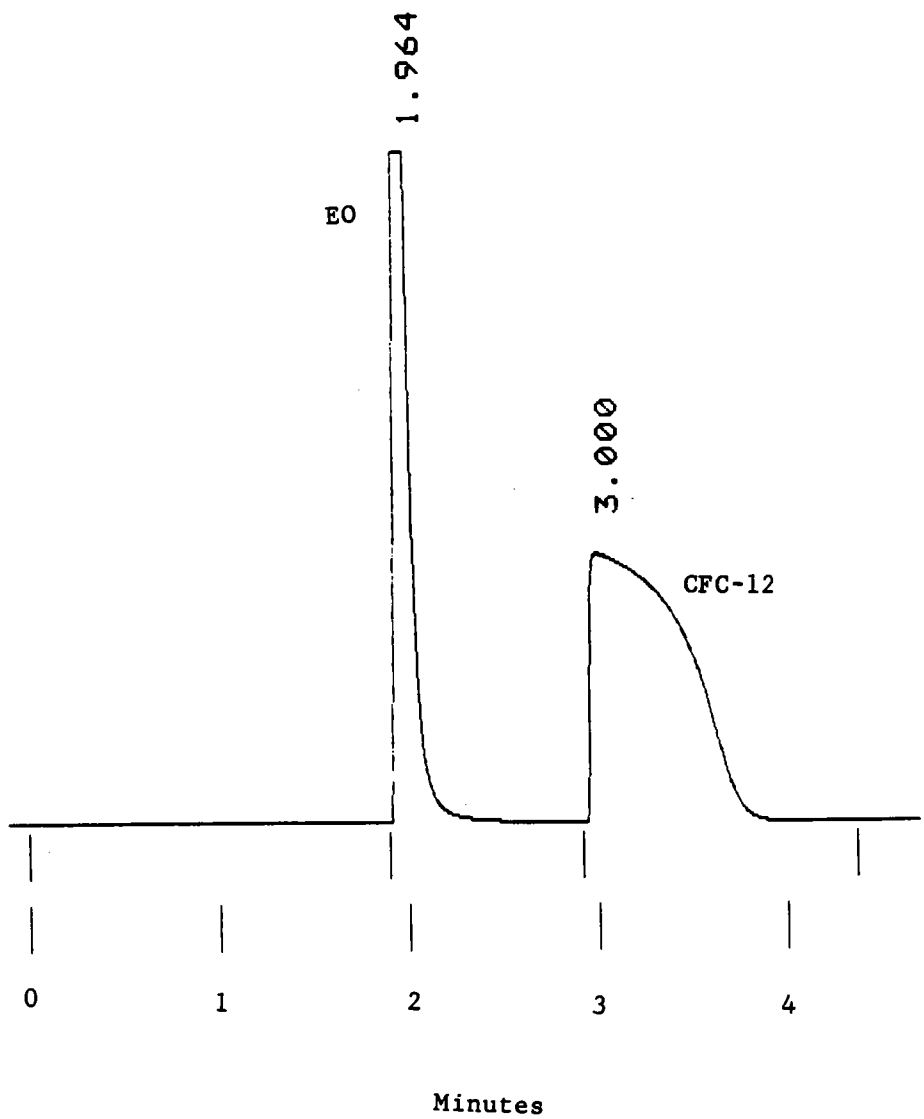

Figure C-3. Chromatogram of 62.5 vol% CFC-12 and 12.5 vol% EO on 5% Fluorcol at 65°C.

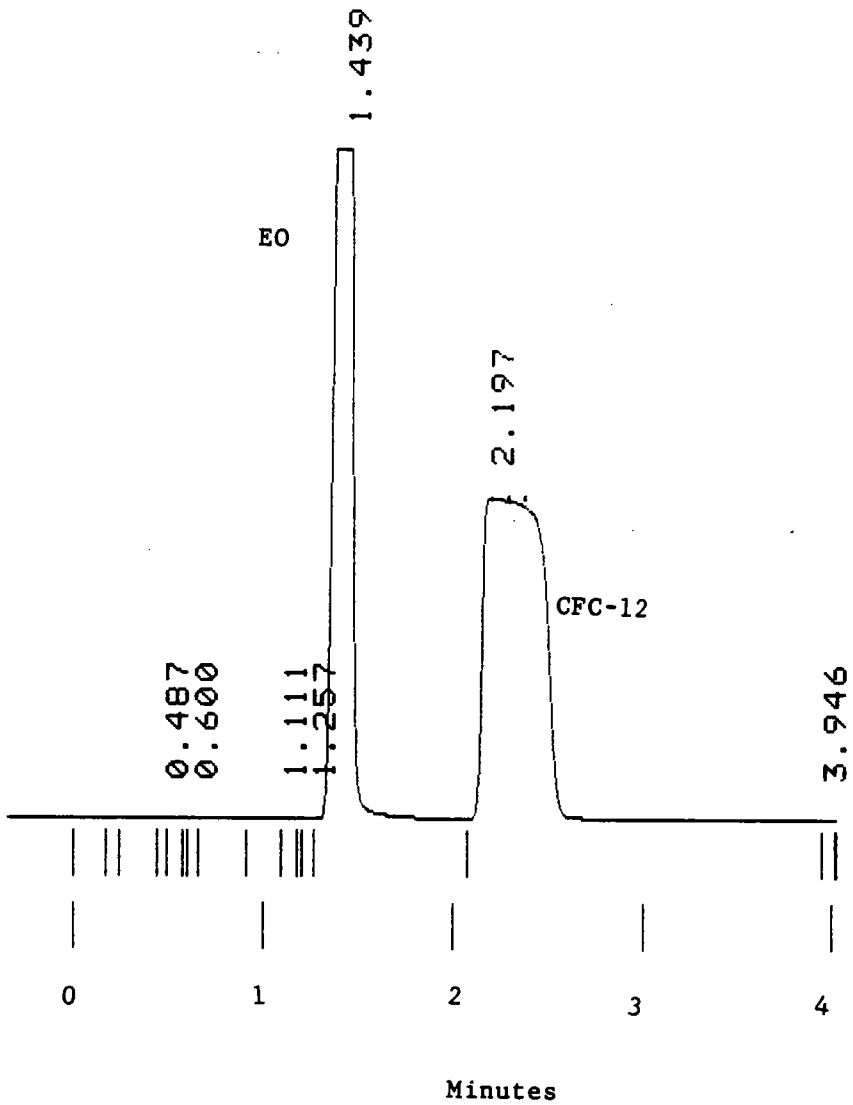

Figure C-4. Chromatogram of 62.5 vol% CFC-12 and 12.5 vol% EO on 1% SP-1000 at 55°C.

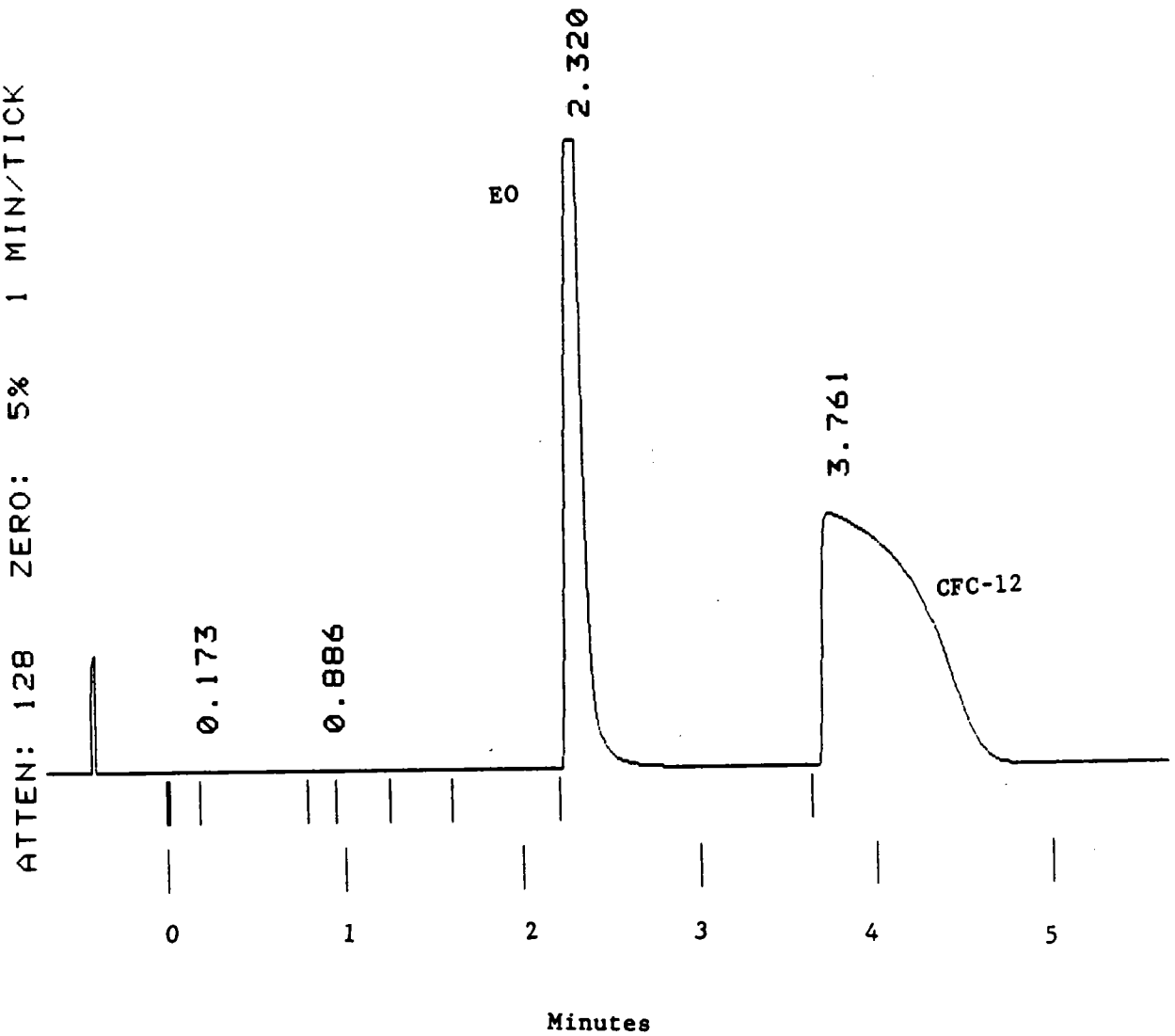

Figure C-5. Chromatogram of 62.5 vol% CFC-12 and 12.5 vol% EO on 5% Flurocol at 55°C.

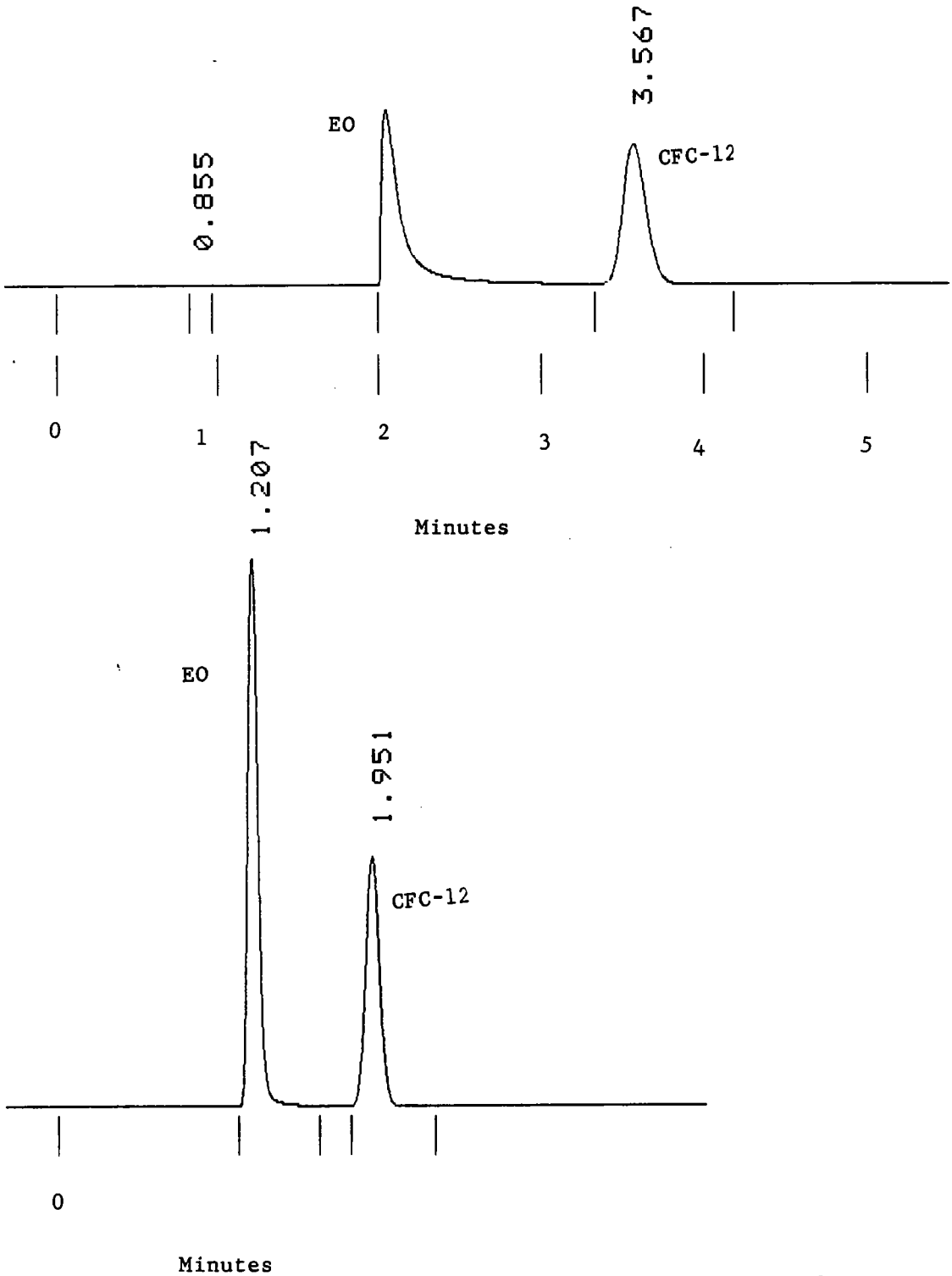

Figure C-6. Chromatograms of 6,022 ppmv CFC-12 and 2,508 ppmv EO on 5% Fluorcol (top) and 1% SP-1000 (bottom) at 65°C.

APPENDIX D

VACU-SAMPLER DESCRIPTION

The Monitoring People

Vacu-Sampler

Disposable Air Sampling Collection System

- **Samples ambient air, breath, stacks, pressure lines**
- **Safe in explosive atmospheres**
- **Precise vacuum level assures good quantitative results**
- **Chemically inert**
- **Valve and septum integrity allows long shelf life before and after use**

The Vacu-Sampler is a reliable, low cost device that untrained personnel can use to collect samples of gases and vapors for laboratory analysis. This easy to use device meets the needs of both industry and government.

Vacu-Sampler is an aerosol-type can which has been completely evacuated and then back filled with nitrogen to a partial vacuum of 20 inches of mercury (246.6 cc of N_2 at standard temperature and barometric pressure). When activated, Vacu-Sampler will inhale 123.3 cc of vapors or gases (at standard temperature and pressure). The nitrogen background allows effective collection of samples in high dew point environments. During analysis of the sample, the effect of the nitrogen background is eliminated by using a dilution correction factor.*

***References**

Principe, Andrew H., "The Vacu-Sampler, A New Device for the Encapsulation of Breath and Other Gaseous Samples," presented at the 25th Annual Meeting of the Academy of Forensic Science, Las Vegas, NV, Feb. 19-23, 1973.

Principe, Andrew H., "Vacu-Sampler: A Unique Grab Sampling Device."

Miller, Robert W., et al, "Vacu-Samplers, A Simple Method for Taking Accurate Quantitative Gas and Vapor Samples Using Partially Evacuated Steel Containers," presented at the American Industrial Hygiene Conference, Minneapolis, MN, June, 1975.

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The Monitoring People

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Introduction

The Vacu-Sampler is a partially evacuated rigid container, back-filled with nitrogen, with a total volume of 370 cc. When activated, it will inhale vapor or gas by equalizing the pressure difference between the inside of the container and the sampling point. When the sample is taken at standard temperature and pressure, each container will inhale 123.3 cc. The effect of sample dilution with nitrogen may be eliminated during analysis by using a correction factor, detailed below in the section entitled Quantitation.

Caution: Be sure you fully understand these instructions before using the Vacu-Sampler. If you have any questions call our toll-free number: 800-323-2000 (In Illinois 312/634-2800).

Taking A Sample

Break the tape seal and remove the safety cover to expose the white plastic actuator button. **Caution:** Do not use the Vacu-Sampler if the tape seal is broken; integrity of a sample can only be assured if the seal is intact.

Atmospheric Sampling

1. Position the intake nozzle in the space to be sampled.
2. Hold the container firmly, depress the actuator button, and hold down for 10 seconds to inhale a sample of the atmosphere.
3. Record the sample data immediately, including the ambient temperature.
4. Replace the safety cover.

Pressure Sampling

1. Place the end of the supplied Tygon tubing with partial split on the Vacu-Sampler nozzle.
2. Attach the other end of the Tygon tubing to the pressure system to be sampled. The most convenient method is to slip the Tygon tubing over a length of copper or stainless steel tubing connected to the pressure system.
3. Open the pressure system valve and allow pressurized gas to vent out of the slit in the Tygon tubing for a few seconds.
4. Hold the Vacu-Sampler firmly, depress the actuator button, and hold down for 10 seconds to inhale a sample.
5. Close the pressure system valve, remove the tubing, record the sample data, including the temperature, and replace the safety cover on the Vacu-Sampler.

Breath Sample

The most representative sample of alveolar "air" can be taken using the Tygon tubing with partial split.

1. Place the end of the Tygon tubing with partial split on the Vacu-Sampler nozzle. Place the other end of the tubing in the subject's mouth.
2. Instruct the subject to begin exhaling into the tubing. Approximately three seconds after the subject begins, and while the subject continues to exhale, hold the Vacu-Sampler firmly, depress the actuator button, and hold down for 10 seconds to inhale a sample.
3. Remove the tubing, record the sample data, and replace the safety cover. Record 34° C. (normal body temperature) as the sample temperature.

Analyzing A Sample

Gas chromatography, or another technique may be used to analyze the sample. Be sure the safety seal is in place, and that the Vacu-Sampler container is carefully packed for shipment.

Extracting A Sample

1. Remove the safety cover. Carefully remove the white plastic actuator assembly.
2. With a sharp, pointed punch, such as an ice pick or small finishing nail, carefully puncture the metal can-top seal. Make a hole just large enough to accept the needle of a gas-tight syringe. Carefully remove the punch; if the rubber septum below the metal seal is invaded by the punch, the septum will reseal when the punch is removed, maintaining the integrity of the sample.
3. Insert the syringe needle through the septum and withdraw a sample for laboratory analysis.

Quantitation

Accurate analysis requires eliminating the dilution of the sample from nitrogen. The Dilution Correction Factor is a function of sample temperature when taken related to sample temperature when analyzed in accordance with gas laws:

$$\text{Dilution Correction Factor} = 3\ \frac{T_1}{T_2}$$

where T_1 = Sample Temperature (°K) at time of sampling
T_2 = Vacu-Sampler Temperature (°K) at time of analysis

Example

Assume that we sample acetone vapor from a room with an ambient temperature of 35° C. Following the analysis procedures for gas chromatography, utilizing standards, we find that the sample from the Vacu-Sampler gives us an apparent value of 25 ppm when analyzed at 21° C.

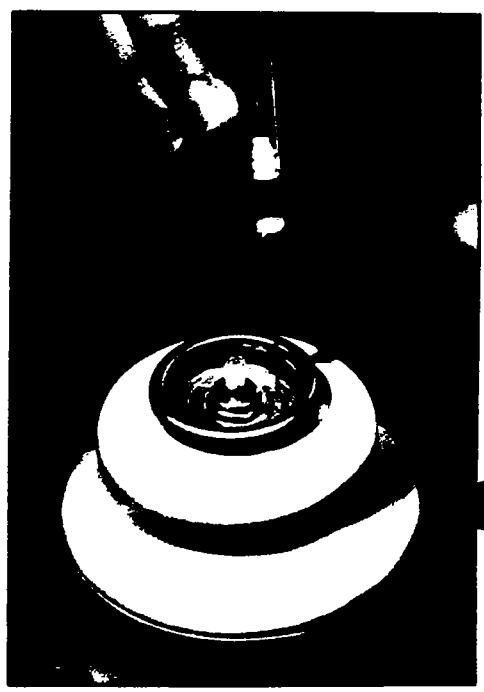
Using the formula above:

$$\text{since } T_1 = 273 + 35 = 308°K.$$
$$\text{and } T_2 = 273 + 21 = 294°K.$$
$$\text{Dilution Factor} = 3 \times \frac{308}{294} = 3.14$$

Correcting the apparent value:

$$25 \text{ ppm} \times 3.14 = 78.5 \text{ ppm}$$

More detailed quantitative instructions are included with each case of Vacu-Samplers.



Cat. No. 970214 12/85 10M

APPENDIX E

GRAB SAMPLING DATA SHEETS

ETHYLENE OXIDE SAMPLING DATA SHEET

DATE 6/21

RUN ID 1

SAMPLER WPG/PRL/JLS

SCHEDULE: INITIAL EXHAUST 1 bag/min

AIR WASHES 3/wash

FACILITY Burron

BAROMETRIC PRESSURE 30.47

TIME	EXHAUST #	START 13:03	CONTAINER	ID	TEMPERATURE (F) VENT	t'	PUMP	HEAT TRACE	PERCENT OXYGEN	Ps (IN H2O)	NOTES
13:04	I	13:04	BAG	1	90	79	163	103	19.5	.2	
13:05	↓	↓	↓	2	92	77	163	162	20.0	.2	
:06				3	93	76	162	102	14.0	.2	
:07				4	94	75	160	101	4.0	.4	
:08				5	95	74	159	100	0.5	.5	
:09				6	96	74	158	100	0.0	.4	
:10				7	98	73	157	100	~~0.4~~ 0.0	0.4	
:11				8	98	73	156	100	0.0	.2	
:12				9	100	72	155	101	0.0	.2	
:13				10	100	72	155	102	0.0	.1	
:14				11	100	72	154	102	0.0	.1	

ETHYLENE OXIDE SAMPLING DATA SHEET

DATE 6/21

RUN ID 1

SAMPLER

SCHEDULE:

INITIAL EXHAUST 1

AIR WASHES ~~16~~ 5

FACILITY Burton

BAROMETRIC PRESSURE

TIME	EXHAUST #	START	CONTAINER	ID	TEMPERATURE (F) VENT	t'	PUMP	HEAT TRACE	PERCENT OXYGEN	Ps (IN Hg)	NOTES
13:15	I	13:03	BAG	12	100	72	154	102	0.0	.1	
:16	↓	↓	↓	13	100	71	153	103	0.0	.1	
:17				14	100	72	153	103	0.0	.1	
:18				15	100	72	153	103	0.0	.1	
:19				16	100	72	152	103	0.0	.05	
:20				17	99	72	151	103	0.0	.05	
:21				18	98	73	150	103	0.0	.05	
:22				19	97	73	150	102	0.0	.05	
:23				20	97	73	150	102	0.0	.—	
:24				21	101	72	150	101	0.0	.4	← Prevac for another unit
:25				22	104	71	150	102	0.0	.4	

ETHYLENE OXIDE SAMPLING DATA SHEET

DATE 6/21/88 SCHEDULE: INITIAL EXHAUST 1 FACILITY Burton

RUN ID 1 AIR WASHES 5 BAROMETRIC PRESSURE

SAMPLER

TIME	EXHAUST #	START	CONTAINER	ID	TEMPERATURE (F) VENT	t'	PUMP	HEAT TRACE	PERCENT OXYGEN	Ps (IN Hg)	NOTES
13:26	I	13:03 ~~23~~	BAG	23	106	70	149	101	0.0	.3	
13:27	↓		↓	24	107	69	148	100	0.0	.3	
					END	of	Initial	Exhaust			
	AW-1	13:58	BAG								
14:00			↓	—					14.0		Looks like residual O_2
14:00:30				—					15.5		from earlier prevac.
14:03				—					15.0		— Air Inbleed for #3 sterilizer
14:08	AW-1	14:08	BAG	—	121				0.0		Airwash #1 starts
14:10			↓	—	121	71	151	103	0.0		
14:11				—					1.0		

Not AW1

151

ETHYLENE OXIDE SAMPLING DATA SHEET

DATE 6/21

RUN ID 1

SAMPLER

SCHEDULE:

INITIAL EXHAUST 1

AIR WASHES ~~6~~ 5

FACILITY Burton

BAROMETRIC PRESSURE

TIME	EXHAUST #	START	CONTAINER	ID	TEMPERATURE (F) VENT	t'	PUMP	HEAT TRACE	PERCENT OXYGEN	Ps (IN Hg)	NOTES
14:12	AW-1	14:08	BAG	—	122	69	151	103	6.0	.4	
14:14	↓	↓	↓	#25	122	68	152	109	8.0	.3	
14:17				#26	122	68	154	115	14.0	.1	
14:20				#27	120	69	155	119	18.0	.05	
14:24	↓	END	AW-1	(noticeable)	→	→	→	→	→	→	14:30 – Bill called said ↓ end of wash – low flow not noticeable w/o vane anemometer
		4 of 6									
14:39	AW-2	14:39	BAG	—	112	73	159	12'	16.0	.2	– Fixite fluid change.
14:41		↓	↓	—					15.0		
14:44				#28	121	69	161	124	16.0	.2	
14:47				#29	119	68	161	123	16.5	.1	
14:50				#30	118	69	161	122	16.5	.1	15:00 approx. end of wash per control panel

ETHYLENE OXIDE SAMPLING DATA SHEET

DATE 6/21/88 SCHEDULE: FACILITY Buoron

RUN ID 1 INITIAL EXHAUST 1

SAMPLER _____ AIR WASHES 6 BAROMETRIC PRESSURE _____

TIME	EXHAUST #	START	CONTAINER	ID	TEMPERATURE (F) VENT	t'	PUMP	HEAT TRACE	PERCENT OXYGEN	Ps (IN Hg)	NOTES
15:09	AW-3	15:09	Bag						15.5		
15:14	↓	↓	↓	31	110	70	163	120	16.0	.1	
15:17				32	109	77	164	121	16.0	.1	
15:20				33	108	86	165	123	~~16.0~~ 16.5	—	Ambient
15:38:30	AW-4	15:38	Bag								
15:44	↓	↓	↓	34	110	91	168	128	19.5	.1	
15:47				35	110	89	168	118	20	.1	
WAW ~~16:00~~ 15:50				36	107	90	168	111	20	.1	

frite ✓ = O_2 @ 17.0
Changed sol'n again

15

ETHYLENE OXIDE SAMPLING DATA SHEET

DATE 6/21

RUN ID 1

SAMPLER WPK/PTL/JES

SCHEDULE:

INITIAL EXHAUST 1

AIR WASHES 5

FACILITY Burton

BAROMETRIC PRESSURE

TIME	EXHAUST #	START 16:08	CONTAINER	ID	TEMPERATURE (F) VENT	t'	PUMP	HEAT TRACE	PERCENT OXYGEN	Ps (IN Hg)	NOTES
16:13	AW-5	↓	BAG	37	106	92	170	111	20	.2	
16:16	↓		↓	38	108	90	170	111	↓	.1	
16:19				39	109	90	171	113		.1	

ETHYLENE OXIDE SAMPLING DATA SHEET

DATE 6/22

RUN ID 2

SAMPLER WPG/PTL

SCHEDULE:

INITIAL EXHAUST 1

AIR WASHES 5

FACILITY Burton Med

BAROMETRIC PRESSURE 30.48

TIME	EXHAUST #	START	CONTAINER	ID	TEMPERATURE (F) VENT	t'	PUMP	HEAT TRACE	PERCENT OXYGEN	Ps (IN Hg)	NOTES
	Init.	10:00									
10:05	↓	↓	BAG	40	97	63	141	106	15.0	.2	
10:11			BAG	41	92	61	139	106	1.0	.1	
10:12			V	200A 200B							
10:13			Sy	101 102							
10:17			BAG	42	89	62	138	106	0.5	—	
10:18			Sy	103 104							
Evac End @ 10:56											
	AW-1	10:03									Evacuated #2 ster. between In & AW-1 (Pre sterilize evac)
10:08	↓	↓	BAG	43	102	62	139	114	14 ~~2.0~~	.2	
10:12			BAG	44	101	61	141	115	19 ↓	.1	

Sy = Syringe

V = Vacusampler Can

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2 of 5

ETHYLENE OXIDE SAMPLING DATA SHEET

DATE 6/22

RUN ID 2

SAMPLER WPG/PTL

SCHEDULE:

INITIAL EXHAUST 1

AIR WASHES 5

FACILITY Burton

BAROMETRIC PRESSURE 30.48

TIME	EXHAUST #	START	CONTAINER	ID	TEMPERATURE (F) VENT	t'	PUMP	HEAT TRACE	PERCENT OXYGEN	Ps (IN Hg)	NOTES
11:13	AW-1	11:03	Sy	105 106							
11:14	↓	↓	V	201A 201B							
11:15			BAG	45	98	61	140	113	19.5	.1	
11:16			Sy	107 108							
11:26	END	AIR	WASH	#1							
	AW-2	11:36									
11:41	↓	↓	Bag	46	100	62	140	116	20	.1	
11:45			Bag	47	99	61	140	115	↓	—	
11:46			Sy	109 110							
11:47			V	202A 202B							

ETHYLENE OXIDE SAMPLING DATA SHEET

DATE 6/22

RUN ID 2

SAMPLER WPG/PTL

SCHEDULE:

INITIAL EXHAUST 1

AIR WASHES 5

FACILITY Burton

BAROMETRIC PRESSURE 30.48

TIME	EXHAUST #	START	CONTAINER	ID	TEMPERATURE (F) VENT	t'	PUMP	HEAT TRACE	PERCENT OXYGEN	Ps (IN Hg)	NOTES
11:49	AW-2	11:36	Bag	48	96	62	141	115	20	—	
11:50	↓	↓	Syr	111 112					↓		
					END	AW-2 @ 11:55					(Interim Air Evac from Sterilizer #2)
	AW-3	12:01 ~~12:04~~									
12:~~09~~ 11	↓	↓	BAG	49	103	62	142	116	20	.2	
12:~~15~~ 15			Bag	50	102	61	144	115	↓	.1	
12:~~14~~ 16			Syr	113 114							
12:~~15~~ 17			V	203 A 203 B							
12:~~17~~ 19			Bag	51	102	62	144	117		—	
12:~~18~~ 20			Syr	115 116							
				END	AW-3 @ 12:26						

ETHYLENE OXIDE SAMPLING DATA SHEET

DATE 6/22

RUN ID 2

SAMPLER PTL/WPG

SCHEDULE:

INITIAL EXHAUST 1

AIR WASHES 5

FACILITY Burton

BAROMETRIC PRESSURE 30.48

TIME	EXHAUST #	START	CONTAINER	ID	TEMPERATURE (F) VENT	t'	PUMP	HEAT TRACE	PERCENT OXYGEN	Ps (IN Hg)	NOTES
	AW-4	12:37									
12:42	↓	↓	BAG	52	101	63	146	113	20.5	.1	
12:46			BAG	53	101	63	145	113	↓	.1	
:47			SY	117 118							
:48			V	204A 204B				✓			
12:50			Bag	54	100	64	146	114		—	
12:51			SY	119 120							
				End @		:55					
	AW-5	13:06									
13:11			BAG	55	106	77	147	115	20.6		
13:15			BAG	56	104	76	145	113	↓		

ETHYLENE OXIDE SAMPLING DATA SHEET

DATE 6/22

RUN ID 2

SAMPLER PTL/WPG

SCHEDULE:

INITIAL EXHAUST 1

AIR WASHES 5

FACILITY Burton

BAROMETRIC PRESSURE 30.48

TIME	EXHAUST #	START	CONTAINER	ID	TEMPERATURE (F) VENT	t'	PUMP	HEAT TRACE	PERCENT OXYGEN	Ps (IN Hg)	NOTES
13:16	AW-5	13:06	Sy	121 122					20.0	.1	
13:17	↓	↓	V	205A 205B					↓		
13:19	↓	↓	Bag	57	104	79	148	116	·	.1	
13:20	↓	↓	Sy	123 124							
				13:26 –	END						

ETHYLENE OXIDE SAMPLING DATA SHEET

DATE 6/23/88 SCHEDULE: FACILITY Burton

RUN ID 3 INITIAL EXHAUST 1 WP6

SAMPLER PTL/WP6 AIR WASHES ~~8~~ 4 BAROMETRIC PRESSURE

100% ETO Run

TIME	EXHAUST #	START	CONTAINER	ID	TEMPERATURE (F) VENT	t'	PUMP	HEAT TRACE	PERCENT OXYGEN	Ps (IN Hg)	NOTES
	Initial	11:45									
11:50	↓		Bag	58	77	68	150	120	20	.3	
11:56			Bag	59	80	66	151	124	19.5	.2	
11:57			V	206-A 206-B							
11:58			Sy	101 A 103A							
12:02			Bag	60	79	66	153	125	20.0	—	
12:03			V	207-A 207-B							
						END	@	12:10			
	AW-1	12:58							19.5		
13:03	↓	↓	BAG	61	86	65	156	129	20.5	.2	
13:07			BAG	62	89	65	157	126	20.5	.1	

2 nitrogen purges prior to loading ETO. O_2 #s don't make sense. Also ~~Nitrogen inbleeds~~ ~~as~~ opposed to Air inbleeds w/ 12/88.
↓
WRONG
↓
Air inbleeds

V = Vacu-sampler can

Sy = Syringe

ETHYLENE OXIDE SAMPLING DATA SHEET

DATE 6/23/88 SCHEDULE: FACILITY Burton

RUN ID 3 INITIAL EXHAUST 1 BAROMETRIC PRESSURE

SAMPLER PTL/WPG AIR WASHES 5

TIME	EXHAUST #	START	CONTAINER	ID	TEMPERATURE (F) VENT	t'	PUMP	HEAT TRACE	PERCENT OXYGEN	Ps (IN Hg)	NOTES
13:08	AW-1		V	208 A 208 B	89	65	158	127		.1	
13:09	↓	↓	Sy	109 A 111 A							
13:11			BAG	63	89	65	158	127	20.5	.1	
13:12			V	209 A 209 B							
		end @		13:15T							
	AW-2	13:29									
13:34	↓	↓	BAG	64	88	65	157	124	20.0	.3	
13:38			Bag	65	87	65	158	122	20.5	.2	
13:39			V	210 A 210 B	87	65	156	122	↓	–	
13:40			Sy	117 A 119 A							
13:42			Bag	66	87	65	156	122		–	
13:43			V	211 A 211 B							

END @ 13:43

ETHYLENE OXIDE SAMPLING DATA SHEET

DATE 6/23/88 SCHEDULE: INITIAL EXHAUST 1 FACILITY Burron

RUN ID 3 AIR WASHES 5 BAROMETRIC PRESSURE

SAMPLER RTC/WPG

TIME	EXHAUST #	START	CONTAINER	ID	TEMPERATURE (F) VENT	t'	PUMP	HEAT TRACE	PERCENT OXYGEN	Ps (IN Hg)	NOTES
	AW-3	13:55									
14:00	↓	↓	Bag	67	91	65	153	119	20.5	.3	
14:04			Bag	68	89	65	149	116	↓		
14:05			V	212 A 212 B							
14:06			Sy	126 A 126 A	(Unused)						
14:08			Bag	69	89	65	146	115		—	
14:09			V	213 A 213 B							
				END @ 14:09							
	AW-4	14:23									
14:28	↓	↓	Bag	70	92	65	145	114	20.0	.2	
14:31			Bag	71	91	65	145	113	↓	.1	

ETHYLENE OXIDE SAMPLING DATA SHEET

DATE 6/23/88

RUN ID 3

SAMPLER PTL/WPG

SCHEDULE:

INITIAL EXHAUST 1

AIR WASHES 5

FACILITY Burton

BAROMETRIC PRESSURE

TIME	EXHAUST #	START	CONTAINER	ID	TEMPERATURE (F) VENT	t'	PUMP	HEAT TRACE	PERCENT OXYGEN	Ps (IN Hg)	NOTES
14:32	AW4	14:23	V	214A 214B							
14:33	↓	↓	Sy	127A 128A	3 unused						
14:34			Bag	72	92	66	145	114	20.5	—	
14:35			V	215A 215B							

APPENDIX F

CHAMBER TEMPERATURE AND PRESSURE DATA

164

	ELAPSED TIME (MIN)	GAS TEMP (C)	CHAMBER TEMP (C)	CHAMBER PRESS (PSIA)
	8.7	35.3	44.0	7.3
IZE	9.2	35.3	44.5	6.9

12/88 CYCLE PARAMETERS:

DATE: 6 / 21 / 88
TIME: : :
CODE: # Run #1

PREVAC		
SPL	2.0	P
HUMIDITY		
STEAM LEVEL	3.1	P
DWELL TIME	15.0	M
CHARGE		
ETO LEVEL	23.7	P
STERILIZE		
TIME	15.0	M
TEMP	52.0	C
POSTVAC AIR		
SPL	2.0	P
SPH	10.0	P
ALARMS		
HIGH PRESS	25.0	P
HIGH TEMP	60.0	C

165

E/ M	ELAPSED TIME (MIN)	GAS TEMP (C)	CHAMBER TEMP (C)	CHAMBER PRESS (PSIA)
AC	19.9	33.9	50.2	14.4
	20.0	34.0	50.0	14.0
	22.0	34.0	47.5	11.1
	24.0	34.0	45.7	8.9
	26.0	34.0	45.6	7.1
	28.0	34.1	46.3	5.7
	30.0	34.2	46.2	4.6
	32.0	34.3	46.8	3.8
	34.0	34.4	47.7	3.4
	36.0	34.4	47.9	3.0
	38.0	34.5	48.3	2.5
	40.0	34.6	48.8	2.3
	42.0	34.6	49.5	2.1
DITY	42.7	34.6	49.1	2.0
	44.0	34.7	50.1	2.4
	46.0	34.8	50.6	2.6
	48.0	34.8	51.0	2.8
	50.0	34.9	50.6	3.0
	52.0	35.0	51.5	3.1
DITY	52.9	35.0	51.6	3.2
	54.0	35.0	51.4	3.1
	56.0	35.1	51.4	3.1
	58.0	35.1	51.3	3.1
	60.0	35.1	51.5	3.1
	62.0	35.2	51.4	3.1
	64.0	35.3	51.5	3.1
	66.0	35.3	51.7	3.1
GE	68.0	32.5	51.8	3.2
	70.0	51.6	52.8	4.6
	72.0	50.3	53.6	6.2
	74.0	49.2	54.2	7.6
	76.0	47.7	54.4	8.9
	78.0	46.0	54.5	10.4
	80.0	46.1	54.5	11.8
	82.0	46.5	54.4	13.3
	84.0	45.3	54.6	14.8
	86.0	45.4	54.6	16.2
	88.0	44.6	54.4	17.6
	90.0	43.4	54.2	19.0
	92.0	42.3	54.2	20.4
	94.0	40.7	54.2	21.8
	96.0	41.5	54.2	23.3
ILIZE	96.7	41.8	54.0	23.8
	98.0	40.6	53.8	24.2
	100.0	40.9	53.2	24.2
	102.0	41.0	52.6	24.2
	104.0	41.1	52.4	24.2
	106.0	41.2	52.2	24.2

106

	110.0	41.1	54.4	24.1
JST	111.6	41.0	54.4	24.1
	112.0	41.0	56.5	24.1
	114.0	40.9	56.3	22.9
	116.0	40.7	55.5	21.1
	118.0	40.6	55.4	19.6
	120.0	40.5	55.5	18.4
	122.0	40.4	55.8	17.4
	124.0	40.3	56.1	16.5
	126.0	40.1	56.4	15.9
	128.0	40.1	56.7	15.4
	130.0	40.0	57.0	15.1
	132.0	39.9	57.2	14.9
VAC AIR	133.6	39.8	51.4	14.7
	134.0	39.8	51.4	14.3
	136.0	39.7	50.0	12.3
	138.0	39.6	49.4	10.7
	140.0	39.5	49.3	9.2
	142.0	39.5	49.4	8.0
	144.0	39.4	49.6	7.0
	146.0	39.4	49.6	6.1
	148.0	39.4	49.7	5.2
	150.0	39.4	49.9	4.6
	152.0	39.4	50.1	4.1
	154.0	39.3	50.9	3.7
	156.0	39.3	50.8	3.3
	158.0	39.3	50.9	3.1
	160.0	39.3	51.1	2.8
	162.0	39.3	51.2	2.5
	164.0	39.3	51.5	2.3
	166.0	39.3	51.5	2.2
	168.0	39.3	51.7	2.0
VAC AIR	168.6	39.3	59.2	2.0
	170.0	39.4	60.7	3.2
	172.0	39.4	61.8	5.0
	174.0	39.4	62.4	6.7
	176.0	39.4	62.4	8.2
	178.0	39.4	57.1	10.1
VAC AIR	178.2	39.4	57.0	10.0
	180.0	39.3	53.4	8.5
	182.0	39.2	51.0	6.9
	184.0	39.2	50.4	5.7
	186.0	39.2	50.2	4.7
	188.0	39.1	50.4	4.0
	190.0	39.2	50.7	3.5
	192.0	39.2	51.1	3.0
	194.0	39.2	51.6	2.7
	196.0	39.2	52.4	2.4
	198.0	39.2	52.5	2.2
VAC AIR	199.9	39.2	58.4	2.1
	200.0	39.2	58.3	2.3
	202.0	39.2	60.5	4.1
	204.0	39.3	61.5	5.8
	206.0	39.3	61.8	7.3
	208.0	39.3	61.9	8.8
VAC AIR	209.4	39.2	57.4	10.0
	210.0	39.2	55.7	9.5
	212.0	39.2	52.5	7.8
	214.0	39.1	50.8	6.3
	216.0	39.1	51.0	5.1
	218.0	39.1	50.3	4.1
	220.0	39.0	50.7	3.6
	222.0	39.0	52.2	3.1
	224.0	39.0	51.4	2.7

JST	111.8	41.0	54.4	24.1
	112.0	41.0	56.2	24.1
	114.0	40.9	56.7	22.7
	116.0	40.7	55.5	21.1
	118.0	40.6	55.4	19.6
	120.0	40.5	55.5	18.4
	122.0	40.4	55.8	17.4
	124.0	40.3	56.1	16.5
	126.0	40.1	56.4	15.9
	128.0	40.1	56.7	15.4
	130.0	40.0	57.0	15.1
	132.0	39.9	57.2	14.9
VAC AIR	133.6	39.8	51.4	14.7
	134.0	39.8	51.4	14.3
	136.0	39.7	50.0	12.3
	138.0	39.6	49.4	10.7
	140.0	39.5	49.3	9.2
	142.0	39.5	49.4	8.0
	144.0	39.4	49.6	7.0
	146.0	39.4	49.6	6.1
	148.0	39.4	49.7	5.2
	150.0	39.4	49.9	4.6
	152.0	39.4	50.1	4.1
	154.0	39.3	50.9	3.7
	156.0	39.3	50.8	3.3
	158.0	39.3	50.9	3.1
	160.0	39.3	51.1	2.8
	162.0	39.3	51.2	2.5
	164.0	39.3	51.5	2.3
	166.0	39.3	51.5	2.2
	168.0	39.3	51.7	2.0
VAC AIR	168.6	39.3	59.2	2.0
	170.0	39.4	60.7	3.2
	172.0	39.4	61.8	5.0
	174.0	39.4	62.4	6.7
	176.0	39.4	62.4	8.2
	178.0	39.4	57.1	10.1
VAC AIR	178.2	39.4	57.0	10.0
	180.0	39.3	53.4	8.5
	182.0	39.2	51.0	6.7
	184.0	39.2	50.4	5.7
	186.0	39.2	50.2	4.7
	188.0	39.1	50.4	4.0
	190.0	39.2	50.7	3.5
	192.0	39.2	51.1	3.0
	194.0	39.2	51.8	2.7
	196.0	39.2	52.4	2.4
	198.0	39.2	52.5	2.2
VAC AIR	199.9	39.2	58.4	2.1
	200.0	39.2	58.3	2.3
	202.0	39.2	60.5	4.1
	204.0	39.3	61.5	5.8
	206.0	39.3	61.8	7.3
	208.0	39.3	61.9	8.8
VAC AIR	209.4	39.2	57.4	10.0
	210.0	39.2	55.7	9.5
	212.0	39.2	52.5	7.8
	214.0	39.1	50.8	6.5
	216.0	39.1	51.0	5.1
	218.0	39.1	50.3	4.1
	220.0	39.0	50.7	3.6
	222.0	39.0	52.2	3.1
	224.0	39.0	51.4	2.7
	226.0	39.0	51.6	2.4

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Time wrong Printer Jam

12.0 probably = 228.0

		39.1		51.6		2.1	
IR	13.1		39.1		51.9		2.0
0		39.1		52.6		2.7	
16.0		39.1		55.0		4.2	
19.0		39.2		56.1		6.0	
[illegible]		39.3		62.6		7.7	
22.0		39.3		62.7		9.2	
IR	23.1		39.3		56.8		10.0
[illegible]		39.2		55.5		9.3	
26.0		39.2		52.7		7.5	
28.0		39.2		50.8		6.0	
[illegible]		39.2		50.6		4.8	
32.0		39.2		50.1		3.9	
34.0		39.2		50.7		3.4	
[illegible]		39.2		51.0		3.0	
38.0		39.2		51.2		2.6	
40.0		39.2		51.6		2.3	
[illegible]		39.2		51.7		2.1	
IR	42.8		39.3		59.0		2.1
44.0		39.2		60.8		3.3	
[illegible]		39.3		62.4		4.8	
48.0		39.3		62.9		6.6	
50.0		39.3		63.1		8.2	
[illegible]		39.2		62.9		9.7	
IR	51.4		39.2		57.2		10.0
54.0		39.2		54.4		6.[illegible]	
[illegible]		39.1		51.3		6.9	
58.0		39.1		50.[illegible]		5.5	
60.0		39.0		50.1		4.4	
[illegible]		39.0		50.4		3.7	
64.0		39.0		50.7		3.2	
66.0		39.0		51.0		2.8	
[illegible]		39.1		51.8		2.5	
70.0		39.2		51.5		2.2	
72.0		39.2		51.7		2.0	
IR	73.1		39.2		57.[illegible]		2.1
[illegible]		39.3		60.1		3.8	
76.0		39.3		61.3		5.4	
[illegible]		39.4		61.8		6.9	
80.0		39.5		61.9		8.7	
82.0		39.6		61.7		10.2	
[illegible]		39.6		61.4		11.8	
86.0		39.6		61.0		13.2	
87.3		39.6		60.7		13.9	

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12/88 CYCLE PARAMETERS:

DATE: 6 / 22 / 88
TIME: : :
CODE: # RUN 2

PREVAC
SPL 2.0 P
HUMIDITY
STEAM LEVEL 3.1 P
DWELL TIME 15.0 M
CHARGE
ETO LEVEL 23.7 P
STERILIZE
TIME 15.0 M
TEMP 52.0 C
POSTVAC AIR
SPL 2.0 P
SPH 10.0 P
ALARMS
HIGH PRESS 25.0 P
HIGH TEMP 60.0 C

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HASE/ LARM	ELAPSED TIME (MIN)	GAS TEMP (C)	CHAMBER TEMP (C)	CHAMBER PRESS (PSIA)
REVAC	0.2	35.0	53.9	14.6
	2.0	35.0	52.7	13.8
	4.0	34.9	49.5	10.9
	6.0	34.9	48.4	8.8
	8.0	34.9	48.2	6.9
	10.0	34.9	48.3	5.6
	12.0	34.9	48.5	4.5
	14.0	34.9	49.2	3.8
	16.0	35.0	49.8	3.4
	18.0	35.1	50.1	3.0
	20.0	35.1	50.5	2.6
	22.0	35.1	50.8	2.4
	24.0	35.2	51.0	2.1
JMIDITY	25.6	35.2	59.2	2.0
	26.0	35.2	59.9	2.4
	28.0	35.3	60.7	2.7
	30.0	35.4	61.2	3.0
JMIDITY	31.3	35.4	60.5	3.1
	32.0	35.4	53.6	3.1
	34.0	35.4	54.0	3.0
	36.0	35.4	52.7	3.1
	38.0	35.4	56.6	3.0
	40.0	35.4	52.6	3.0
	42.0	35.5	52.6	3.0
	44.0	35.5	52.7	3.0
	46.0	35.6	52.8	3.0
HARGE	46.2	35.6	60.5	3.0
	48.0	56.2	53.6	4.4
	50.0	57.6	54.3	5.7
	52.0	58.3	56.3	7.2
	54.0	58.7	62.3	8.6
	56.0	58.5	56.3	10.2
	58.0	58.6	55.4	11.6
	60.0	58.6	55.4	12.9
	62.0	58.3	55.4	14.4
	64.0	57.5	55.4	15.6
	66.0	57.3	57.4	17.2
	68.0	56.8	56.3	18.6
	70.0	56.4	56.2	20.2
	72.0	56.1	55.5	21.4
	74.0	55.2	55.2	23.0
TERILIZE	75.3	55.2	55.9	23.8
	76.0	54.8	55.2	24.3
	78.0	54.7	54.2	24.2
	80.0	54.4	53.7	24.1
	82.0	54.0	53.4	24.1
	84.0	53.4	57.9	24.1
	86.0	52.8	57.8	24.0
	88.0	52.3	57.3	24.1
	90.0	51.7	57.0	24.0
HAUST	90.2	51.6	57.2	24.0
	[illegible]	[illegible]	[illegible]	[illegible]

	[illegible]	[illegible]	[illegible]	[illegible]
	98.0	49.[illegible]	56.[illegible]	19.[illegible]
	100.0	49.1	56.5	18.1
	102.0	48.7	56.7	17.2
	104.0	48.2	57.1	16.4
	106.0	47.6	57.2	15.9
	108.0	47.4	57.5	15.4
	110.0	47.0	57.8	15.0
STVAC AIR	111.1	46.8	51.9	14.8
	112.0	46.6	51.5	14.7
	114.0	46.2	50.2	13.7
	116.0	45.9	49.9	11.9
	118.0	45.5	49.8	10.3
	120.0	45.2	49.9	8.9
	122.0	44.9	49.9	7.8
	124.0	44.6	50.0	6.7
	126.0	44.3	50.2	5.8
	128.0	44.[illegible]	50.4	5.1
	130.0	43.5	50.6	4.5
	132.0	43.3	50.9	4.0
	134.0	43.3	51.1	3.6
	136.0	43.1	51.3	3.3
	138.0	43.0	51.3	3.0
	140.0	42.7	51.6	2.8
	142.0	42.6	51.6	2.5
	144.0	42.5	51.6	2.3
	146.0	42.3	51.8	2.1
STVAC AIR	146.2	42.3	60.2	2.0
	148.0	42.2	61.7	2.1
	150.0	42.1	62.5	3.3
	152.0	42.0	62.9	5.2
	154.0	41.9	63.0	6.8
	156.0	41.8	62.8	8.5
STVAC AIR	156.1	41.8	55.7	10.0
	158.0	41.6	53.3	10.1
	160.0	41.3	51.3	8.6
	162.0	41.2	50.6	7.1
	164.0	41.1	50.4	5.8
	166.0	41.0	50.4	4.8
	168.0	40.8	50.9	4.0
	170.0	40.8	51.1	3.5
	172.0	40.6	51.4	3.1
	174.0	40.6	51.6	2.8
	176.0	40.5	51.7	2.4
	178.0	40.4	51.9	2.2
STVAC AIR	178.1	40.5	59.8	2.0
	180.0	40.4	61.4	2.0
	182.0	40.5	62.6	3.5
	184.0	40.4	63.1	5.2
	186.0	40.4	63.0	6.7
	188.0	40.3	57.1	8.6
STVAC AIR	188.1	40.3	56.1	10.0
	190.0	40.2	53.6	10.0
	192.0	40.1	51.0	8.5
	194.0	40.0	50.2	6.8
	196.0	40.0	50.1	5.5
	198.0	40.0	50.3	4.4
	200.0	39.9	50.8	3.7
	202.0	39.9	51.0	3.2
	204.0	39.9	51.2	2.9
	206.0	39.9	51.5	2.5
	208.0	39.9	51.7	2.3
STVAC AIR	208.5	39.9	59.3	2.0
	210.0	39.9	60.7	2.0
	212.0	40.0	62.3	3.1
				4.4

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	216.0	39.7	63.1	8.0
JSTVAC AIR	218.0	39.5	62.7	9.7
	218.5	39.9	56.8	10.0
	220.0	39.9	54.5	9.1
	222.0	39.8	51.8	7.5
	224.0	39.8	50.4	6.0
	226.0	39.7	50.0	4.8
	228.0	39.8	50.0	4.0
	230.0	39.8	50.4	3.8
	232.0	39.8	50.8	3.0
	234.0	39.8	51.0	2.6
	236.0	39.9	51.4	2.4
	238.0	39.9	51.9	2.1
JSTVAC AIR	239.1	39.9	58.6	2.1
	240.0	39.9	59.2	2.7
	242.0	40.0	61.5	4.3
	244.0	40.0	62.3	5.9
	246.0	40.0	62.5	7.5
	248.0	40.0	62.5	9.3
JSTVAC AIR	249.1	40.0	56.5	10.1
	250.0	40.0	55.5	9.3
	252.0	39.9	51.9	7.5
	254.0	39.9	50.3	6.1
	256.0	39.9	49.9	4.9
	258.0	39.9	50.1	3.9
	260.0	40.0	50.4	3.4
	262.0	40.0	50.8	3.0
	264.0	40.0	51.4	2.6
	266.0	40.0	51.5	2.3
	268.0	40.0	51.7	2.1
STVAC AIR	268.9	40.0	59.6	1.9
	270.0	40.1	60.8	3.1
	272.0	40.1	62.8	4.7
	274.0	40.2	63.4	6.1
	276.0	40.2	63.5	7.8
	278.0	40.1	63.4	9.6
STVAC AIR	278.7	40.1	56.7	9.9
	280.0	40.1	54.8	9.0
	282.0	40.1	51.7	7.1
	284.0	40.0	50.3	5.7
	286.0	40.1	49.9	4.6
	288.0	40.0	50.4	3.8
	290.0	40.0	50.8	3.3
	292.0	40.1	50.8	2.9
	294.0	40.0	51.2	2.5
	296.0	40.1	51.4	2.3
	298.0	40.1	51.6	2.0
TVAC AIR	298.3	40.1	59.6	2.0
	300.0	40.2	61.9	3.6
	302.0	40.2	63.1	5.2
	304.0	40.2	63.8	6.7
	306.0	40.3	63.6	8.4
	308.0	40.3	63.5	10.1
	310.0	40.3	63.1	11.5
	312.0	40.3	62.8	13.0
	313.7	40.4	62.3	13.9

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TIME: 6:30 AM

PROGRAM #4 PARAMETERS

-23-88

EVACUATE
SPL..... 1.5 PSI
HUMIDITY
SPH..... 2.6 PSI
DWELL..... 30.0 MINUTES
CHARGE
NIT SPH..... 6.7 PSI
ETO SPH..... 12.1 PSI
NIT CAP..... 13.0 PSI
STERILIZE
TIME..... 125.0 MINUTES
TEMP..... 52.0 CENTIGRADE
PRE/POST NITROGEN PURGE
SPH..... 13.0 PSI
OF CYCLES. 1.0
POST VAC AIR
SPH..... 10.0 PSI
OF CYCLES. 4.0
ALARMS
HI PRESS.... 14.0 PSI
HI TEMP..... 60.0 CENTIGRADE

	CYCLE TIME (MIN)	GAS TEMP (C)	CHMBR TEMP (C)	CHMBR PRESS (PSI)
PRE-VAC	0.0	37.0	43.8	14.2
	2.0	36.9	45.0	13.5
	4.0	36.9	44.9	11.3
	6.0	36.8	44.7	9.4
	8.0	36.7	44.7	7.5
	10.0	36.7	44.7	5.7
	12.0	36.7	45.1	4.4
	14.0	36.6	45.7	3.4
	16.0	36.6	46.3	2.7
	18.0	36.6	47.0	2.1
	20.0	36.6	47.5	1.8
LEAK TEST	21.5	36.6	47.7	1.5
	22.0	36.7	47.7	1.5
	24.0	36.7	48.5	1.5
	26.0	36.7	49.1	1.6
	28.0	36.7	49.6	1.6
	30.0	36.7	50.1	1.6
PRE-NITROGEN PURGE	31.4	36.8	50.3	1.6
	32.0	36.4	50.3	1.8
	34.0	38.0	50.1	2.2
	36.0	40.7	50.1	2.7
	38.0	43.9	50.1	3.2
	40.0	47.2	50.3	3.7
	42.0	50.4	50.6	4.2

	44.0	53.2	50.8	4.7

	32.0	36.4	50.3		1.8
	34.0	38.0	50.1		2.2
	36.0	40.7	50.1		2.7
	38.0	43.9	50.1		3.2
	40.0	47.2	50.3		3.7
	42.0	50.4	50.6		4.2
	44.0	53.2	50.8		4.7
	46.0	55.6	51.0		5.2
	48.0	57.6	51.3		5.7
	50.0	59.2	51.4		6.2
	52.0	60.4	51.6		6.7
	54.0	61.4	51.8		7.2
	56.0	62.2	51.9		7.7
	58.0	62.8	52.0		8.2
	60.0	63.2	52.1		8.7
	62.0	63.4	52.2		9.2
	64.0	63.7	52.2		9.7
	66.0	63.8	52.3		10.2
	68.0	63.9	52.3		10.7
	70.0	64.0	52.3		11.2
	72.0	64.0	52.3		11.7
	74.0	64.1	52.3		12.2
	76.0	64.1	52.3		12.7
	78.0	63.2	52.2		13.0
	80.0	60.6	51.1		11.2
	82.0	58.8	48.9		9.3
	84.0	57.5	47.9		7.3
	86.0	56.4	47.5		5.6
	88.0	55.5	47.6		4.3
	90.0	54.8	48.0		3.4
	92.0	54.1	48.5		2.6
	94.0	53.5	49.0		2.1
	96.0	53.0	49.3		1.8
HUMIDIFICATION	97.6	52.6	49.5		1.5
	98.0	52.5	49.7		1.8
	100.0	52.0	51.0		2.0
	102.0	51.6	52.1		2.2
	104.0	51.2	52.9		2.3
	106.0	50.8	53.4		2.4
	108.0	50.5	54.0		2.5
	110.0	50.1	54.3		2.5
HUMIDITY DWELL	110.1	50.1	54.2		2.6
	112.0	49.7	54.2		2.5
	114.0	49.3	54.1		2.5
	116.0	49.0	54.0		2.4
	118.0	48.7	54.1		2.4
	120.0	48.4	54.0		2.4
	122.0	48.0	53.9		2.4
	124.0	47.8	53.9		2.4
	126.0	47.5	53.8		2.4
	128.0	47.2	53.8		2.4
	130.0	46.9	53.7		2.4
	132.0	46.7	53.7		2.4
	134.0	46.4	53.6		2.4
	136.0	46.1	53.6		2.4
	138.0	45.9	53.5		2.4
NITROGEN CHARGE	139.9	45.7	53.5	132	2.4
	140.0	45.7	53.5		2.4

	132.0	46.7	53.7	2.4
	134.0	46.4	53.6	2.4
	136.0	46.1	53.6	2.4
	138.0	45.9	53.5	2.4
NITROGEN CHARGE	139.9	45.7	53.5	2.4
	140.0	45.7	53.5	2.4
	142.0	47.3	53.3	2.8
	144.0	49.1	53.4	3.3
	146.0	51.1	53.5	3.8
	148.0	53.2	53.6	4.3
	150.0	55.2	53.6	4.8
	152.0	57.1	53.7	5.3
	154.0	58.7	53.8	5.8
	156.0	60.0	53.8	6.3
	158.0	60.1	53.9	6.7
	160.0	57.4	53.6	6.7
	162.0	55.7	53.4	6.7
	164.0	54.5	53.3	6.7
	166.0	53.6	53.2	6.7
ETO CHARGE	167.7	53.1	53.2	6.7
	168.0	53.5	53.2	6.7
	170.0	58.8	53.4	7.6
	172.0	60.6	53.8	8.2
	174.0	61.6	54.2	9.0
	176.0	61.4	54.4	9.6
	178.0	60.6	54.5	10.3
	180.0	59.3	54.4	11.1
	182.0	58.3	54.4	11.8
NITROGEN CAP	183.1	58.0	54.4	12.1
	184.0	37.9	53.6	12.6
	186.0	39.5	52.7	13.0
EXPOSURE	186.1	39.7	52.7	13.0
	188.0	37.5	52.7	12.9
	190.0	36.4	52.7	12.9
	192.0	36.2	52.7	12.9
	194.0	36.3	52.8	12.8
	196.0	36.6	52.8	12.8
	198.0	36.8	52.8	12.8
	200.0	37.0	52.8	12.8
	202.0	37.2	52.8	12.7
	204.0	37.4	52.8	12.7
	206.0	37.5	52.8	12.7
	208.0	37.6	52.8	12.7
	210.0	37.7	52.8	12.7
	212.0	37.8	52.8	12.7
	214.0	37.9	52.7	12.6
	216.0	38.0	52.5	12.6
	218.0	38.1	52.4	12.6
	220.0	38.2	52.5	12.6
	222.0	38.3	52.5	12.6
	224.0	38.4	52.5	12.6
	226.0	38.4	52.5	12.6
	228.0	38.5	52.4	12.6
	230.0	38.6	52.4	12.5
	232.0	38.7	52.3	12.5
	234.0	38.8	52.2	12.5
	236.0	38.8	52.3	12.5
	238.0	38.8	52.2	12.5

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	240.0	38.5	52.2	12.5
	242.0	39.0	52.2	12.5
	244.0	39.0	52.2	12.5
	246.0	39.1	52.2	12.5
	248.0	39.2	52.3	12.5
	250.0	39.3	52.5	12.4
	252.0	39.3	52.2	12.4
	254.0	39.3	52.1	12.4
	256.0	39.4	52.0	12.4
	258.0	39.4	51.9	12.4
	260.0	39.4	51.9	12.4
	262.0	39.4	51.8	12.4
	264.0	39.5	51.9	12.4
	266.0	39.4	51.9	12.4
	268.0	39.5	51.8	12.4
	270.0	39.5	51.8	12.4
	272.0	39.5	51.9	12.4
	274.0	39.5	51.9	12.4
	276.0	39.5	51.8	12.4
	278.0	39.6	51.8	12.4
	280.0	39.6	51.8	12.4
	282.0	39.6	51.9	12.4
	284.0	39.6	51.8	12.3
	286.0	39.6	51.8	12.3
	288.0	39.6	51.8	12.3
	290.0	39.6	51.8	12.3
	292.0	39.6	51.8	12.3
	294.0	39.6	51.8	12.3
	296.0	39.7	51.8	12.3
	298.0	39.7	51.8	12.3
	300.0	39.6	51.8	12.3
	302.0	39.6	51.8	12.3
	304.0	39.6	51.7	12.3
	306.0	39.6	51.8	12.3
	308.0	39.6	51.8	12.3
	310.0	39.7	51.8	12.3
POST-NITROGEN PURGE	310.0	39.7	51.8	12.3
	312.0	39.7	51.7	11.6
	314.0	39.7	50.7	9.6
	316.0	39.6	49.8	7.6
	318.0	39.6	49.2	6.0
	320.0	39.6	49.0	4.8
	322.0	39.7	49.1	3.9
	324.0	39.8	49.3	3.2
	326.0	39.8	49.4	2.7
	328.0	39.8	49.7	2.3
	330.0	39.9	49.9	2.0
	332.0	39.9	50.1	1.8
	334.0	40.0	50.3	1.6
	336.0	40.1	50.4	1.8
	338.0	41.7	50.3	2.2
	340.0	44.0	50.4	2.7
	342.0	46.3	50.5	3.2
	344.0	48.7	50.8	3.8
	346.0	51.0	51.1	4.3
	348.0	53.1	51.3	4.8
	350.0	54.8	51.6	5.3
	352.0	56.1	51.8	5.8
	354.0	57.3	52.0	6.1

	346.0	53.0	51.1	4.3
	348.0	53.1	51.3	4.8
	350.0	54.8	51.6	5.3
	352.0	56.1	51.8	5.8
	354.0	57.3	52.0	6.3
	356.0	58.1	52.2	6.8
	358.0	58.8	52.3	7.3
	360.0	59.3	52.4	7.8
	362.0	59.7	52.5	8.3
	364.0	60.0	52.5	8.8
	366.0	60.2	52.5	9.3
	368.0	60.4	52.6	9.9
	370.0	60.7	52.6	10.4
	372.0	60.8	52.7	10.9
	374.0	60.7	52.7	11.4
	376.0	60.8	52.7	11.9
	378.0	60.9	52.7	12.4
	380.0	61.0	52.8	12.9
POST-AIR PURGE	380.3	61.0	52.8	13.0
	382.0	59.3	52.6	12.4
	384.0	57.6	51.0	10.6
	386.0	56.3	49.5	8.6
	388.0	55.2	48.6	6.7
	390.0	54.4	48.4	5.2
	392.0	53.9	48.6	4.1
	394.0	53.2	48.9	3.2
	396.0	52.8	49.2	2.6
	398.0	52.4	49.4	2.1
	400.0	52.0	49.8	2.0
	402.0	51.7	50.3	2.1
	404.0	51.3	50.9	2.8
	406.0	51.1	52.2	5.0
	408.0	50.8	53.2	6.9
	410.0	50.5	53.9	8.8
	412.0	50.2	54.4	10.0
	414.0	49.8	52.2	8.2
	416.0	49.5	49.8	6.4
	418.0	49.2	48.9	5.0
	420.0	48.8	48.9	3.9
	422.0	48.5	49.0	3.1
	424.0	48.3	49.2	2.5
	426.0	48.1	49.6	2.0
	428.0	47.9	50.2	2.1
	430.0	47.8	50.5	2.1
	432.0	47.6	51.3	3.3
	434.0	47.5	52.7	5.4
	436.0	47.4	53.6	7.5
	438.0	47.2	54.1	9.3
	440.0	46.9	53.6	8.6
	442.0	46.7	50.7	6.7
	444.0	46.5	49.4	5.2
	446.0	46.3	48.9	4.0
	448.0	46.2	48.9	3.1
	450.0	46.0	49.2	2.5
	452.0	45.9	49.6	2.1
	454.0	45.8	50.2	2.0
	456.0	45.7	50.6	2.1
	458.0	45.6	51.3	3.3
	460.0	45.6	52.9	5.1

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	406.0	51.1	52.2	5.0
	408.0	50.8	53.2	6.9
	410.0	50.5	53.9	8.8
	412.0	50.2	54.4	10.0
	414.0	49.8	52.2	8.2
	416.0	49.5	49.8	6.4
	418.0	49.2	48.9	5.0
	420.0	48.8	48.9	3.9
	422.0	48.5	49.0	3.1
	424.0	48.3	49.2	2.5
	426.0	48.1	49.6	2.0
	428.0	47.9	50.2	2.1
	430.0	47.8	50.5	2.1
	432.0	47.6	51.3	3.3
	434.0	47.5	52.7	5.4
	436.0	47.4	53.6	7.5
	438.0	47.2	54.1	9.3
	440.0	46.9	53.6	8.6
	442.0	46.7	50.7	6.7
	444.0	46.5	49.4	5.2
	446.0	46.3	48.9	4.0
	448.0	46.2	48.9	3.1
	450.0	46.0	49.2	2.5
	452.0	45.9	49.6	2.1
	454.0	45.8	50.2	2.0
	456.0	45.7	50.6	2.1
	458.0	45.6	51.3	3.3
	460.0	45.6	52.9	5.1
	462.0	45.5	53.8	7.3
	464.0	45.5	54.3	9.3
	466.0	45.4	54.6	10.0
	468.0	45.2	51.9	8.0
	470.0	45.1	49.9	6.1
	472.0	44.8	49.0	4.8
	474.0	44.8	48.6	3.7
	476.0	44.8	48.9	2.9
	478.0	44.7	49.3	2.3
	480.0	44.7	49.7	2.0
	482.0	44.6	50.3	2.1
	484.0	44.6	50.7	2.1
	486.0	44.5	51.9	3.9
	488.0	44.6	53.3	5.9
	490.0	44.6	54.1	8.1
	492.0	44.5	54.7	9.9
	494.0	44.5	55.5	11.9
	496.0	44.4	55.9	13.3
CYCLE COMPLETE	497.5	44.4	55.4	14.0

0.0	44.4	55.4	14.0

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Office of Air Quality
Planning and Standards
Research Triangle Park NC 27711

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Air

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Final

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1.0 INTRODUCTION

This report contains the results of a study of air emissions from hospital waste combustion. It represents an effort to gather currently available data in a manner that will allow the EPA to assess the need for and feasibility of regulating multipollutant emissions from hospital waste combustion. The work was performed by Radian Corporation under contract to EPA's Pollutant Assessment Branch of the Office of Air Quality Planning and Standards (OAQPS).

During the course of this study, information was gathered from State and local environmental agencies, from vendors of incineration equipment, from the open technical literature, from the American Hospital Association, and from visits to three incineration facilities. Information was sought concerning feed characteristics, combustor designs and operating characteristics, emissions of air pollutants, applied and potential control technology, numbers and locations of hospital waste combustors, and applicable regulations. In addition, parameters needed to model exposure and health risk have been developed for use in EPA's Human Exposure Model.

A final draft report for this study was prepared in October 1987. This report was widely circulated by EPA/OAQPS for review and comments by EPA Regional Offices, State agenices, related trade associations, incinerator vendors, and interested individuals. Comments received were evaluated and incorporated into this report where appropriate. While some new emissions data were received, they were of a preliminary nature and thus have been reported as a separate category of data in Section 3.

The remainder of Section 1 is devoted to a description of the industry (Section 1.1) and characterization of hospital waste (Section 1.2). Section 2.0 contains information about the processes and equipment used for hospital waste combustion. Data gathered concerning air pollutants emitted from hospital waste incinerators and their formation in the combustion process are presented in Section 3.0. Section 4.0 contains a discussion of control techniques and possible control efficiencies. environmental regulations affecting hospital waste combustion are presented in Section 3.0. Section 4.0 contains a discussion of control techniques and possible control efficiencies. Environmental regulations affecting hospital waste combustion are presented in Section 5.0. Model plants suitable for EPA's use in assessing regulatory strategies are developed in Section 6.0.

1.1 DESCRIPTION OF THE INDUSTRY

"Hospital waste" refers to wastes produced by a hospital or hospital-type facility. These wastes include both infectious wastes (i.e., materials which come in contact with hospital patients and which have a potential to carry disease-producing organisms) and non-infectious or general housekeeping wastes. The volume of infectious waste produced by a facility can vary widely, depending primarily on guidelines or practices employed. Based upon CDC guidelines, infectious waste would only comprise 3 to 5 percent of the total hospital waste.[1] Conversely, hospital infectious waste could comprise 80 percent or more of total waste based upon the Universal Isolation Precaution Guidelines of August 1987. In addition to these guidelines, the waste segregation practices employed by hospitals will influence the total volume of waste which is considered infectious. Although segregation of infectious and non-infectious waste introduces additional handling complications and expense, comments received from the American Society for Hospital Engineering (of the American Hospital Association) indicate that most hospitals have waste segregation programs in place.[2]

In many States, laws have been enacted in the past ten years which prohibit the disposal of infectious wastes in landfills. To qualify for disposal, wastes must first be rendered innocuous. The two primary sterilization methods used by hospitals are autoclaving and incineration. Sterilization with ethylene oxide and waste shredding followed by chemical disinfection are available alternatives but are not commonly used. Due to limitations associated with autoclaving (i.e., limited capacities, handling problems, and questionable effectiveness) and ethylene oxide units (i.e., worker health risks), incineration has become the most practical waste sterilization and disposal option for many hospital facilities,[3] according to authorities in Illinois.

Incineration reduces waste volumes by up to 90 percent. Hence, the volume and cost of ultimate disposal of residual wastes in a landfill can be reduced significantly by this method. An additional benefit of incineration systems, in some cases, is that they can be designed for heat recovery with the potential to supply a portion of the hospital's steam or hot water requirements.

The total number and capacity of hospital waste incinerators in the United States is uncertain. As of 1985, there were a reported 6,872 hospitals in the nation with 1,318,000 beds.[4] Estimates of waste generation rates range from about 8 to 45 lb/bed/day.[5,6,7] For example, Table 1-1 shows hospital waste generation per bed for seventeen hospitals in the State of Florida. The waste generation rate for these seventeen hospitals ranged from 8 to 45 lb/bed/day and averaged 23 lb/bed/day. Using this average generation rate and an average occupancy rate of 69 percent, the total hospital waste generation rate in the United States is estimated to be about 10,500 tons/day. However, not all hospital waste is sent to incinerators, as discussed above. To estimate actual incinerator tonnage, this rate would need to be reduced by the amount of infectious waste handled by other treatment processes and the amount of general waste that is segregated and sent via trash disposal to landfills. Unfortunately, it is not possible to estimate these quantities based on the information gathered to date. As a point of reference, however, about 18,000 tons/day of municipal solid waste were disposed of by combustion by municipalities in 1985.[8]

With regard to geographic distribution, hospitals are located in every State as well as in the District of Columbia. At least one hospital was located in almost all metropolitan and non-metropolitan statistical areas in 1985 according to American Hospital Association statistics[9] Of the total number of hospitals, approximately 53 percent were located in metropolitan statistical areas with the balance in non-metropolitan areas.

Detailed statistics are available only for community hospitals, which comprised over 83 percent of the total number of hospitals in 1985. During the 1975 to 1985 period, the number of community hospitals declined by 2.4 percent; the total number of beds increased by 6.2 percent, however, a shift attributed to hospital closures, mergers, and conversion to nonacute-care facilities.[10] Although the occupancy rate for community hospitals declined from 75 to about 65 percent, the number of surgical operations (which produce higher levels of infectious waste) increased by almost 21 percent. Taking these off-setting factors into account, the

TABLE 1-1. WASTE GENERATION RATES FOR SEVENTEEN HOSPITALS IN THE STATE OF FLORIDA[a]

Hospital	Pathological	Infectious	General	Food	Cardboard	Total	Average # Beds	#/Bed/Day
Miami Jewish Home & Hospital	--	23	1,350	6,120	405	7,898	376	21
Coral Reef Hospital	--	320[b]	2,567[c]	--	--	2,887	127	23
Miami General	2	685	3,570[c]	--	--	4,257	237	18
North Ridge General	17	95	3,440[d]	--	301	3,853	168	23
South Miami Hospital	--	300	3,400	1,700	567	5,967	350	17
Cedars Medical Center	--	900	6,800	500	1,000	9,200	355	26
American Hospital of Miami	--	3,140	4,586[c]	--	--	7,726	300	26
Bascom Palmer Eye Institute	--	103[b]	2,304[c]	--	--	2,407	100	24
Larkin General Hospital	10%	15%	55%	10%	10%	N/A	60	N/A
Miami Children's	3	103	1,413	100	1	1,620	137	12
Grant Center Hospital	--	93	1,800[e]	2,592	--	4,485	100	45
North Gables Hospital	7	4.7	205	630	29	876	53	16.5
Miami Heart Institute	--	1,200[b]	7,440[c]	--	--	8,640	191	45
Pembroke Pines General	21	137	1,350[c]	--	--	1,508	195	8
James Archer Smith	29	857	143	71	143	1,243	80	16*
Baptist Hospital of Miami	1,500	750	5,500	4,500	2,000	14,250	383	37*
Doctor's Hospital	--	333[b]	2,160[e]	3,888	--	6,381	165	39*

[a]Reference 7. Rates are in lb/day unless noted otherwise.

[b]Amount includes Pathological wastes.

[c]Amount includes Food and Cardboard wastes.

[d]Amount includes Food wastes.

[e]Amount includes Cardboard wastes.

*These questionnaires arrived after the computations were completed and so are not included in the average lbs/bed/day figure.

overall hospital waste generation rate appears to have remained relatively constant over this 10-year period. No factors were identified which would significantly change this trend in the near future.

No comprehensive information was found during this study regarding the total population of hospital waste incinerators in the nation. One manufacturer's representative estimated that over 90 percent of operating hospitals have an incinerator on-site, if only a small retort-type unit for pathological or special wastes.[11] The number of larger, controlled air type incinerators operating on hospital wastes is not known. However, based on discussions with two of the leading controlled-air incinerator manufacturers, it is estimated that at least 1,200 of these systems have been installed at United States hospitals over the past 20 years.[12,13] This implies that there are approximately 5,000 retort-type incinerators installed. While some of these units have been retired, a great majority are felt to be currently in operation.[14]

Some insight into the incineration population distribution was gained by examining a recent New York State data base which was developed from an in-state survey of over 400 hospital waste incinerator units. This data base, and the analysis conducted by Radian Corporation during this study, are described in detail in Section 6.1. Highlights of the analysis are as follows:

- Almost 60 percent of the New York incinerators have design feed capacities of less than 200 lb/hr.
- The population distribution is bimodal with respect to feed capacity, with peaks in the 50 to 74 lb/hr range and in the 100 to 124 lb/hr range.
- About 14 percent of the incinerator population in New York is above 600 lb/hr feed capacity and about 6.5 percent is above 1,000 lb/hr feed capacity.

A comparison of the New York and total U.S. hospital populations indicates that the two populations have similar overall distributions although there is a greater proportion of large hospitals above the 500-bed size in NY than in the nation as a whole. The conclusions drawn from this analysis is that

there are many small hospital waste incinerators but that the larger incinerators account for a significant fraction of total waste handling capacity.

1.2 WASTE CHARACTERIZATION

Hospital waste is characteristically heterogeneous, consisting of ofjects of many different sizes and composed of many different materials. The daily activities and procedures within a hospital can vary dramatically from day-to-day, thus making it difficult to predict what will be thrown away. During the course of this study, very little data were found on the composition of hospital waste. This may be due to the fact that the amount of sampling and chemical analyses required to generate representative characterization data would be extensive and costly. In addition, industry practice for many years has been to utilize the simplified waste classification system developed by the Incinerator Institute of America (IIA), discussed below, rather than to sample and chemically analyze waste. Table 1-2 contains one general breakdown of the composition of typical hospital waste.

As discussed above, the experience of hospitals in Illinois indicates that above 85% of a hospital's waste stream can be categorized as general refuse, while the remaining 15% is contaminated with infectious agents.[15] This is only a generalization, however, and actual wastes from a given hospital can vary significantly from day to day and from hour to hour. For example, refuse collected after a major surgical procedure, such as a heart transplant, may contain significantly more infectious wastes and disposable plastics than is usually generated in a routine operation.[16] Also, to the extent that the infectious waste is mixed with a hospital's general waste, more waste will be generated that is considered infectious.[17]

Most of the public attention concerning hospital waste management has centered on infectious waste. Unfortunately, a number of general and vague terms are used to refer to these wastes, including "pathological waste," "biological waste," "hazardous waste," "biomedical waste," and "contaminated waste." In Canada, the term biomedical waste is popular and a color-code classification scheme for the waste has been developed as shown in Table 1-3. In the United States, all these categories of wastes are generally classified as "red bag" waste.[18]

TABLE 1-2. HOSPITAL WASTE CHARACTERIZATION[a]

Product	Approximate Percent by Weight[b]
Paper	65
Plastic	30
Moisture	10
Other	5

[a]Reference 19.
[b]Percentages do not add to 100 since they are approximations.

TABLE 1-3. CANADIAN CHARACTERIZATION OF BIOMEDICAL WASTE[a]

Waste Class	Component Description	Typical Component weight percent (as fired)
A1 (Red Bag)	Human Anatomical	95-100
	Plastics	0-5
	Swabs, Absorbents	0-5
	Alcohol, Disinfectants	0-0.2
A2 (Orange Bag)	Animal Infected Anatomical	80-100
	Plastics	0-15
	Glass	0-5
	Beddings, Shavings, Paper, Fecal Matter	0-10
A3a (Yellow Bag)	Gauze, Pads, Swabs, Garments, Paper, Cellulose	60-90
	Plastics, PVC, Syringes	15-30
	Sharps, Needles	4-8
	Fluids, Residuals	2-5
	Alcohols, Disinfectants	0-0.2
A3b (Yellow Bag) Lab Waste	Plastics	50-60
	Sharps	0-5
	Cellulose Materials	5-10
	Fluids, Residuals	1-20
	Alcohols, Disinfectants	0-0.2
	Glass	15-25
A3c (Yellow Bag) R&D on DNA	Gauze, Pads, Swabs	5-30
	Plastics, Petri Dishes	50-60
	Sharps, Glass	0-10
	Fluids	1-10
B1 (Blue bag)	Non-infected Animal Anatomical	90-100
	Plastics	0-10
	Glass	0-3
	Beddings, Shavings, Fecal Matter	0-10

[a]Reference 6.

In Europe, hospital wastes are divided into the general categories of normal housekeeping wastes and "hazardous" wastes. The latter category consists of bacterially infected pathological waste, oil and chemical waste, and radioactive isotopic contaminated waste.[20] A typical cross-section of this type of waste has included the following items:

Disposable linens
Paper
Flowers
Waste food
Cans
Diapers
Plastic cups
Syringes
Scalpels
Tweezers
Rubber gloves
Pathological objects
Blood test tubes
Test tubes from miscellaneous service
Petri dishes
Dropper bottles
Medicine bottles
Drop infusion equipment
Transfusion equipment
Suction catheters
Bladder catheters
Urinal catheters
Colostomi bags

The general practice in the United States is to classify wastes according to the IIA system described in Table 1-4. The popularity of this system is reinforced by the fact that most incinerator manufacturers rate their equipment in terms of these categories.[21]

While useful for general design purposes, the IIA classification scheme does not address concerns such as the plastics content of waste or possible hazardous components. Hospital wastes typically can contain about 20 percent plastics with levels as high as 30 percent being reported.[22] The types of plastic most commonly encountered include polyethylene, polypropylene, and polyvinyl chloride.[23] Potential combustion products from

the burning of these plastics, including hydrochloric acid and toxic air contaminants, are discussed in Section 3.1. Ultimate analyses for four common plastics are shown in Table 1-5.

Hospital waste may also contain potentially toxic components. For example, red bag waste in the United States may contain potentially toxic compounds generated by hospital operations that are currently exempt from regulations under the Resource Conservation and Recovery Act (RCRA).[24] Such chemicals include waste pharmaceuticals, cytotoxic agents used in chemotherapy, and anti-neoplastic agents.[25] Mercury from dental clinics and other heavy metals used in hospitals may also cause air emission concerns if they enter the combustor along with other hospital wastes.

TABLE 1-4. INCINERATOR INSTITUTE OF AMERICA SOLID WASTE CLASSIFICATIONS[a]

Type 0	Trash, a mixture of highly combustible waste such as paper, cardboard, cartons, wood boxes, and combustible floor sweepings from commercial and industrial activities. The mixtures contain up to 10 percent by weight of plastic bags, coated paper, laminated paper, treated corrugated cardboard, oily rags, and plastic or rubber scraps. This type of waste contains 10 percent moisture, 5 percent incombustible solids and has a heating value of 8,500 Btu per pound as fired.
Type 1	Rubbish, a mixture of combustible waste such as paper, cardboard cartons, wood scrap, foliage, and combustible floor sweepings, from domestic, commercial, and industrial activities. The mixture contains up to 20 percent by weight of restaurant or cafeteria waste, but contains little or no treated papers, plastic, or rubber wastes. This type of waste contains 25 percent moisture, 10 percent incombustible solids, and has heating value of 6,500 Btu per pound as fired.
Type 2	Refuse, consisting of an approximately even mixture of rubbish and garbage by weight. This type of waste is common to apartment and residential occupancy, consisting of up to 50 percent moisture, 7 percent incombustible solids, and has a heating value of 4,300 Btu per pound as-fired.
Type 3	Garbage, consisting of animal and vegetable wastes from restaurants, cafeterias, hotels, hospitals, markets and like installations. This type of waste consists of up to 70 percent moisture, up to 5 percent incombustible solids, and has a heating value of 2,500 Btu per pound as-fired.
Type 4	Human and animal remains, consisting of carcasses, organs, and solid organic wastes from hospitals, laboratories, abattoirs, animal pounds, and similar sources, consisting of up to 85 percent moisture, 5 percent incombustible solids, and having a heating value of 1,000 Btu per pound as fired.

TABLE 1-4. INCINERATOR INSTITUTE OF AMERICA SOLID WASTE CLASSIFICATIONS[a] (Continued)

Type 5	Byproduct waste, gaseous, liquid or semiliquid, such as tar, paints, solvents, sludge, fumes, etcs., from industrial operations. Btu values must be determined by the individual materials to be destroyed.
Type 6	Solid bydproduct waste, such as rubber, plastics, wood waste, etc., from industrial operations. Btu values must be determined by the individual materials to be destroyed.

[a]Reference 26.

TABLE 1-5. ULTIMATE ANALYSES OF FOUR PLASTICS[a]
(Weight Percent)

	Polyethylene	Polystyrene	Polyurethane	Polyvinyl Chloride
Moisture	0.20	0.20	0.20	0.20
Carbon	84.38	86.91	63.14	45.04
Hydrogen	14.14	8.42	6.25	5.60
Oxygen	0.00	3.96	17.61	1.56
Nitrogen	0.06	0.21	5.98	0.08
Sulfur	0.03	0.02	0.02	0.14
Chlorine	tr	tr	2.42	45.32
Ash	1.19	0.45	4.38	2.06
Higher heating value, Btu/lb	19,687	16,419	11,203	9,754

[a]Reference 27.

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2.0 PROCESSES AND EQUIPMENT

The primary objectives of hospital waste incinerators are (1) to render the waste innocuous, and (2) to reduce the size and mass of the waste. These objectives are accomplished by exposing the waste to high temperatures over a period of time long enough to destroy threatening organisms and by burning all but the incombustible portion of the waste. As discussed in Section 1.1, incineration has become the primary sterilization and disposal option for many hospital facilities.

The design of a hospital waste incinerator, like any combustion system, requires consideration of a number of interrelated factors including residence time, temperature, and turbulence (i.e., the three "T"'s of combustion). Other factors which can influence combustion performance are fuel feeding patterns, air supply and distribution, heat transfer, and ash disposal.[1] Like municipal solid waste (MSW), hospital waste is a difficult fuel to combust relative to conventional fuels such as oil, gas, coal, or wood. Some of the problems associated with hospital wastes which must be considered by the combustion system designer and equipment operator are:

- Fuel of non-homogenous and variable composition - The physical and chemical composition of hospital waste is highly variable. Furthermore, the waste feed consists of chemically diverse articles of different sizes and shapes. Hospital waste is seldom pre-processed; it is burned in bulk on a mass feed basis. Non-homogenous and variable compositions should be accounted for in system design and operation to ensure that these factors do not pose problems in feeding, flame stability, particle entrainment and emission control.

- Variable ash content - Hospital waste contains varying amounts of glass, metals and ceramics which are not consumed in the combustion process. Fluctuations in ash composition and combustion temperatures can lead to clinker formation, slagging and fouling in some systems. To avoid these problems, primary combustion chamber temperatures are generally maintained below 1800°F.[2] However, this tends to reduce carbon burnout and the overall energy utilization efficiency.

- Low heating value - Hospital wastes often have low heating values due to high moisture contents. This causes flame stability problems and, in some cases, it becomes necessary to fire an auxiliary fuel to maintain proper combustion conditions.

Alternately, dry waste batches (especially those with a high plastics content) can produce high flame temperatures which result in overheating of the hearth or other combustion system components. To avoid these problems, the combustion conditions (principally excess air, air distribution, and auxiliary fuel firing rate) must be controlled closely.

- Corrosive materials - Hospital wastes contain varying amounts of fluorine and chlorine, principally from plastics. The acid gases produced from the incineration of these materials can corrode combustion and air pollution control equipment, especially convective heat transfer tubes. For this reason, hospital incinerators should be constructed of corrosion - resistant materials.

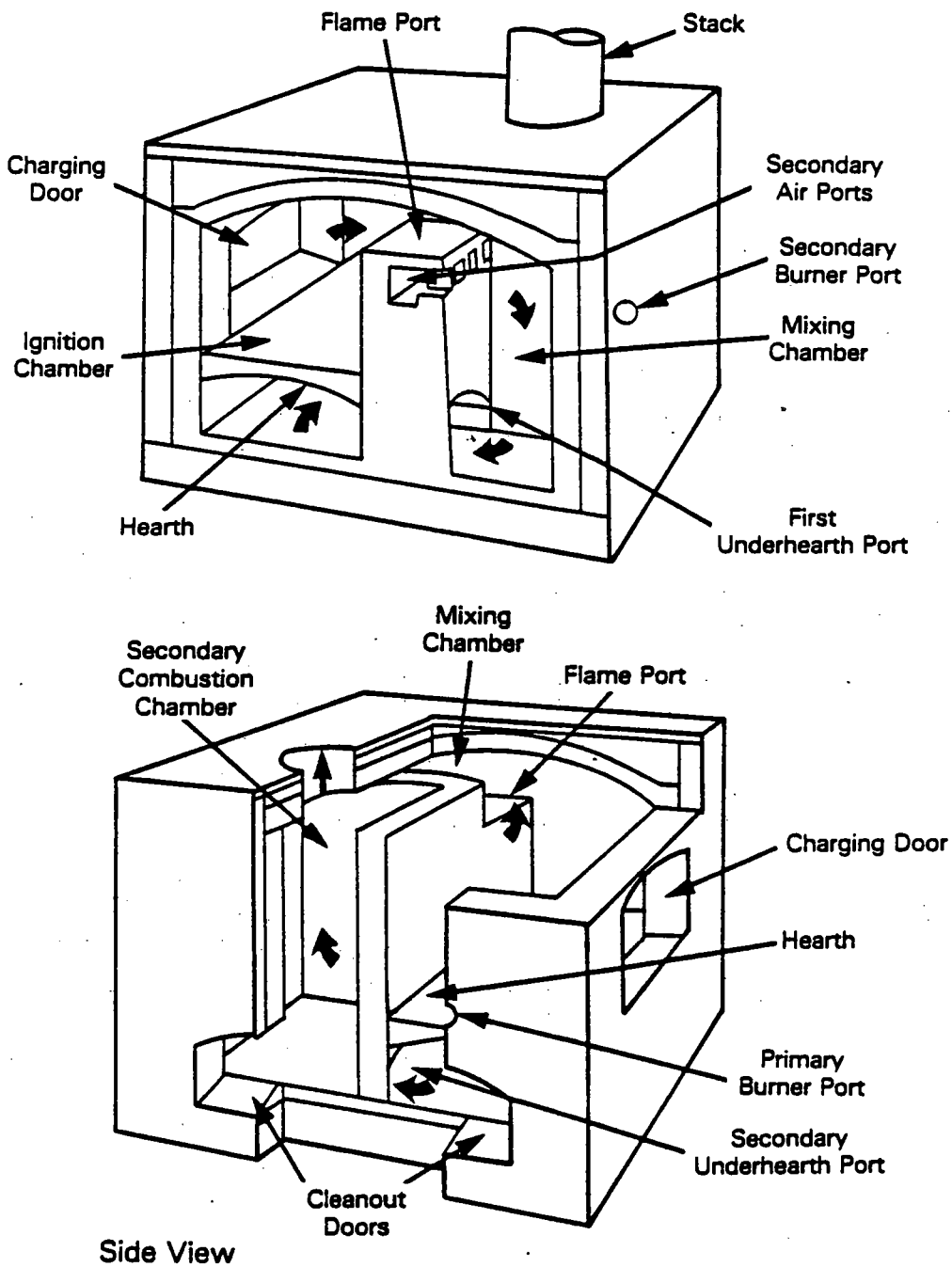
2.1 INCINERATOR TECHNOLOGY

There are three major types of incinerators currently used to incinerate hospital wastes in the United States: excess air, controlled air, and rotary kiln. The design and operating principles for each of these three major types are discussed in this section.

2.1.1 Retort Incinerators

Retort incinerators are variable capacity units which are mostly field fabricated. These units also typify older, existing hospital incinerators. They are also referred to as "pyrolitic," "multiple chamber," and "excess air" incinerators in the literature. These incinerators appear as a compact cube from the outside with a series of chambers and baffles on the inside. The two principal design configurations for retort incinerators are illustrated in Figures 2-1 and 2-2.

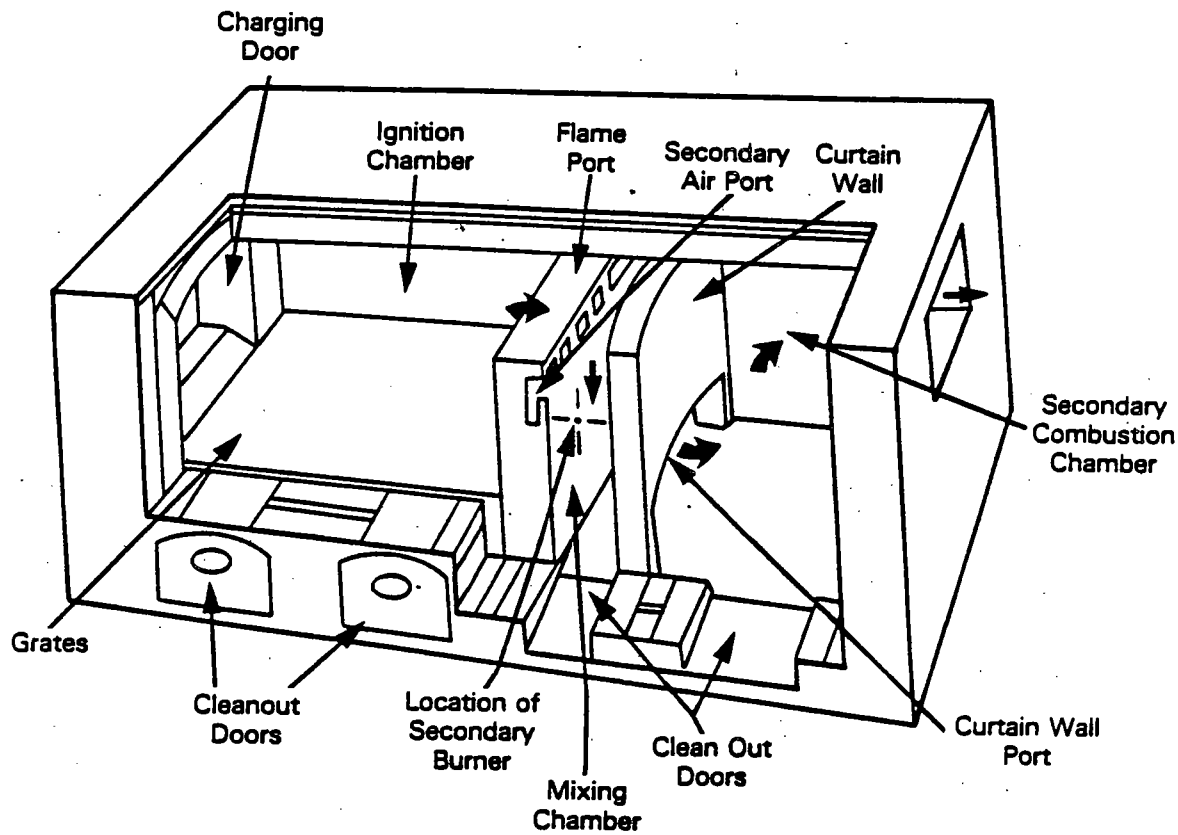
In both types of retort incinerators, combustion of the waste begins in the primary, or ignition, chamber. The waste is dried, ignited, and combusted by heat provided by a primary chamber burner as well as by hot chamber walls heated by flue gases. Moisture and volatile components in the waste feed are vaporized and pass, along with combustion gases, out of the primary chamber and through a flame port connecting the primary chamber to the secondary, or mixing, chamber. Secondary air is added through the flame port and is mixed with the volatile components in the secondary chamber.



Source: Reference 3.

Figure 2-1. Multiple-Chamber Pathological Waste Incinerator

0981469R



Source: Reference 4.

Figure 2-2. In-Line Multiple-Chamber Incinerator

0981468R

Burners are also fitted to the secondary chamber to maintain adequate temperatures for combustion of the volatile gases. Incinerators designed to burn general hospital waste operate at total excess air levels of up to 300 percent; if only pathological wastes (i.e., animal and human remains) are combusted, excess air levels near 100 percent are more common.[5]

For in-line incinerators, combustion gases pass in a straight-through fashion from the primary chamber to the secondary chamber and out of the incinerator with 90 degree flow direction changes only in the vertical direction. The other common configuration for retort incinerators, on the other hand, causes the combustion gases to follow a more "tortuous" path through the incinerator with 90 degree flow direction changes in both the horizontal and vertical directions. These flow direction changes, as well as contraction and expansion of the combustion gases, enhance turbulent mixing of air and gases.[6] In addition, fly ash and other particulate matter drop from the gas stream as a result of the direction and gas velocity changes and collect on chamber floors. Gases exiting the secondary chamber are directed to the incinerator stack.

Retort incinerators are described as "unwieldy" by one source in sizes above 500 lb/hr capacity while in-line incinerators are felt to be most suitable in capacities of 750 lb/hr or greater.[7]

2.1.2 Controlled Air Incinerators

Controlled air incineration has become the most widely used hospital waste incinerator technology over the past 10 to 15 years and now dominates the market for new systems at hospitals and similar medical facilities.[8] This technology is also known as "starved air" incineration, "two-stage" incineration, and "modular" combustion. While there are some similarities in operating principles between retort and controlled-air incinerators, overall equipment design and appearance are quite different, as illustrated in Figure 2-3. The two-stage incinerator shown in Figure 2-3 is capable of 99.9 percent combustion efficiency.[9]

Like retort incinerators, combustion of waste in controlled air incinerators occurs in two stages. Waste is fed into the primary, or lower, combustion chamber which is operated, as the name implies, with less than the full amount of air required for combustion. Under these sub-stoichiometric

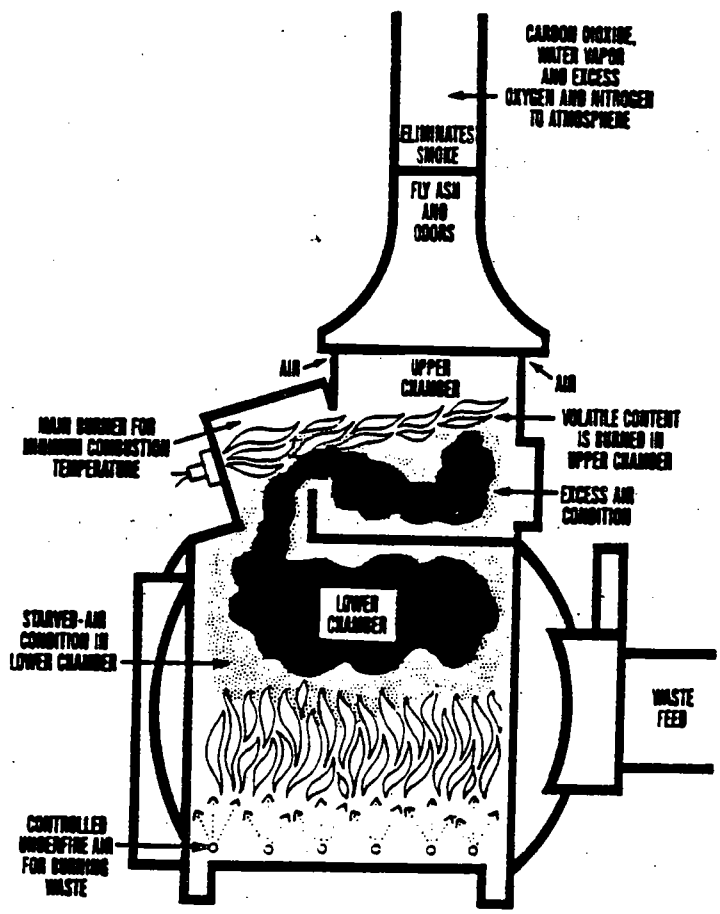


Figure 2-3. Schematic for Controlled Air Incinerator

conditions, the waste is dried, heated, and pyrolized, thereby releasing moisture and volatile components. The non-volatile, combustible portion of the waste is burned in the primary chamber to provide heat while the non-combustible portion accumulates as ash. Depending on the heating value of the waste and its moisture content, additional heat may be provided by auxiliary burners to maintain desired temperatures. Combustion air is added to the primary chamber either from below the waste through the floor of the chamber or through the sides of the chamber. The air addition rate is usually 40 to 70 percent of stoichiometric requirements.[10]

Because of the low air addition rates in the primary chamber, and corresponding low flue gas velocities and turbulence levels, the amount of solids entrained in the gases leaving the primary chamber is minimized. As a result, most controlled air incinerators can meet current State and local particulate matter emission limits without add-on gas cleaning devices.

Moisture, volatiles, and combustion gases from the primary chamber flow upward through a connecting section where they are mixed with air prior to entering the secondary, or upper combustion chamber. If the primary chamber gases are sufficiently hot, they will self-ignite when mixed with air. A second burner is located near the entrance to the upper chamber, however, to provide additional heat for ignition of the combustible gases and to maintain a flame in the chamber at all times of operation. Mixing of these gases with air is enhanced by the flow direction changes and contraction/expansion step which the gases undergo as they pass from the lower to upper chambers. The air injection rate in the secondary chamber is generally between 100 and 140 percent of total stoichiometric requirements (based on the waste feed).[11] Thus, the total air added to both chambers can vary between 140 and 210 percent of stoichiometric requirements (i.e., between 40 and 110 percent excess air).

The secondary chamber burner is located near the entrance to this chamber to maximize the residence time of gases at high temperatures in this chamber. Bulk average gas residence times in the secondary chamber typically range from 0.25 to 2.0 second. Design exit gas temperatures generally range from 1400 to 2000°F.[12] Natural gas or distillate oil are the normal fuels used for both primary and secondary chamber burners. Temperatures in the primary and secondary chambers are monitored by

thermocouples and controlled automatically by modulating the air flow to each chamber. Thermocouples are normally located near the exits of these chambers. In the primary (air-starved) chamber, combustion air flow is kept substoichimetric to release volatiles and to keep the gas velocities low to prevent particulates from going out through the secondary combustion chamber. In the secondary combustion chamber, air is generally increased to burn the volatile organics and to create extra turbulence to get mixing between the air and volatiles for proper combustion efficiencies. The logic for this control scheme is illustrated in Figure 2-4. Flue gases exiting the secondary chamber are sent either directly to a stack, to air pollution control equipment (if required), or to a waste heat recovery boiler.

Both the primary and secondary chambers are usually lined with refractory material. One manufacturer, however, offers a membrane water wall in the primary chamber. Most chambers are cylindrical; however, some are rectangular. Smaller units (i.e., with waste feed capacities less than 500 lb/hr) are usually vertically oriented with both chambers in a single casing. Larger units generally include two separate horizontal cylinders located one above the other.[13] Some manufacturers offer a third chamber for final air addition to the combustible gases and a fourth chamber for gas conditioning (i.e., gas cooling and condensation of vapors) to minimize effects on downstream heat recovery equipment or air pollution control equipment.[14]

Waste feed capacities for controlled air incinerators range from about 75 to 6500 lb/hr of Type 0 waste (at 8500 Btu/lb). Capacities for lower heat content wastes may be higher since feed capacities are limited by primary chamber heat release rates. Heat release rates for controlled air incinerators typically range from about 15,000 to 25,000 Btu/hr-ft^3.[16]

2.1.3 Rotary Kiln Incinerators

Like other incinerator types, rotary kiln incineration consists of a primary chamber in which waste is heated and volatilized and a secondary chamber in which combustion of the volatile fraction is completed. In this case, however, the primary chamber consists of a horizontal, rotating kiln. The kiln is inclined slightly so that the waste material migrates from the waste charging end to the ash discharge end as the kiln rotates. The waste migration, or throughput, rate is controlled by the rate of rotation and the

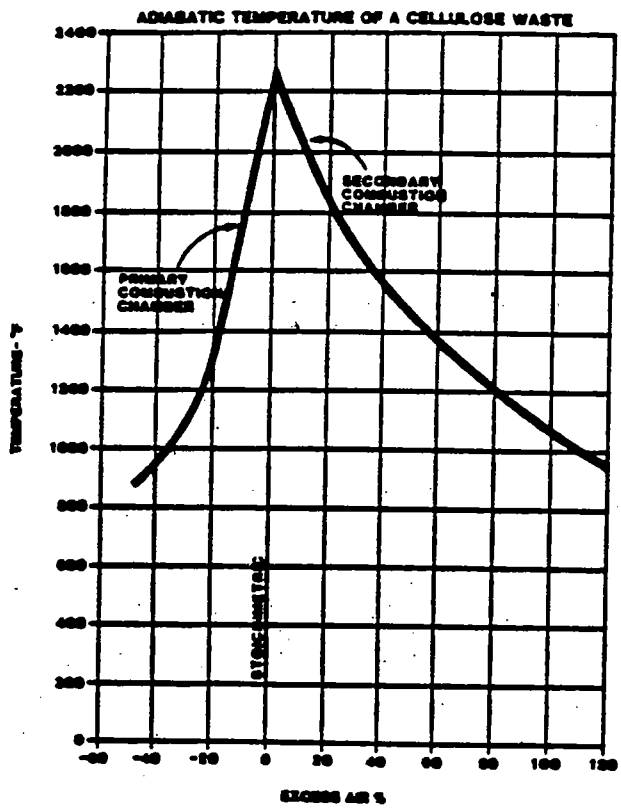


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Figure 2-4. Adiabatic Temperature Versus Excess Air for a Controlled Air Incinerator

angle of incline, or rake, of the kiln. Air is injected into the primary chamber and mixes with the waste as it rotates through the kiln. A primary chamber burner is generally present for heat-up purposes and to maintain desired temperatures. Both the primary and secondary chambers are usually lined with refractory brick, as shown in the schematic drawing in Figure 2-5.

Volatiles and combustion gases from the primary chamber pass to the secondary chamber where combustion is completed by the addition of additional air and the high temperatures maintained by a second burner. Like other incinerators, the secondary chamber is operated at above-stoichiometric conditions. Due to the turbulent motion of the waste in the lower primary chamber, particle entrainment in the flue gases is higher for rotary kiln incinerators than for the other two chamber incinerator designs previously discussed. As a result, rotary kiln incinerators generally require stack gas clean-up to meet applicable particulate matter and/or opacity limits.[17]

2.2 WASTE FEED AND ASH HANDLING SYSTEMS

Feed systems for hospital waste incinerators range from manually operated charging doors to fully automatic systems. Ash removal systems also range between periodic manual removal of ash by operators to continuous automated quench and removal systems. In general, automated systems are prevalent among large continuously-operated incinerators while manual systems are employed on smaller incinerators or those which operate on an intermittent basis. Waste feed and ash removal systems are discussed below for each of the major incinerator design types.

For retort incinerators, waste loading is almost always accomplished manually by means of a charging door on the incinerator. The charging door is attached to the primary chamber and may be located either at the end farthest away from the flame port (for burning general wastes) or on the side (for units handling pathological wastes such as large animals or cadavers). As much as 10 percent of the total air supplied to retort units is drawn through these charging doors.[19] Ash removal from retort units is accomplished manually with a rake and shovel at the completion of the incinerator cool-down period. Typical operation for a retort incinerator

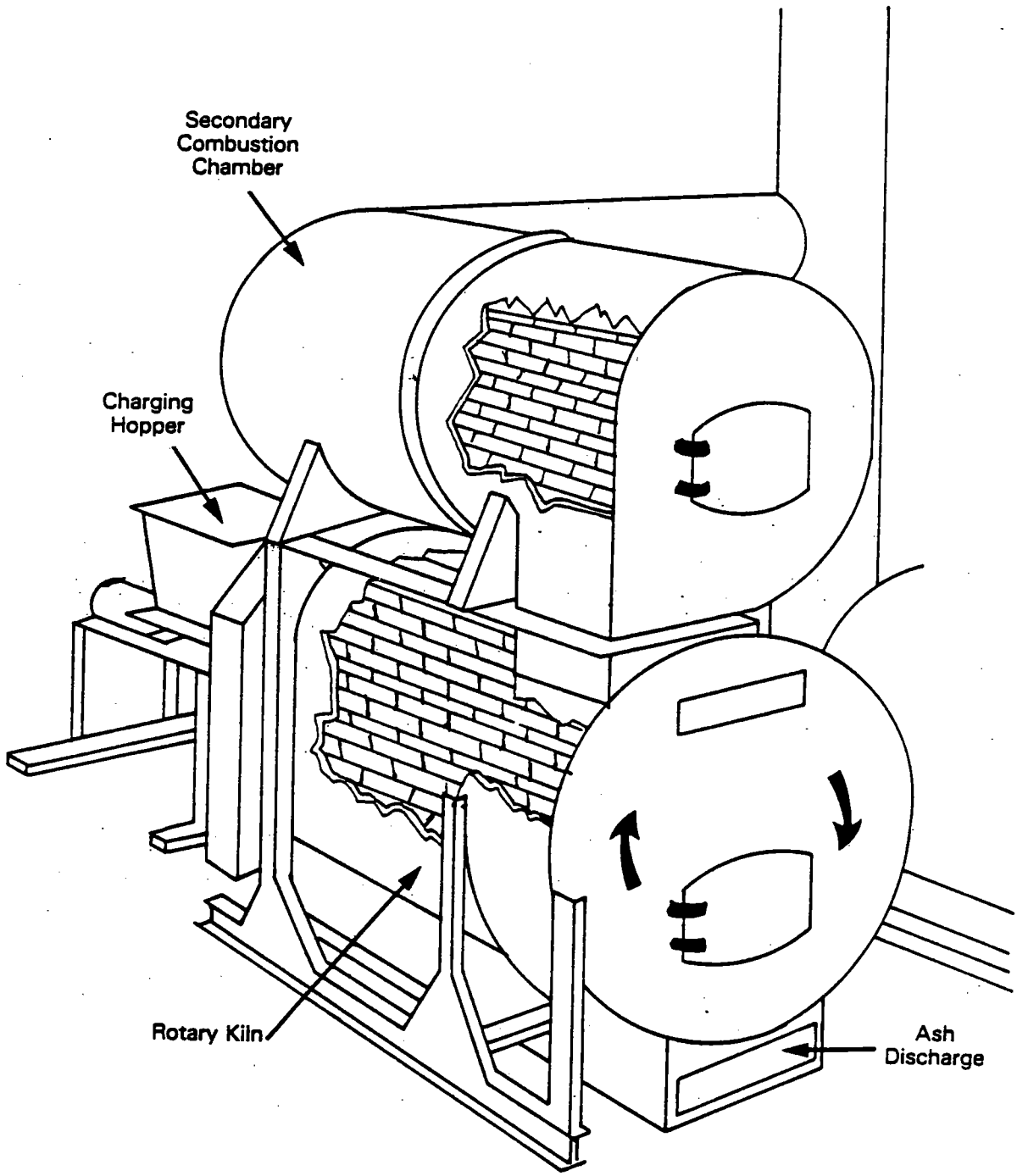

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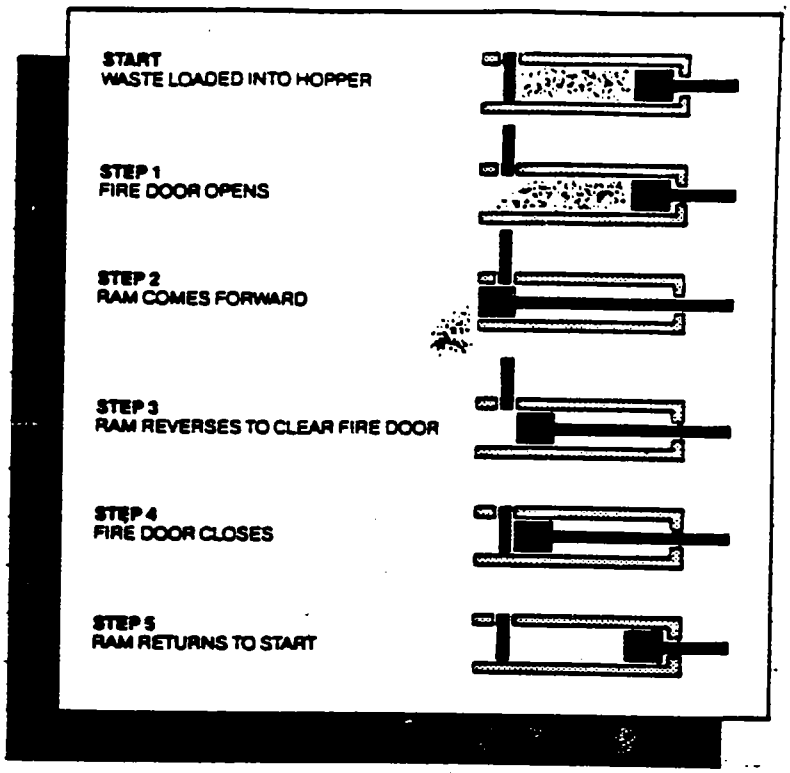
Figure 2-5. Refractory Rotary Kiln System

calls for incinerator heat up and waste charging at the end of the operating day, waste combustion and burnout by morning, and cool-down and ash cleanout during the following day.[20]

Controlled-air incinerators may be equipped with either manual or mechanical loading devices. For units with capacities less than 200 lb/hr, manual loading through a charging door in the primary chamber is typically the only option. Mechanical loaders, on the other hand, are standard features for incinerators with capacities above 500 lb/hr waste. For units between these size ranges, mechanical feed loaders are usually available as an option.[21] Most mechanical loader designs currently offered employ a hopper and ram assembly, as illustrated in Figure 2-6. In this system, waste is loaded into a charging hopper and the hopper cover is closed. The fire door isolating the hopper from the incinerator opens and a ram comes forward to push the waste into the front section of the incinerator. After reaching the end of its travel, the ram reverses and retracts to the point where it just clears the fire door. The fire door closes and the ram retracts to its starting position. These operations are normally controlled by an automatic control panel. For smaller incinerators, waste loading into the charging hopper is usually accomplished manually, bag by bag. Larger systems frequently use such waste loading devices as car dumpers, conveyors, skid-steer tractors, or pneumatic systems.[23]

In addition to improving personnel and fire safety, mechanical loaders limit the amount of ambient air which can leak into the incinerator during waste feeding operations. This is important for controlled air incinerators since excess air in-leakage can cause lower temperatures, incomplete combustion, and smoking at the stack. Mechanical loaders also permit the feeding of smaller waste batches at more frequent, regular intervals. As the intervals become shorter, this feeding procedure approximates continuous or steady-state operation and helps to dampen fluctuations in combustion conditions.[24]

Ash removal techniques for controlled air incinerators also range from manual to mechanical systems. For smaller units below about 500 lb/hr capacity (and units constructed before the mid-1970s), operators must rake and shovel ash from the primary combustion chamber into disposal containers.



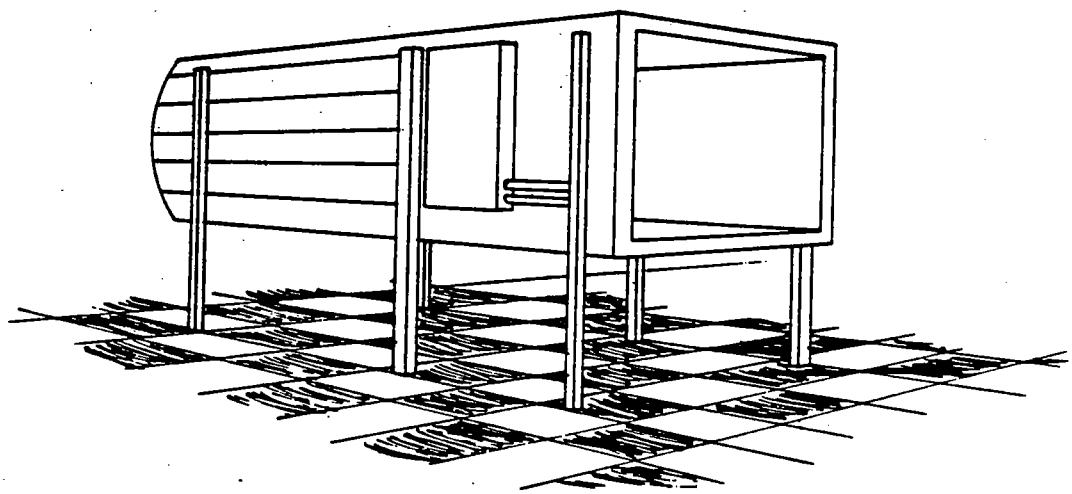


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Figure 2-6. Schematic and Example of a Mechanical Loading System

For larger systems, mechanical ash removal may be accomplished by extension of the waste charging ram, augmented by internal transfer rams. The positive displacement action of the rams pushes the ash along the bottom of the primary chamber until it reaches a drop chute. Another mechanical system offered by one manufacturer uses a "pulsed hearth" whereby ash is moved across the chamber floor by pulsations created by end-mounted air cushions.[25] After falling through the drop chute, ash either falls into a drop cart positioned within an air-sealed enclosure or into a water quench trough. The drop cart is removed manually, generally after spraying the ash with water for dust suppression. In the water trough system, quenched ash is removed either by a drag conveyor or a backhoe trolley system.[26]

When estimating air emissions for controlled air incinerators with manual ash removal, it is important to recognize that operating, and hence emission, rates will vary over time. A typical operating cycle for such a unit is given by:[27]

Operation	Duration
Ash-clean-out	15-30 minutes
Preheat	15-60 minutes
Waste loading	12-14 hours
Burn-down	2-4 hours
Cool-down	5-8 hours

The waste loading period of 12 to 14 hours per operating day is a maximum value for units with manual ash removal; based on observations at one incinerator a more typical value might be 5 to 6 hours since this corresponds to waste incineration during one shift per day.[28] On the other hand, large incinerators with continuous mechanical ash removal systems may operate on an around-the-clock basis.

Since rotary kiln systems operate in a continuous mode, the waste feed system and ash removal system which service these incinerators must also be of a continuous or semi-continuous type.[29] A charging hopper and ram system is commonly used to load waste into the kiln. After travelling through the kiln, ash is discharged on a continuous basis either into an ash cart or water quench system. Both this feed system and ash removal system are described above for controlled air incinerators.

2.3 WASTE HEAT RECOVERY

Waste heat recovery operations are generally not considered for excess air incinerators due to the smaller gas flow rates, lower temperatures, higher particulate matter loadings, and intermittent operations that characterize these systems. For controlled air and rotary kiln incinerators, however, the relatively higher stack gas temperatures and flow rates can make heat recovery economically attractive in cases where steam or hot water generation rates can be matched with the needs of the hospital. For most systems, heat is recovered by passing hot gases through a waste heat boiler to generate steam or hot water. Boiler equipment can range from a spool piece with heat exchange coil inserted in the stack to a single-drum D-type watertube waste heat boiler. Most manufacturers, however, use conventional firetube boilers because they are low in cost and simple to operate.[30] Options for these boilers include supplemental firing of oil or natural gas and automatic soot-blowing systems. Outlet temperatures from waste heat boilers are generally limited to about 400°F by stack gas dew point considerations. As mentioned above, one manufacturer also offers a waterwall membrane in the primary chamber to enhance heat recovery.

Other methods to improve overall system efficiency in controlled air incinerators and, thereby, to reduce the need for expensive auxiliary fuels, are modulating burners and air preheating.[31] EPA-sponsored testing programs of controlled air incinerators equipped with these types of systems have shown that heat recovery efficiencies are typically limited to about 50 to 60 percent of the theoretical maximum.[32]

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15. Reference 2. p. 16.

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29. Reference 2. p. 12.

30. Reference 8. p. 9.

31. Reference 8. p. 9.

32. Reference 8. p. 9.

3.0 AIR EMISSIONS/FACTORS FOR HOSPITAL WASTE INCINERATORS

Many sources of information were used to collect available hospital incinerator emissions data. A survey of pertinent literature was performed and contacts were made within EPA, State and local government organizations, trade organizations, and incinerator vendors.

Table 3-1 contains a list of pollutants covered by this study. The compounds shown here are those for which emissions data could be located for hospital incinerators. As expected, data for some pollutants were plentiful, while few data were found for others. One large data gap in the current hospital waste incinerator emissions data base is for lower molecular weight organic compounds. In addition, emission data located were primarily for larger, controlled air incinerators; few data were located for the smaller, retort-type incinerators which comprise a large portion of the existing population by number.

This section first contains brief descriptions of formation mechanisms for pollutants for which data were found. Where applicable, information on formation mechanisms for these compounds has been taken from the municipal solid waste (MSW) literature. Next, the emissions test data are presented along with other data which were located as part of the study. A discussion relating emissions data to design and operating factors follows. Finally, the emissions factors developed for each pollutant are presented.

3.1 FORMATION MECHANISMS

3.1.1 Acid Gases

The acid gases considered in this study were hydrogen chloride, sulfur dioxide, and nitrogen oxides.

3.1.1.1 Hydrogen Chloride. Based on thermodynamic considerations, chlorine which is chemically bound within the hospital waste in the form of polyvinyl chloride (PVC) or other compounds will be predominately converted to hydrogen chloride (HCl), assuming there is hydrogen available to react with the chlorine. However, the rate of HCl formation is inhibited and subsequently reversed when too much excess air is added to the combustion chambers.[1] Too much excess air can lower the combustion temperature by dilution and increase the oxygen content, thereby promoting greater free

TABLE 3-1. POLLUTANTS MEASURED/TESTED

Trace Metals	Polycyclic Organic Matter	Low Molecular Weight Organic Compounds	Acid Gases	Others
Arsenic	Dioxins	Ethane	Hydrochloric Acid	Particulate Matter
Cadmium	Furans	Ethylene	Sulfur Dioxide	Carbon Monoxide
Chromium		Propane	Nitrogen Oxides	Pathogens
Iron		Propylene		Viruses
Manganese		Trichlorotrifluoroethane		
Nickel		Trichloroethylene		
Lead		Tetrachloroethylene		

chlorine exhaust concentrations. Considering the high hydrogen content of hospital waste owing to its high paper, plastics, and moisture content, there should be a ready supply of hydrogen available in most cases to promote HCl formation.

Swedish studies have found that 60 to 65 percent of the fuel-bound chlorine in MSW is converted to HCl.[2] There is no apparent thermodynamic reason for the less than full conversion. HCl has also been shown by other studies to be the predominate chlorine product at high temperatures.[3]

3.1.1.2 Sulfur Dioxide. Sulfur, which is chemically bound within the materials making up hospital waste, is oxidized during the combustion process to form SO_2. The rate of SO_2 emissions is, therefore, directly proportional to the sulfur content of the waste. Some SO_2 removal may take place through reaction of the SO_2 with alkaline reagents also present within the waste; however, the amount of removal is expected to be negligible due to the high HCl content of the flue gas. Because it is a stronger acid than SO_2, HCl will react more quickly with available alkaline compounds than SO_2. The high HCl content of flue gases will likely tie-up the alkaline compounds before they have a chance to react with SO_2.

3.1.1.3 Nitrogen Oxides. Nitrogen oxides, or NO_x, represent the mixture of NO and NO_2. In combustion systems, predominantly NO is produced due to kinetic limitations in the oxidation of NO to NO_2. NO_x is formed by one of two general mechanisms. "Thermal NO_x" is the result of the reaction between molecular nitrogen and molecular oxygen, both of which enter the combustion zone in the combustion air. "Fuel NO_x" results from the oxidation of nitrogen which enters the combustion zone chemically bound within the waste material.

Although the detailed mechanism of thermal NO_x formation is not well understood, it is widely accepted that the thermal fixation in the combustion zone is described by the Zeldovich equations:[4]

$$N_2 + O \rightleftharpoons NO + N$$

$$N + O_2 \rightleftharpoons NO + O$$

The first reaction is the rate limiting step and is strongly endothermic due to the requirement of breaking the N_2 triple bond. It is the high endothermicity of this process which has led to the term "thermal NO_x." The reaction rates of these equations are highly dependent on both the mixture stoichiometric ratio (i.e., the molecular equivalent air-to-fuel ratio, with rich and lean describing the fuel amount) and the flame temperature. The maximum NO_x formation levels occur at slightly lean fuel mixture ratios due to the excess availability of oxygen for reaction within the hot flame zone. A rapid decrease in NO_x formation is seen for ratios which are slightly higher or lower than this. The rate of thermal NO_x formation is extremely sensitive to the flame temperature, dropping almost an order of magnitude with every 100°C drop in flame temperature.

The mechanisms by which nitrogen compounds (primarily organic) contained in liquid and solid fuels evolve and react to form NO_x are much more complex than the Zeldovich model, and the empirical data are less conclusive.

The impact of temperature and fuel nitrogen on NO_x emissions for excess air conditions is shown in Figure 3-1. The figure indicates that thermal NO_x formation is extremely sensitive to temperature, but fuel NO_x formation is less sensitive.

3.1.2 Particulate Matter

Particulate matter (PM) is emitted as a result of incomplete combustion and by the entrainment of noncombustibles in the flue gas stream. PM may exist as a solid or an aerosol, and may contain heavy metals or polycyclic organics. Depending on the method used to measure the PM in the flue gas, lower boiling point volatile compounds (i.e., boiling point below 100°C) may or may not be included in the measurement.

There are three general sources of PM[6]:

- inorganic substances contained in the waste feed that are carried into the flue gas from the combustion process,
- organometallic substances formed by the reactions of precursors in the waste feed, and
- uncombusted fuel molecules.

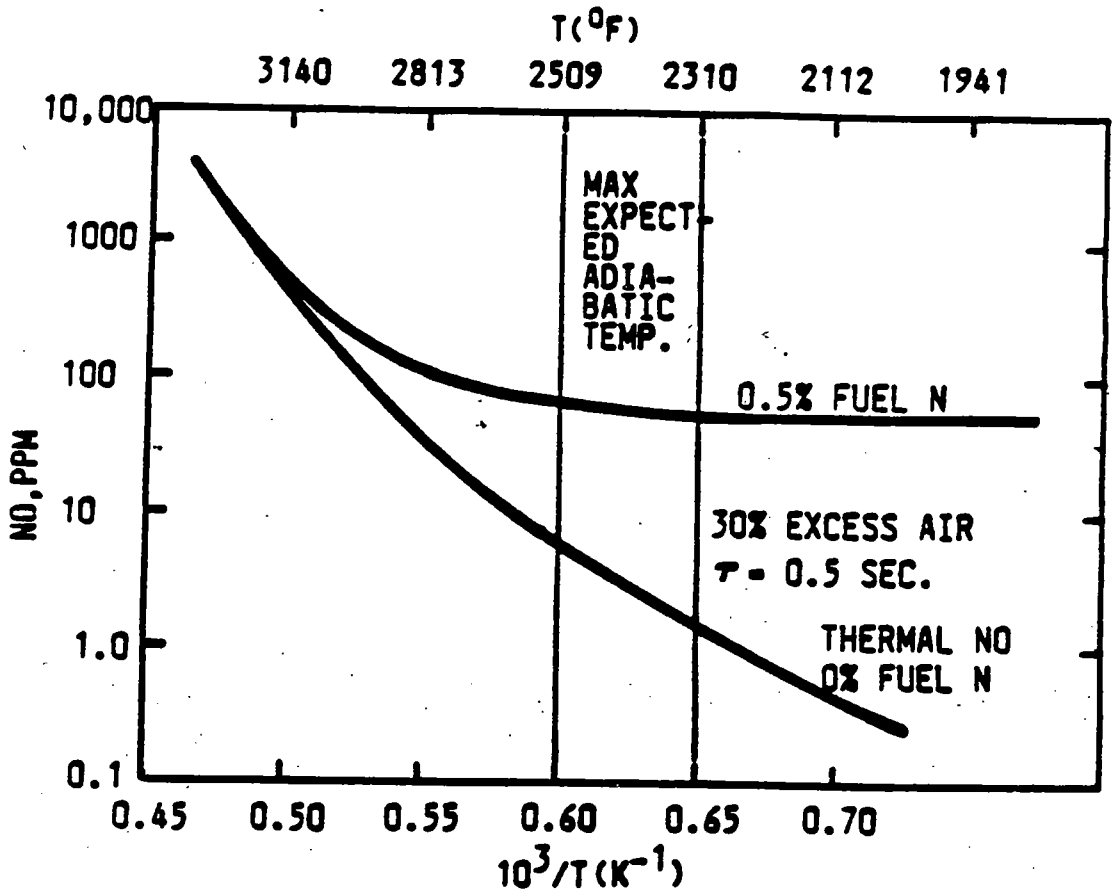

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Figure 3-1. Impact of Temperature and Fuel Nitrogen on NOx Emissions for Excess Air Conditions

Inorganic matter is not destroyed during combustion; most of this material leaves the incinerator as ash. Some, however, becomes entrained in the stack gas as PM.

Organometallic compounds present in the waste stream which is being incinerated can be volatilized and oxidized under the high temperatures and oxidizing conditions in the incinerator. As a result inorganic oxides or salts of metals can be formed. Elemental analysis of flyash from MSW incinerators has shown that particulate emissions are largely inorganic in nature and that they are from one-third to one-half soluble in water. The water soluble phase is principally chloride and sulfate salts of Na, P, Ca, Zn, and NH_4^+. The insoluble phase is comprised of oxides, silica, and phosphate salts of Al, Si, Ca, Pb, Zn, and Fe along with some insoluble carbon compounds.[7] To the extent that a particular hospital waste is similar to municipal waste, the resulting ash might be expected to be similar. (See Section 1.2 for discussion of hospital waste composition and categorization.) The fuel molecules themselves can also contribute significantly to PM formation. It is known that pyrolitic reactions can lead to the formation of large organic molecules. Inorganics, which may act as nucleation sites, may then further induce growth. The result can then be organic particles with inorganic cores.[8]

In general, good combustion conditions which depend on residence time, temperature, and turbulence, lead to lower PM emissions. As the residence time increases, particle size and the mass of PM tend to decrease. Smaller particle sizes and lower PM emissions are also associated with higher temperatures since, at higher temperatures, oxidation rates are increased so that more of the combustible PM is oxidized to gaseous products.

3.1.3 Trace Metals

The amount of trace metals in the flue gas is directly related to the quantity of trace metals contained in the incinerator waste. Some of the trace metal sources in the waste feed include surgical blades, foil wrappers, plastics, and printing inks. Plastic objects made of PVC contain cadmium heat stabilizing compounds. In addition, cadmium, chromium, and lead may also be found in inks and paints.

Some metals are selectively deposited on the smaller particulate sizes which are emitted. This is known as fine-particle enrichment. Although such data were not found for hospital incinerators, metals generally thought to exhibit fine-particle enrichment are As, Cd, Cr, Mn, Ni, Mo, Pb, Sb, Se, V, and Zn.[9] Results of one study performed at a MSW facility indicate that trace metals are found predominately in the respirable particulate fraction, even when the bulk of the particulate matter emissions are in the nonrespirable fraction.[10] Studies conducted by Trichon, et. al. have shown that certain metals when exposed to a reducing atmosphere can be converted to sub-oxides or even pure metal vapors. The end product of these overall reactions can result in particulate distributions less than 0.1 microns.[11]

There are three general factors affecting enrichment of trace metals on fine particulate matter[12]:

- o particle size,
- o number of particles, and
- o flue gas temperatures.

The influence of particle size on trace metal enrichment of fine particles is thought to be due to specific surface area effects (i.e., the ratio of particle surface area to mass). Particles with large specific surface areas show more enrichment since there is more surface area for condensation per unit mass of PM. The influence of the number of particles is simply due to the increased probability of contact associated with higher particle population. There is some evidence that less enrichment occurs at higher flue gas temperatures.[13] Higher temperatures are thought to lead to increased activity levels which, in turn, make the metals less likely to condense and bond with PM.

Mercury, due to its high vapor pressure, does not show significant particle enrichment; rather it is thought to leave largely in the vapor form due to high typical exit gas temperatures. For example, the results of one study performed at a MSW facility indicated that less than 25 percent of the mercury emissions were found to be in the particulate phase of the stack gas.[14]

3.1.4 Organic Emissions

Figure 3-2 presents a schematic of the processes which are involved during hospital waste combustion in a two-stage incinerator. After startup,

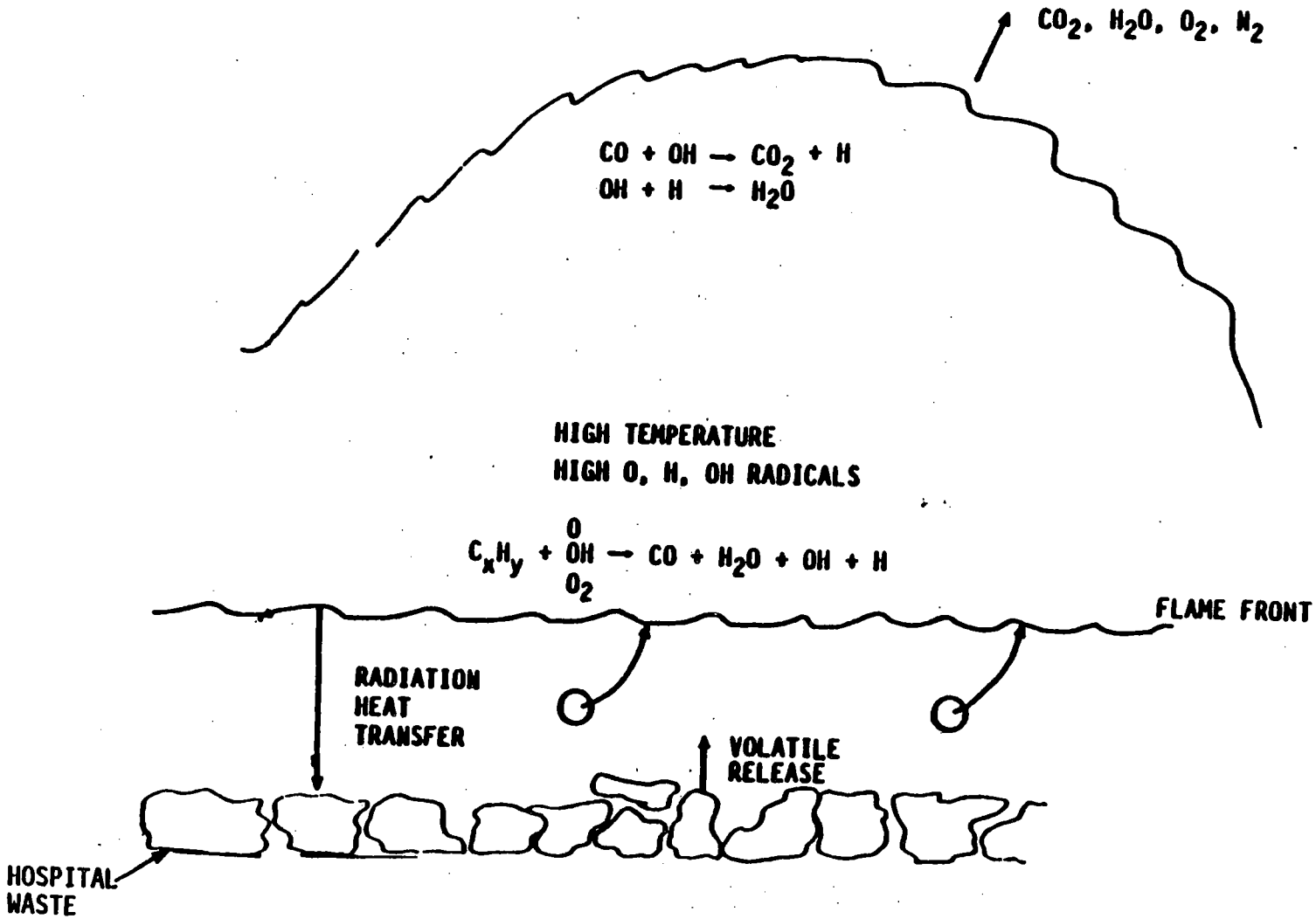


Figure 3-2. Process Schematic for Primary Chamber Hospital Waste Combustion

the hospital waste is heated by the burning gases being combusted in the primary chamber and by the natural gas or oil burner operating in that chamber. It is the burning of volatile matter above the waste bed which provides the heat which continues the pyrolysis and volatile matter evolution from the waste. The amount of radiant heat transfer to the waste is strongly dependent on the local flame temperature of the compounds being combusted; the flame temperature, in turn, is a function of moisture content, volatile matter heating value, and the local air stoichiometry. Not all the volatile matter is combusted in the primary chamber. Combustion gases are swept from the primary chamber to the secondary chamber where volatile matter combustion continues, augmented by the heat generated by a second fossil fuel burner.

The volatile matter combustion process is controlled by chemical kinetics and proceeds through complex reactions involving O, H, and OH radicals. The kinetics of these processes are strongly temperature dependent. An efficient burning process will result in a high degree of conversion of volatile organics to CO_2 and H_2O. Failure to achieve efficient combustion can result in high emission rates of unreacted or partially reacted organics.

Generally, insufficient combustion can occur as a result of charging the incinerator with waste materials in a batch mode. A study has shown that when waste materials are initially charged into the incinerator, the oxygen level in the incinerator is momentarily reduced, resulting in higher emission rates of unburned gaseous and particulate hydrocarbons.[15]

The unreacted or partially reacted combustion products discussed in this report include the chlorinated isomers of dibenzo-p-dioxin (CDD) and dibenzofuran (CDF), lower molecular weight organic compounds for which emissions data were available, and carbon monoxide (CO). A brief description of the formation mechanism and factors which influence the formation of these compounds is presented in the following subsections. Other important classes (e.g., PICs, BaP, PCBs, PAH, POM) are not included due to lack of emissions data.

3.1.4.1 <u>Dioxins and Furans</u>. Many factors are believed to be involved in the formation of CDDs and CDFs and many different theories exist

concerning their formation. The best supported theories are illustrated in Figure 3-3.[16] The first theory shown involves the breakthrough of unburned CDD/CDF present in the feed.[17] A few measurements of MSW feed streams have indicated the presence of trace quantities of CDD/CDF in the refuse feed. No such measurements have been made for hospital waste streams, but some potential for CDD/CDF in the feed may exist due to similarities in the wastes.

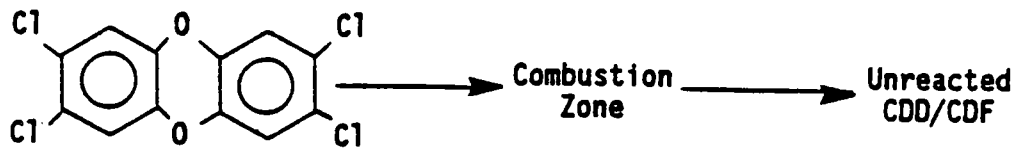
The second mechanism shown in Figure 3-3 involves the more plausible combination of precursor species which have structures similar to the dioxins and furans to form the CDD/CDF compounds. Such a reaction would involve the combination of chlorophenols or polychlorinated biphenyls to form CDD/CDF. These precursors can be produced by pyrolysis in oxygen-starved zones, such as those which exist in multichamber incinerators.[18] The potential for PVC-bearing wastes, a typical component of hospital waste, to form precursors during combustion has been studied by several researchers.[19,20]

The third mechanism shown in Figure 3-3 involves the synthesis of CDD/CDF from a variety of organics and a chlorine donor.[21] The simplest mechanisms here involve the combination of those species which are structurally related. Many plausible combustion intermediates can also be proposed which lead to precursors and eventually to CDD/CDFs. Analysis of intermediates formed during the combustion of complex fuels such as coal or wood indicate measureable yields of unchlorinated dioxin and furan species. These compounds could become chlorinated in systems such as hospital waste incinerators where high concentrations of molecular chlorine exist in the combustion zone.

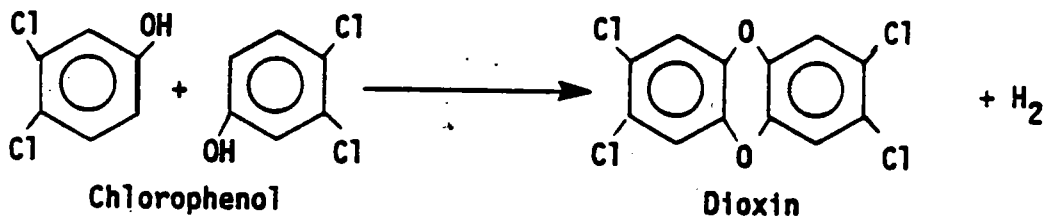
The final mechanism presented in Figure 3-3 involves catalyzed reactions on fly ash particles at low temperatures. In research sponsored by the Ontario Ministry of Environment, formation of CDDs/CDFs were observed when the thermolysis products of PVC combusted in air were heated to 300°C in the presence of clean fly ash.[22]

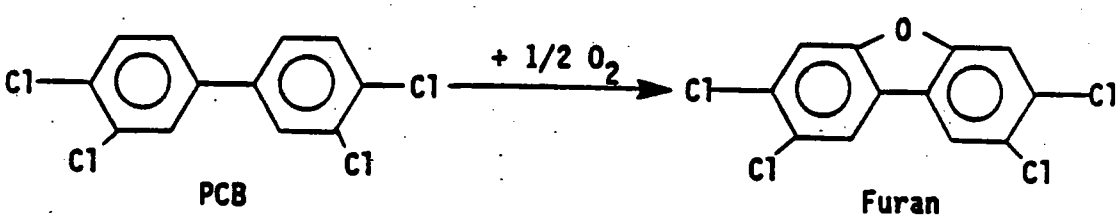
There is a growing consensus that the formation of dioxins and furans in combustion furnaces requires excess air.[23] Excess air combustion leads

I. DIOXIN IN REFUSE

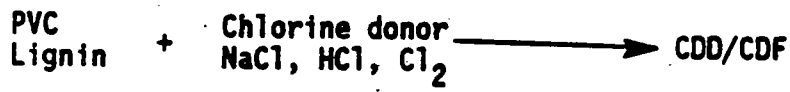


II. FORMATION FROM RELATED CHLORINATED PRECURSORS

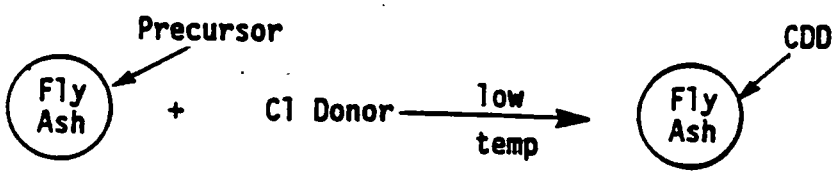




III. FORMATION FROM ORGANICS AND CHLORINE DONOR



IV. SOLID PHASE FLY ASH REACTION



Source: Reference 16

Figure 3-3. Hypothetical Mechanisms of CDD/CDF Formation Chemistry

to lower combustion temperatures which favor in-situ chlorine formation over HCl formation. The additional presence of chlorine is then believed to promote the formation of dioxins and furans.

CDDs and CDFs may exist in both the vapor phase and as fine particulate in hospital waste incinerator emissions. They may be split between phases with as much as 80 percent in the vapor phase.[24] At temperatures below 300°F, they condense onto the fine particulate. Furthermore, based on a national study of combustion sources, a range of 0.05 to 135 ppb of PCDD and 0.07 to 3,734 ppb of PCDF has been detected in the bottom and fly ashes of four hospital incinerators.[25]

3.1.4.2 Low Molecular Weight Organic Compounds. Low molecular weight organic compounds (LC) are products of incomplete combustion of the volatiles which are evolved from the waste. They may be present due to some of the same mechanisms previously discussed above for dioxins and furans; that is, they may be compounds which were present in the fuel, combinations of precursors, or the dioxin and furan precursors themselves. LCs are produced when the combustion conditions are other than optimal. In general, the optimum combustion conditions can be characterized by the three T's; time, temperature, and turbulence. The longer the time, the higher the temperature, and the greater the degree of turbulence in the zone where the organics are combusted, the better the combustion and the lower the LC emissions will be.

3.1.4.3 Carbon Monoxide. Carbon monoxide (CO) is also a product of incomplete combustion. As shown, CO is one chemical reaction away from being CO_2 which represents the end product of combustion and this signifies complete combustion. Its presence can also be related to the time, temperature, and turbulence conditions which exist above the region in which the LCs are vaporized.

3.2 EMISSIONS TEST DATA

Two different categories of emissions test data were collected during this study: 1) data which had been reviewed and were considered final and 2) preliminary data which had not received final review and inspection. Both categories of data are reported in this section for the sake of completeness but only the final data are used to calculate typical emission

factors. Final emissions data were acquired from seven comprehensive emissions tests of hospital incineration units.[26-29,40-42] In addition, results of several less detailed tests at hospital incinerator units were located through the literature. A description of each of the seven units for which comprehensive information was obtained and the operating conditions recorded during the emissions tests are presented in Table 3-2. As shown, most of the units are large incinerators near the upper end of the size range for hospital incinerators. The smallest unit for which comprehensive test results were located is an 175 lb/hour unit and the largest was a 2000 lb/hr unit. Over the period of the comprehensive emissions tests, four of the units operated at 82 to 99 percent of feed rate design capacity. The remaining three incinerator feed rates ranged from 396 to 1,493 lb/hr during the test; maximum design capacities for these incinerators are not known.

All of the units shown in Table 3-2 are starved air incinerators with two combustion chambers. The operating temperature of the secondary combustion chamber is slightly lower for the Illinois hospital incinerator than for the other units. It should be noted that the secondary chamber temperature data for the Illinois incinerator include both start-up and shutdown periods. Thus, the lower end of this range most likely corresponds to these transient operating conditions. Three of the test reports did not include incinerator design specifications.

The stack parameters for all of the units are within what was determined to be the normal design range (see Section 6.0). Unfortunately, little information is available regarding the operating conditions of the Illinois, Queen of the Valley, Swedish-American, and University of Michigan units. No information was available regarding the characteristics of the hospital wastes which were incinerated by any of these units. In addition, sufficient flue gas composition data were not available to normalize emission values to a single O_2 or CO_2 level.

No emissions data were located for the smaller retort-type incinerators which comprise a large portion of the total population by number. It is important to remember that the emission data and factors discussed in this

TABLE 3-2. TEST SITE DESIGN AND OPERATING PARAMETERS FOR COMPREHENSIVE EMISSION TEST

	Cedar Sinai[a] Medical Center Los Angeles, CA	St. Agnes[b] Medical Center Fresno, CA	Royal Jubilee[c] Hospital Victoria, BC	Illinois[d] Hospital Test
Incinerator Mfg.	Ecolaire	Ecolaire	Consumat	N/A
Model #	1,500 TES	1,000 TE	C-760	N/A
Design Feed Rate (lb/hr)	1,200	800	2,200	N/A
Actual Feed Rate (lb/hr)	980	783	1,930	500-800
Incinerator Load (%)	82	98	88	N/A
Operating Temperature (^{o}F):				
Primary Chamber	1,600-1,800	1,500-1,600	1,400	1,350-1,900
Secondary Chamber	1,800-2,000	1,800-2,000	1,700	1,200-1,950
Stack Parameters:				
Temperature (^{o}F)	332	238	312	390-500
Flowrate (dscfm)	2,710	2,766	7,000	N/A
Velocity (ft/s)	43	34.7	37.9	N/A
Diameter (in.)	18	19	29	N/A
Moisture (vol %)	9.3	9.6	6.4	N/A
No. of Tests	3	3	8	-

[a]Reference 26.

[b]Reference 27.

[c]Reference 28.

[d]Reference 29.

TABLE 3-2. TEST SITE DESIGN AND OPERATING PARAMETERS FOR DETAILED TESTS (Continued)

	Queen of the Valley Hospital Napa, CA[e]	Swedish-American Hospital Rockford, IL[f]	University of Michigan Hospital Ann Arbor, MI[g]
Incinerator Mfg.	NR	Consumat	Basic Environmental Engineering
Model #	NR	C-75-P	1500
Design Feed Rate (lb/hr)	NR	175	NR
Actual Feed Rate (lb/hr)	Avg = 396	174	1493
Incinerator Load (%)	NR	99%	NR
Operating Temperature (^{o}F):			
Primary Chamber	NR	NR	NR
Secondary Chamber	NR	NR	1800
Stack Parameter:			
Temperature (^{o}F)	275	601	385
Flowrate (DSCFM)	760	1170	6333
Velocity (ft/s)	16.0	16.9	38
Diameter (in.)	15	21	30
Moisture (vol %)	10.2	6	10
No. of Tests	3	5	3

[e]Reference 40.

[f]Reference 41.

[g]Reference 42.

section are based on the performance of relatively large controlled air incinerators. More data are needed to accurately characterize emissions from smaller, retort incinerators.

3.2.1 Acid Gases

Hydrogen Chloride. Table 3-3 contains a summary of the hydrogen chloride (HCl) emissions data which were gathered during this study. Emissions factors are also shown for each of the units. The HCl emissions results of Table 3-3 include the units described in Table 3-2 as well as units in the United States and Canada for which information was obtained from a survey article.[30] There is no apparent correlation between the unit feed rates and the HCl emissions. This is understandable because, as previously stated, the level of HCl emissions should be directly related to the percentage of chlorine-containing compounds in the waste fed to the unit. Unfortunately, no information was given regarding the chemical composition of the wastes being burned.

Two of the units for which emissions data are available have scrubbers which are used for acid gas control. These units have the lowest emissions rates of those shown. The type of wet scrubbers used was not identified in Reference 30.

Sulfur Dioxide and Nitrogen Oxides. Table 3-4 summarizes the emissions data and calculated emission factors for SO_2 and NO_x. As can be seen, there are limited data available for these compounds. The only two sources found were two test reports from the state of California.

On a concentration basis, the emission rates for the pollutants in Table 3-4 are relatively low. For the highest SO_2 concentration, 50 ppmv, an equivalent SO_2 emissions rate of 0.15 lb/million Btu would be expected, assuming a mean heat content of 10,000 Btu/lb for hospital waste. A mean heating value of 5,000 Btu/lb would correspond to an SO_2 emissions rate of 0.3 lb/million Btu. The corresponding maximum NO_x emissions rates (based on the 270 ppmv concentration) are 0.4 and 0.8 lb/million Btu for heat contents of 10,000 and 5,000 Btu/lb, respectively.

3.2.2 Particulate Matter

A great deal of PM emissions data have been collected for controlled air hospital waste incinerators. Some of the most readily available data are shown in Table 3-5. Much of this data has been collected because

TABLE 3-3. DATA/FACTORS FOR HYDROGEN CHLORIDE EMISSIONS FROM HOSPITAL WASTE INCINERATORS

Hospital	Add On Control Device/ Heat Recovery	Incinerator Feed Rate (lb/hr)	HCl Concentration (ppmv)	Emissions Factor (lb/ton feed)
Cedar Sinai[a]	Fabric Filter/Yes	980		
High			521.0	16.3
Low			403.0	12.7
Average			462.0	14.5
St. Agnes[b]	None	783		
High			926.0	15.5
Low			764.0	12.0
Average			845.0	13.7
Royal Jubilee[c]	None	1,930		
High			1,520.0	65.7
Low			983.0	42.5
Average			1,252.0	54.1
Illinois Unit[d]	None	500-800		
High			1,490.0	10.6[e]
Low			170.0	6.6[e]
Average			550.0	8.6[e]
Queen of the Valley[h]	NR			
High		412	445	8.7
Low		374	282	6.4
Average		396	341	7.2
Swedish-American[i]	NR			
High		175	174	12
Low		172	172	12.9
Average		174	173	12.5
University of Michigan[j]	NR			
High		1493	928	45.4
Low			644	31.1
Average			788	87.8

TABLE 3-3. DATA/FACTORS FOR HYDROGEN CHLORIDE EMISSIONS FROM HOSPITAL WASTE INCINERATORS (CONTINUED)

Hospital	Add On Control Device/ Heat Recovery	Incinerator Feed Rate (lb/hr)	HCl Concentration (ppmv)	Emissions Factor (lb/ton feed)
Athabasca[f]	None	85	41.0	68.1
Misericordia[f]	None	740	670.0	63.1
Misericordia[f]	None	740	687.3	63.1
Royal Alex[f]	None/Yes	1,160	553.0	84.5
Royal Alex[f]	None/Yes	1,200	562.0	79.6
Foothills[f]	None	2,500	702.0	72.8
Lethbridge Gen.[f]	Wet Scrubber/Yes	1,060	44.6	5.9[g]
Univ. of Alberta[f]	Wet Scrubber/Yes	1,400	64.7	0.7[g]
Univ. of Alberta[f]	Wet Scrubber/Yes	1,400	25.4	4.4[g]
Bonnyville[f]	None	130	62.2	16.5
Willingdon[f]	None	130	308.0	24.3
Lacombe[f]	None	150	234.5	14.6
Ft. McMurray[f]	None	265	700.0	48.6
Ontario Hospitals[k]	None	408	NR	17.4
St. Michaels[k]	None	465	2,095.0	99.4
Queen Elizabeth II[k]	None	575	115.0	22.3
Queen Elizabeth II[k]	None	700	287.0	19.1
Queen Elizabeth II[k]	None	700	378.0	25.3

TABLE 3-3. DATA/FACTORS FOR HYDROGEN CHLORIDE EMISSIONS FROM HOSPITAL WASTE INCINERATORS (CONTINUED)

Hospital	Add On Control Device/ Heat Recovery	Incinerator Feed Rate (lb/hr)	HCl Concentration (ppmv)	Emissions Factor (lb/ton feed)
Mediwaste[l]	None	1,200	NR	9.5
Shore Memorial[m]	None	650	NR	9.2
Nyack Hospital[n]	None	NR	NR	2.9

[a]Reference 26.
[b]Reference 27.
[c]Reference 28.
[d]Reference 29.
[e]Based on emissions factors presented in Reference 29.
[f]Reference 30.
[g]Wet scrubber may have reduced HCl emisssions.
[h]Reference 40.
[i]Reference 41.
[j]Reference 42.
[k]Reference 43.
[l]Reference 46.
[m]Reference 47.
[n]Reference 48.
NR - Not Recorded

TABLE 3-4. DATA/FACTORS FOR SO_2 AND NO_x EMISSIONS FROM HOSPITAL WASTE INCINERATORS

Pollutant	Cedar Sinai[a] Medical Center Los Angeles, CA (ppmv)	Cedar Sinai[a] Medical Center Los Angeles, CA (lb/ton feed)	St. Agnes[b] Medical Center Fresno, CA (ppmv)	St. Agnes[b] Medical Center Fresno, CA (lb/ton feed)	Emissions Factor (lb/ton feed)
Sulfur Dioxide					
High	50	3.01	20	1.54	3.01
Low	25	1.51	19	1.47	1.47
Average	37	2.22	19	1.47	1.85
Nitrogen Oxides					
High	270	7.82	155	5.75	7.82
Low	160	4.64	155	5.75	4.64
Average	217	6.29	155	5.75	6.02

[a]Reference 26.
[b]Reference 27.

TABLE 3-5. DATA/FACTORS FOR PARTICULATE EMISSIONS FROM HOSPITAL WASTE INCINERATORS[m]

Hospital	Add-On Control Device/ Heat Recovery	Incinerator Feed Rate (lb/hr)	Particulate Loading (gr/dscf)	Emissions Factor (lb/ton feed)
Cedar Sinai[a]	Fabric Filter/Yes	980		
High			0.002	0.10
Low			0.001	0.05
Average			0.001	0.07
Swedish-American[i]	NR			
High		175	0.209[g]	2.39
Low		172	0.050[g]	0.57
Average		174	0.127[g]	1.45
Queen of the Valley[h]	NR			
High		412	0.105	1.4
Low		374	0.073	0.85
Average		396	0.084	1.1
St. Agnes[b]	None/Yes	783		
High			0.090	5.45
Low			0.080	4.84
Average			0.080	5.15
Illinois Unit[d]	None/No	500-800		
High			0.170	3.20[e]
Low			0.020	2.00[e]
Average			0.040	2.60[e]
University of Michigan[j]	NR			
High			0.0468	3.42
Low			0.0382	2.77
Average		1493	0.0438	3.16
Royal Jubilee[c]	None/No	1930		
High			0.028	1.82
Low			0.022	1.37
Average			0.025	1.60
Athabasca[f]	None/No	85	0.050	26.92
Willingdon	None/No	130	0.070	1.69
Bonnyville	None/No	130	0.080	11.85

TABLE 3-5. DATA/FACTORS FOR PARTICULATE EMISSIONS FROM HOSPITAL WASTE INCINERATORS[m] (CONTINUED)

Hospital	Add-On Control Device/ Heat Recovery	Incinerator Feed Rate (lb/hr)	Particulate Loading (gr/dscf)	Emissions Factor (lb/ton feed)
Lacombe	None/No	150	0.070	5.87
Ft. McMurray	None/No	265	0.050	13.28
W.C. McKen.	None/No	275	0.020	3.20
Red Deer	None/Yes	410	0.080	36.49
St. Michaels	None/No	465	0.080	1.70
Queen Elizabeth II	None/No	575	0.030	6.12
Queen Elizabeth II	None/No	700	0.030	2.70
Misericordia	None/No	740	0.060	2.97
Misericordia	None/No	740	0.100	4.76
Northwest Medical Center	None	1,015	0.22[g]	6.7
Royal Alex	None/Yes	1,160	0.030	3.41
Royal Alex	None/Yes	1,200	0.070	3.30
Foothills	None/No	2,500	0.060	1.76
Lethbridge Gen.	Wet Scrubber/Yes	1,060	0.040	2.12
Univ. of Alberta	Wet Scrubber/Yes	1,400	0.020	1.23
North Erlanger[1]	NR			
High			0.0752	
Low			0.0434	
Average			0.0565	
South Erlanger[1]	NR			
High			0.0913	
Low			0.0536	
Average			0.0743	

TABLE 3-5. DATA/FACTORS FOR PARTICULATE EMISSIONS FROM HOSPITAL WASTE INCINERATORS[m] (CONTINUED)

Hospital	Add-On Control Device/ Heat Recovery	Incinerator Feed Rate (lb/hr)	Particulate Loading (gr/dscf)	Emissions Factor (lb/ton feed)
Mediwaste[n]	None	1,200	0.08	5.6
Shore Memorial[o]	None	600	0.06	1.5
Nyack Hospital[p]	None	NR	0.16	1.5

[a]Reference 26.

[b]Reference 27.

[c]Reference 28.

[d]Reference 29.

[e]Based on emissions factors presented in Reference 29.

[f]All of the information from Athabasca to Univ. of Alberta are from Reference 30.

[g]Corrected to 12 percent CO_2

[h]Reference 40.

[i]Reference 41.

[j]Reference 42.

[k]Reference 44.

[l]Reference 45.

[m]All the incinerators identified in this table were two-stage controlled air units. The University of Alberta unit had a rotating hearth for a primary chamber; all other units had a fixed primary chamber.

[n]Reference 46.

[o]Reference 47.

[p]Reference 48.

several states require hospital incineration units to meet PM emission limits. Therefore, testing is carried out on a routine basis. In addition, as previously stated, vendors frequently offer guarantees regarding PM emissions.

The PM emission results in Table 3-5 include the results of the comprehensive emissions tests (the first four hospitals) and test results obtained from the survey article.[31] These units are the same units for which HCl data were presented. The data shown from the survey article are arranged in order of ascending feed rate to show any effect of unit size on PM emissions. The emission factors in Table 3-5 show no clear trend between specific PM emission rates and unit size. It is interesting to note that the highest emission factors (above 10 lb/ton feed) are associated with the smaller units (below 400 lb/hr). Based on the information in Section 2.1, these units may well be retort-type incinerators. Unfortunately, no design information is available to confirm this hypothesis.

Emissions results for units operating with PM control equipment are also shown in Table 3-5. The Cedar Sinai unit, which was installed with a fabric filter for PM control, had the lowest PM emissions factor of those presented. The control efficiency for the filter was 98 percent. The other two units which had PM control equipment are the Lethbridge General and University of Alberta units. The emissions factors for these two units are considerably higher and are not markedly different from incinerators operated without PM control equipment. Both wet scrubber systems for Lethbridge General and the University of Alberta are designed and operated for acid gas control and not for PM removal. In general, wet scrubbers designed for acid gas removal operate at low gas-side pressure drops for purposes of low energy consumption. High energy and high gas-side pressure drops are required to obtain high efficiencies for PM control. Unfortunately, no inlet data were given for these units, so the control efficiencies could not be determined.

3.2.3 Trace Metals

Table 3-6 contains a summary of the available trace metal emission data for hospital waste incinerators. An emissions factor based on the waste feed rate to the unit is also given for each of the emissions rates

TABLE 3-6. DATA/FACTORS FOR TRACE ELEMENT EMISSIONS FROM HOSPITAL WASTE INCINERATORS

	PM Device	As gr/dscf ($x10^{-6}$)	As lb/ton ($x10^{-4}$)	Cd gr/dscf ($x10^{-6}$)	Cd lb/ton ($x10^{-4}$)	Cr gr/dscf ($x10^{-6}$)	Cr lb/ton ($x10^{-4}$)	Fe gr/dscf ($x10^{-6}$)	Fe lb/ton ($x10^{-4}$)	Mn gr/dscf ($x10^{-6}$)	Mn lb/ton ($x10^{-4}$)	Ni gr/dscf ($x10^{-6}$)	Ni lb/ton ($x10^{-4}$)	Pb gr/dscf ($x10^{-6}$)	Pb lb/ton ($x10^{-4}$)
Cedar Sinai[a,d]															
High	Y	0.00086	0.00041	0.103	0.053	0.069	0.032	0.516	0.245	0.112	0.053	0.645	0.304	2.15	1.02
Low	Y	0.00079	0.00037	0.112	0.050	0.016	0.008	0.474	0.227	0.103	0.051	0.593	0.214	1.98	0.94
Average	Y	0.00084	0.00039	0.109	0.051	0.046	0.021	0.502	0.238	0.109	0.051	0.628	0.267	2.09	0.99
High	N	5.99	2.92	140	68.0	7.46	3.63	153	72.6	9.23	4.37	2.34	1.12	1190	580
Low	N	3.02	1.47	59	29.0	2.15	1.02	85	41.2	6.74	3.29	2.22	1.08	620	304
Average	N	4.30	2.08	92	44.4	4.09	1.98	65	55.3	8.30	1.96	2.28	1.10	896	434
St. Agnes[b,d]															
High	N	4	2.14	67	40.9	11	6.07	166	101.6	7	3.93	5	2.80	916	559
Low	N	1	0.71	46	24.8	5	2.88	68	39.8	3	1.58	3	1.58	532	310
Average	N	2	1.19	55	31.9	8	4.69	130	75.1	5	2.88	4	2.38	749	433
Royal Jubilee[c,d]															
High	N	N/A	N/A	52.4	33.2	30.9	19.5	292	183	18.1	11.4	8.0	5.0	686	434
Low	N	N/A	N/A	24.7	15.5	16.3	10.2	284	180	12.3	7.8	5.8	3.6	638	399
Average	N	N/A	N/A	38.6	24.4	23.6	14.9	238	182	15.2	9.6	6.9	4.3	662	417
Overall Uncontrolled[d]															
High	N	--	2.92	--	68.0	--	19.5	--	183	--	11.4	--	5.0	--	580
Low	N	--	0.71	--	15.5	--	1.02	--	39.8	--	1.58	--	1.08	--	304
Average	N	--	1.81	--	35.2	--	7.22	--	103	--	5.40	--	2.53	--	371

[a]Reference 26.
[b]Reference 27.
[c]Reference 28.
[d]High and low values are results of individual test runs.

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presented. In addition, for the Cedar Sinai unit, results for upstream and downstream of the fabric filter are presented.

No additional trace metals data were identified by the study. Because two of the reports are from California, a state recently beginning to require testing, it can be assumed that future tests will be a source for additional data.

Analysis of the Cedar Sinai data indicate that there is a substantial reduction in trace element emissions across the fabric filter. No apparent trends in the data were observed relating trace metal concentration to incinerator size.

3.2.4 Organic Emissions

Tables 3-7 and 3-8 contain summaries of the available emissions data for CDD and CDF compounds from hospital incinerators. An emissions factor based on waste feed rate to the unit is also given for each of the concentration value presented. The homolog emission data from three emissions tests are shown. Limited isomer emission data were available for the Cedar Sinai and St. Agnes tests. For the Cedar Sinai unit results from both upstream and downstream of the fabric filter are presented.

At this time, these are the only finalized CDD and CDF emissions test results for hospital incinerator units which have been reported. An additional unit located at Stanford University Medical Center in California was also recently tested for CDDs and CDFs.[32] The results of this test were not available as of the writing of this report. The California Air Resource Board (CARB) has recently begun to require testing for CDDs and CDFs at newly installed hospital incinerators, so additional data will be available through CARB in the future.

Analysis of the emissions data presented for the unit at Cedar Sinai indicates that for most of the dioxin and furan homologs, a slight reduction occurs across the fabric filter. The subgroups for which this reduction was not seen are the TCDD and TCDF homologs. Ash analyses for the Cedar Sinai incinerator are presented in Table 3-9.

No statements can be made relative to trends in the data related to unit size or operating characteristics because too little is known about the operation of each of the facilities during testing.

TABLE 3-7. DATA/FACTORS FOR CHLORINATED DIBENZO-P-DIOXINS EMISSIONS FROM HOSPITAL WASTE INCINERATORS

	Cedar Sinai[a,d] Medical Center Los Angeles, CA (Fabric Filter)		Cedar Sinai Medical Center Los Angeles, CA (Uncontrolled)		St. Agnes[b,d] Medical Center Fresno, CA (Uncontrolled)		Royal Jubilee[c,d] Hospital Victoria, BC (Uncontrolled)		Emissions Factor (Uncontrolled)
	(ng/nM^3)	(lb/ton feed) ($x10^{-6}$)	(ng/nM^3)	(lb/ton feed) ($x10^{-6}$)	(ng/nM^3)	(lb/ton feed) ($x10^{-6}$)	(ng/nM^3)	(lb/ton feed) ($x10^{-6}$)	(lb/ton feed) ($x10^{-6}$)
(Tetra) TCDD									
High	6.09	0.13	6.7	0.13	38.5	1.07	ND	ND	1.07
Low	5.85	0.12	2.1	0.04	3.3	0.09	ND	ND	0.04
Average	5.97	0.12	4.3	0.08	20.9	0.58	ND	ND	0.33
(Penta) PeCDD									
High	18.30	0.38	16.2	0.32	23.5	0.66	28.6	0.76	0.76
Low	14.50	0.30	11.0	0.20	18.2	0.48	4.1	0.11	0.11
Average	16.40	0.34	12.9	0.24	20.9	0.57	10.2	0.42	0.41
(Hexa) HxCDD									
High	27.40	0.57	36.3	0.71	54.4	1.52	9.7	0.52	1.52
Low	20.40	0.42	24.7	0.45	38.7	1.02	19.2	0.27	0.27
Average	23.90	0.49	31.9	0.60	46.6	1.27	13.8	0.37	0.75
(Hepta) HpCDD									
High	51.10	1.05	94.8	1.76	137.0	3.83	19.2	0.50	3.83
Low	49.40	1.02	62.1	1.14	85.5	2.25	11.4	0.32	0.32
Average	50.25	1.04	77.2	1.45	111.3	3.04	16.7	0.45	1.65
(Octa) OCDD									
High	39.20	0.81	114.0	2.12	196.0	5.47	26.7	0.74	5.47
Low	26.50	0.55	62.5	1.15	145.0	3.81	12.4	0.34	0.34
Average	32.85	0.68	83.8	1.58	170.5	4.64	22.8	0.61	2.28
Total PCDD									
High	130.00	2.69	259.0	4.82	450.0	12.52	83.5	2.23	12.52
Low	129.00	2.67	163.0	2.99	290.0	7.64	51.8	1.43	1.43
Average	129.50	2.68	210.3	3.96	370.0	10.08	68.9	1.85	5.30

[a] Reference 26.
[b] Reference 27.
[c] Reference 28.
[d] High and low values are results of individual test runs.

TABLE 3-8. DATA/FACTORS FOR CHLORINATED DIBENZOFURANS EMISSIONS FROM HOSPITAL WASTE INCINERATORS

	Cedar Sinai[a,d] Medical Center Los Angeles, CA (Fabric Filter)		Cedar Sinai Medical Center Los Angeles, CA (Uncontrolled)		St. Agnes[b,d] Medical Center Fresno, CA (Uncontrolled)		Royal Jubilee[c,d] Hospital Victoria, BC (Uncontrolled)		Emissions Factor (Uncontrolled)
	(ng/nM^3)	(lb/ton feed) (x10^{-6})	(ng/nM^3)	(lb/ton feed) (x10^{-6})	(ng/nM^3)	(lb/ton feed) (x10^{-6})	(ng/nM^3)	(lb/ton feed) (x10^{-6})	(lb/ton feed) (x10^{-6})
(Tetra) TCDF									
High	67.10	1.38	79.8	1.55	78.7	2.07	34.9	0.93	2.07
Low	56.50	1.17	35.5	0.65	64.9	1.81	18.9	0.50	0.50
Average	61.80	1.28	59.2	1.12	71.8	1.94	27.0	0.73	1.26
(Penta) PeCDF									
High	103.00	2.12	106.0	2.06	136.0	3.79	53.1	1.45	3.79
Low	80.40	1.67	68.9	1.91	130.0	3.42	48.3	0.90	0.90
Average	91.70	1.89	92.6	1.74	133.0	3.61	46.2	1.24	2.20
(Hexa) HxCDF									
High	118.00	2.44	163.0	3.03	202.0	5.63	57.5	1.51	5.63
Low	90.90	1.88	116.0	2.12	170.0	4.46	29.8	0.82	0.82
Average	104.45	2.16	144.0	2.71	186.0	5.04	42.9	1.15	2.97
(Hepta) HpCDF									
High	110.00	2.27	204.0	3.79	232.0	6.46	35.4	0.96	6.46
Low	109.00	2.25	152.0	2.82	160.0	4.19	20.8	0.55	0.55
Average	109.50	2.26	169.7	3.19	196.0	5.33	25.7	0.70	3.07
(Octa) OCDF									
High	49.10	1.02	163.0	3.03	166.0	4.35	27.7	0.75	4.35
Low	38.00	0.78	67.7	1.24	150.0	4.19	7.7	0.21	0.21
Average	43.55	0.90	105.1	1.97	158.0	4.27	13.8	0.37	2.21
Total PCDF									
High	435.00	8.98	695.0	10.74	785.0	21.87	196.5	5.36	21.87
Low	106.00	8.01	441.0	8.09	704.0	18.51	117.3	3.25	3.25
Average	270.50	8.50	570.7	10.74	744.5	20.19	155.6	4.19	11.71

[a] Reference 26.
[b] Reference 27.
[c] Reference 28.
[d] High and low values are results of individual test runs.

TABLE 3-9. FABRIC FILTER DIOXIN/FURAN ASH ANALYSIS FOR CEDAR SINAI INCINERATOR[a]

	Loadings (ng/g)
Dioxins	
Tetra	1.6
Penta	3.7
Hexa	8.9
Hepta	33.6
Octa	65.7
Total PCDD	114.0
Furans	
Tetra	13.6
Penta	19.0
Hexa	22.6
Hepta	42.2
Octa	43.5
Total PCDF	141.0

[a]Reference 26.

Table 3-10 contains emissions factors for the low molecular weight organics for which emissions results were identified. These factors were determined from information collected at three of the comprehensive test sites.

3.2.5 Carbon Monoxide

The CO emissions data which were identified during this study are presented in Table 3-11. Also presented are the hydrocarbon (HC) data which were found. It should be noted that the HC data are reported as propane. The CO concentrations measured were below the detection limit of 50 ppmv and are, therefore, reported as less than 50 ppmv for two of the three incinerators tested. The concentration of CO from the Swedish-American incinerator was reported at 9.5 ppmv.

A comparison of the HC emissions factors of Table 3-11 to the LC factors of Table 3-10 suggests that only a small portion of the total HC reported in Table 3-11 is comprised of the compounds listed in Table 3-10. A definitive conclusion can not be reached, however, because the results presented are from different tests.

3.2.6 Pathogens Bacteria

There are primarily two routes by which pathogens may be released into the environment from incineration of infectious materials. These are: 1) discharge air streams; and 2) post-incineration residue.

As part of a recent test, 15 samples were taken from the stack of a hospital waste incinerator which had been charged with hospital waste containing pathogenic material[33]. Bacteria with a mean concentration of 231 colonies/m^3 of gas sampled were found in the stack as opposed to an ambient mean level of 148 colonies/m^3. However, due to experimental uncertainty, no statistically significant difference could be found between the two measurements.

Tables 3-12 and 3-13 show the results of a U. S. Department of Health Study which measured the bacterial population of residues from various types of municipal solid waste incinerators.[34] No data were located regarding bacterial populations in residue from hospital waste incinerators.

Evaluations of atmospheric release of pathogens in incinerator discharge air streams have primarily focused on the minimum operating temperature required to prevent this release. Laboratory studies report

TABLE 3-10. EMISSION FACTORS FOR SELECTED ORGANIC LOW MOLECULAR WEIGHT ORGANICS FROM HOSPITAL WASTE INCINERATORS

	Emissions Factor (lb/ton feed)	Reference Source
Ethane	<0.003	24
Ethylene	<0.02	24
Propane	<0.024	24
Propylene	<0.022	24
Trichlorotrifluoroethane	8.25×10^{-5}	21, 22
Tetrachloromethane	9.91×10^{-5}	21, 22
Trichloroethylene	2.39×10^{-5}	21, 22
Tetrachloroethylene	2.49×10^{-4}	21, 22

TABLE 3-11. EMISSIONS/FACTORS FOR CARBON MONOXIDE AND HYDROCARBON EMISSIONS FROM HOSPITAL WASTE INCINERATORS

Pollutant	Cedar Sinai[a] Medical Center Los Angeles, CA		St. Agnes[b] Medical Center Fresno, CA		Swedish-American[cd] Hospital Rockford, IL		Emissions Factor
	(ppmv)	(lb/ton feed)	(ppmv)	(lb/ton feed)	(ppmv)	(lb/ton feed)	(lb/ton feed)
Carbon Monoxide							
High	<50[e]	<1.32	<50	<1.69	19.0	1.17	<1.69
Low	<50	<1.32	<50	<1.69	0.0	0.0	<1.32
Average	<50	<1.32	<50	<1.69	9.5	0.59	<1.2
HC (as Propane)							
High	7	0.29	4	0.21			0.29
Low	3	0.12	1	0.05			0.05
Average	4	0.17	2	0.11			0.14

[a]Reference 26.
[b]Reference 27.
[c]Reference 41.
[d]Corrected to 50 percent excess air.
[e]Below detection limits.

TABLE 3-12. CHARACTERISTICS OF INCINERATORS EVALUATED FOR DESTRUCTION OF MICROFLORA[a]

Characteristics	Incinerator I	Incinerator II	Incinerator III	Incinerator IV
Design Capacity[b]	500	500	1,200	200
No. of furnaces	2	4	4	2
Feed mechanism	Continuous	Batch	Continuous	Batch
Grate	Traveling	Circular	Rotary-kiln	Reciprocating
Operating temperature	1,800-2,000°F (980-1,090°C)	1,800-2,000°F (980-1,090°C)	1,200-1,700°F (primary) (650-925°C) 1,700-2,200°F (secondary) (925-1,205°C)	1,800-2,000°F (980-1,090°C)
Duration of burning (hr)	1.75-2.0	1.5-1.75	0.5-1.5	1.0
Total burning rate (tons/hr)	22	20	50	6.5
Quench water recirculated	No	No quench water	Yes	No quench water
Estimated volume reduction	80-85%	80-85%	80-85%	80-85%

[a]Source: Reference 34.

[b]Expressed as tons per 24-hour period.

TABLE 3-13. EFFICACY OF INCINERATOR OPERATIONS IN THE DESTRUCTION OF THE MICROFLORA ASSOCIATED WITH MUNICIPAL SOLID WASTE[a]

Material	Bacterial Population[b]	Incinerator[d] I	II	III	IV
Solid waste	Total cells	7.6×10^7	4.1×10^8	5.6×10^7	3.8×10^8
	Heat resistant[c]	4.2×10^4	6.8×10^4	2.7×10^4	1.7×10^4
	Total coliforms	6.2×10^5	4.8×10^6	5.4×10^5	1.2×10^5
	Fecal coliforms	9.1×10^4	4.0×10^5	1.2×10^3	2.3×10^4
Residue	Total cells	4.4×10^7	1.7×10^6	1.2×10^6	7.1×10^3
	Heat resistant[b]	1.0×10^5	2.0×10^4	3.9×10^3	4.4×10^3
	Total coliforms	1.5×10^4	2.3×10^2	4.1×10^1	5
	Fecal coliforms	2.4×10^3	9	5	<1

[a]Source: Reference 34.
[b]Expressed as counts per gram.
[c]Expressed as spores per gram.
[d]See Table 3-12 for incinerator characteristics.

chamber temperature requirements of 575°F (302°C) for destruction of vegetative cells and 1,600°F (871°C) for spores.[35,36] The minimum operating temperature is an incinerator-specific phenomenon which can be determined only by challenging the unit with highly resistant organisms and measuring bacterial content of stack emissions to determine the temperature required for sterilization.[37]

3.2.7 Preliminary Emission Test Data

Presented in this section are preliminary emissions data for six hospital incinerators. Tables 3-14 through 3-16 present preliminary emissions data for three hospital incinerators located in California; these data, presented at the Hospital Waste Combustion Workshop in Baltimore, Maryland in May 1988, represent the high emission values obtained during stack tests.[38] Table 3-17 presents preliminary results of emissions tests performed at three biomedical waste incinerators (BWI) located in Canada.[39] All these emissions test data are preliminary; the accuracy of the data has not been assessed. For the sake of completeness and for future reference, these data are presented separately from the previous emissions data. Furthermore, due to the preliminary nature of the data, these data have not been included in the estimates of the emission factors.

In reference to Table 3-17, it should be noted that the concentrations of HCl reported for incinerators B1 and B2 are arithmetic averages and do not account for the variable flow rates as a result of batch testing. No microorganisms were detected in the air emissions or ash deposits of the three Canadian biomedical waste incinerators.

Continuous monitors were used to measure opacity, THC, and CO emissions at two of the Canadian biomedical waste incinerators. Measurements were taken over 24-hour periods when the incinerators were operating as well as when they were not operating (i.e., during "dormant" periods). The preliminary results showed that opacity levels were significant even during dormant periods and peaked during the ash clean-out period prior to incinerator startup. In addition, THC and CO emissions were also significant during dormant periods. These emissions are ascribed to the continued pyrolysis of unburned waste present in the ash and left in the furnace overnight, sustained by air entering through open doors or leaks.[50]

TABLE 3-14. PRELIMINARY HCl AND PM EMISSIONS TEST DATA

Hospitals	Emissions Controls	Incinerator Feed Rate (lb/hr)	HCl (ppm)	PM (gr/dscf)
A[a]	Wet Scrubber	550-805	1.86	0.003
B[b]	None	369-593	315	0.057
C[c]	None	70-100	770	0.04

[a]Two-chamber controlled air incinerator.
[b]Two-chamber controlled air incinerator.
[c]Single chamber incinerator with afterburner.
ND - Not Detected

TABLE 3-15. PRELIMINARY METALS EMISSIONS TEST DATA[a]

Hospital	Arsenic	Cadmium	Chromium	Iron	Manganese	Nickel	Lead
A[a]	0.01	0.50	0.07	5.90	0.06	ND	11.58
B	0.01	1.55	0.25	24.0	0.60	ND	27.9
C	0.29	7.43	ND	16.86	0.86	ND	102.57

[a]Units for all data are gm/ton.
ND- Not Detected

TABLE 3-16. PRELIMINARY DIOXIN AND FURAN EMISSIONS TEST DATA[a]

	Dioxin				Furan			
Hospital	TCDD	PeCDD	HxCDD	HpCDD	TCDF	PeCDF	HxCDF	HpCDF
A[a]	0.02	0.10	0.49	1.72	0.21	1.37	3.86	5.11
B	0.14	14.60	44.10	169.00	6.05	67.6	213.9	292.4
C	0.004	0.038	0.196	1.575	0.038	1.492	1.829	5.242

[a]Units for all data are ng/sec.

TABLE 3-17. PRELIMINARY RESULTS OF THREE BIOMEDICAL WASTE INCINERATORS LOCATED IN CANADA[a]

Hospital Incinerator	Total Particulate (g/kg)	Dioxins/Furans PCDDs (ng/dscm)	Dioxins/Furans PCDFs (ng/dscm)	Chlorobenzenes (ng/dscm)	Polychlorinated Biphenyls (PCBs) (ng/dscm)	Polyaromatic Hydrocarbons (ng/dscm)	HCl (ppm)	Total Hydrocarbons (ppm)	SO_2 (ppm)	NO (ppm)
B1	1	10	30	4 to 8	ND	ND	478	3	25	68
B2	1	32	260	NA	NA	NA	612	18	23	63
RF	13	NA	NA	NA	NA	NA	1,250	14	30	100

[a]Reference 39.

NA - Not Analyzed

ND - Not Detected

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4.0 CONTROL TECHNOLOGIES AND EFFICIENCIES

To date, hospital waste incinerators have operated largely without requirements for add-on pollution control equipment or special combustion modification techniques. Municipal waste incinerators, on the other hand, have received closer scrutiny in recent years and considerable attention has been given to potential emission control techniques. The process equipment and systems used to incinerate these two types of wastes are similar in design and operation, at least for the larger, controlled air incinerators. This section extrapolates knowledge which has been gained from municipal waste incinerators to hospital waste incinerators and considers the applicability of various emission control techniques.

There are three broad categories of methods which can be applied to the control of emissions from waste incinerators:

(1) Source Separation,
(2) Combustion Control, and
(3) Flue Gas Controls (add-on control devices).

The application of each of these categories of emission control to hospital waste incinerators is addressed in this section.

4.1 SOURCE SEPARATION

Source separation refers to both the segregation of infectious and non-infectious wastes and the removal of specific compounds from the waste stream prior to incineration. As discussed in Section 1.2, from the experience of hospitals in Illinois, it may be estimated that about 85 percent of a hospital's waste stream can be categorized as general refuse, while the remaining 15 percent is contaminated with infectious agents. Thus, segregation of wastes at the point of generation can reduce the volume of infectious waste significantly. During a visit of project personnel to the Iredale Hospital in Statesville, North Carolina, such waste segregation practice was observed through the use of colored trash bags. The extent to which this practice reduced infectious waste volume was not known, however.

After segregation of infectious and non-infectious wastes, further segregation of the non-infectious portion could be possible. Plastics and metal-containing components of the waste, such as sharps, could be segregated; this could result in lower HCl, polychlorinated dibenzo-p-dioxins (PCDDs), polychlorinated dibenzo-p-furans (PCDFs), and trace metal emission rates. However, no data are available on the effectiveness of such practices at hospital waste incinerators in lowering these emissions. Another approach to possibly lowering HCl and PCDD/PCDF emission rates would be to have hospitals use low chlorine content plastics. This could be accomplished if the health care industry were to use plastics such as polyethylene and polystyrene in place of polyvinyl chloride, which contains over 45 weight percent chlorine. Again, no data are available to indicate the effectiveness of such practices on emissions from hospital waste incinerators.

4.2 COMBUSTION CONTROL

Data presented in Section 3 illustrate that there is significant variation in the uncontrolled emission rates from hospital incinerators. These variations are partially due to variability in chemical and physical properties of hospital wastes, partially due to variations in incinerator design, and partially due to variation in operating practices. This section addresses how waste combustion processes influence emission rates for the pollutants of interest and how combustion process control may be used as an emission control strategy. The general format is to address each pollutant group separately, discussing how combustion processes influence the emission rate and how the adjustable process parameters may be used to reduce emissions and achieve emission control.

The following sections provide discussions of the relationships between combustion processes and emissions of major pollutants of concern, namely:

- acid gases,
- particulate matter,
- trace metals, and
- polycyclic organic matter (including dioxin and furans).

4.2.1 Acid Gas Control

The primary acid gas that will be emitted from a hospital waste incinerator is hydrochloric acid. As stated in Section 3.1, based on thermodynamic equilibrium considerations, any chlorine content in the waste will be effectively converted to HCl, assuming that there is sufficient hydrogen available. Therefore, based on the thermodynamic and kinetic consideration presented in Section 3.1, combustion modification does not appear to be a viable control approach for hydrochloric emissions from hospital incineration units.

From a combustion control standpoint, emissions of SO_2 are similar to HCl. Thus, combustion modification is not a viable approach for SO_2 emissions either.

Based on NO_x reduction techniques applied to other combustion processes, at least three control options may be applicable to reduce NO_x emissions from incinerator processes: flue gas recirculation (FRG), reburning, and ammonia (NH_3) injection. However, none of these techniques are currently being applied to hospital incinerators even though they are being used on MSW incinerators.

Flue gas recirculation is a technology which has been used for the control of NO_x in boilers. FGR introduces a thermal diluent and reduces combustion temperatures. However, lowering of flame and furnace temperatures could be counter to the control of PCDD/PCDF. The significance of the detrimental impact of reduced bulk temperatures on PCDD/PCDF emissions has yet to be determined. Testing completed on the Pittsfield MSW incinerator by the State of New York could provide information addressing the impacts of FGR when they become available. Information gained from this test and other future tests could be used to further evaluate the potential application of FGR to hospital incinerator units.

Reburning is used for a control technique which uses a hydrocarbon-type fuel such as natural gas or oil as a reducing agent. Hydrocarbon radicals produced by the reburning fuel react with NO_x to form N_2, H_2O, and CO_2. This control technology is being developed for use in fossil fuel-fired

boilers because only minor modifications are required to the main heat release zone. The effectiveness of reburning for NO_x control in boilers has been shown to be a function of:

- Initial NO_x level: the reduction decreases as the initial NO_x level decreases.
- Reburning fuel type: nitrogen-free reburning fuels are most effective, particularly at low initial NO_x levels.
- Temperature: reburning effectiveness increases as the temperature of the reburning zone increases.
- Residence time: gas residence time in the reburning zone of at least 0.5 seconds is required to maximize the effectiveness of reburning.

Two aspects of the reburning process make it attractive for hospital incinerators. First, it is a relatively effective control technique, potentially reducing NO_x on the order of 50 percent. Second, the process of burning the secondary fuel increases both the flue gas temperature and the concentration of O, H, and OH radicals. The high radical concentrations in the fuel-rich reburning zone drive the gas speciation towards the equilibrium state of complete combustion (i.e., CO_2 and H_2O as products). Thus, reburning not only provides an approach for destroying NO_x, it also creates an environment which favors the destruction of any dioxins or furans created in the primary flame zone. Extensive research and development efforts would be required to develop reburning for hospital incineration, but the potential exists for a multi-purpose combustion control technology.

A third option available for NO_x reduction on incinerators is NH_3 injection. When injected into combustion gases, NH_3 can react with NO_x to form diatomic nitrogen (N_2) and water. The optimum temperature range for promotion of this NO_x reduction reaction is near 870 to 1000°C. Thus, for application to a controlled-air hospital waste incinerators, NH_3 would likely be injected either into the secondary chamber or into a seciton of the stack immediately following the secondary chamber. When this system (under the process name Thermal De-NO_x) was applied to an MSW incinerator, with NH_3 injectors located above the main combustion zone in the 870-930°C area, NO_x emissions were reduced by over 40 percent.[1] To date, no known NH_3 injection systems have been applied to hospital waste incinerators.

4.2.2 Particulate Matter Control

As stated previously, particulate matter exiting the furnace consists of both inorganic material entrained into the combustion gases and organic materials which were not completely burned. In evaluating the influence of combustion control on PM emissions, it is necessary to separate the organic and inorganic fractions and to distinguish between the volatile and non-volatile inorganic contributions.

When waste is fed into an incinerator, it is heated by radiant energy from the hot furnace walls and from burning combustion products above the bed. The waste is dried and, as the temperature increases, a devolatilization (pyrolysis) process begins. The released volatile matter is entrained by the underfire air and begins to burn. Heat transfer from the burning volatiles to the bed material helps to ignite the waste in the bed and sustain the combustion process. The non-volatile, inorganic constituents of the waste generally remain in the ash pit. Non-volatile inorganics can contribute to the PM emission rate if an ash-containing particle is entrained by the underfire air and bed combustion products as they pass through the waste bed into the primary chamber.

An ash-containing particle in the bed will be subjected to a series of forces including a drag force tending to accelerate the particle to the local air velocity and a gravity force tending to hold the particle in the bed. The drag force is proportional to the frontal area of the particle times the velocity differential squared. The opposing gravity force is simply gravitational acceleration times particle density times particle volume. Assuming a spherical particle, the gravity force varies with the diameter cubed. The ratio of drag force to gravity force will vary inversely with particle diameter. Thus, small particles are more likely to be entrained by the primary chamber combustion gases.

If it is assumed that the ash content of hospital waste is approximately 25 percent and that emitted PM is totally inorganic, then the uncontrolled PM emission rate data presented earlier in Table 3-5 may be used to estimate the extent of entrainment. The PM emission rates were shown to vary from 36.5 to 1.37 lb/ton refuse. This estimate would indicate that between 92.7 and 99.7 percent of the ash remains in the ash pit.

The volatile inorganic material in the feed will also contribute to the total PM emission rate. It is convenient to discuss combustion control of this PM fraction in the context of trace metal emission even though all of the trace metals emitted may not be associated with the particulate. A discussion of trace metal emissions is presented in Section 4.2.3.

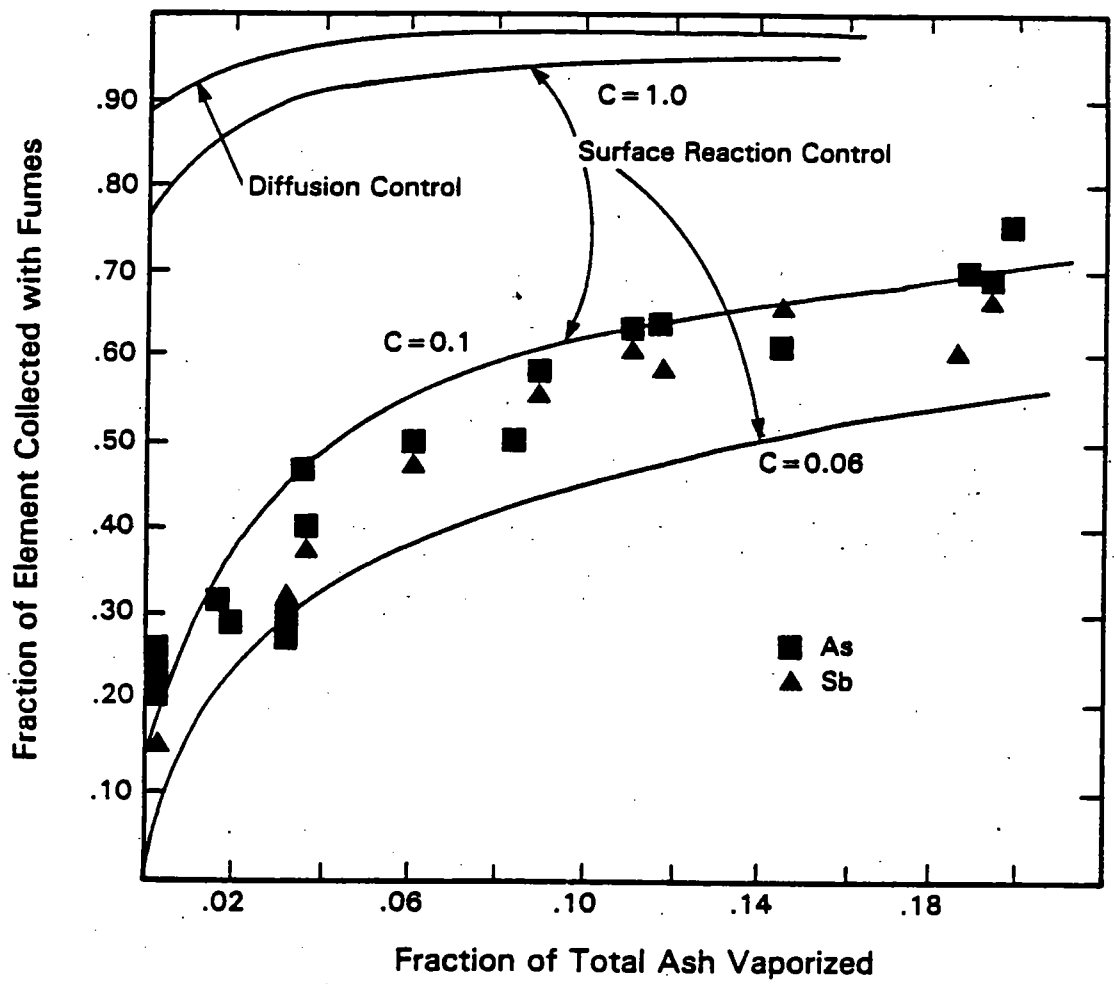
Finally, organic compounds are also associated with emitted PM. These organic components are generally heavy hydrocarbons, products of incomplete combustion (PICs), or polycyclic organic matter (POM). An extensive discussion of these emissions and potential combustion control is presented in Section 4.2.4.

4.2.3 Trace Metals Control

In Section 3.0, the available trace metal emissions data from hospital incinerators were discussed and it was pointed out that many of the volatile metals of concern tend to selectively deposit on the smaller particles. The physical processes responsible for these phenomena are complex, as is the potential influence of combustion processes on the associated phenomena. The following provides a brief review of key features which may be significant relative to hospital incineration combustion control.

The majority of the available research concerning the process of fine particle metal enrichment has been performed on pulverized coal-fired utility boilers. Those conditions are somewhat different from the conditions found in hospital incinerators, but the basic processes should be similar in both systems. It has been found that the distribution of volatile metals among the different size fractions of ash is influenced by the quantity of ultra-fine particulate matter produced during combustion. Figure 4-1 illustrates this point in a plot of the fraction of arsenic and antimony collected with the ultra-fine particles (referred to as fume) versus the fraction of the total ash vaporized. A surface deposition model to interpret these data was developed. The model's predictions for quantities of trace metal deposited on ultra-fine particles are presented as solid lines on Figure 4-1.

The issue of how the metals are distributed throughout the total fly ash as a function of particle size has health effect implications as well as being an issue of engineering significance. Based on the probable



Source: Reference 2

Figure 4-1. Fraction of As and Sb collected with Fume as a Function of the Extent of Total Ash Vaporization (Data Points)

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mechanisms of fine particulate formation, it is suspected that the trace metals should tend to concentrate on the surface of fine particles rather than being uniformly distributed throughout the entire particle size range. The theory is that refractory oxides which are vaporized in the flame would be the first species to condense and would become the nuclei for the fine particulate matter. As the combustion gases cool, volatile salts of alkali metals and other volatile trace species would be expected to condense on the outer surface of these particles.

A group at MIT, led by Professor Adel Sarofim, has confirmed this theory in several experimental studies.[2] Figure 4-2 illustrates their findings in a plot of the concentration of selected species versus reciprocal particle diameter. The elements Fe and Mg, which form the core of the particles, show no size dependence while those present as a surface coating show concentration variation proportional to 1/d. Note that the trace metals of concern for hospital incinerators were largely present as surface coatings.

The key to the above observation is that the ultra-fine particles present a very high specific surface area and, thus, receive a disproportionate share of the condensing elements. Based on the findings of this research, any process that enhances refractory oxide vaporization would be expected to increase the number of sub-micron particles and to enhance the fine particle enrichment process.

The above information provides clues relative to the mechanisms responsible for trace metal enhancement on sub-micron particles. It does not, however, define a combustion control approach to minimize trace metal emissions. Incinerators operated with relatively higher temperatures in the fuel combustion zones should have higher concentrations of sub-micron particles which could potentially increase the trace metal enrichment process. Therefore, the use of controlled air, or two-stage, incineration with its lower primary combustion zone temperatures should reduce or minimize trace metal emissions. Unfortunately, data from retort-type incinerators are not available as yet to confirm this hypothesis.

4.2.4 Polycyclic Organic Matter (POM), PCDDs, and PCDFs

Available data from MSW incinerators indicate that the PCDD and PCDF emission rates are closely related to efficiency of the combustion process.

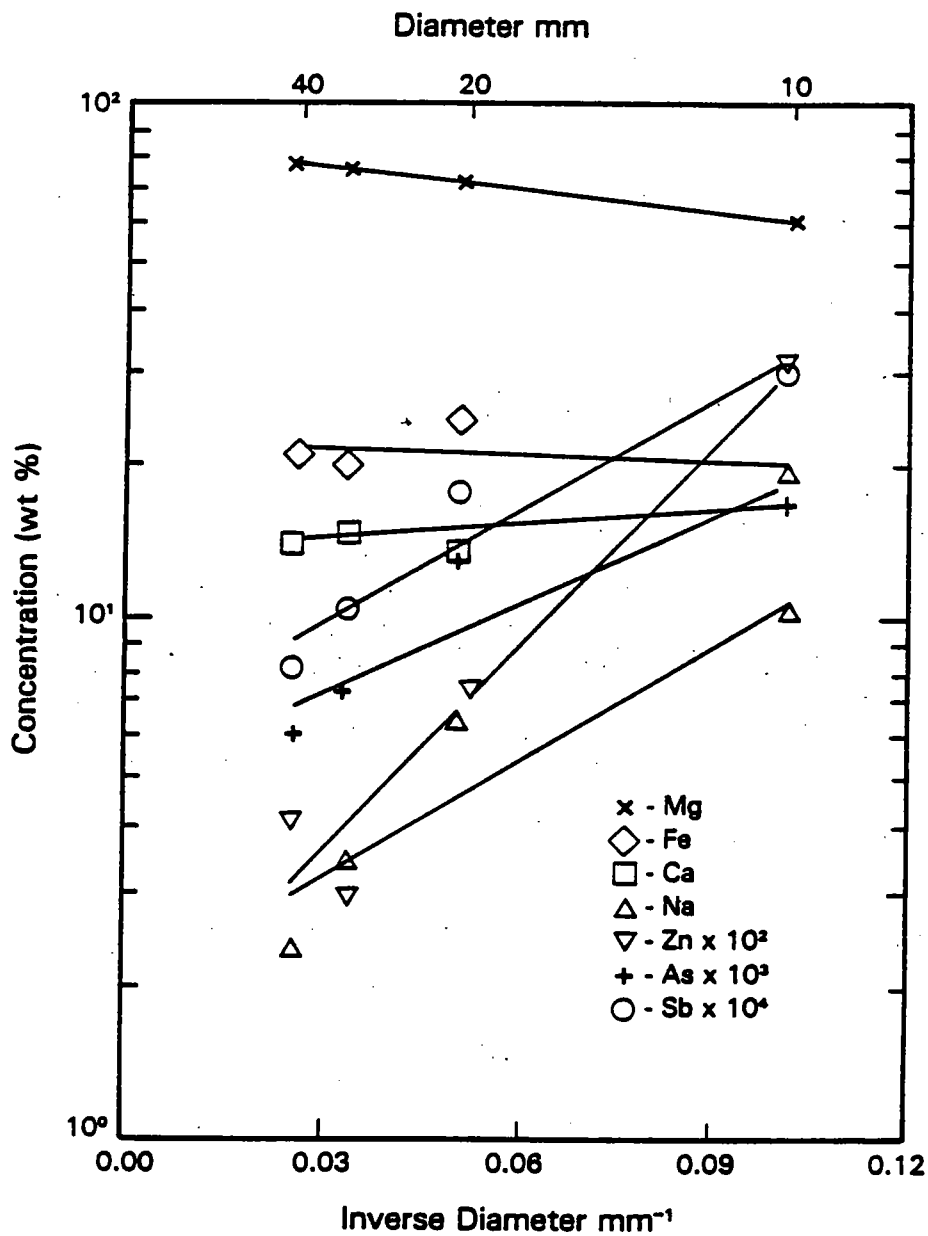

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Figure 4-2. Concentration of Selected Elements in Ultrafine Particulates as a Function of Reciprocal Particle Diameter

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Generally speaking, when the flame temperature and combustion efficiency are increased, PCDD and PCDF emission rates decrease. Due to the overriding toxiological importance of these pollutant species, discussion will be presented on how poor combustion conditions can lead to POM, dioxin and furan emissions and how the combustion process may be controlled to minimize these emissions. Emissions and their control will be considered from the standpoint of the thermodynamic equilibrium and kinetics of combustion reactions. In addition, the formation of dioxins/furans subsequent to the combustion zone will be considered.

The vast majority of the information on dioxin and furan emissions has been obtained only recently and primarily consists of stack emission rate measurements from municipal waste combustors. This information is taken primarily from testing results at large industrial and municipal incinerators; little work has been done on smaller hospital waste incinerators. There are also essentially no data from experimental programs specifically designed to identify the combustion processes responsible for PCDD/PCDF formation or to verify the effectiveness of proposed combustion control approaches on hospital waste incinerators. In the absence of direct data, discussion of how combustion modification might be used to control PCDD or PCDF emissions must be considered theoretical in nature.

The PCDD and PCDF compounds are dicyclic, nearly planar, aromatic hydrocarbons within the broad category of POM. Polycyclic organic matter emissions have been the subject of intense investigation for many years with multi-ring compounds such as benzo(a)pyrene (BaP) being the primary species of interest. The following discussion is based on available information on how POM emissions are influenced by the combustion process. In basing the discussion on POM, the implicit assumption is made that variation in POM emissions corresponds to variation in dioxin and furan emissions.

Equilibrium Considerations. If waste material is mixed with air and allowed to react for sufficient time, the concentration of the resultant products is determined by the elemental composition of the mixture (moles of

C, H, N, O, Cl, etc.), the reaction temperature, and the thermodynamic properties of the species. Consider first the case of oxidizing conditions (excess air) in which the overall oxidation process is represented by:

$$\text{Waste} + n_1O_2 \longrightarrow n_2CO_2 + n_3H_2O$$

where n_1, n_2 and n_3 are the stoichiometric coefficients required to balance the reaction and are dependent on the chemical structure of the waste. The equilibrium level of the unreacted waste in the combustion products is related to the concentrations of CO_2, O_2 and H_2O by the equilibrium constant:

$$K_p = \frac{P_{CO_2}^{n_2} \, P_{H_2O}^{n_3}}{P_{waste} \, P_{O2}^{n_1}}$$

where P represents the partial pressure of a given constituent and K_p is the equilibrium constant. The equilibrium constant is related fundamentally to a measurable thermodynamic property called the Gibbs free energy ($\triangle G$) by:

$$K_p = EXP\ (-\triangle G/RT)$$

where T is temperature and R is the universal gas constant. Gibbs free energy values are compiled in many sources. For typical stack gas CO_2, H_2O and O_2 concentrations of 8 percent, the Gibbs free energy required for there to be 1 ppb equilibrium level of waste at 1,000K is roughly 40 Kcal/mole. The Gibbs free energy of furan at 800K is reported to be 492 Kcal/mole.[3] Thus, Gibbs free energy considerations predict an equilibrium furan partial pressure of less than 10^{-100}. The Gibbs free energy values for dioxins are even larger than those for furans; thus, the equilibrium concentration under oxidizing conditions would be expected to be even less. These considerations show that given sufficient reaction time and mixing, the

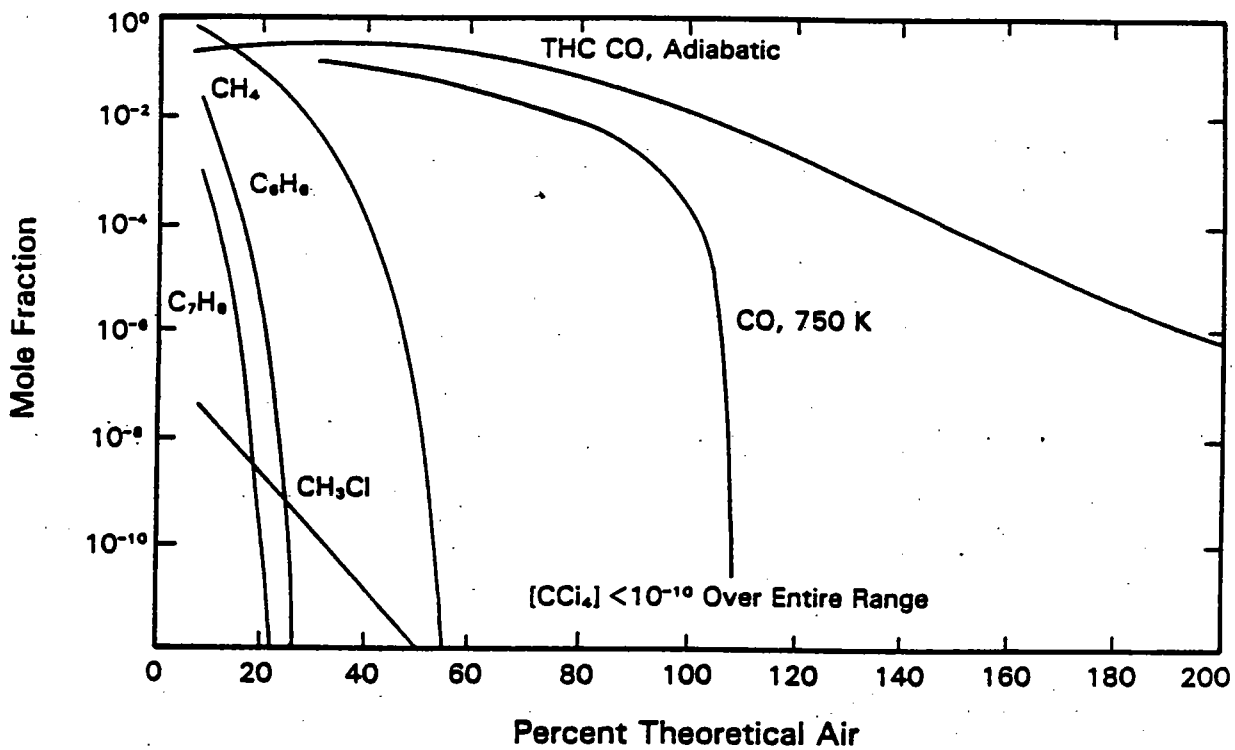
fundamental equilibrium limit for dioxins and furans may be considered zero for overall fuel-lean conditions, even at typical incineration operating temperatures.

Since PCDDs and PCDFs can be formed in hospital incinerators, it is important to identify conditions where their presence is thermodynamically favored. An obvious area to examine is the high temperature, oxygen starved environment which is characteristic of isolated regions within poorly mixed combustion processes. An initial area to examine is high temperature pyrolysis without air which is the limiting case for poor mixing.

TRW, Inc. performed an extensive series of equilibrium calculations for incineration of military pesticides.[4] An initial set of calculations indicated that solid carbon (graphite) was a predominant species. Recognizing the kinetic limitations of graphite formation, a second set of calculations were performed eliminating graphite as a possible product species. Those results indicated greater than 1 ppm concentrations of a wide variety of POM species as well as chlorobenzenes and chlorophenols (potential precursors to dioxins and furans).

The issue of poor mixing can also be addressed by examining the equilibrium product distributions for combustion of various chlorinated benzene/air mixtures.[5] Sample results are shown in Figure 4-3 as concentration versus percent theoretical air assuming that the mixture is at the adiabatic flame temperature. With at least 45 percent theoretical air, formation of light hydrocarbon gases (e.g., CH_4 and C_2H_2) is avoided. At 20 percent theoretical air, the formation of benzene or toluene as equilibrium products is avoided. This leads to the postulation that POM, dioxins and furans are thermodynamically favored only if the incinerator creates very fuel-rich (and hence oxygen-poor) pockets of gas at low temperatures in the presence of chlorine.

The above discussion illustrates two significant aspects of combustion control for POM. First, existence of these species (either in the flame or the exhaust) indicates a combustion process characterized by insufficient mixing and by local fuel-rich pockets of gas. These are the conditions which characterize the primary combustion chambers of controlled air incinerators. However, at temperature levels typically encountered in these



Source: Reference 5.

Figure 4-3. Adiabatic Equilibrium Species Distribution

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units, there is no thermodynamic barrier to achieving essentially zero emission levels for these species and their precursors that are below the ppt levels.

Kinetic Considerations. The preceding discussion addressed equilibrium formation of POM under excess air and starved air conditions. It is important to recognize that combustion of any fuel proceeds through a complex series of reaction steps leading toward (but not necessarily reaching) the product distribution predicted by equilibrium calculations. Some of these steps may be kinetically limited, however, causing certain reactions to be effectively terminated at an intermediate state.

Consideration of equilibrium conditions (see Figure 4-3) indicate that light hydrocarbon gases are thermodynamically not favored at mixture ratios above 45 percent theoretical air. Chemical kinetic limitations may, however, result in substantial concentrations of unburned hydrocarbon at stoichiometric ratios well above 45 percent. Experimental data obtained in the development of the EPA's low-NO_x heavy oil burner may be used to illustrate this fact.[6] Figure 4-4 indicates the measured total hydrocarbon (THC) concentration exiting the fuel-rich zone of a two-stage heavy oil flame. As shown, substantial THC was detected at first stage stoichiometric ratios below 80 percent theoretical air. The principal factor responsible for this hydrocarbon breakthrough was depressed flame temperature due to heat loss through the furnace walls. The kinetic rates of chemical processes vary exponentially with local temperature. Similar experiments, conducted in a higher temperature environment, showed negligible THC concentrations until the fuel-rich zone stoichiometry was less than about 60-65 percent theoretical air.

In the above tests, the transition from fuel-rich to fuel-lean conditions was achieved through the use of multiple air jets designed to achieve thorough mixing of air with the effluent from the fuel-rich zone. By changing the split between primary and secondary air, it was possible to vary the fuel-rich zone stoichiometry while maintaining a constant overall excess air condition. In many respects, this is similar to the basic design in a controlled air incinerator. An important observation is that whenever the primary zone stoichiometry was sufficiently fuel-rich to cause

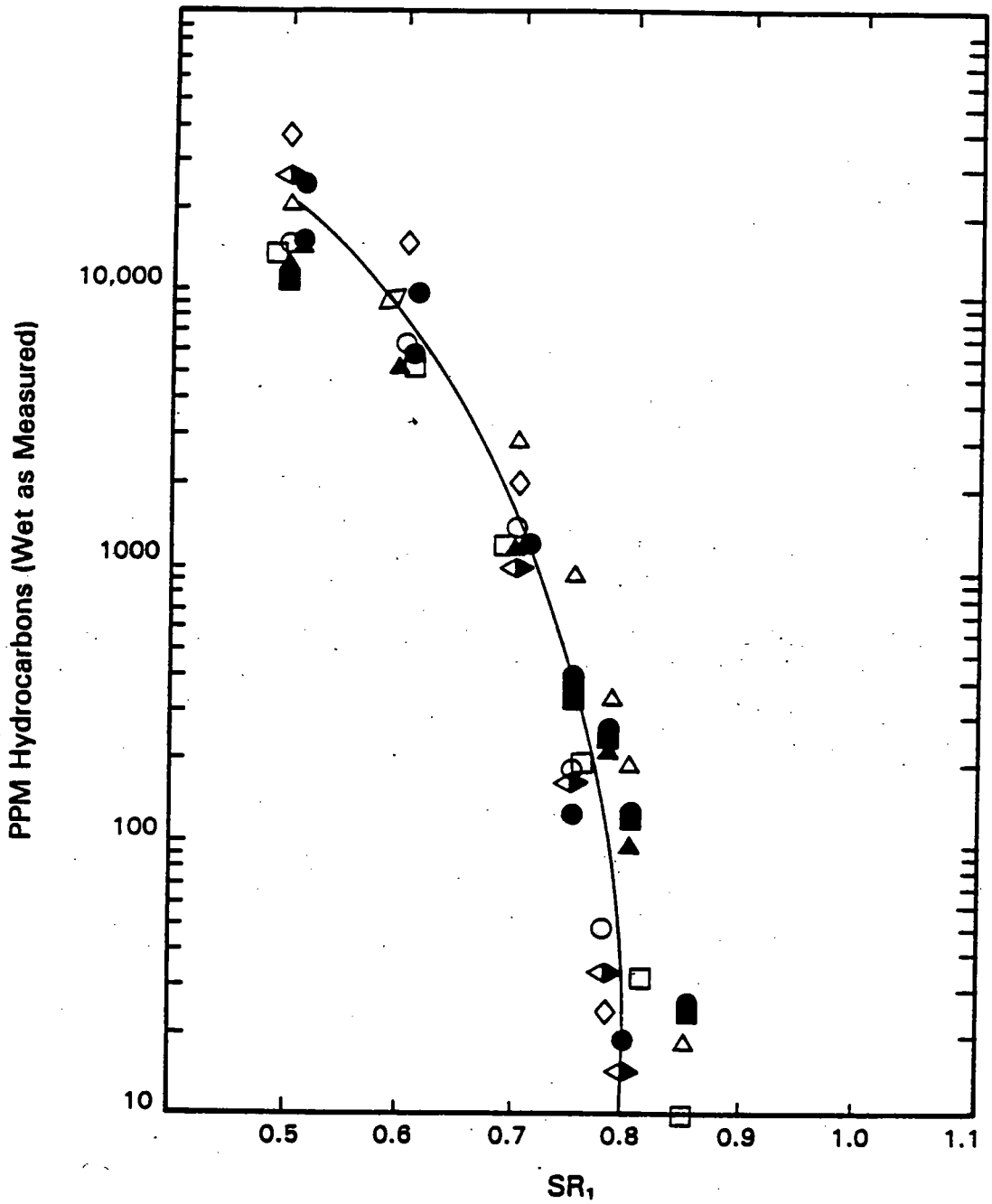

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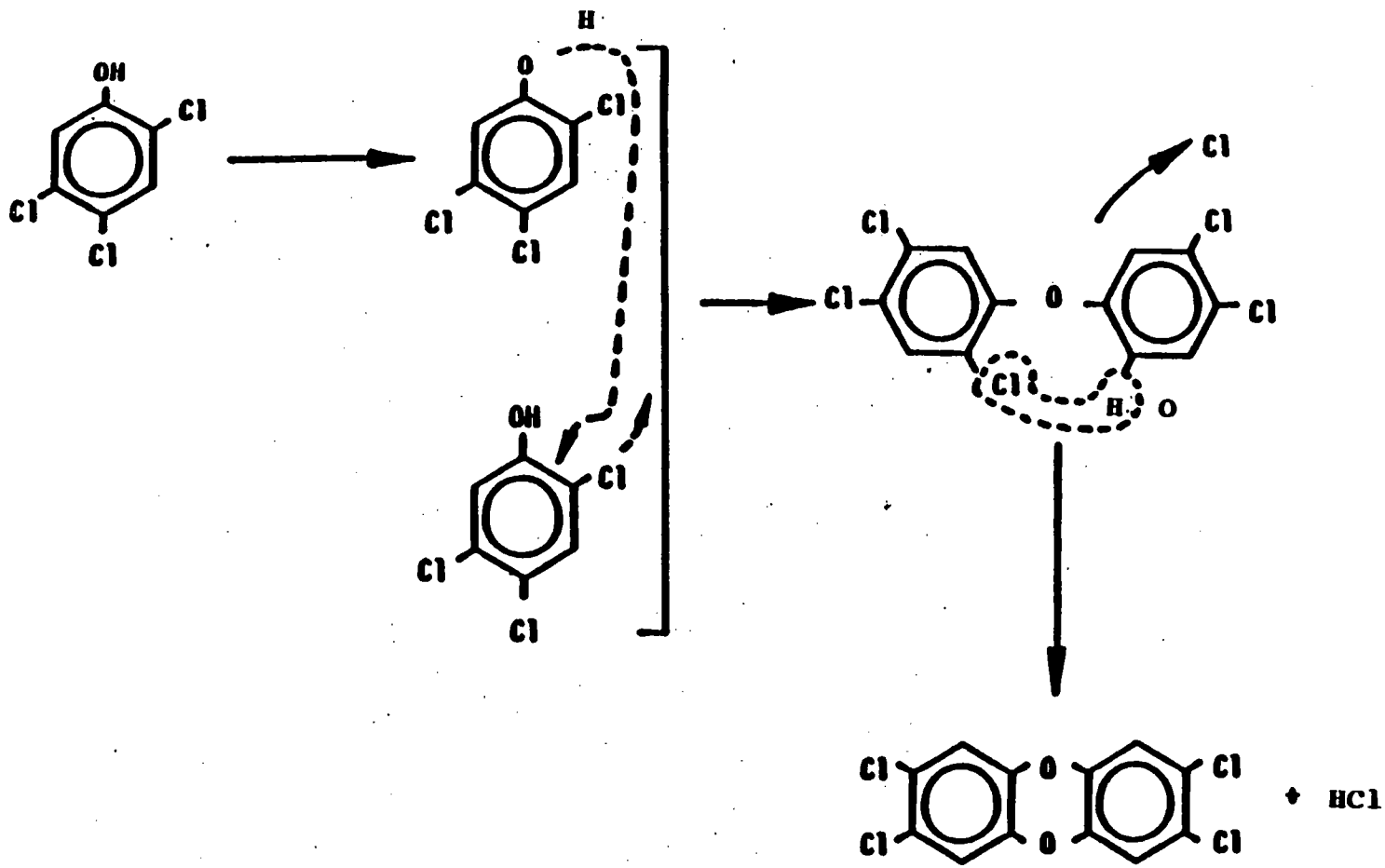
Figure 4-4. First Stage Hydrocarbon Production

hydrocarbon breakthrough in the primary zone exhaust, there was a precipitous increase in the boiler exhaust smoke level. The important point relative to hospital incineration is that the presence of substantial hydrocarbon concentrations in fuel-rich regions can easily result in the formation of soot and organic particulate matter. The secondary chamber must be designed to accommodate these materials to achieve complete burn-out.

Equilibrium product distribution calculations for very fuel-rich conditions indicate ppm level concentrations of chlorobenzenes and chlorophenols. In one study, the likely chemical kinetic processes leading to formation of PCDDs were reviewed and it was concluded that the prime dioxin precursors are chlorinated phenols.[7] Shaub and co-workers suggested a kinetic path for forming 2,4,7,8-TCDD, illustrated in Figure 4-5. The process proceeds by removal of hydrogen from the OH group, joining of two phenols to form a reactive 2-phenoxyphenol, and an elimination reaction to form dioxin.

The above discussion provides several important insights into the combustion processes controlling the formation of POM, dioxins and furans. Those same insights indicate important incinerator design and operating parameters which might be used to minimize emissions of those species. Equilibrium and kinetic considerations both indicate that an essential feature required for the formation of POM, dioxin or furans is a fuel-rich pocket of gas. Defining how rich that pocket must be to form these species will depend on the local gas temperature. Increased temperature reduces the thermodynamic stability of the species (and their precursors) as well as accelerating the kinetic rate of destruction reactions. The discussion suggests that these POM compounds are, in all likelihood, formed in the primary chamber of controlled air hospital incinerators. However, these compounds must pass through the oxidizing zones in the primary and secondary chambers before being emitted to the atmosphere. The residence time and temperature characteristics of the overall combustion process will dictate, in large measure, the extent to which these materials are destroyed before flue gases are emitted.



Source: Reference 7.

Figure 4-5. One Possible Formation Mechanism for 2,3,7,8 - TCDD

Fuel Effects. A third issue to be examined is whether the chemical form of hospital waste has a significant impact on POM, dioxin or furan emissions. It is difficult (if not impossible) to accurately quantify the chemical form of waste being fed into an incinerator over the time period required to extract a sample for POM analysis. There are, however, data quantifying POM emissions from gas, oil, and coal-fired boilers. Figure 4-6 shows benzo(a)pyrene (BaP) emissions data from different size boilers firing coal, oil or natural gas. The shaded area in this figure represents coal-fired boiler results. Units with heat inputs greater than 10^{10} cal/hr were utility boilers while units in the 10^7 cal/hr range were small stoker-fired or hand-stoked coal furnaces. The measured BaP emissions from gas and oil-fired boilers were generally on the same order as those from coal-fired utility boilers.

Utility boilers burn pulverized coal in large diffusion flames which are very similar to the flame types in gas and oil-fired boilers. The flame produced by a hand-stoked boilers is similar to that in a poorly designed and operated mass fed MSW incinerator.

As noted in Figure 4-6, the BaP emission rates from gas-, oil and coal-fired boilers with similar flame shapes are generally below 1 g/Mcal.[8] For comparison with other data in this report 1 g/Mcal is approximately equal to 500 ng/m^3 which is on the same order as the PCDD and PCDF emission rates indicated in Tables 3-7 and 3-8 for hospital incinerators. The BaP emission rates from the hand-stoked coal boilers are as much as 5 orders of magnitude above the levels produced by the diffusion flames. These comparisons suggest that the chemical structure of the fuel may have a relatively minor influence on POM emissions but that other parameters related to the manner in which the fuel is burned can have a significant influence. This underlines the fact that combustion controls, through careful incinerator design and operation, have the potential to achieve significant PCDD and PCDF emission reductions.

Air Distribution Effects in Controlled Air Incinerators. Using the waste burning process description of Section 3.1.4.1 in conjunction with the equilibrium, chemical kinetic, and fuel composition considerations of this section, it is possible to identify a variety of combustion control approaches for POM, PCDD and PCDF emissions, all based on elimination of

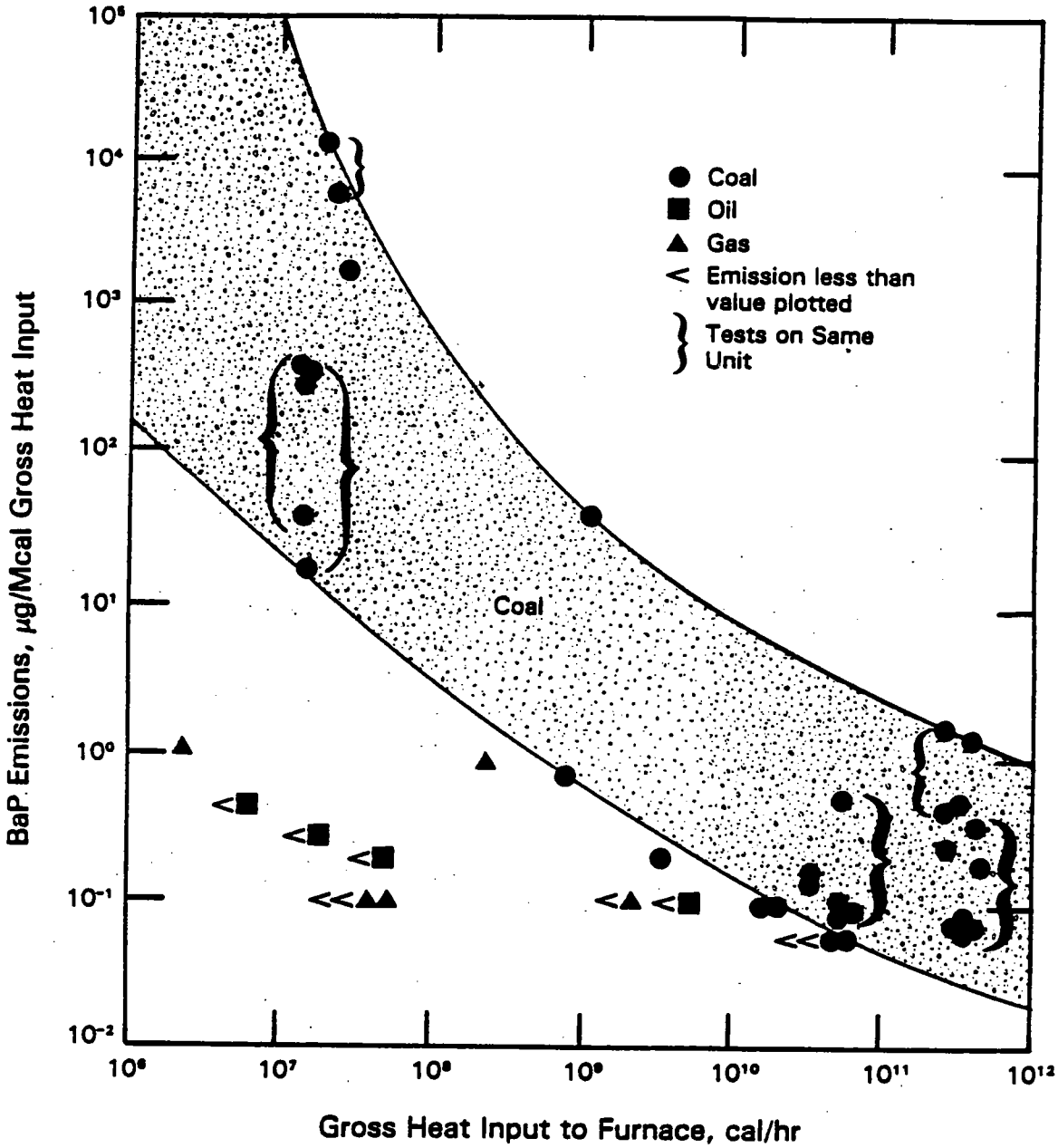


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Figure 4-6. Benzo(a)Pyrene Emissions from Coal, Oil, and Natural Gas Heat-Generation Process

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fuel-rich, low temperature pockets. A discussion of the design or operating conditions which lead to the formation of these pockets follows.

Controlled air incinerators will be used for the purpose of discussing air distribution effects on combustion control techniques for control of POM, PCDD, and PCDF. This type unit is chosen because of its wide use in the past 10 to 15 years. Retort incinerators share some similarities with controlled air units because of their two-stage design; this discussion will therefore also have some relevance to retort units. The design and operation of these units will be discussed by combustion stage.

Primary Combustion. As stated in Section 2.1.2, waste is fed into the primary combustion chamber which is operated with less than the full amount of air required for combustion. The air addition rate is usually 40 to 70 percent of stoichiometric requirements. Under these sub-stoichiometric conditions the waste is dried, heated, and pyrolized, thereby releasing moisture and volatile components. The primary chamber can therefore be considered a large fuel-rich pocket from the standpoint of POM, PCDD and PCDF formation. Conditions for formation of these compounds can, therefore, be considered optimum in the primary stage.

Waste is fed to the primary combustion chamber by either manual or mechanical loading devices. Manual loading is done by charging a bag at a time into the primary chamber while most mechanical loaders employ a hopper and ram assembly. Both feed mechanisms are non-continuous feed processes which deliver the feed in a batch-type manner. Therefore, the potential for an extremely fuel-rich system exists when waste is initially charged to the incinerator. A dynamic air supply system which can follow the transient is required if the system is to maintain its stoichiometric set point. Failure to maintain a consistent air-to-fuel ratio will make control in the secondary combustion chamber more difficult.

Most incinerators control combustion in the primary combustion chamber by measuring the temperature in the primary chamber and adjusting the air flow rate to that chamber to meet a temperature set-point. When temperatures are too low, air is added to accelerate the burning process. Conversely, the air rate is decreased when the temperature is too high.

In conclusion, the operation of the primary combustion chamber is such that a fuel-rich combustion environment exists. Smooth control of the air-to-fuel ratio is needed to counteract transients due to the feed mechanism; this will minimize the amount of fluctuation in the gas rate and characteristics of the gas entering the secondary combustion chamber.

Secondary Combustion. Moisture, volatiles, and combustion gases from the primary chamber flow upward through a connecting section where they are mixed with air prior to entering the secondary combustion chamber. If the gases from the primary chamber are hot enough they will self-ignite when mixed with the secondary chamber air. However, a burner is located near the entrance to the secondary chamber to provide additional heat when it is needed. The air injection rate into the second chamber is generally between 100 and 140 percent of total stoichiometric requirements. Thus, the total combustion process in the incinerator (including both stages) operates at between 40 to 110 percent excess air.

If operation of the secondary air flow is kept at design levels, the amount of oxygen added to the combustion process is sufficient to complete the combustion process without exceeding the lean fuel flammability limits. The critical issue is that the fuel-rich exhaust from the primary chamber must be mixed with air on a molecular level to achieve complete destruction of all POM, PCDD and PCDF, and potential precursors. Simply injecting additional air into the secondary chamber is not sufficient to ensure high combustion efficiencies. Consequently, great care must be taken in designing the secondary air chamber so that complete and thorough mixing will occur. One design approach to increase mixing currently in use is to introduce air at right angles to the flow of primary chamber gases and to use a series of staggered manifolds on either side of the gas. A second design approach is the enlargement of the secondary combustion chamber. This approach leads to greater residence times at temperature while also increasing the chance for mixing.

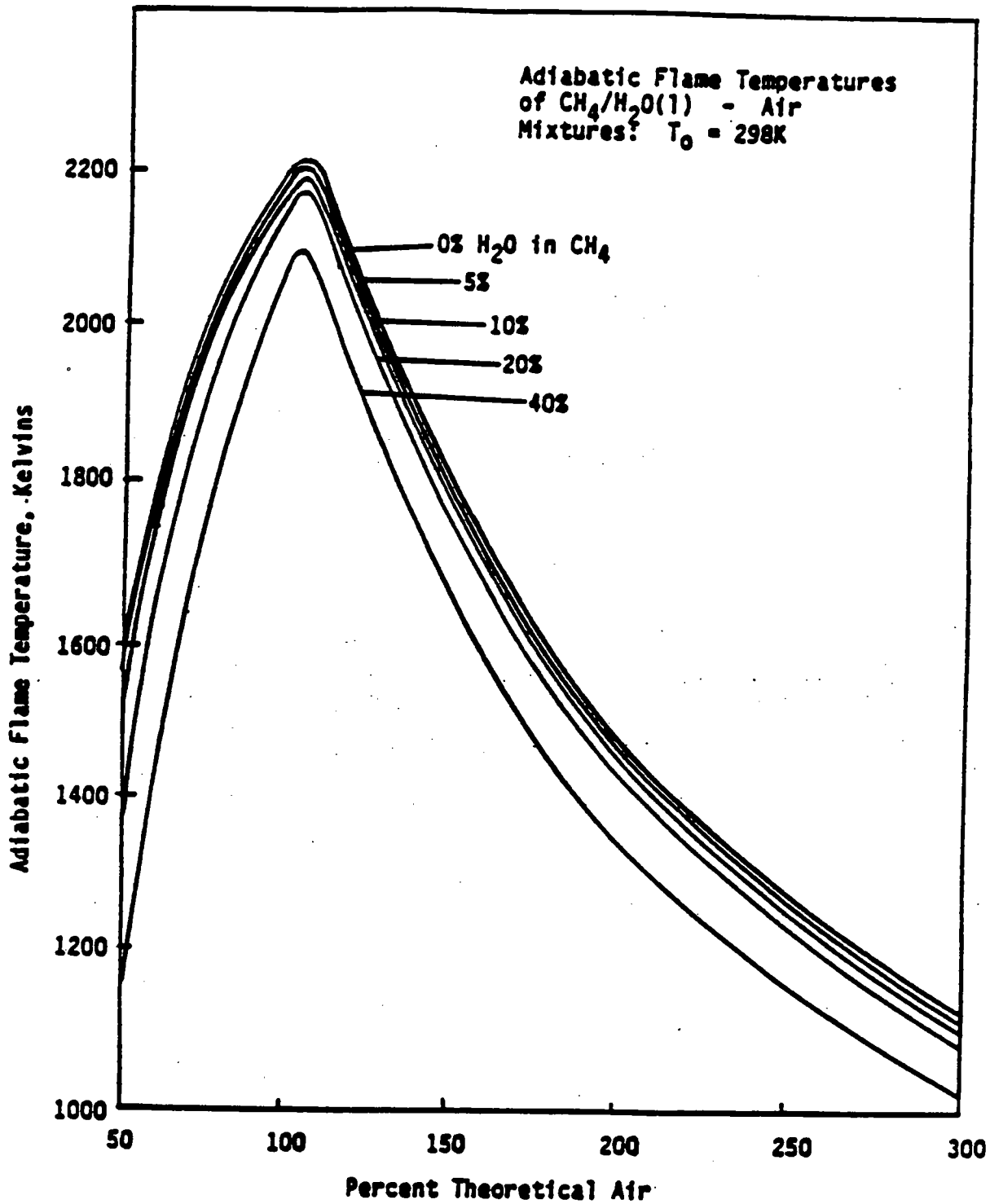
From an operational standpoint, the primary air flow rate control, secondary air flow rate control, and the extent of mixing in the secondary chamber, all could have a significant impact on POM, PCDD and PCDF emissions. Further research is required to better understand how incinerator design and operating parameters influence these emissions.

Thermal Environment. In EPA's Tier 4 study, it was observed that trends in PCDD and PCDF emissions could be detected based on the combustion temperature.[9] It was also noted in this report that MSW incinerators burning high moisture content waste tended to have low combustion temperatures and higher PCDD/PCDF emissions. The following discussion considers the theoretical relationship between temperature and emission rates for PCDDs, PCDFs, and other POMs.

Thermal environment and chemical kinetic processes are intimately related to each other. Flame temperature rise is the result of chemically converting fuel to combustion products while the rate of the chemical reactions is exponentially dependent upon the local temperature. In the discussion of equilibrium considerations it was shown that formation of fuel-rich pockets of gas favors production of POM, PCDD and PCDF. In the discussion of kinetic processes, Figure 4-4 showed that substantial hydrocarbons can persist in 80 percent theoretical air mixtures if there is heat extraction. Thus, removing heat from combusting gases tends to increase the stoichiometric ratio at which hydrocarbon species can persist.

An important set of variables influencing flame temperature is the excess oxygen level in the combustor and the moisture content of the waste. To illustrate these effects, a series of adiabatic flame temperature calculations were performed as a function of percent theoretical air. To demonstrate that flame temperature is controlled by combustion of waste volatile matter, methane was used as the fuel for these calculations. To simulate the moisture content of the waste, various quantities of liquid water (0-40 percent) was added to the "fuel." Results from these calculations are presented in Figure 4-7.[10] As shown, increasing the combustion air from 150 to 200 percent of the theoretical requirement decreases the adiabatic flame temperature by approximately 300°C (540°F). At 150 percent theoretical air (50 percent excess air), increasing the moisture content from 0 to 40 percent decreases the adiabatic flame temperature by approximately 150°C (270°F).

The important operational consideration is to maintain the excess air in a range which is high enough to insure that oxygen is available for fuel burnout but low enough to prevent excessive depression of the flame temperature. The requirement for operation within an excess air window is



Source: Reference 10

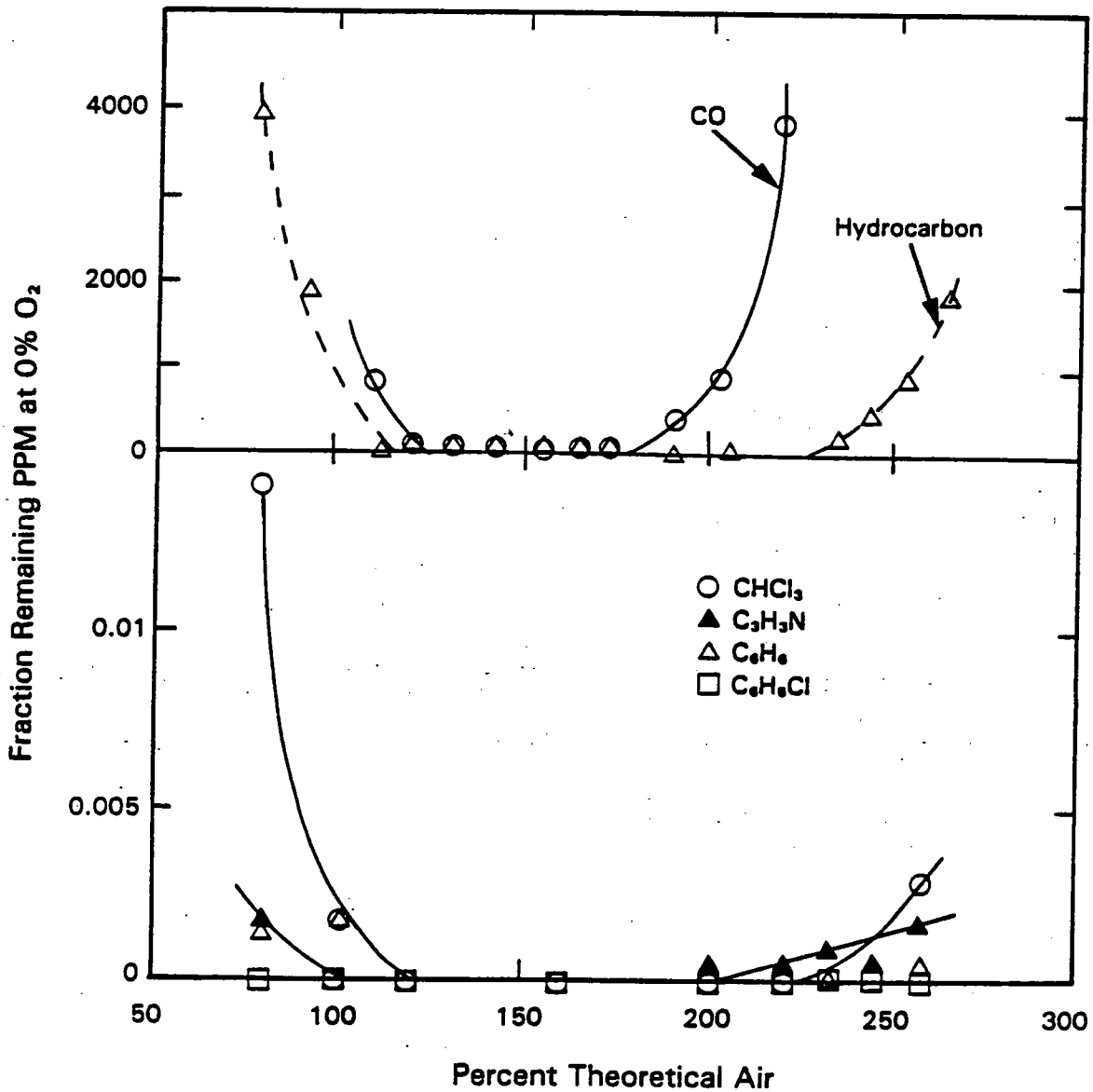
Figure 4-7. Variation of Adiabatic Flame Temperature with Percent Theoretical Air and Percent Moisture in the MSW

illustrated in Figure 4-8 which shows the measured total hydrocarbons in the exhaust of a highly cooled laboratory furnace as a function of excess air level (see Reference 5). It should be noted that the data in this figure are hardware-specific and that the acceptable excess air operating window will vary with both incinerator design details and characteristics of the waste being burned (e.g., heating value, moisture content, and halogen content).

The moisture content of hospital waste is dependent on the daily operation of the hospital. As illustrated in Figure 4-7, adjusting the excess air level can offset the thermal influence of large variations in moisture content. The thermal influence of adding 40 weight percent water to the fuel may be offset by decreasing excess air level by about 20 percent. From a combustion control standpoint, hardware could be developed to continuously monitor the exhaust gas H_2O content; that data could be used in a control system to appropriately adjust the excess air level. Research is required to define the proper mode of excess air control, but theoretical considerations indicate that it is likely that minimum POM, dioxin and furan emissions control would be achieved by adjusting excess air rates in the primary and secondary chambers to achieve desired temperature levels and gas residence times.

An additional operational consideration influencing thermal environment and possibly having a major impact on POM, PCDD and PCDF emissions is the unit start-up and shut-down procedure. Some facilities may have greatly different warm-up periods depending on operator awareness. Based on considerations presented earlier in this section, extensive warm-up using auxiliary fuel (natural gas or distillate oil) is the preferable operating procedure. The start-up period may have little impact on steady-state emission rates but a substantial mass of POM, PCDD and PCDF could be emitted during start-up with cold walls. By the same token, sufficient air and temperature levels should be maintained during burn-down periods to assure complete combustion.

Post-Combustion Formation Mechanisms. In addition to formation in fuel-rich pockets of the incinerator combustion zone, it is possible that PCDD and PCDF may be formed by flue gas reactions taking place downstream of the first or second stage combustors.



Source: Reference 11

Figure 4-8. Hydrocarbon Breakthrough as a Function of Percent Theoretical Air

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Several mechanisms have been hypothesized by various researchers to account for the formation of PCDD and PCDF downstream of the combustion chamber in municipal waste combustors. These hypotheses include a) reaction of products of incomplete combustion, for example, chlorophenols and chlorobenzenes in the gas phase or on the fly ash to form PCDD and PCDD; b) de novo synthesis of PCDD/PCDF on fly ash involving metal chloride catalysis; or c) de novo synthesis from particulate carbon. All of the hypothesized mechanisms include temperature "windows" for the formation reactions. For example, recent studies of PCDD formation and destruction by Vogg and Steiglitz indicate that formation of PCDD in fly ash can occur at temperatures between approximately 430°F and 750°F (220°C and 400°C), peaking at 570°F (300°C).[12] The authors heated fly ash for two hours and found no change in PCDD/PCDF concentrations below 390°F (200°C), a 10-fold increase at 570°F (300°C) and complete destruction at 1110°F (600°C).[13,14] Other researchers have proposed that PCDD/PCDF can be formed from particulate carbon in MWC flue gases at temperatures of about 570°F (300°C).[15]

Summary. The above discussion illustrates that emissions of POM, PCDD and PCDF are either the products of incomplete combustion or are formed by post-combustion mechanisms. A critical component in the combustion formation process is presence of fuel-rich pockets of gas. The primary combustion chamber in a controlled air incinerator is operated as a large fuel-rich pocket. To maximize the extent of combustion, the following steps can be taken:

- Control the combustion air supply to the primary chamber to minimize transients in the outlet flow rate and composition;
- Proportion combustion air between the primary and secondary chambers to maintain desired temperatures; and
- Promote efficient mixing of air and combustion gases in the secondary chamber.

Each of these combustion parameters are adjustable during the incinerator design and/or as part of the unit operating procedure. The assertion that combustion-generated PCDD and PCDF emissions can be reduced by combustion control is clear, but the types of modifications likely to be

effective will depend upon the specific design and operating conditions of a given model and size. That is, combustion modifications must be tailored to the specific type of incineration hardware under consideration. Appropriate control strategies for existing facilities must be evaluated on a case-by-case basis and some processes may require extensive hardware modification and/or altered operational procedures.

To the extent that PCDD/PCDF emissions are formed downstream of the combustion chambers, emission reductions will be influenced by the mechanisms involved and practices employed in this area. If emissions are the result of reactions between products of incomplete combustion (PICs), these products must be avoided in the temperature window in which the reactions occur. Possible emission reduction techniques would be the elimination of PICs in the secondary combustion chamber by operating the chamber at higher temperatures and/or larger gas residence times. Another approach would be to remove the PICs from the flue gas stream either by scrubbing an adsorption. If PCDD/PCDF emissions are the result of de novo synthesis on fly ash or from particulate carbon within a given temperature window, then the removal of fly ash and carbon at temperatures above the critical window would reduce flue gas emissions. However, it may still be necessary to rapidly quench the captured particles (e.g., with a scrubbing liquid or air) or to cover their active surface area with an inert material (e.g., powdered lime) in order to minimize subsequent de novo synthesis from captured particles. The processes available for such flue gas treatments are discussed in the next section.

4.3 FLUE GAS CONTROLS

Add-on devices may be employed for post-combustion treatment of flue gas. As shown in Section 3.0, two devices presently in use on hospital incinerators are fabric filters (baghouses) and wet scrubbers. Other potential add-on controls not presently in use are dry scrubbers and dry injection. Dry scrubbers and dry injection have demonstrated acid gas and organic emissions control on MSW incinerators and, when coupled with fabric filters, offer good particulate control as well. In addition, after-burners are potential controls for organic compound emissions. These same devices are candidates for control of emissions from hospital waste incinerators.

4.3.1 Fabric Filters (Baghouses)

Fabric filters offer very high efficiencies for particle removal from flue gas with attainable efficiencies greater than 99.9 percent. Currently, there are at least four MSW incinerator installations utilizing baghouses in the U. S.[16] Similar efficiencies would be expected for hospital waste incinerators because of the similar nature of the wastes. At least one baghouse has been installed and operated on a hospital waste combustor (see Section 3.2.2).

Fabric filters rely on porous glass fabric to facilitate removal of very fine PM. Figure 4-9 shows a typical arrangement. Collected PM is "shaken," either mechanically or by air, from the bag and disposed of with bottom ash from the incinerator. Some advantages and disadvantages of baghouses are as follows:[17]

Advantages

1. High PM removal efficiencies can be obtained.
2. High efficiencies for finer PM means good removal of those metals which concentrate on fine PM.
3. There are no wastewater disposal requirements.
4. Variations in flue gas flow rate or chemical composition do not usually affect fabric filter performance.
5. Submicron particle collection improves as the thickness of the dust layer on the collection surface increases.

Disadvantages

1. Fabric filters are designed only for PM control and do little to control gaseous pollutants.
2. High pressure drops may occur if bags become plugged with solids which could lead to large power requirements.
3. The upper temperature limit of most widely used filter media is about 260°C (500°F).
4. "Sparklers" (i.e., incandescent waste particles) carried by the flue gas can cause fires in the fabric filter.

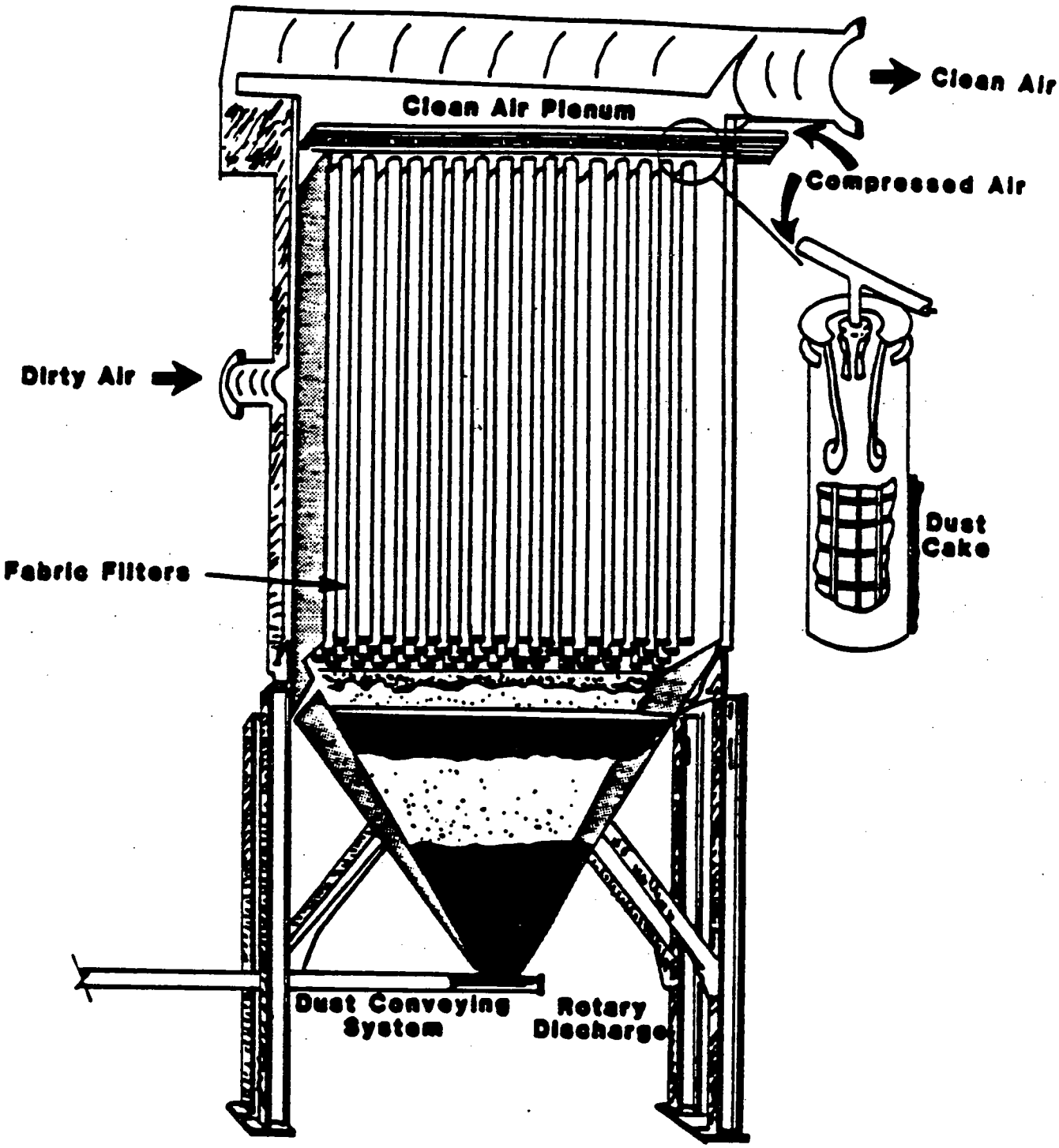

Figure 4-9. Typical Fabric Filter System

5. The dew point of the flue gas must be considered. An excursion below the dew point can result in condensation and hence blinding of bags. In addition, due to the typically high HCl content of hospital waste incinerator flue gases, condensation can lead to the formation of corrosive HCl acid.

4.3.2 Scrubbers and Dry Injection Systems

Wet scrubbers currently in use offer lower efficiencies for the collection of PM but higher efficiencies for acid gas removal. Wet scrubbers use liquid to remove pollutants from the gas stream. Scrubber design and the type of liquid solution used largely determine contaminant removal efficiencies. Efficiencies for the removal of acid gases with plain water are in the range of 30 percent, while the addition of $Ca(OH)_2$, $CaCo_3$, or CaO to the scrubber liquor has been shown to result in efficiencies of 93-96 percent.[18] In general, high gas-side pressure drops must be used to obtain high efficiencies for PM control.

There are basically three types of wet scrubbers:

(1) low energy (spray tower),

(2) medium energy (impingement scrubbers such as packed column, baffle plate, and liquid impingement), and

(3) high energy (venturi).

Low energy scrubbers (spray towers) are usually circular in cross-section (see Figure 4-10). The liquid is sprayed down the tower as the gases rise. Large particles are removed by impingement on the liquor pool, and finer particles are removed as the flue gas rises through the tower. Low energy scrubbers mainly remove particles in the 5-10 micron range and larger.[19]

Medium energy devices mostly rely on impingement to facilitate removal of PM. This can be accomplished through a variety of configurations, two of which are diagrammed in Figures 4-11 and 4-12.

High energy scrubbers use a venturi mechanism for PM removal (see Figure 4-13). The flue gases impinge on the liquor stream in the venturi section. As the gases pass through the orifice, the shearing action atomizes the liquor into fine droplets. As the gas leaves the venturi

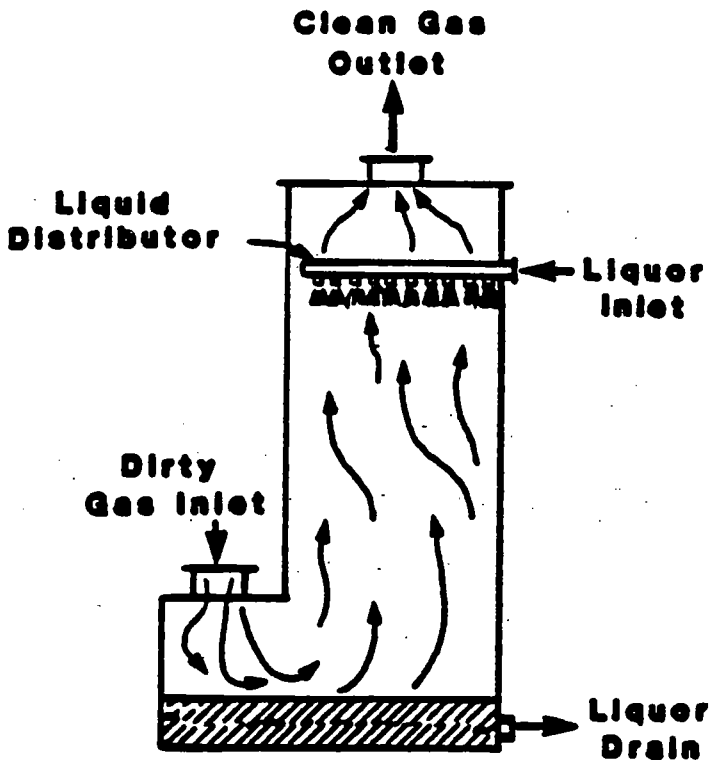

Figure 4-10. Open Spray Tower Scrubber

14. Hagenmaier, H., M. Kraft, H. Brunner, and R. Haag. "Catalytic Effects of Fly Ash from Waste Incineration Facilities on the Formation and Decomposition of Polychlorinated Dibenzo-p-dioxins and Polychlorinated Dibenzofurans." Environmental Science adn Technology, November 1987, Vol. 21, No. 11, p. 1080-1084

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5.0 REGULATORY STATUS AND STRATEGIES

Regulatory strategies in the United States to control air emissions from hospital waste incinerators have not been addressed to date at the Federal level but have been a focus of attention at the State level. Because of their relatively small size, emissions from hospital waste incinerators are not subject to Federal regulations which control emissions from larger MSW incinerators and solid waste-fired boilers. Instead, hospital waste incinerators are subject to a "patchwork quilt" of State and local guidance and regulations. Currently, most States recommend, but do not require, the control of particulate matter (PM) emissions and opacity for hospital waste incinerators. However, with the growing public concern over handling and disposal of hospital wastes, several States have developed emission limit regulations for incinerators which have recently been promulgated or are now in the proposal stage.

This section discusses the current regulatory environment for hospital waste incinerators at both the Federal and State level. The information presented on State programs is accurate as of June 1988. However, due to the rapidly changing nature of these programs, this information is expected to become quickly out-of-date.

In addition to Federal and State regulations in the United States, this section also reviews regulations which have been established for hospital waste incineration in Canada and European countries.

5.1 FEDERAL REGULATIONS AND PROGRAMS

5.1.1 New Source Performance Standards

Hospital waste incinerators are not currently a source category subject to New Source Performance Standards (NSPS). However, they would be subject to the NSPS for industrial, commercial, and institutional steam generating units (i.e., boilers) at 40 CFR Part 60 Subpart Db if units have a heat input capacity above 100 million Btu/hr and recover heat to generate steam or to heat water (or other heat transfer media). At 8,500 Btu per pound of

Type 0 (see Table 1-3) waste, a hospital incinerator must be sized to feed over 11,700 lb/hr of waste to be subject to the boiler NSPS. The largest system offered for on-site hospital waste incineration is approximately 6,000 lb/hr capacity, and most units are well below this size. Hence hospital waste incinerators are unlikely to be impacted by the current boiler NSPS.

EPA is currently evaluating NSPS for smaller boilers with capacities below 100 million Btu/hr. The lower size cutoff is one of the factors to be determined during the rulemaking process. A lower size cutoff below 50 million Btu/hr would affect at least a fraction of new, modified, or reconstructed hospital waste incinerators. The pollutants being evaluated for the small boiler NSPS are PM, opacity, NO_x, and SO_2. Proposal of this standard is scheduled for June 1989.

NSPS limiting PM emissions to 0.08 gr/dscf (equivalent to about 0.18 lb/million Btu) corrected to 12 percent CO_2 have been promulgated at 40 CFR Part 60 Subpart E for incinerators having a design capacity of 50 ton/day (i.e., 4,167 lb/hr) or greater and which burn more than 50 percent municipal type waste. This waste is defined as "waste consisting of a mixture of paper, wood, yard wastes, food wastes, plastics, leather, rubber, and other combustibles, and noncombustible materials such as glass and rock." Although hospital waste would seem to qualify under this definition, the size limit for Subpart E would apply to only the largest of hospital waste incinerators.

5.1.2 National Emission Standards for the Hazardous Air Pollutants

Of the 12 NESHAPs promulgated pursuant to Section 112 of the Clean Air Act which address hazardous pollutants, none pertain to hospital waste incinerators.

5.1.3 Resource Conservation and Recovery Act Requirements

As a first step in fulfilling the Congressional mandate to establish a hazardous waste management system, EPA published proposed regulations in the Federal Register on December 18, 1978, which included a proposed definition and treatment methods for infectious waste.[1] During the public comment

period for this rulemaking, EPA received approximately sixty comments which specifically addressed the infectious waste provisions of the proposed regulations.[2]

On May 19, 1980, EPA published the first phase of the hazardous waste regulations. The Agency stated in the preamble to the regulations that the sections on infectious waste would be published when work on treatment, storage, and disposal standards was completed. Recently, EPA published a Federal Register notice of data availability and request for comment on issues pertaining to infectious waste management.[3]

5.1.4 Prevention or Significant Deterioration Requirements

Hospital waste incinerators are not among the 28 named prevention of significant deterioration (PSD) source categories. Even though waste generation rates vary among hospitals, emissions from incinerators are typically less than 250 tons per year. Therefore, in most states best available control technology (BACT) is not required for emitted pollutants.

5.2 STATE REGULATIONS AND PROGRAMS

5.2.1 State Requirements for Waste Handling

Most states have requirements for licensing of hospital that may include general requirements for infectious waste disposal. Usually, these general requirements are limited in scope and do not apply to other sources of infectious waste, such as crematoria.[4] The only restriction on the pathological or biomedical waste incinerators in many states is that they not create a public nuisance. That has meant that no odors are to be generated and that the opacity is to be low.[5]

A majority of states have passed hazardous waste legislation to control the treatment, storage, and disposal of infectious waste (as part of their hazardous waste program). Some states have already promulgated regulations controlling infectious waste, while other states are preparing such regulations. Since there is no unanimity of opinion on the hazards posed by

infectious waste and appropriate techniques for safe disposal of these wastes, state control varies.[6] Most states do not have specific requirements for hospital incineration that limit air pollutant emissions.

To determine what efforts different states have taken to regulate infectious wastes, the National Solid Wastes Management Association's (NSWMA) Infectious Waste Task Force surveyed the state health and environmental agencies in January 1987. The general purpose of the survey was to determine where treatment and disposal of infectious waste are subject to regulations distinct from those that apply to municipal solid waste (MSW).[7] The survey's results indicated the following:[8]

- The solid waste and/or health departments in 28 states do define infectious waste items and subject these items to special rules or recommendations in management.
- Some states such as Massachusetts and Louisiana expect to revise their definitions soon to capture all generators of infectious wastes and not just hospitals.
- In general, hospitals and health-care facilities are prevented from disposing of wastes in a landfill without rendering the wastes non-infectious.
- Thirteen states have written or endorsed specific guidelines or requirements for transporting untreated infectious wastes.

5.2.2 State Air Emission Requirements

Radian has contacted several states to clarify their infectious waste management requirements; the information collected from the states is presented in Appendix A. The appendix contains an updated list of infectious waste regulations and requirements as well as a list of state offices that may be contacted for additional information. Where data were missing from non-contacted states, data available from the EPA Guide for Infectious Waste Management were listed. Most states did not list a specific regulation concerning the incineration of hospital or infectious waste.

Pennsylvania has recently established best available control technology guidance for hospital infectious waste incineration. These guidelines require stack emission limitations on particulate matter, carbon monoxide,

hydrochloric acid and visible air contaminants. The guidelines are listed in Table 5-1 along with guideline emission limits set by New York, New Jersey, Connecticut, and Illinois.

5.2.3 State Air Toxics Programs

A majority of states and localities use some form of ambient guidelines or standards for the control of toxic air emissions from hospital incinerators. Several states regulate new hospital waste incinerators in a manner similar to that required by the Resource Conservation and Recovery Act (RCRA) hazardous waste incineration regulations, i.e.; 100 ppm CO, 90% control or 4 lb/hr HCl emissions, and 0.08 gr/dscf (corrected to 12 percent CO_2) for particulates.[9] The city of Philadelphia is requiring that new hospital incinerators have scrubbers, which are used to control acid gases and toxic air contaminants.[10]

The State of Pennsylvania also requires ambient impact analyses for arsenic, cadmium, hexavalent chromium, lead, mercury, nickel, polychlorinated dibenzo-p-dioxins, and polychlorinated dibenzofurans. The acceptable ambient air concentrations for these pollutants are listed in Table 5-2. Stack sampling is required to demonstrate compliance with ambient limits based on dispersion modeling calculations.

The State of New York has drafted operating guidelines for hospital waste combustion. These guidelines require stack emission limitations for particulate matter, carbon monoxide, hydrochloric acid, and visible air contaminants. Also, continuous monitoring and recording of temperature in the secondary chamber are required to show an exit temperature of at least 1800°F. In addition, the State requires demonstration of compliance with acceptable ambient air quality levels for toxic air contaminants (or acceptable risk assessments for carcinogens) under its Air Guide policy (see Table 5-2).[11,12]

In the State of California each local air quality district can establish its own emission limit requirements. Presently, guidelines on emission limits MSW and hazardous waste facilities are serving as guidelines for hospital waste incineration. However, California is in the process of developing new restrictions that pertain directly to hospital waste incineration.

TABLE 5-1. GUIDELINE EMISSION LIMITS FOR INCINERATORS BURNING HOSPITAL WASTE[a]

State/Facility	Pollutant				
	Particulate Matter	Opacity	HCl	CO	SO_2
New York	0.015 gr/dscf (at 7% CO_2)	maximum continuous 6-minute average <10%	50 ppmv 3-hour average or shall be reduced by 90% or uncontrolled rate less than 4 lb/hr for facilities below 580 lb/hr total charging rate	100 ppm hourly average (at 7% O_2	--
Pennsylvania (Facility with capacity ≤500 lb/hr)	0.08 gr/dscf (at 12% CO_2)	<30% at all times; maximum 3-minute average <10% in any hour	<4lb/hr or shall be reduced by 90% by weight	100 ppmv hourly average (at 7% O_2)	--
Pennsylvania (Facility with capacity >500 lb/hr, ≤2000 lb/hr)	0.03 gr/dscf (at 7% O_2)	<30% at all times; maximum 3-minute average <10% in any hour	30 ppmv hourly average (at 7% O_2) or shall be reduced by 90% by weight	100 ppmv hourly average (at 7% O_2)	30 ppmv hourly average (at 7% O_2) or shall be reduced by 75% by weight
Pennsylvania (Facility with capacity >1000 lb/hr)	0.015 gr/dscf (at 7% O_2)	<30% at all times; maximum 3-minute average <10% in any hour	30 ppmv hourly average (at 7% O_2) or shall be reduced by 90% by weight	100 ppmv hourly average (at 7% O_2)	30 ppmv hourly average (at 7% O_2) or shall be reduced by 75% by weight
New Jersey	0.02 gr/dscf (at 12% CO_2)	--	--	--	--
Connecticut	0.02 gr/dscf (at 12% CO_2)	--	--	--	--
Illinois (Facility with capacity >6000 lb/hr)	0.05 gr/scf (at 12% CO_2)	30%	--	--	--
Illinois (Facility with capacity >2000 lb/hr, <6000 lb/hr)	0.08 gr/scf (at 12% CO_2)	30%	--	500 ppm at 50% excess air	--
Illinois (Facility with capacity <2000 lb/hr)	0.1-0.20 gr/scf (at 12% CO_2)	30%	--	--	--

[a]References 21-25.

CML.027

TABLE 5-2. ACCEPTABLE ANNUAL AMBIENT CONCENTRATIONS REPORTED FOR SELECTED POLLUTANTS[a]

Metal/Compound	Pennsylvania	New York
Arsenic and Compounds	0.23×10^{-3}	0.67
Beryllium and Compounds	0.42×10^{-3}	-
Cadmium and Compounds	0.56×10^{-3}	2.0
Hexavalent Chromium and Compounds	0.83×10^{-4}	0.167
Lead and Compounds	0.50	1.5[b]
Mercury and Compounds	0.08	0.167
Nickel and Compounds	0.33×10^{-2}	3.3
PCDD and PCDF[c]	0.30×10^{-7}	-[d]

[a]References 26 and 27; all concentrations in ug/m^3.

[b]Federal standard for lead; not yet officially adopted by New York State, but currently being applied to determine compliance status.

[c]Expressed as tetrachlorinated dibenzo-p-dioxin equivalents

[d]Emission sources of chlorinated dibenzofurans and dibenzodioxins are reviewed on a case-by-case basis by the Department of Health (DOH). The NY State DOH has determined that basing an acceptable ambient level on TCDDs does not adequately represent public health risks for the dioxin compounds.

5.2.4 State Permitting Requirements

Radian contacted several states with relatively stringent air emission limitations to discuss procedures and analyses required to obtain an operating permit for an infectious waste incinerator. The objective of this effort was to identify the range of analyses and requirements currently associated with the permitting process. Operator training and ash disposal requirements are also addressed, where applicable. The results of the contacts are summarized below, by state, in alphabetical order:

Connecticut - Department of Environmental Protection[13]

- Infectious wastes are currently regulated as special wastes.
- BACT analysis is required in lieu of emission limits for any pollutant emitted at rates greater than 5 tons/year. This includes HCl, PM, and toxics.
- Ambient impact/risk analysis are not required, although stack emissions are limited to levels dictated by ambient Hazard Limiting Values (HLV) at the facility fenceline. The HLVs are based on the State's air toxics control program.
- Incinerator ash is evaluated using the Extraction Procedure (EP) toxicity test. If the ash fails the test, it must be handled as a hazardous waste. If the ash passes the test, which is more common, it is sent to a permitted special waste landfill. The ash must be isolated and contained in a separate cell at the landfill.

Illinois - Environmental Protection Agency[14]

- No BACT or ambient impact analyses are required unless the source qualifies under Federal PSD rules.
- Infectious waste incinerator ash is treated as a hazardous waste. It must be sent to a permitted special waste landfill. The ash must be shipped in accordance with the State's manifest system.
- If the waste is to be incinerated, the permit applicant must describe the incinerator to be used; wastes to be incinerated; gas cleaning devices; methods to dispose of bottom ash, fly ash and/or scrubber sludge; and indicate operating temperatures and gas residence time.

Massachusetts - Division of Air Quality Control[15]

- A BACT analysis is required for all infectious waste incinerators. Emissions of concern include PM, PM_{10} acid gases, dioxins, furans,

pathogens, and metals. The analysis is performed from a "top-down" perspective (i.e., the most stringent technology applicable must be examined and rejected on the basis of costs or other factors before less stringent alternatives can be considered).

- In addition to the BACT analysis results, permit applicants must specify procedures for incineration warm-up, burn-down, feed charging, and waste handling which meet State requirements. For example, infectious waste must be placed in boxes prior to disposal.

Michigan - Department of Natural Resources[16]

- Applicants for a permit to operate must submit a complete description of the incineration and potential pollution control equipment which includes the following:

  -Plot plan and nearby building information

  -Description of the incinerator

  -Description of the waste stream

  -Operating schedule

  -Temperature profile and retention time

  -Temperature monitoring and recording system

  -Procedures to insure that prescribed temperatures are monitored

  -Flue gas volume and composition

  -Description of combustion controls

  -Discussion of the physical and economic feasibility of installing and operating an acid gas scrubbing system and a high efficiency particulate collector

  -Description of proposed emission control equipment

  -Description of emission control equipment by-pass, if applicable

  -Discussion of stack sampling ports

  -Description of ash handling system

  -Description of preventative maintenance and malfunction abatement system

-Maximum uncontrolled and controlled emission rates for specified pollutants

-Demonstration that the proposed emissions will not cause injurious effects to human health and safety

- In lieu of their own emissions data, applicants may use the DNR's statistical emission rate data (95th percentile) compiled on the basis of available test data.

- To demonstrate that emissions do not cause injurious effects to human health and safety, applicants must perform dispersion modeling and determine ambient concentrations at both ground level and air intake levels for nearby buildings. Acceptable ambient air concentrations have been established for the following pollutants:

  -Particulate matter

  -Sulfur dioxide

  -Nitrogen oxides

  -Carbon monoxide

  -Polychlorinated biphenyls

  -Mercury

  -Arsenic

  -Cadmium

  -Chromium

  -Total polychlorinated dibenzo-p-dioxins (PCDD)

  -Total polychlorinated dibenzofurans (PCDF)

  -Hydrogen chloride

  The applicant may request the DNR to perform the necessary dispersion analysis using the methods developed by the Michigan Air Pollution Control Commission.

- As discussed, ambient pollutant concentrations must be below acceptable levels at both ground and air intake levels. Options to remedy predicted concentrations above required levels are to increase stack height and to install emission control equipment such as scrubbing systems and baghouses.

New York - Department of Environmental Conservation[17]

- Applicants must submit engineering data relative to waste characterization, incinerator design, combustion air systems, incinerator control devices, and flue gas cleaning devices.

- An ambient air quality impact analysis must be performed with respect to the following pollutants:

  -Total particulates

  -Sulfur dioxide

  -Nitrogen dioxide

  -Carbon monoxide

  -Hydrocarbons

  -Hydrogen chloride

  -Lead

  -Cadmium

  -Chromium

  -Arsenic

  -Mercury

  -Nickel

  -Polycyclic aromatic hydrocarbons

  -Polychlorinated biphenyls

  -2,3,7,8 tetrachlorinated dibenzo-p-dioxins (TCDD)

  -Total TCDD

  -Total PCDD

  -Total PCDF

Pennsylvania - Department of Environmental Resources[18]

- Ambient impact analyses must be conducted for: a) arsenic and compounds; b) beryllium and compounds; c) cadmium and compounds; d) hexavalent chromium and compounds; e) lead and compounds; f) mercury and compounds; g) nickel and compounds; h) PCDD and PCDF expressed as 2,3,7,8 TCDD equivalents using toxicity equivalents

factors (TEF). Using available emission factors, the emissions from the facility must be estimated and the analyses must be conducted by performing dispersion modeling using the facility's exhaust characteristics.

- If the application is subject to "Prevention of Significant Deterioration" (PSD) requirements, the analyses shall be conducted in accordance with the "Guidelines on Air Quality Modeling" dated January 1983 (as revised). The applicant is advised to discuss the modeling requirements with the Department prior to starting any modeling study. The analysis must show that predicted concentrations do not exceed the levels shown in Table 5-2.

- Compliance must be verified by stack sampling. Using the actual stack emission rates, the exhaust parameters from each test and the dispersion modeling techniques specified in the application as approved by the Department, the calculated maximum annual ambient concentrations must not exceed the stated levels.

- Incinerator ash must be landfilled. The landfill must be permitted by the Department to accept such wastes. By the end of the decade, the Department intends that only landfills that meet new municipal waste disposal regulates, similar to these for hazardous waste landfills, continue to operate.

- An application for disposal of special waste must be filed and approved which includes a detailed description of the type and source of waste and of the incinerating conditions. The Department requires ash to be tested under conditions that simulate a landfill and may, if necessary, impose special disposal conditions in a permit to prevent loading of heavy metals.

- Before construction, hospital waste incinerators must undergo a plan review in which the Department reviews the design to insure that all applicable standards are capable of being met. The plan approval application must include a description of each specific waste and approximate quantity of each such wastes which will be charged to the incinerator. The application must, as a minimum, contain the final design specifications of the incinerator and the associated air pollution control devices with dimensioned drawings indicating the locations of burners, air injection ports and monitors.

- In addition to emission estimates and the results of the ambient impact analyses, the plan must include a set of calculations for estimating secondary chamber residence times using specified procedures.

- Facilities capable of burning hospital/infectious wastes at rates greater than or equal to 50 tons per day must also meet the permitting criteria established for municipal waste incinerator.

- Prior to startup, all incinerator operators must be trained as to proper operating practices and procedures. The content of the training program must be submitted to the Department for approval. The applicant must submit a copy of a certificate verifying the satisfactory completion of a training program by all operators prior to issuance of an operating permit.

5.3 FOREIGN REGULATIONS

In Canada, air pollution regulations are established by each provincial government. Table 5-3 lists emission limits established in Alberta, Canada and technical requirements established in several European countries. This study did not include the investigation per se of foreign procedures or regulations. However, the data presented in Table 5-3 were extracted from References 19 and 20.

TABLE 5-3. FOREIGN EMISSION REGULATIONS FOR HOSPITAL WASTE[a]

Pollutant	Alberta, Canada	European[a]
Particulate matter	0.20 kg/1000 kg of gaseous effluent[b]	200 mg/Nm^3 dry at 7% CO_2 maximum
	0.60 kg/1000 kg of gaseous effluent[c]	--
HCl	100 ppm at 50% excess air	300 mg/Nm^3 dry at 7% CO_2 maximum
CO	--	500 mg/Nm^3 dry at 7% CO_2 maximum
SO_2	--	200 mg/Nm^3 dry at 7% CO_2 maximum
HF	--	5 mg/Nm^3 dry at 7% CO_2 maximum
Opacity	--	Not to exceed 30%

[a]References 19 and 20.

[b]For incinerators with a capacity of greater than 227 kg/h.

[c]For incinerators with a capacity of less than 227 kg/h.

5.4 REFERENCES

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27. Reference 12, p. 27 to 31.

6.0 HOSPITAL WASTE INCINERATOR MODEL PLANTS

One of the objectives of this study was to develop modeling parameters emissions and exposure from hospital incinerator units. The parameters developed in this study will be used in EPA's Human Exposure Model (HEM). Results of the HEM analysis will then be used to provide a preliminary estimate of chronic exposure to emissions from hospital waste incinerators. This objective was accomplished by developing input data for model incinerators which are felt to be representative of the general population instead of using actual hospital incinerator sites and stack parameters. This approach was taken because of the difficulty involved in characterizing the capacity and location of all hospital incinerators on a national level.

The approach used was to analyze a segment of the population for which detailed information could be obtained regarding unit capacity, stack parameters, and operation. In this case, a recent database of hospital incinerators in the State of New York was located during the study and used as a population segment. Through analysis of the distribution of incinerator capacities in the New York population, model plants were identified. The appropriate stack parameters (height, diameter, gas velocity, and temperature) were then determined by further evaluation of this data set. Finally the emissions factors of Section 3.0 were applied to to these model plants to estimate the short-term and long-term emissions rates.

This section contains a brief discussion of the relationship between hospital populations and incinerator populations. Next, the model incinerator capacities and stack parameters selected for the analysis are presented. Finally, the corresponding emissions rates for pollutants of concern are presented for the model plants, based on the emissions data from Section 3.

6.1 POPULATION CHARACTERISTICS

6.1.1 Population Distribution

As noted in Section 1.1, there are currently over 6,000 hospitals in the U.S.; it is estimated that over 90 percent of these facilities operate

incinerator equipment of some kind, if only a small retort-type unit. The population of controlled air incinerators is smaller but still substantial. The development of a national inventory of hospital incinerators was not feasible for this study. Instead, an analysis of a subset of the population for which the necessary information was available was performed. A recent New York (NY) State database was located during the study which contained information gained through an in-state survey of incinerator units.[1] This database contained unit size, location, annual operation, and stack parameters for 433 incinerators located in NY.

To estimate the "representativeness" of the NY hospital population relative to the U.S. population, the distribution of hospital sizes was examined. The distribution of hospital sizes according to bed number is presented for both NY and the U.S. in Figure 6-1.[2] Both these distributions have similar shapes for hospital sizes between 0 and 500 beds. However, there is a greater proportion of hospitals above the 500 bed size in NY than in the U.S. population. This is probably due to the fact that NY has several densely populated areas. Therefore, a model incinerator capacity which corresponds to hospitals with greater than 500 beds was selected to model hospitals in densely populated areas in the U.S. The potential impact of these larger incinerator units on the associated populations will likely be of interest to EPA.

No information was found during this study which relates hospital size to the use of incineration or to incinerator capacity. Therefore, a correlation between hospital size and incinerator capacity could not be developed. A study of the population distribution of incinerator units within the NY incinerator database was, therefore, undertaken. Figure 6-2 presents the results of this investigation. As shown, 59.6 percent of the population are units with design feed capacities of less than 200 lb/hr. A model incinerator was, therefore, chosen from within the less than 200 lb/hr capacity range.

A further breakdown of the smaller size incinerator population in NY by unit capacity is shown in Figure 6-3. As can be seen, this population is bimodal with peaks for units between 50 and 74 lb/hr and 100 and 124 lb/hr. A detailed analysis of these two size ranges reveals that the majority of units in each of the ranges are 50 and 100 lb/hr, respectively. Since a

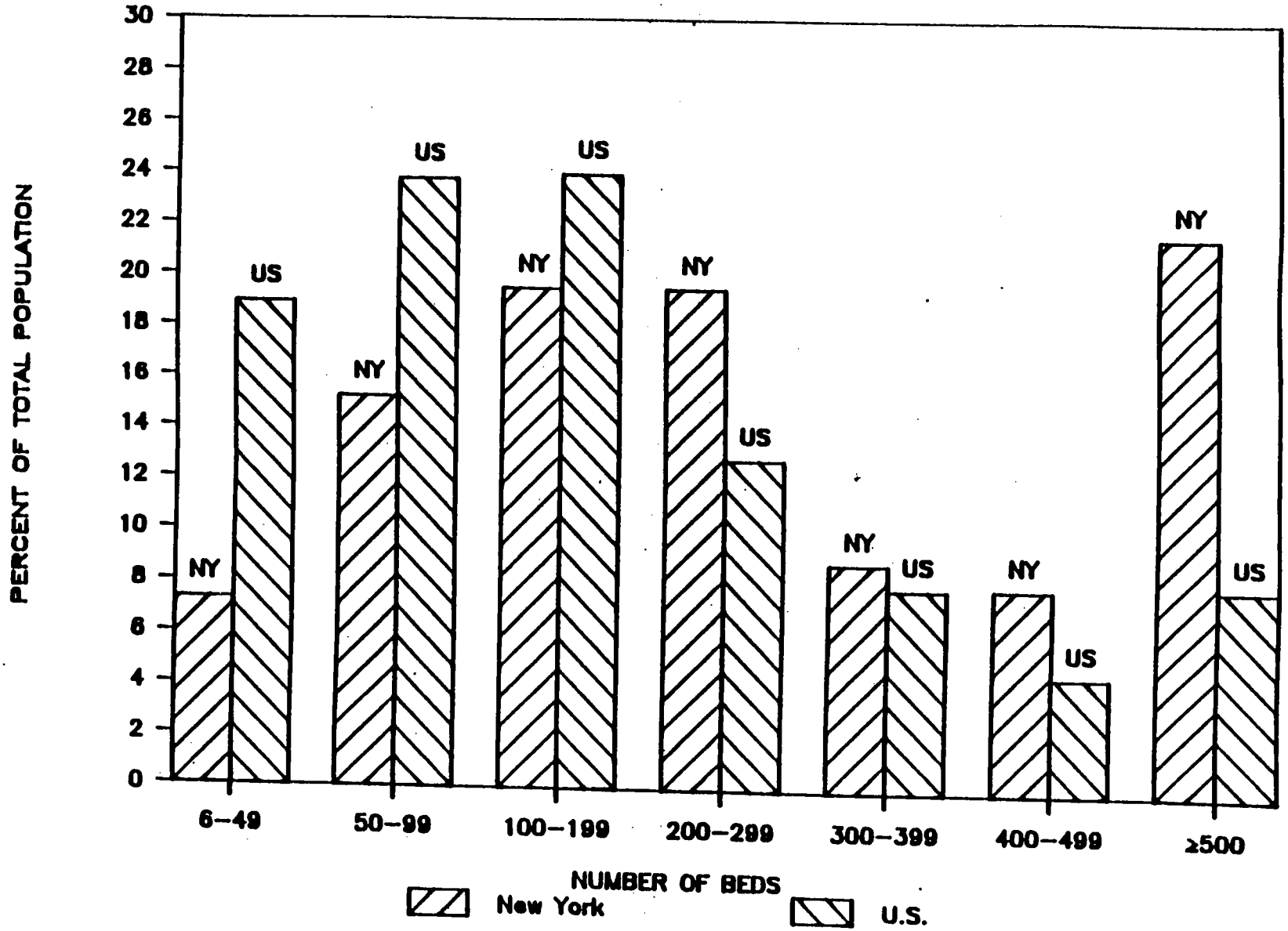

Figure 6-1. Distribution of Hospital Sizes According to Bed Number

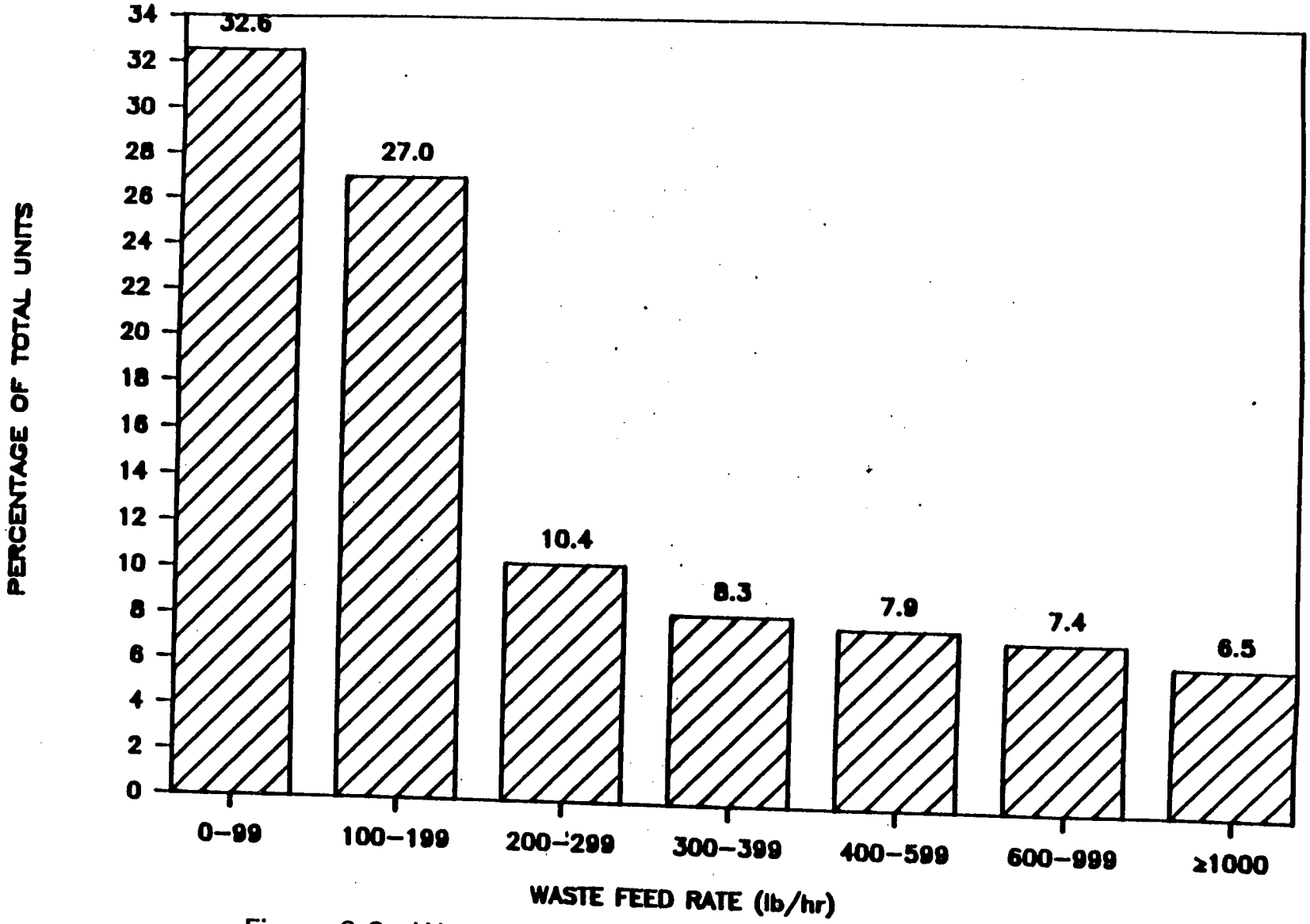

Figure 6-2. Waste Feed Rate Distribution of Incinerators in N.Y. Database by Number

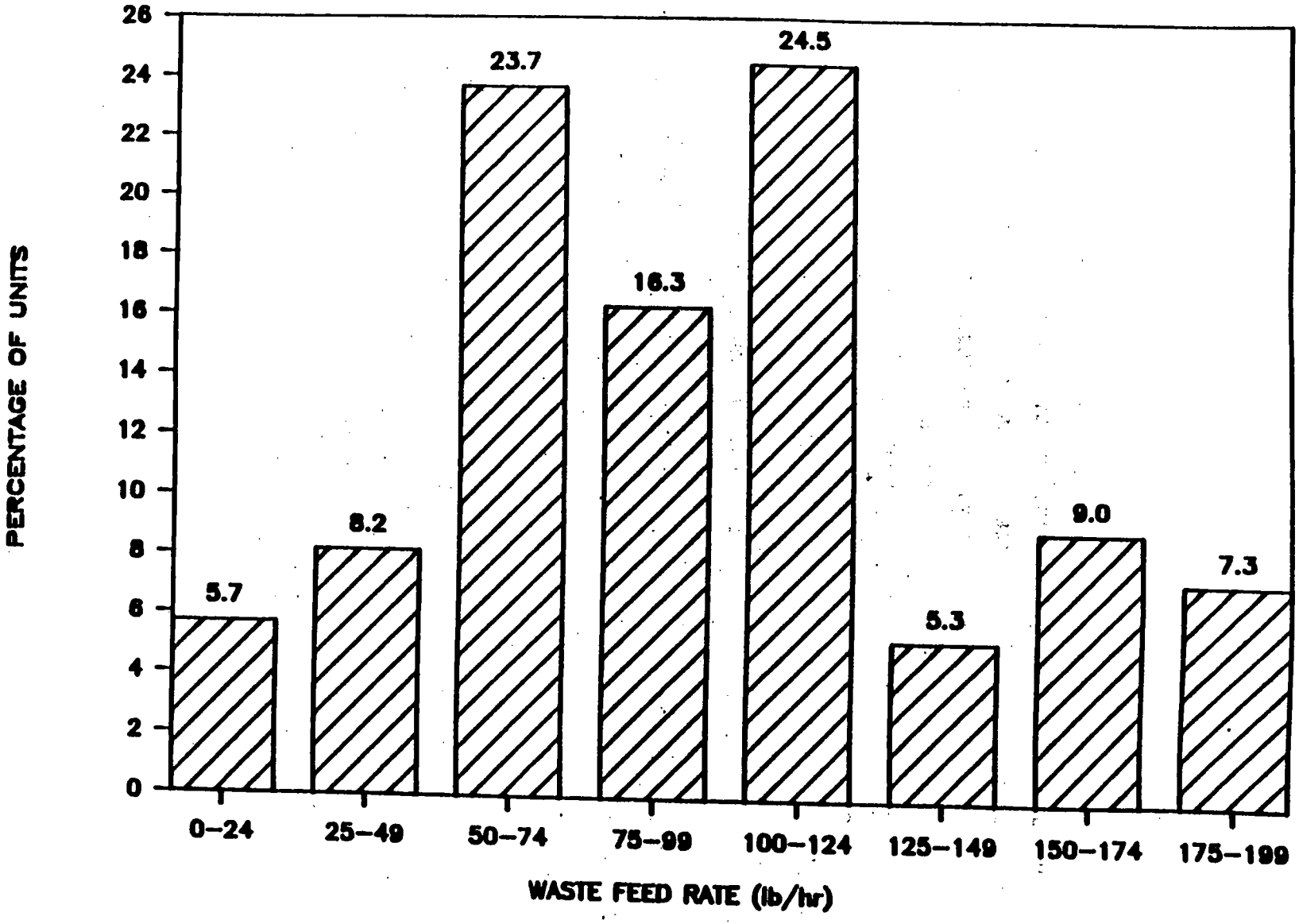

Figure 6-3. Waste Feed Rate Distribution of Small (Less Than 200 lb/hr) Incinerators in N.Y. Database by Number

100 lb/hr feed rate is closer to the median of this population segment than the 50 lb/hr feed rate, a model incinerator of 100 lb/hr capacity was chosen to represent the small incinerator population.

A study of the capacity distribution for the incinerators in the NY database was also undertaken. Figure 6-4 presents the results of this investigation. As can be seen, incinerator units which burn 1,000 lb/hr or greater make up 33.5 percent of the incineration capacity. Units which burn 600 lb/hr or greater make up 52 percent of the incineration capacity. A model unit size of 1,000 lb/hr was chosen to represent this half of the incineration population. The 1,000 lb/hr model size was chosen because it represents the median point within the population of units with feed rates of 600 lb/hr or above (see Figure 6-2) and is an order of magnitude greater than the 100 lb/hr model incinerator capacity.

6.1.2 Model Incinerator Stack Parameters

The stack parameters required as inputs to the HEM include stack height, diameter, and exit gas temperature and velocity. The NY incinerator database was used to determine values for each of these stack parameters for modeling purposes. The approach taken was to evaluate a given stack parameter as a function of the previously presented incinerator capacity ranges of Figure 6-2. From this analysis, the variation of a given parameter was evaluated as a function of unit capacity. If the given stack parameter appeared to be a function of unit capacity, then a value based on units in a similar capacity range to the model was chosen. If the parameter of interest was not a function of unit size, then a mean value based on the entire population of units was used.

Stack Height. The average, high, and low stack height values for a given feed rate range are shown as a function of feed rate ranges in Figure 6-5. The data shown are for incinerators with feed rates ranging from 1 to 2,700 lb/hr. As can be seen, stack heights vary greatly within a given capacity range. Also, stack height values as low as 6 to 8 feet were observed within the database. Although these low stack heights appear to be unrealistic, no reasons were identified which could be used to discount their use. One possible explanation is that this is the height of the stack above the nearest adjacent building and not above the base of the incinerator. Its inclusion as part of an average value for HEM modeling

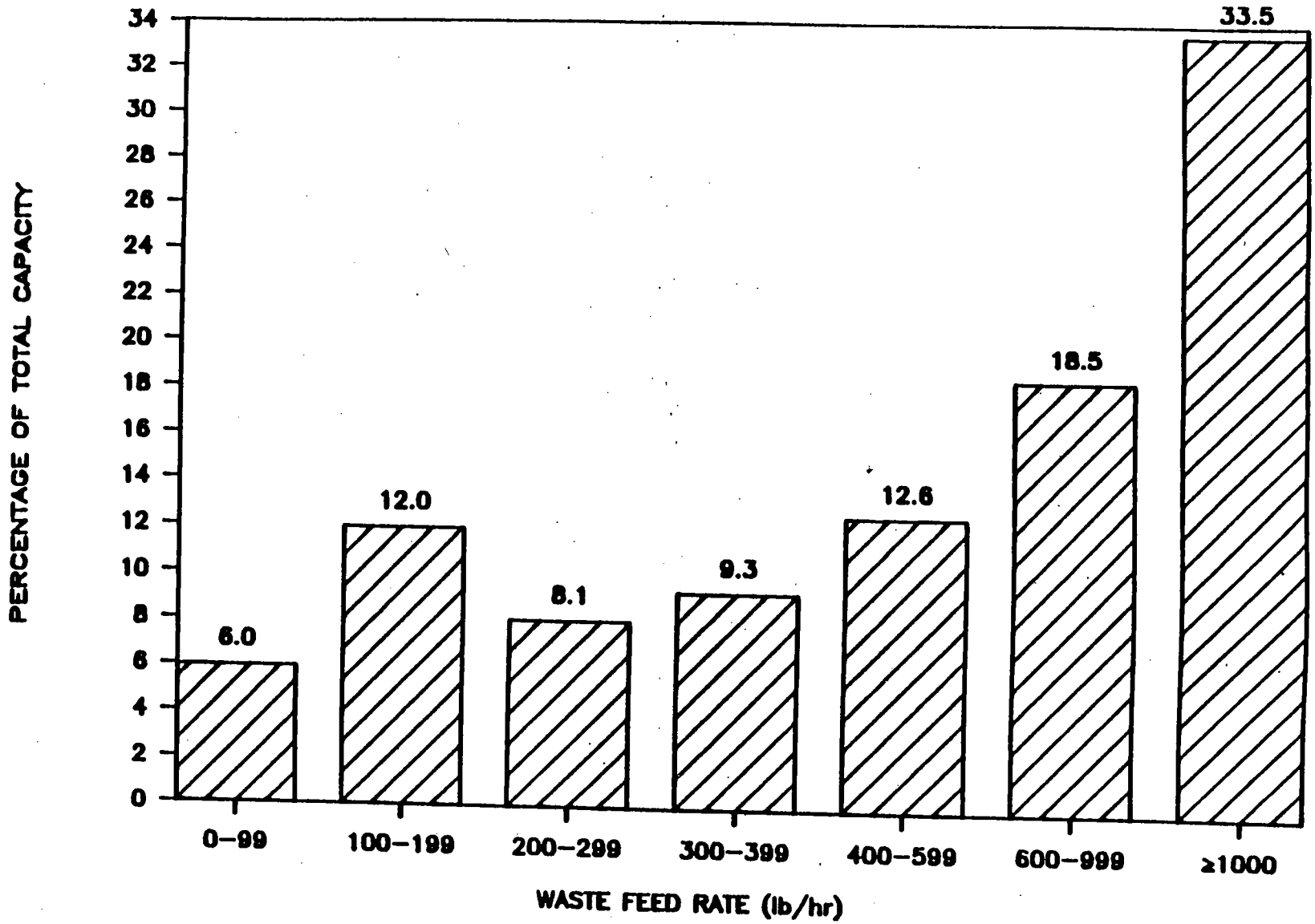

Figure 6-4. Waste Feed Rate Distribution of Incinerators in N.Y. Database by Capacity

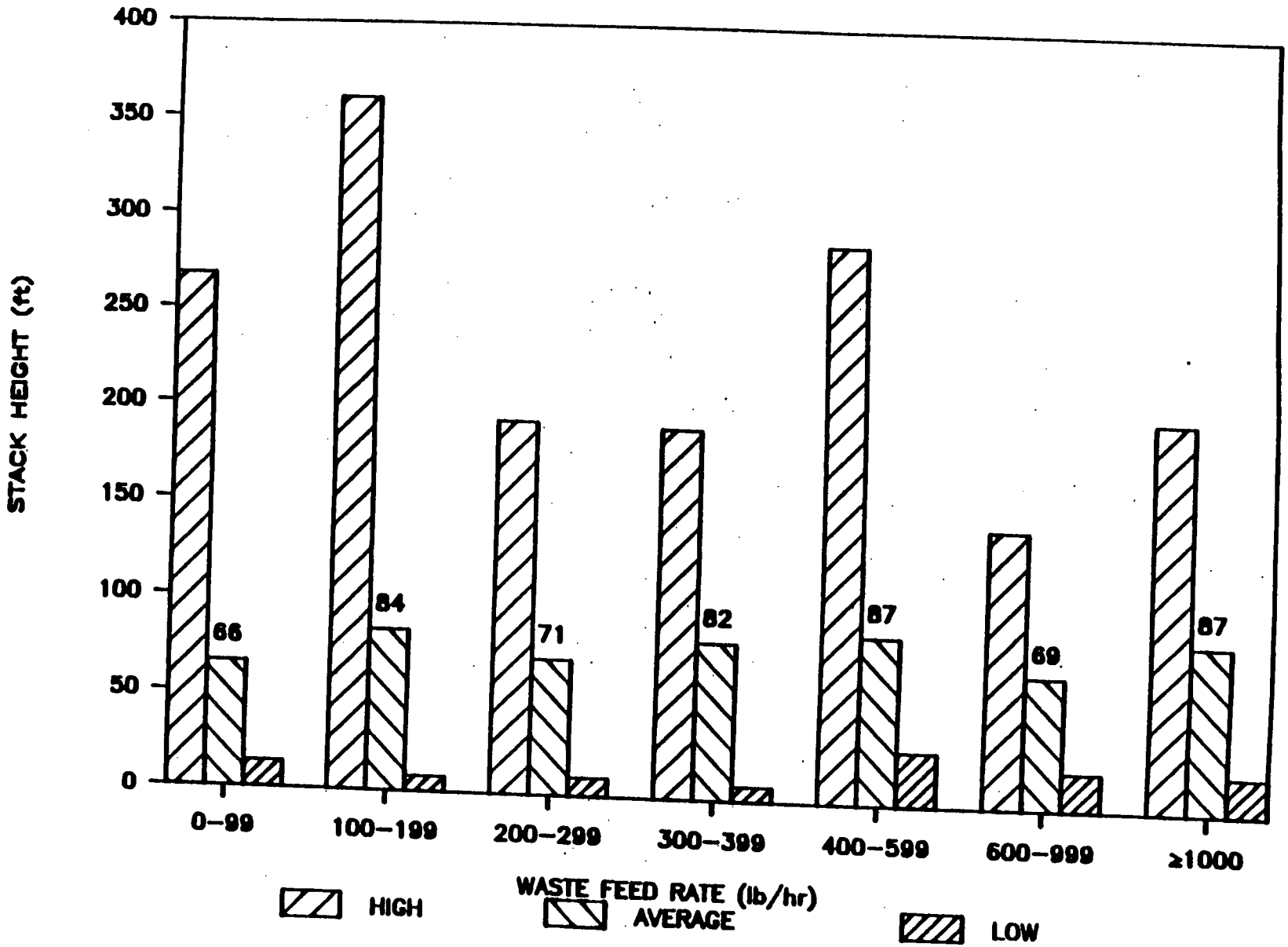

Figure 6-5. Average, High and Low Stack Heights According to Selected Feed Rate Ranges

purposes should have a conservative effect on the stack height estimates. A lower stack height should correspond to higher exposure levels for the population and therefore a conservative estimate of the associated risk.

The results presented in Figure 6-5 show little variation in the average stack height between ranges of unit capacities. In addition, no correlation was found between stack gas temperature (as an indicator of heat recovery equipment) and stack height. The highest of the average stack heights is 87 feet and the lowest is 66 feet. An average stack height of 78 feet would therefore be a representative value for use as the HEM input value, regardless of unit size or heat recovery equipment.

Stack Gas Temperature. The average, high, and low exhaust gas temperature values within a given feed rate range are shown as a function of feed rate ranges in Figure 6-6. As can be seen, the low in all cases is 400°F. Analysis of the NY database indicated several vent streams with exit gas temperatures of less than 400°F. Because it was known that outlet temperatures for units which have heat recovery equipment are limited to approximately 400°F by the stack gas dew point, units with exit gas temperatures which were below 400°F were excluded from analysis. A high value of 2,220°F is shown. Little variation is seen in the average exhaust gas temperatures over the entire range of capacities. For the entire population, the high value of the average temperatures is 1,237°F and the low value is 1,081°F. The average stack gas temperature for the entire database is 1,144°F. This temperature could be used for both the 100 and 1,000 lb/hr model incinerators. Because heat recovery is known to be employed on larger units, an additional 1,000 lb/hr model unit with an exit stack gas temperature of 450°F could be used to show the effects of heat recovery in the modeling. An exit gas temperature of 450°F is appropriate because it provides a comfortable margin above the 400°F acid dew point. This temperature also corresponds to a known unit located at the University of Michigan.[3] If heat recovery equipment is employed, an induced draft fan is often added to overcome the associated pressure drop and maintain design pressures in the combustion chambers.[4] Thus, stack heights should not be affected by the addition of heat recovery equipment.

Stack Gas Exit Velocity. The average, high, and low stack gas exit velocities for a range of feed rates are shown in Figure 6-7. Once again,

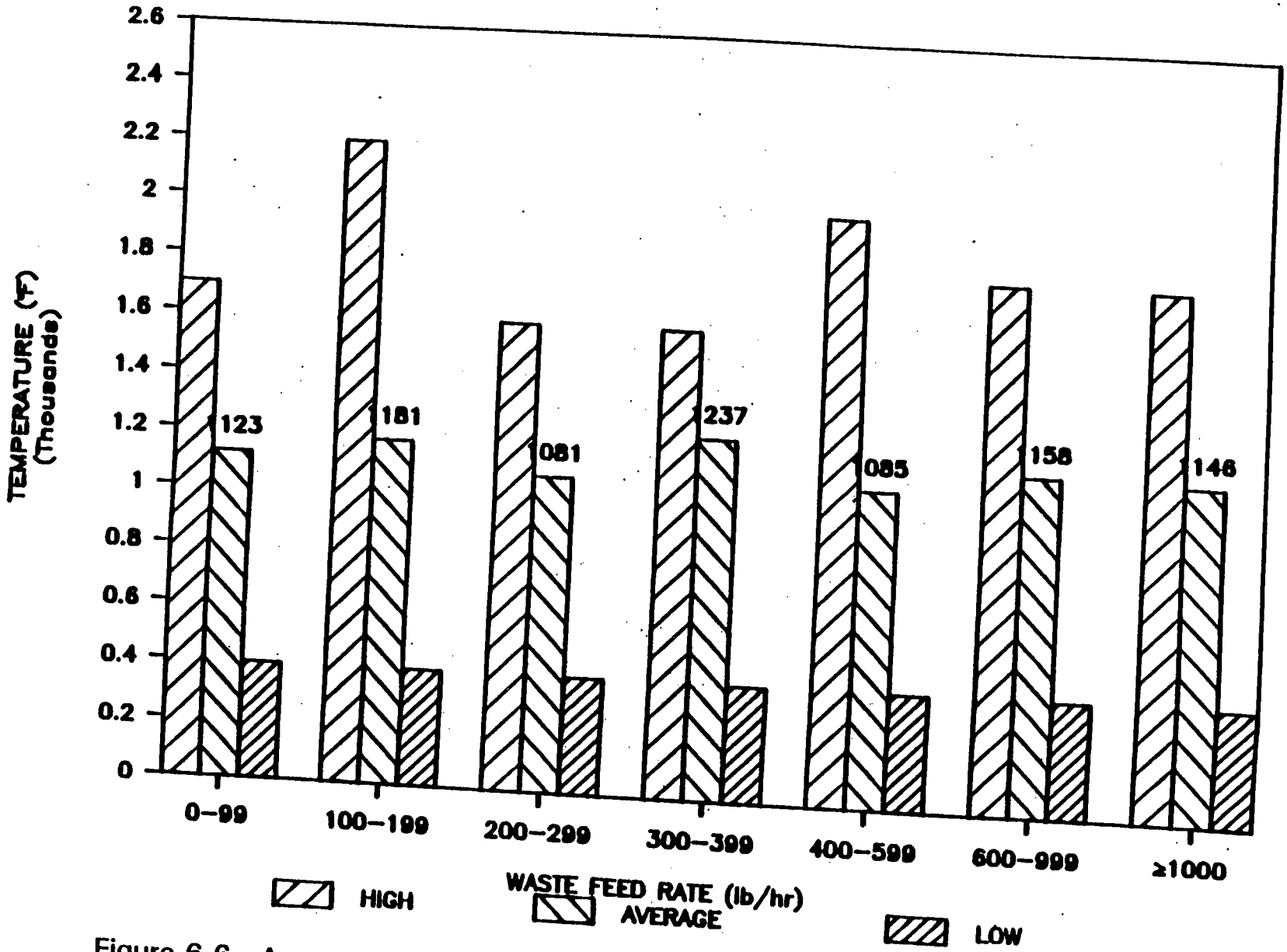

Figure 6-6. Average, High and Low Stack Gas Exit Temperature According to Selected Feed Rate Ranges

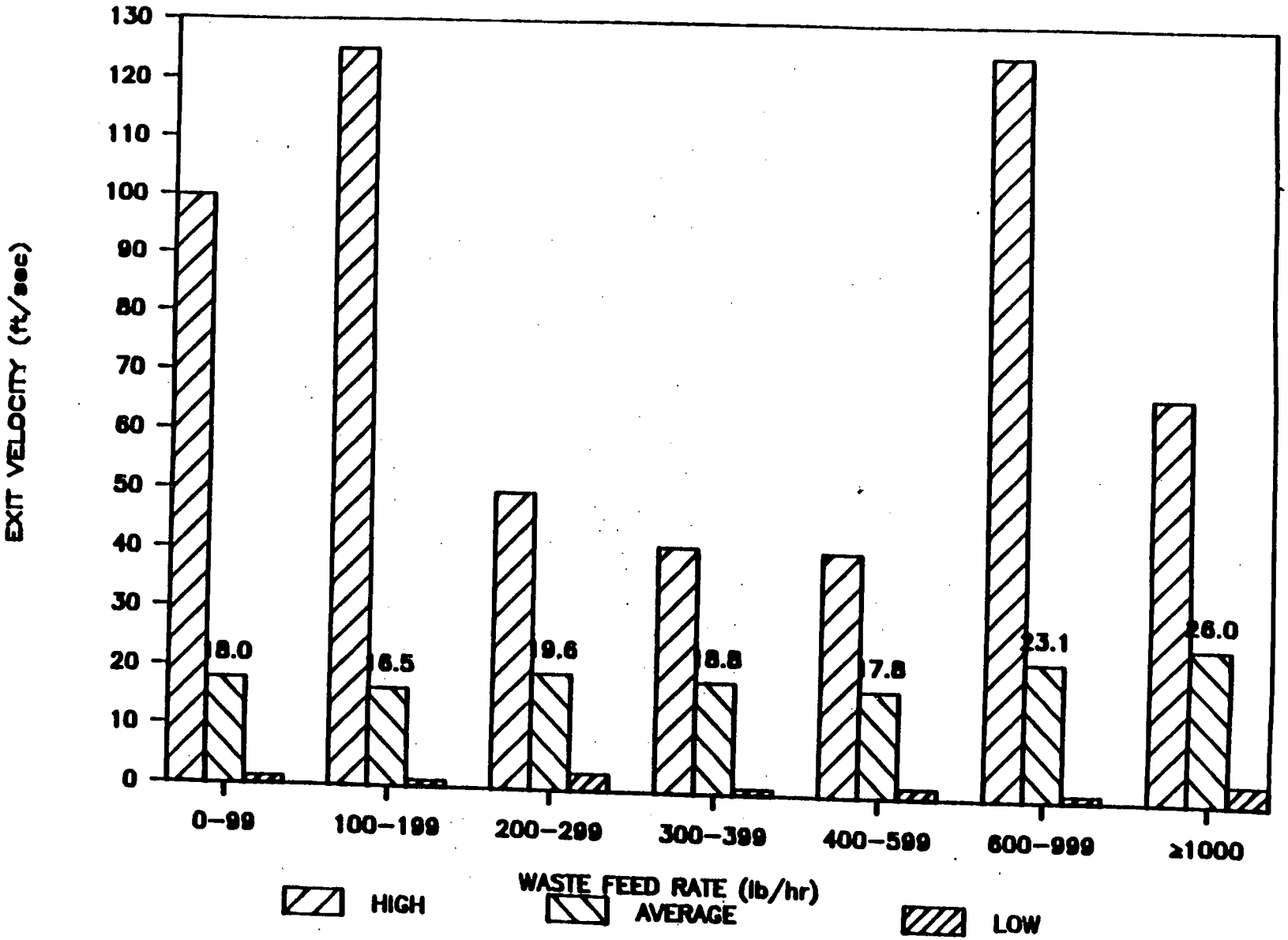

Figure 6-7. Average, High and Low Stack Gas Exit Velocities According to Selected Feed Rate Ranges

the variation within a given capacity range is large. In general, the average stack velocities shown also increase with the capacity of the unit. This is understandable in view of the increasing volumetric flow rate of stack gases with increasing incinerator capacity. Therefore, the average stack gas velocity that applies to a particular model incinerator should be used for modeling. Exit gas velocities of 16.5 and 26.0 ft/sec would be appropriate for the 100 and 1,000 lb/hr model incinerators, respectively. The exit gas velocity for the 1,000 lb/hr heat recovery model should be reduced to 14.8 ft/sec to reflect the reduced exit gas temperature.

Stack Diameter. The average, high, and low stack diameter values for ranges of feed rates are shown in Figure 6-8. As was the case for the other stack parameters, the stack diameters vary within a given size range.

If the same approach used to determine the velocities is used to determine the stack diameters, diameters of 25 and 34 inches would be determined for the 100 and 1,000 lb/hr models, respectively. Unfortunately, these diameters are not realistic when the volumetric flow rate associated with the two models are considered; the volumetric flow for a 1,000 lb/hr unit would be expected to be 10 times greater than the volumetric flow from a 100 lb/hr unit.

Instead, after allowing for the gas velocity differences discussed above, the 25 and 34 inch diameters correspond to a volumetric flow ratio of only 3. To address this inconsistency, the diameter for the 100 lb/hr model was chosen as a base point. The diameter for the 1,000 lb/hr unit was then determined by assuming a gas flow rate 10 times greater than that for the smaller unit. The resultant diameter for the 1,000 lb/hr model unit, after allowing for volume and velocity differences, would be 63 inches. For the case of the 1,000 lb/hr heat recovery model, the diameter was assumed to remain constant. In actual practice, the stack diameters for these units would be determined by the tradeoff between stack draft flow losses and costs.

The results of the stack parameter analysis of the NY database are summarized in Table 6-1. Model incinerators of 100 and 1,000 lb/hr, with two cases for the 1,000 lb/hr model, are recommended as representative for

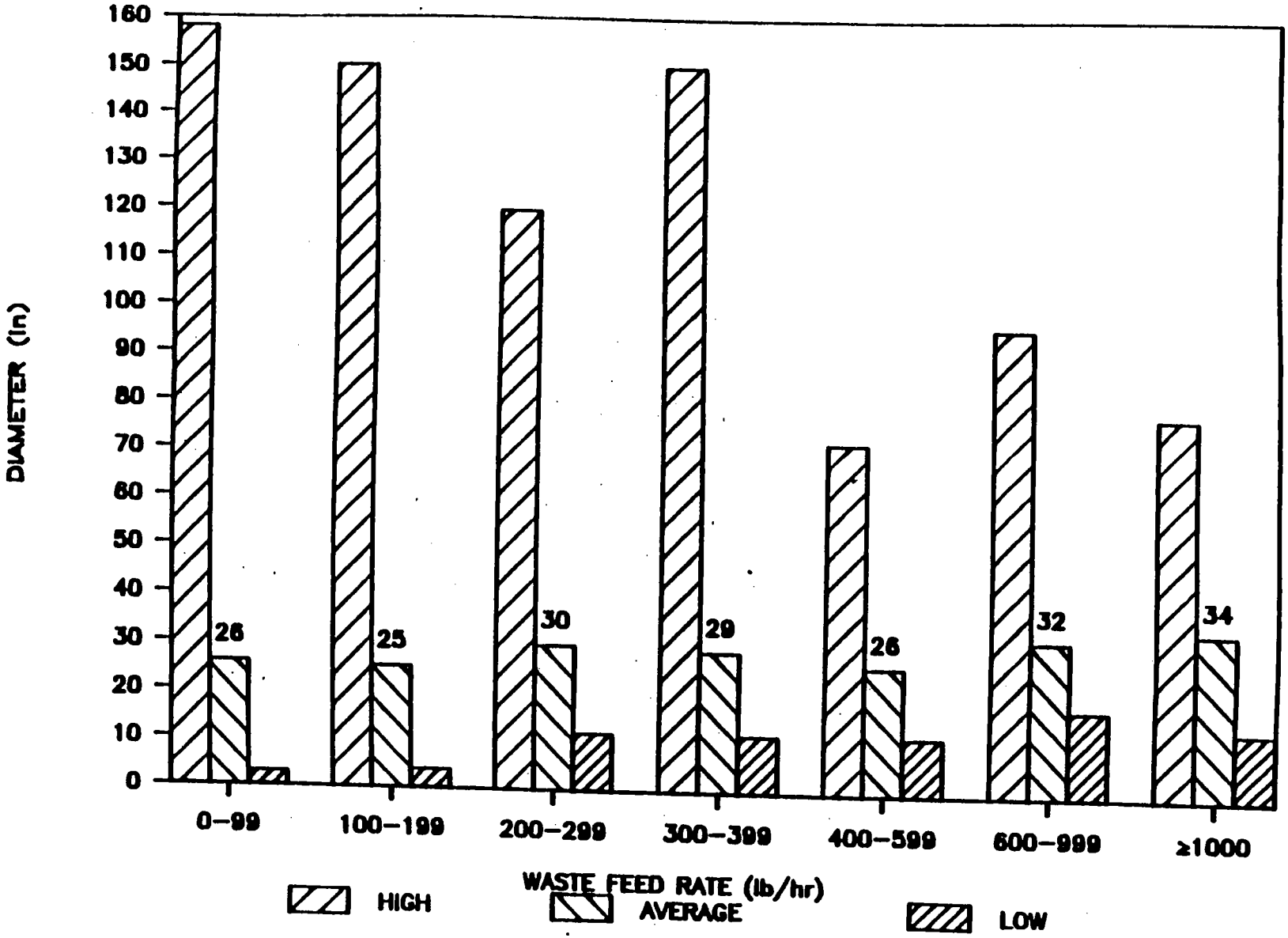

Figure 6-8. Average, High and Low Stack Diameters According to Selected Feed Rate Ranges

TABLE 6-1. SUMMARY OF MODEL INCINERATOR STACK PARAMETERS

	100 lb/hr Model Incinerator with No Heat Recovery	1,000 lb/hr Model Incinerator with No Heat Recovery	1,000 lb/hr Model Incinerator with Heat Recovery
Stack Height			
ft	78	78	78
(m)	(24)	(24)	(24)
Exit Gas Temperature			
°F	1,144	1,144	450
(K)	(891)	(891)	(506)
Exit Gas Velocity			
ft/sec	16.5	26.0	14.8
(m/s)	(5.0)	(7.9)	(4.5)
Stack Diameter			
in	25	66	66
(m)	(0.64)	(1.60)	(1.60)

modeling purposes. The recommended stack height, stack exit gas temperature, and velocity values for each of these models are shown in the table.

6.1.3 Model Incinerator Operating Parameters

The operating parameters required as inputs to the HEM include the annual operating hours and hourly and yearly emissions rates. To determine values for each of these operating parameters, the NY incinerator database was again used to determine the annual operating hours associated with each of the model incinerators. Next the hourly emission rates were determined for each of the models by combining the emissions factor of Section 3.0 with the model capacities previously developed. Finally, the yearly emission rates for each of the models were determined by applying the annual operating hours to the hourly emissions rates.

Annual Operating Hours. The average annual operating hours for a given feed rate range are shown as a function of feed rate ranges in Figure 6-9. As can be seen, the number of annual operating hours increases with increasing unit capacity. Smaller units (less than 200 lb/hr), which operate approximately 1,000 hrs/year, can be characterized as operating five days a week for about 4 hours each day. Larger units (greater than 600 lb/hr), which operate approximately 2,350 hrs/year, can be characterized as operating five days a week for 8 to 10 hrs each day. Therefore, annual operating operating hours of 1,000 and 2,350 may be considered representative for the 100 and 1,000 lb/hr model sizes, respectively.

Hourly Emissions Rates. The emission factors previously developed in Section 3.0 are shown in Table 6-2 along with the corresponding hourly and yearly emissions rates for each of the model incinerators. High and low emissions rates are given for each of the compounds for which data exist. For compounds where only one data point exists, only one rate in shown.

Different particulate matter (PM) emissions rates were used for the two model capacities because, as previously stated, for units of less than 400 lb/hr capacity a larger variation in PM emissions was seen over those of larger units. The high and low emission rates corresponding to this capacity breakpoint are shown. A controlled PM emissions rate is also shown. This rate is based on the baghouse data from the St. Agnes emission test.

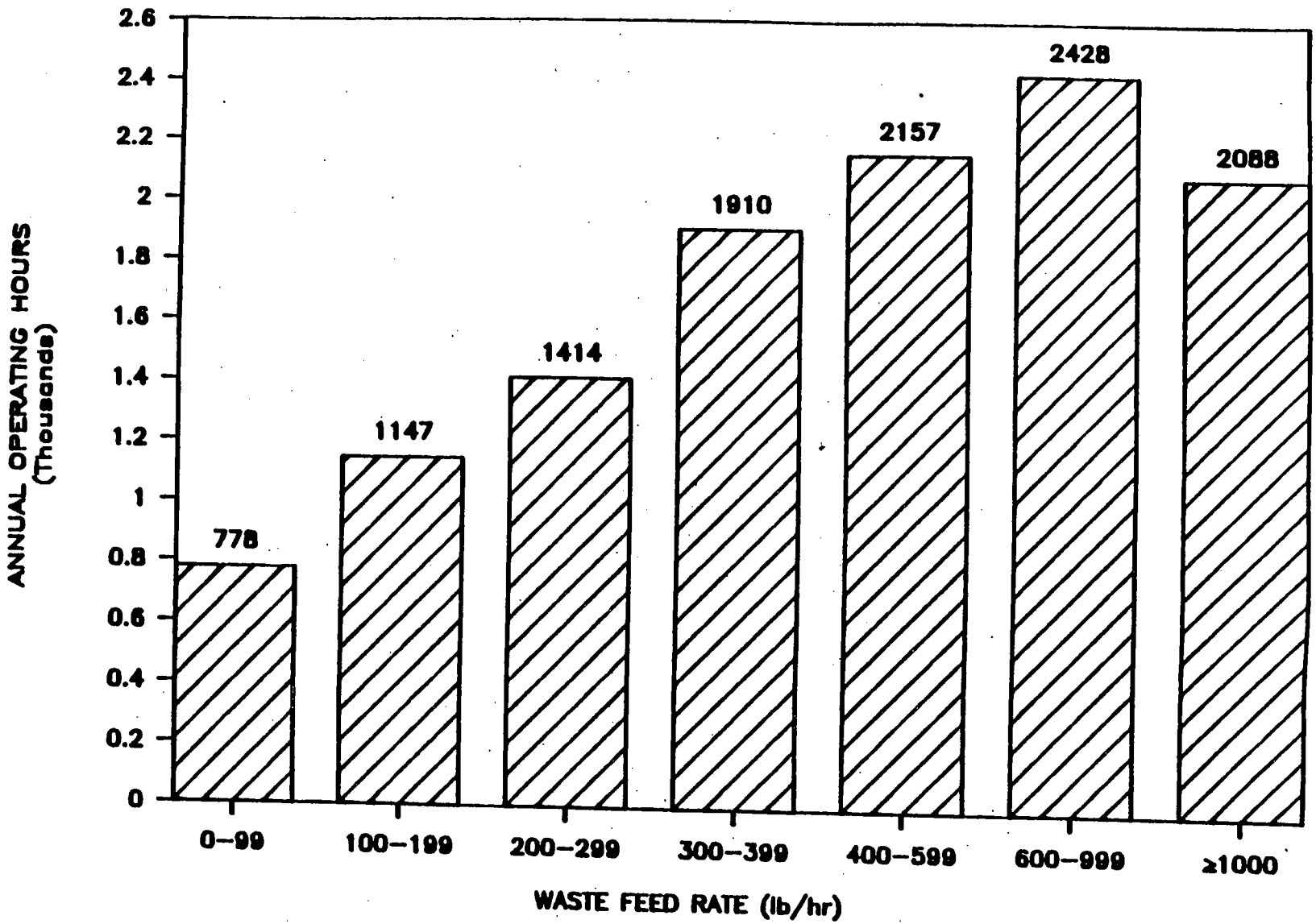

Figure 6-9. Annual Operating Hours According to Selected Feed Rate Changes

TABLE 6-2. SUMMARY OF EMISSIONS FACTORS AND RATES FOR HOSPITAL INCINERATOR MODEL SIZES

Group/Compound	Emissions Factor (kg/Mg feed)	Hourly Emissions Rates (kg)		Yearly Emissions Rates (kg)	
		100 lb/hr Model	1,000 lb/hr Model	100 lb/hr[a] Model	1,000 lb/hr[b] Model
Acid Gases					
Hydrochloric Acid					
High	49.700	2.2564	22.5638	2,256.38	53,024.93
Low	1.450	.0658	.6580	65.80	1,545.59
Sulfur Dioxide					
High	1.505	0.0683	0.6833	68.33	1,605.68
Low	0.735	0.0334	0.3337	33.37	784.17
Nitrogen Oxides					
High	3.910	0.1775	1.7751	177.51	4,171.58
Low	2.320	0.1053	1.0533	105.33	2,475.21
Particulate Matter					
Uncontrolled (100 lb/hr)					
High	13.460	0.6111		611.08	
Low	.285	.0129		12.90	
Uncontrolled (1,000 lb/hr)					
High	18.24		8.2758		19,448.13
Low	0.685		0.3110		730.83
Controlled (all sizes)					
High	1.06	.0481	.4808	48.10	1,129.88
Low	.025	.0011	.0114	1.14	26.67
Trace Metals (Uncontrolled)					
Arsenic					
High	1.46×10^{-4}	6.62×10^{-6}	6.62×10^{-5}	6.6×10^{-3}	1.56×10^{-1}
Low	3.55×10^{-5}	1.61×10^{-6}	1.61×10^{-5}	1.61×10^{-3}	3.79×10^{-2}
Cadmium					
High	3.40×10^{-3}	1.54×10^{-4}	1.54×10^{-3}	1.54×10^{-1}	3.63
Low	7.75×10^{-4}	3.51×10^{-5}	3.51×10^{-4}	3.51×10^{-2}	.824
Chromium					
High	9.75×10^{-4}	4.42×10^{-5}	4.42×10^{-4}	4.42×10^{-2}	1.04
Low	5.10×10^{-5}	2.32×10^{-6}	2.32×10^{-5}	2.32×10^{-3}	5.44×10^{-2}
Iron					
High	9.15×10^{-3}	4.15×10^{-4}	4.15×10^{-3}	4.15×10^{-1}	9.76
Low	1.99×10^{-3}	9.03×10^{-5}	9.03×10^{-4}	9.03×10^{-2}	2.12

TABLE 6-2. SUMMARY OF EMISSIONS FACTORS AND RATES FOR HOSPITAL INCINERATOR MODEL SIZES (CONTINUED)

Group/Compound	Emissions Factor (kg/Mg feed)	Hourly Emissions Rates (kg)		Yearly Emissions Rates (kg)	
		100 lb/hr Model	1,000 lb/hr Model	100 lb/hr[a] Model	1,000 lb/hr[b] Model
Manganese					
High	5.70×10^{-4}	2.59×10^{-5}	2.59×10^{-4}	2.59×10^{-2}	6.08×10^{-1}
Low	7.90×10^{-5}	3.59×10^{-6}	3.59×10^{-5}	3.59×10^{-3}	8.43×10^{-2}
Nickel					
High	2.50×10^{-4}	1.14×10^{-5}	1.14×10^{-4}	1.14×10^{-2}	2.67×10^{-1}
Low	5.40×10^{-5}	2.45×10^{-6}	2.45×10^{-5}	2.45×10^{-3}	5.76×10^{-2}
Lead					
High	2.9×10^{-2}	1.31×10^{-3}	1.31×10^{-2}	1.31	30.8
Low	1.52×10^{-2}	6.90×10^{-4}	6.90×10^{-3}	6.90×10^{-1}	16.2
Dioxins					
(Tetra)TCDD					
High	5.35×10^{-7}	2.43×10^{-8}	2.43×10^{-7}	2.43×10^{-5}	5.71×10^{-4}
Low	2.00×10^{-8}	9.08×10^{-10}	9.08×10^{-9}	9.08×10^{-7}	2.13×10^{-5}
(Penta)PeCDD					
High	3.80×10^{-7}	1.73×10^{-8}	1.73×10^{-7}	1.73×10^{-5}	4.05×10^{-4}
Low	5.50×10^{-8}	2.50×10^{-9}	2.50×10^{-8}	2.50×10^{-6}	5.87×10^{-5}
(Hexa)HxCDD					
High	7.60×10^{-7}	3.45×10^{-8}	3.45×10^{-7}	3.45×10^{-5}	8.11×10^{-4}
Low	1.35×10^{-7}	6.13×10^{-9}	6.13×10^{-8}	6.13×10^{-6}	1.44×10^{-4}
(Hepta)HeCDD					
High	1.92×10^{-6}	8.69×10^{-8}	8.69×10^{-7}	8.69×10^{-5}	2.04×10^{-3}
Low	1.60×10^{-7}	7.26×10^{-9}	7.26×10^{-8}	7.26×10^{-6}	1.71×10^{-4}
(Octa)DCDD					
High	2.74×10^{-6}	1.24×10^{-7}	1.24×10^{-6}	1.24×10^{-4}	2.92×10^{-3}
Low	1.70×10^{-7}	7.72×10^{-9}	7.72×10^{-8}	7.72×10^{-6}	1.81×10^{-4}
Total PCDD					
High	6.26×10^{-6}	2.84×10^{-7}	2.84×10^{-6}	2.84×10^{-4}	6.68×10^{-3}
Low	7.15×10^{-7}	3.25×10^{-8}	3.25×10^{-7}	3.25×10^{-5}	7.63×10^{-4}
Furans					
(Tetra)TCDF					
High	1.04×10^{-6}	4.70×10^{-8}	4.70×10^{-7}	4.70×10^{-5}	1.10×10^{-3}
Low	2.50×10^{-7}	1.14×10^{-8}	1.14×10^{-7}	1.14×10^{-5}	2.67×10^{-4}
(Penta)PeCDF					
High	1.90×10^{-6}	8.60×10^{-8}	8.60×10^{-7}	8.60×10^{-5}	2.02×10^{-3}
Low	4.50×10^{-7}	2.04×10^{-8}	2.04×10^{-7}	2.04×10^{-5}	4.80×10^{-4}

TABLE 6-2. SUMMARY OF EMISSIONS FACTORS AND RATES FOR HOSPITAL INCINERATOR MODEL SIZES (CONTINUED)

Group/Compound	Emissions Factor (kg/Mg feed)	Hourly Emissions Rates (kg)		Yearly Emissions Rates (kg)	
		100 lb/hr Model	1,000 lb/hr Model	100 lb/hr[a] Model	1,000 lb/hr[b] Model
(Hexa)HxCDF					
High	2.82×10^{-6}	1.28×10^{-7}	1.28×10^{-6}	1.28×10^{-4}	3.00×10^{-3}
Low	4.10×10^{-7}	1.86×10^{-8}	1.86×10^{-7}	1.86×10^{-5}	4.37×10^{-4}
(Hepta)HeCDF					
High	3.23×10^{-6}	1.47×10^{-7}	1.47×10^{-6}	1.47×10^{-4}	3.45×10^{-3}
Low	2.75×10^{-7}	1.25×10^{-8}	1.25×10^{-7}	1.25×10^{-5}	2.93×10^{-4}
(Octa)DCDF					
High	2.18×10^{-6}	9.87×10^{-8}	9.87×10^{-7}	9.87×10^{-5}	2.32×10^{-3}
Low	1.05×10^{-7}	4.77×10^{-9}	4.77×10^{-8}	4.77×10^{-6}	1.12×10^{-4}
Total PCDF					
High	1.09×10^{-5}	4.96×10^{-7}	4.96×10^{-6}	4.96×10^{-4}	1.17×10^{-2}
Low	1.63×10^{-6}	7.38×10^{-8}	7.38×10^{-7}	7.38×10^{-5}	1.73×10^{-3}
Low Molecular Organics					
Ethane	0.0015	0.0001	0.0007	0.07	1.60
Ethylene	0.0100	0.0005	0.0045	0.45	10.67
Propane	0.0120	0.0005	0.0054	0.54	12.80
Propylene	0.0110	0.0050	0.0050	0.50	11.74
Trichlorotrifluoroethylene	4.13×10^{-5}	1.87×10^{-6}	1.87×10^{-5}	1.87×10^{-3}	4.40×10^{-2}
Tetrachloromethane	4.96×10^{-5}	2.25×10^{-6}	2.25×10^{-5}	2.25×10^{-3}	5.29×10^{-2}
Trichloroethylene	1.20×10^{-5}	5.43×10^{-7}	5.43×10^{-6}	5.43×10^{-4}	1.27×10^{-2}
Tetrachloroethylene	1.24×10^{-4}	5.65×10^{-6}	5.65×10^{-5}	5.65×10^{-3}	1.33×10^{-1}
Carbon Monoxide					
High	0.85	0.0384	0.3836	38.36	901.53
Low	0.66	0.0300	0.2996	29.26	704.15

[a]Based on 1,000 hours of yearly operation.

[b]Based on 2,350 hours of yearly operation.

6.2 REFERENCES

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APPENDIX A

APPENDIX A

STATE REGULATIONS PERTAINING TO INFECTIOUS WASTE MANAGEMENT[1]

State	Statutory Authority and Regulation Citation	Summary of Requirements	State Agency
Alabama	1975 Code of Alabama, Section 22-21-20. Alabama State Board of Health Rules and Regulations for Nursing Homes and Hospitals.	All infectious waste generated by nursing homes and hospitals must be incinerated on site.	Bureau of Licensure and Certification State Health Department Room 652 State Office Building Montgomery, Alabama 36130-1701 (205) 261-5105
	No regulations.	Policy is to recommend treatment of infectious waste prior to disposal.	Alabama Department of Environmental Management Land Division 1751 Federal Drive Montgomery, Alabama 36130 (205) 271-7700
Alaska	Laws of Alaska, Title 44, Chapter 46; Title 46, Chapter 3.	All infectious waste generated by medical and veterinary facilities must be incinerated prior to final disposal.	Air and Solid Waste Management Department of Environmental Conservation Pouch O Juneau, Alaska 99811 (907) 465-2666
		The state has statutory authority to regulate infectious waste, but has not yet promulgated regulations.	
Arizona	Arizona Revised Statutes, Title 36, Article 2, General Hospitals. Regulation R9-10-220, Environmental Services, Subsection E.	All infectious waste must be either (1) autoclaved and disposed of in an approved sanitary landfill, or (2) incinerated in an approved incinerator. Variances are given for disposal of untreated waste when there is insufficient treatment capacity.	Bureau of Health Care Institution Licensure Arizona Department of Health Services 1740 West Adams Street Phoenix, Arizona 85007 (602) 255-1115
Arkansas	Act 414 of 1961, as amended by Act 444 of 1965 and Act 454 of 1965. Rules and Regulations for Hospitals and Related Institutions in Arkansas.	All infectious waste generated by hospitals and related institutions must be incinerated or disposed of by other approved methods. Revisions are expected in 1986.	Department of Health Division of Health Facilities Services 4815 W. Markham Street Little Rock, Arkansas 72205-3867 (501) 661-2201

APPENDIX A (CONTINUED)

State	Statutory Authority and Regulation Citation	Summary of Requirements	State Agency
	The Solid Waste Management Act (237) of 1971. Arkansas Hazardous Waste Management Act of 1979 (Act 406 of 1979).	The state has statutory authority to regulate infectious waste as a hazardous waste, but has not yet promulgated regulations.	Solid Waste Management Division Department of Pollution control and Ecology P.O. Box 9583 8001 National Drive Little Rock, Arkansas 72219 (501) 562-7444
California	California Health and Safety Code Chapter 6.5, Article 2, Section 25117.5 California Administrative Code, Title 22. Division 4, Chapter 30: Minimum Standards for Management of Hazardous and Extremely Hazardous Waste; Infectious Waste Regulations, effective November 16, 1985.*	Infectious waste must be incinerated, sterilized or treated by other approved methods.	California Department of Health Services Hazardous Materials Management Section 714/744 P Street Sacramento, California 95814 (916) 324-1798
Colorado	Colorado Revised Statutes, 1973, as amended; Title 25, Article 15, Parts 1, 2, and 3: Hazardous Waste Management Act.	The state has statutory authority to regulate infectious waste as a hazardous waste, but has not yet promulgated regulations.	Waste Management Division Colorado Department of Health 4210 E. 11th Avenue Denver, Colorado 80220 (303) 320-8333 Ext. 4364
	Chapter 4, Regulations Governing General Hospitals.	Pathological waste must be incinerated. Off-site disposal in approved sites is possible.	Division of Health Facilities Regulations Colorado Department of Health 4210 E. 11th Avenue Denver, Colorado 80220 (303) 320-8333 Ext. 6306
Connecticut	Connecticut General Statutes of 1979, Public Act 79-605. Code 22A-4483 and 22A-115.	The state has statutory authority to regulate infectious waste as a hazardous waste, but has not yet promulgated regulations.	Hazardous Waste Management Department of Environmental Protection State Office Building 165 Capitol Avenue Hartford, Connecticut 06106 (203) 566-4869 or 566-5712
Delaware	Delaware Code, Title 7, Chapter 60: Solid Waste Act. Delaware Solid Waste Disposal Regulations, August 1974.	Infectious waste disposal is approved on a case-by-case basis. None has been allowed to go to landfills untreated since the approval process was initiated. Revised regulations have been proposed.	Waste Management Section Department of Natural Resources and Environmental Control 89 King Highway P.O. Box 1401 Dover, Delaware 19903 (302) 736-4781

APPENDIX A (CONTINUED)

State	Statutory Authority and Regulation Citation	Summary of Requirements	State Agency
District of Columbia	District of Columbia Hazardous Waste Management Act of 1977, D.C. Law 2-64.	The District has statutory authority to regulate infectious waste as a hazardous waste, but has not yet promulgated regulations.	Department of Consumer and Regulatory Affairs and Environmental Control Division 5010 Overlook Avenue, SW Washington, DC 20032 (202) 767-8414
Florida	Florida Resource Recovery and Management Act (Florida Statutes Annotated, Title 27, Public Health, Chapter 403, Part IV, Enacted by the Laws of 1974, Chapter 342, as amended). Florida Resource Recovery and Management Regulations: Rules of the Department of Environmental Regulation, Chapter 17-7.04.*	Infectious waste must be incinerated or treated by an approved treatment method before being placed in a landfill.	Solid Waste Management Program Department of Environmental Regulation Twin Towers Office Building, 6th Floor 2600 Blair Stone Road Tallahassee, Florida 32301 (904) 488-0300 and Department of Health and Rehabilitative Services 1317 Winewood Boulevard Tallahassee, Florida 32301 (904) 488-2905
Georgia	Code of Georgia, Annotated, Title 43, Chapter 43-16: Solid Waste Management Act of 1972, as amended. Georgia Department of Natural Resources Rules and Regulations for Solid Waste Management, Chapter 391-3-4, 1972, as amended through 1974.	Infectious waste is considered a special waste. Policy is to require incineration or autoclaving before land disposal.	Land Protection Branch Environmental Protection Division Department of Natural Resources Room 724 270 Washington Street, SW Atlanta, Georgia 30334 (404) 656-2833
Hawaii	Hawaii Environmental Laws and Regulations, Vol. I, Title 19, Chapter 342, Part V, as amended by Chapter 230, Laws of 1974. Title II, Department of Health, Chapter 58, Solid Waste Management Control Regulations, November 1981.	All infectious waste must be treated or otherwise rendered safe before disposal. Double bagging is considered a means of rendering an untreated waste safe.	Air and Solid Waste Permit Section Department of Health Amelco Building, 3rd Floor 645 Halekau Wila Street Honolulu, Hawaii 96313
Idaho	Idaho Code, Title 39, Chapter 1. Idaho Solid Waste Management Regulations, Title I, Chapter 6.	All solid waste must be managed to prevent health hazards, public nuisances, and pollution of the environment during treatment, storage and disposal. Policy is to recommend that infectious waste be double bagged prior to disposal.	Hazardous Materials Bureau Department of Health and Welfare State House Boise, Idaho 83720 (208) 334-4107

APPENDIX A (CONTINUED)

State	Statutory Authority and Regulation Citation	Summary of Requirements	State Agency
Illinois	Illinois Revised Act 101-105, January 1985. State of Illinois Rules and Regulations 35, Subtitle G, Subpart F, Sections 700.601-700.605.	All infectious hospital waste must be rendered innocuous by sterilization or incineration before disposal.	Division of Land Pollution Control Environmental Protection Agency 2200 Churchill Road Springfield, Illinois 62706 (217) 782-6762 or 782-6760
Indiana	Indiana Code, Title 13, Article 7, Environmental Management Act.*	The state has statutory authority to regulate infectious waste as a hazardous waste, but has not yet promulgated regulations. Regulations are being drafted.	Division of Land Pollution Control State Board of Health 1330 West Michigan Street Room A304 Indianapolis, Indiana 46206 (317) 243-9100
	Refuse Disposal Act: Recodified as Indiana Solid Waste Disposal Law IC-36-9-30. Rule 330 IAC 4.	Written approval must be obtained before disposal of infectious waste in a sanitary landfill. A 5-year permit system was established in April, 1987.*	
Iowa	Iowa Code 1985, Section 455B.304. 900--100.3(2) Iowa Administrative Code (IAC)	Land disposal of infectious waste is prohibited unless a special waste authorization is granted that requires autoclaving or formalin treatment before land disposal.	Air and Waste Permit Branch Program Operations Division Iowa Department of Water, Air and Waste Management Henry A. Wallace Building 900 East Grand Street Des Moines, Iowa 50319 (515) 281-8692
Kansas	Kansas Statutes Annotated, Chapter 65, Article 34, as amended. Kansas Administrative Regulations, Title 28. Public Health, Article 29, Regulation 27, Effective May 1984.	Infectious waste must be incinerated, treated before land disposal, or ground to the sewer. Untreated infectious waste may be sent to a hazardous waste land disposal facility or to a sanitary landfill with authorization from the Department.	Solid Waste Management Section Department of Health and Environment Forbes Field, Building 321 Topeka, Kansas 66620 (913) 862-9360, Ext. 309
Kentucky	Kentucky Revised Statutes, 224.005(227)(a).	The state has statutory authority to regulate infectious waste as a hazardous waste, but has not yet promulgated regulations.	Division of Waste Management Cabinet of Natural Resources and Environmental Protection 18 Reilly Road Frankfort, Kentucky 40601 (502) 564-6716

APPENDIX A (CONTINUED)

State	Statutory Authority and Regulation Citation	Summary of Requirements	State Agency
	Certificate of Need and Licensure Law, as revised, (originally effective January 1, 1973). 902 Kentucky Administrative Regulations, 20:009, Hospital Facility Regulation.	Hospitals must have an incinerator capable of destroying infectious waste. Hospitals which satisfy the treatment, packaging, and transportation requirements can secure waivers to incinerate the waste in city facilities. Revised regs effective 6/4/85 require that sharp waste (needless, glass, etc.) be separated from other infectious waste. Sharp waste is to be packaged in rigid containers for either incineration or disposal in approved landfills.	Division for Licensing and Regulation Department of Human Resources 275 E. Main Street Frankfort, Kentucky 40601 (502) 564-2800
Louisiana	Louisiana Revised Statutes, Act 449, 30: 1133, Environmental Affairs Act.*	The state has statutory authority to regulate infectious waste as a hazardous waste, but has not yet promulgated regulations. Policy is to allow disposal of treated infectious waste in selected sanitary landfills. Revisions are expected.	Hazardous Waste Division Department of Natural Resources P.O. Box 44066 Baton Rouge, Louisiana 70804 (504) 342-1216
Maine	Title 38 of Main Revised Statutes Annotated.	The state has statutory authority to regulate infectious waste as a hazardous waste, but has not yet promulgated regulations.	Bureau of Oil and Hazardous Waste Materials Department of Environmental Protection State House, Station 17 Augusta, Maine 04333 (207) 289-2651
Maryland	Annotated Maryland Code, Health Environment Article, Sections 9-210(g) and 9-229, effective July 1, 1984.	Infectious waste cannot be disposed of in a landfill.	Air Management Administration Department of Health and Mental Hygiene 201 West Preston Street, 2nd Floor Baltimore, Maryland 21201 (301) 225-5260
	Amended Guidelines for the Disposal of Infectious Waste, effective July 1, 1984.	Incineration is the preferred method of treatment.	

APPENDIX A (CONTINUED)

State	Statutory Authority and Regulation Citation	Summary of Requirements	State Agency
Massachusetts	Massachusetts General Laws, Chapter 111, Subsections 3 and 51-56, and Chapter 111D. 105 CMR 130.354 and 130.355. Hazardous Infectious Waste Disposal Regulations; and 105 CMR 180.275, Regulation for Disposal of Infectious Materials from Independent Laboratories. Massachusetts General Laws, Chapter 21-C.*	Infectious waste must be incinerated or treated before disposal.	Massachusetts Department of Public Health 150 Tremont Street Boston, Massachusetts 02111 (617) 727-2700
	Massachusetts General Laws, Chapter 21-C.*	The state has statutory authority to regulate infectious waste as a hazardous waste, but has not yet promulgated regulations.	Division of Solid and Hazardous Waste 1 Winter Street Boston, Massachusetts 02108 (617) 292-5582
Michigan		As of December 28, 1985, Michigan deleted its list of infectious wastes from the regulations.	Office of Hazardous Waste Management Michigan Department of Natural Resources P.O. Box 30038 Lansing, Michigan 48909 (517) 373-1220
Minnesota	Minnesota Statutes Annotated, Chapters 115A and 116, Enacted by Laws of 1980, as amended. Minnesota Code of Agency Rules, Title 6, Part 4, as amended SW1-12 and SW6-2viii.	Land disposal of infectious waste is prohibited.	Division of Solid and Hazardous Waste Minnesota Pollution Control 1935 West County Road B-2 Roseville, Minnesota 55113 (612) 296-7373
Mississippi	No laws or regulations pertaining to infectious waste management.		Division of Solid/Hazardous Waste Management Bureau of Pollution Control Department of Natural Resources P.O. Box 10385 Jackson, Mississippi 39209 (601) 961-5171
Missouri	Missouri Hospital Licensing Law, Chapter 197 of Missouri Revised Statutes, Rules and Regulations for Hospitals.	Infectious waste generated by hospitals must be either incinerated or autoclaved before being sent to a landfill permitted to accept the waste. Waste is required to be treated on site. The state expects to revise regulations.	Missouri Department of Health Bureau of Hospital Licensing P.O. Box 570 Jefferson City, Missouri 65102 (314) 751-2713

APPENDIX A (CONTINUED)

State	Statutory Authority and Regulation Citation	Summary of Requirements	State Agency
	Missouri Hazardous Waste Management Law, Chapter 260 of Revised Statutes of Missouri, 1985, as amended.	The state has statutory authority to regulate infectious waste as a hazardous waste, but has not yet promulgated regulations.	Waste Management Program Department of Natural Resources P.O. Box 176 Jefferson City, Missouri 65102 (314) 751-3241
	Missouri Solid Waste Management Law, Chapter 260.200 of Revised Statutes of Missouri, 1975. Missouri Solid Waste Management Rules and Regulations, 10CSR80, Chapters 1-5.	Sterilized infectious waste may be disposed of in any permitted solid waste landfill.	
Montana	Montana Solid Waste Management Act of 1976. Administrative Rules of Montana, Title 16, Chapter 14, Subchapter 5, Solid Waste Management/Refuse Disposal.	Policy is to recommend treatment of infectious waste before land disposal.	Solid and Hazardous Waste Management Bureau Department of Health and Environmental Sciences Cogswell Building, Room B201 Helena, Montana 59620 (406) 444-2821
	Montana Hazardous Waste Act of 1981.	The state has statutory authority to regulate infectious waste as a hazardous waste, but has not yet promulgated regulations.	
Nebraska	Nebraska Environmental Protection Act, Section 81-1501 through 81-1540.	The state has statutory authority to regulate infectious waste as a hazardous waste, but has not yet promulgated regulations.	Land Quality Division Department of Environmental Control State House Station P.O. Box 94877 Lincoln, Nebraska 68509 (402) 471-2186
Nevada	Nevada Revised Statutes, Chapter 459, Hazardous Waste Disposal and Solid Waste Disposal. Regulations Governing Solid Waste Management, Effective 1977.	The state has statutory authority to regulate infectious waste as a hazardous waste, but has not yet promulgated regulations. Infectious waste generated by hospitals may be placed in a land disposal facility only under approval of the Department.	Division of Environmental Protection Department of Conservation and Natural Resources Capital Complex Carson City, Nevada 89710 (702) 885-4670

APPENDIX A (CONTINUED)

State	Statutory Authority and Regulation Citation	Summary of Requirements	State Agency
New Hampshire	New Hampshire Revised Statutes Annotated 151, 1979. Health Facilities Rules and Regulations, effective February 1984. General Requirements for all Facilities, HEP-801.	Infectious waste generated by health care facilities must be incinerated.	Bureau of Health Facilities Administration Division of Public Health Department of Health and Welfare 6 Hazen Drive Concord, New Hampshire 03301 (603) 271-4592
New Jersey	New Jersey Statues Annotated, Title 13: Conservation and Development, Chapter 1E-1. New Jersey Administrative Code, Title 7, Chapter 26, as amended. New regulations dealing with hazardous wastes expected.*	Infectious waste must be rendered noninfectious in accordance with the standards of the New Jersey Department of Health.	Division of Waste Management Department of Environmental Protection 33 East Hanover Street Trenton, New Jersey 08625 (609) 292-9877
	New Jersey Health Care Facilities Planning Act. New Jersey Administrative Code 8:43-B-3.6.*	All infectious waste generated by hospitals must be treated before land disposal. Infectious waste that is not autoclaved or incinerated can be double-bagged for land disposal by a method approved by the Department of Environmental Protection.	New Jersey Department of Health Division of Health Facilities Evaluation CN 370 Trenton, New Jersey 08625 (609) 292-7834
New Mexico	Hazardous Waste Act, Section 74-4-3, as amended through 1981.	No specific regulations on infectious waste. Incineration or sterilization of infectious waste followed by land disposal is recommended.	Solid and Hazardous Waste Management Programs Health and Environment Department P.O. Box 968 Santa Fe, New Mexico 87504-0968 (505) 827-5271 or 827-0020
New York	Environmental Conservation Law, Article 27. Title 6 NCRR part 364. Collection and Transport of Industrial, Commercial, and Certain Other Wastes.*	Anyone transporting a hospital waste off-site (including infectious waste) must have a waste transporter's permit.	Division of Solid and Hazardous Waste Department of Environmental Conservation 50 Wolf Road, Room 417 Albany, New York 12233 (518) 457-3254
	Parts 219 and 222: General Regulation of Refuse and Waste Incineration.*	These regulations limit emissions of particulate matter and smoke.	New York State Department of Environmental Conservation 50 Wolf Road Albany, New York 12233 (518) 457-5618

APPENDIX A (CONTINUED)

State	Statutory Authority and Regulation Citation	Summary of Requirements	State Agency
	10 NYCRR 405.3(b)(5): Handling of Potentially Infections Waste.*	The various categories of potentially infections waste and acceptable methods of disposal for each are presented. All waste must be autoclaved or incinerated prior to disposal.	New York State Department of Health Office of Health Services Management Nelson A. Rockefeller Empire State Plaza Corning Tower, Room 1821 Albany, New York 12237 (518) 474-2121
North Carolina	North Carolina Solid and Hazardous Waste Act, as revised, July 1983. 10 NCAC 10G, Solid Waste Management, July 1, 1985.	Infectious waste must be treated by an approved method prior to disposal in a landfill.	Solid and Hazardous Waste Management Branch Division of Health Services Department of Human Resources P.O. Box 2091 Raleigh, North Carolina 27602 (919) 733-2178
North Dakota	No governing statute or regulations.	Policy is to require autoclaving or incineration of all infectious waste generated by hospitals and nursing homes. No untreated infectious waste may be disposed of in a landfill. Every hospital and nursing home must have access to a double-chambered, approved incinerator in order to be licensed.	Division of Health Facilities Department of Health State Capitol Building Bismark, North Dakota 58505 (701) 224-2352
Ohio	Ohio Revised Code, Title 37, Chapter 34, as amended. Ohio Administrative Code, Regulations 3745-27 and 3745-37, effective July 29, 1976.	The state has statutory authority to regulate infectious waste as a hazardous waste, but has not yet promulgated regulations.	Division of Solid and Hazardous Waste Management Ohio Environmental Protection Agency 361 East Broad Street Columbus, Ohio 43215 (614) 466-7220
Oklahoma	Oklahoma Statues, Title 63, 1981, Section 1-2001 et seq., Oklahoma Controlled Industrial Waste Disposal Act.*	The state has statutory authority to regulate infections waste as a hazardous waste, but has not yet promulgated regulations. Current policy is based on CDC guidelines. Infectious waste regulations are being drafted.	Institutional Services, Medical Facilities Department of Health P.O. 53551 1000 N.E. 10th Street, 4th Floor Oklahoma City, Oklahoma 73152 (405) 271-6811
Oregon	Oregon Revised Statutes, Chapter 459, as amended. Oregon Administrative Rules, Chapter 340, Division 61.	Land disposal of infectious waste is controlled through the permitting process for land disposal facilities.	Hazardous and Solid Waste Division Department of Environmental Quality P.O. Box 1760 Portland, Oregon 97207 (503) 229-6266

APPENDIX A (CONTINUED)

State	Statutory Authority and Regulation Citation	Summary of Requirements	State Agency
Pennsylvania	Pennsylvania Statutes, 62 PS 901-1059, Public Welfare Code. Pennsylvania Code, Title 28, Chapter 147.74, Pennsylvania State Health Department Regulations: Disposal of Bacterial and Pathological Wastes that are Generated in Hospitals and Medical Care Facilities.*	Current policy is to allow off-site sterilization of infectious waste. New regulations are being drafted.	Bureau of Waste Management Department of Environmental Resources Fulton Building, 8th Floor P.O. Box 2063 Harrisburg, Pennsylvania 17120 (717) 787-6239
	25 Pa. Code 127.12(a)(5)*	Best Available Technology requirements for hospital/ infections waste incinerator facilities include stack emission limitations, ambient impact analyses, operating, testing and monitoring requirements. These regulations are in draft review, effective June 9, 1987.	Bureau of Air Quality Control Department of Environmental Resources Fulton Building, 18th Floor P.O. Box 2063 Harrisburg, Pennsylvania 17120 (717) 787-4324
Rhode Island	Rhode Island Hazardous Waste Management Act of 1978. Hazardous Waste Rules and Regulations for Hazardous Waste Generation, Transportation, Treatment, Storage and Disposal - Effective July 18, 1984.	Infectious waste is regulated as a hazardous waste.	Division of Air Hazardous Materials Department of Environmental Management 204 Cannon Building 75 Davis Street Providence, Rhode Island 02908 (401) 277-2797
South Carolina	Code of Laws of South Carolina, 1976, Sections 44-56-10 through 44-56-140, Hazardous Wastes.	The state has statutory authority to regulate infectious waste as a hazardous waste, but has not yet promulgated regulations. The state recommends that infectious hospital waste be incinerated or otherwise treated before land disposal.	Bureau of Solid and Hazardous Waste South Carolina Department of Health and Environmental Control 2600 Bull Street Columbia, South Carolina 29201 (803) 758-5681
South Dakota	South Dakota Codified Laws, Chapter 34A-6-2, Solid Waste Disposal Act.	The state has statutory authority to regulate infectious waste as a hazardous waste, but has not yet promulgated regulations.	Office of Air Quality and Solid Waste Department of Water and Natural Resources Joe Foss Building 523 East Capitol Avenue Pierre, South Dakota 57501 (605) 773-3153

APPENDIX A (CONTINUED)

State	Statutory Authority and Regulation Citation	Summary of Requirements	State Agency
Tennessee	Tennessee Hazardous Waste Management Act of 1977, as amended. Tennessee Solid Waste Disposal Act, as amended.*	The state is initiating rulemaking action.	Division of Solid Waste Management Tennessee Department of Public Health and Environment Customs House, 4th Floor 601 Broadway Street Nashville, Tennessee 37219-5403 (615) 741-3424
	Tennessee Code Annotated, 6811-201 through 217 Minimum Standards and Regulations for Hospitals, 1974.*	All infectious waste generated by hospitals must be incinerated in closed incinerators on elevated platforms.	Hospital Licensing Board 283 Plus Park Nashville, Tennessee 37210 (615) 367-6200
Texas	Revised Civil Statutes of the State of Texas Annotated, Article 4477-7 Texas Solid Waste Disposal Act; and Article 4477-1, Texas Sanitation and Health Protection Law, as amended. Texas Administrative Code 325.136(b)(1), Texas Department of Health, Municipal Solid Waste Management Regulations, effective July 1983, as amended.*	Infectious waste is regulated as a special waste. Incineration is the preferred method of treatment. Untreated waste may be double bagged and disposed of in a Type I municipal landfill.	Bureau of Solid Waste Management Texas Department of Health 1100 West 49th Street, T601A Austin, Texas 78756 - 3199 (512) 458-7271
Utah	Utah Code Annotated, Title 26, Chapter 14, Utah Solid and Hazardous Waste Act, Effective June, 1981.	The state has statutory authority to regulate infectious waste as a hazardous waste, but has not yet promulgated regulations.	Bureau of Solid and Hazardous Waste Department of Health P.O. Box 45500 Salt Lake City, Utah 84145-0501 (801) 533-4145
Vermont	Vermont Statutes Annotated, Title 10, Chapter 159. Hazardous Waste Management Regulations, as amended September 13, 1984, Section 6602(2)(a)(14).	Infectious waste is regulated as a hazardous waste.	Hazardous and Solid Waste Management Division Department of Water Resources and Environmental Engineering Agency of Environmental Conservation State Office Building Montpelier, Vermont 05602 (802) 828-3395
Virginia	Code of Virginia, Title 32.1, Chapter 6, Article 3. Virginia Regulations Governing Disposal of Solid Waste, April, 1971.	Infectious wastes are not as regulated as hazardous wastes. Waste generators must have special permission to dispose of nonmunicipal waste. Rules do not preclude land disposal of untreated infectious waste.	Division of Solid and Hazardous Waste Management Department of Health Monroe Building, 11th Floor 101 North 14th Street Richmond, Virginia 23219 (804) 225-2667

APPENDIX A (CONTINUED)

State	Statutory Authority and Regulation Citation	Summary of Requirements	State Agency
Washington	Revised Code of Washington, Hazardous Waste Disposal Chapter 70.105.	The state has statutory authority to regulate infectious waste as a hazardous waste, but has not yet promulgated regulations.	Hazardous Waste Section Department of Ecology Mail Stop PV-11 Olympia, Washington 98504-8711 (206) 459-6322
	Revised Code of Washington, Hospital Licensing and Regulation Statute, Chapter 70.41. Washington Administrative Code, 248-180-170, Hospital Rules and Regulations.	Infectious waste generated by hospitals must be incinerated or disposed of by other approved methods. Approved methods include autoclaving, retorting, or double bagging before land disposal.	Department of Social and Health Services Facility Licensing Certification Section of the Health Services Division Mail Stop ET-31 Olympia, Washington (206) 753-7039
West Virginia	Code of West Virginia, Chapter 20, Article SE, Effective July 7, 1981.*	Infectious waste must be autoclaved and/or incinerated before land disposal. Infectious waste regulations are being revised.	State Health Department 1800 Washington Street, East Charleston, West Virginia 25305 (304) 348-2970
Wisconsin	Wisconsin Statutes Annotated, Chapter 144, as amended.	The state has statutory authority to regulate infectious waste as a hazardous waste, but has not yet promulgated regulations.	Bureau of Solid Waste Management Department of Natural Resources P.O. Box 7921 Madison, Wisconsin 53707 (608) 266-2111
	Chapter NR 181, and guidance summary "Handling and Disposal of Pathological Waste."	Policy is to recommended incineration of infectious waste. Infectious waste which as been autoclaved or sterilized may be bagged and disposed of in an engineered landfill.	
Wyoming	No regulations pertaining to infectious waste management.		Solid Waste Management Program State of Wyoming Department of Environmental Quality Herschler Building 122 West 25th Street Cheyenne, Wyoming 82002 (307) 777-7752 Department of Health and Social Services Division of Health and Medical Services 4th Floor Hathaway Building Cheyenne, Wyoming 82002 (307) 777-7121

*Denotes regulations as of June, 1987.

APPENDIX B

APPENDIX B - ADDITIONAL HOSPITAL WASTE INCINERATOR EMISSIONS DATA

The Monitoring and Laboratory Division of the California Air Resources Board conducted evaluation tests on the refuse incinerator at the Stanford University Environmental Safety Facility, Stanford, California, and a retest on a hosital refuse incinerator at the Sutter General Hospital, Sacramento, California. The results of these tests are presented in two reports titled "Evaluation Retest on a Hospital Refuse Incinerator at Sutter General Hospital, Sacramento, CA." April 1988 (ARB/ML-88-026) and "Evaluation Test on a Refuse Incinerator at Stanford University Environmental Safety Facility," Stanford, CA., August 1988 (ARB/ML-88-025). To provide these test results, EPA has extracted tables of emissions data for particulate matter, hydrogen chloride, chlorinated dibenzo-p-dioxins and dibenzofurans and other compounds from these reports and incorporated them into Appendix B.

Test Data for the Hospital Refuse Incinerator at Sutter General Hospital, Sacramento, CA., California Air Resources Board Test Report, ARB/ML-88-026, April 1988.

The staff of the California Air Resources Board tested and, after design modifications were made, retested the dual chamber, Thermtec - Model/No. 67-SA, hospital refuse incinerator at the Sutter General Hospital, Sacramento, CA. The hospital has a heat recovery system, Model HR-1000-2-SK-9 manufactured by Thermtec, to recover heat from the exhaust gases. The initial tests were conducted from April 28 through May 1, 1987. The system was modified to reduce the amount of dilution air entering the exhaust gas system. The system was then retested during the period from July 29 through August 3, 1987. The results of these tests are presented in the following tables:

TABLE 1

Average Refuse Feed Rate to the Incinerator During the Test Period

DATE	TIME	NUMBER OF a/ INFECTIOUS BOXES (pounds)	NUMBER OF b/ CARTS (pounds)	PROCESS WEIGHT RATE, LB/HR
7-29-87	1300-1800	13 (264)	36 (2700)	593
7-30-87	0900-1400	14 (284)	29 (2175)	492
7-31-87	0900-1900 c/	37 (751)	49 (3675)	443
8-3-87	1300-2300	34 (690)	40 (3000)	369

a/ Infectious boxes weigh 20.3 pounds each
b/ Typical cart trash weight is 75 pounds
c/ On July 31, 1987 the refuse loading ram to the bottom chamber was inoperative from approximately 1000 to 1500 HOURS. During this period the bottom chamber was in a burndown configuration with an increased natural gas comsumption in the upper chamber to satisfy boiler heating requirements.

TABLE B-2

DAILY AVERAGE STACK CONDITIONS FOR INCINERATOR
AT SUTTER GENERAL HOSPITAL

Date	Stack Gas Velocity (Ft/Sec)	Stack Gas Flow Rate (DSCFM)	Moisture Content, (% By Volume)	Stack Gas Temperature (°F)
7-29-87	10.9	2687	13.2	328
7-30-87	13.4	3145	13.2	369
7-31-87	13.0	2833	15.5	409
8-3-87	11.9	2894	10.9	357

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C-67-090

TABLE B-3

DAILY AVERAGE CONCENTRATIONS OF SELECTED GASEOUS AIR POLLUTANTS FROM THE SUTTER GENERAL INCINERATOR

DATE	PM d/	O2 a/	CO2 a/	CO a/	NOX b/	SO2 b/	HC bc/	-CL c/
	GR/DSCF	PERCENT	PERCENT	PPMV	PPMV	PPMV	PPMV	PPMV
7-29-87	-	15.6	4.0	<50	130	50	<2	-
7-30-87	-	12.1	5.5	<50	90	13	<2	315
7-31-87	0.024 f/	12.5	5.2	<50	80	11 e/	<2	224 g/
8-3-87	0.050 h/	13.9	4.8	<50	100	22	12	-

a/ THE O2, CO2 AND CO VALUES WERE USED TO DETERMINE THE MOLECULAR WEIGHT OF THE STACK GAS.
b/ NOX, SO2 AND HC VALUES ARE CORRECTED TO 3 PERCENT O2.
c/ TOTAL HYDROCARBON DATA REPORTED AS PROPANE.
d/ REPORTED AT ACTUAL FLUE GAS O2 CONCENTRATIONS.
e/ SO2 ANALYZER INOPERATIVE DURING PART OF TEST PERIOD.
f/ AVERAGE OF FOUR TEST RUNS (0.037 , 0.021 , 0.023 AND 0.024 GR/DSCF)
g/ AVERAGE OF TWO TEST RUNS (283 AND 159 PPMV)
h/ AVERAGE OF TWO TEST RUNS (0.043 AND 0.057 GR/DSCF)

SYMBOL (<) INDICATES BELOW DETECTABLE LIMIT.

TABLE B-4

DAILY AVERAGE CONCENTRATIONS OF OXYGEN,CARBON DIOXIDE, CARBON MONOXIDE,OXIDES OF NITROGEN,SULFUR DIOXIDE, TOTAL HYDROCARBONS,PARTICULATE MATTER AND HYDROCHLORIC ACID IN THE STACK GAS AT SUTTER GENERAL HOSPITAL, SACRAMENTO,CA

DATE	PM	O2 a/	CO2 a/	CO a/	NOX b/	SO2 b/	HC bc/	HCL b/
	GR/DSCF	PERCENT	PERCENT	PPMV	PPMV	PPMV	PPMV	PPMV
4-28-87	0.023	19.4	1.2	<50	70	20	<1	860
4-29-87	0.023	19.4	1.3	<50	70	30	<1	2500
5-1-87	0.012	19.3	1.1	<50	60	6	<1	2130

a/ THE O2,CO2 AND CO VALUES WERE USE TO DETERMINE THE MOLECULAR WEIGHT OF THE STACK GAS.

b/ NOX,SO2,HC AND HCL DATA CORRECTED TO 3 PERCENT O2.

c/ TOTAL HYDROCARBON DATA REPORTED AS PROPANE.

SYMBOL (<) INDICATES BELOW DETECTABLE LIMIT.

C-86-018

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TABLE B-5

PARTICULATE MATTER AND HYDROCHLORIC ACID CONCENTRATIONS AND MASS EMISSION RATES

		PM		HCl	
		GR/DSCF	LB/HR	PPM	LB/HR
DATE RUN	NO.				
7-30-87	HCl-1S	-	-	315	5.79
7-31-87	HCl-2S	-	-	282	4.46
	HCl-3S	-	-	159	2.59
	M5-1S	0.027	0.74	-	-
	M5-2S	0.021	0.50	-	-
	M5-3S	0.023	0.55	-	-
	M5-4S	0.024	0.53	-	-
8-3-87	M5-5S	0.043	1.09	-	-
	M5-6S	0.057	1.38	-	-

	PM		HCL	
Date	GR/DSCF	LB/HR	PPM	LB/HR
4-28-87	0.023	0.94	72	1.98
4-29-87	0.023	1.05	210	6.54
5-1-87	0.012	0.49	191	5.21

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TABLE B-6

PCDD/PCDF MASS EMISSION RATES
(ng/sec)

RUN #	DT-1S	DT-2S	DT-3S	DT-4S
DIOXINS				
2,3,7,8-TCDD	<0.042	<0.039	0.058	<0.035
Total TCDD	<0.394	<0.058	3.958	<0.033
1,2,3,7,8-PeCDD	<0.167	<0.111	0.241	<0.159
Total PeCDD	<0.256	0.544	6.830	<0.095
1,2,3,4,7,8-HxCDD	<0.394	<0.212	0.252	<0.089
1,2,3,6,7,8-HxCDD	<0.361	<0.226	0.427	<0.089
1,2,3,7,8,9-HxCDD	<0.328	<0.162	<0.213	<0.089
Total HxCDD	0.788	1.452	10.63	0.542
1,2,3,4,6,7,8-HpCDD	3.778	0.949	9.003	0.620
Total HpCDD	6.932	2.011	18.55	1.239
Total OCDD	7.294	2.793	19.60	2.556
Total PCDD	15.66	6.860	59.57	4.466
FURANS				
2,3,7,8-TCDF	0.072	0.131	0.760	<0.092
Total TCDF	<0.328	3.910	45.94	2.459
1,2,3,7,8-PeCDF	0.124	0.586	3.244	0.356
2,3,4,7,8-PeCDF	<0.147	0.357	2.200	0.224
Total PeCDF	<1.839	5.558	40.84	5.151
1,2,3,4,7,8-HxCDF	0.328	0.687	2.755	<0.309
1,2,3,6,7,8-HxCDF	<0.325	0.391	2.871	<0.580
1,2,3,7,8,9-HxCDF	<0.689	0.148	0.970	<0.383
2,3,4,6,7,8-HxCDF	<1.084	0.139	2.957	<0.735
Total HxCDF	<3.548	6.675	42.96	5.500
1,2,3,4,6,7,8-HpCDF	2.858	2.905	28.29	2.420
1,2,3,4,7,8,9-HpCDF	0.108	0.614	5.906	0.519
Total HpCDF	2.858	5.865	52.51	5.151
Total OCDF	0.591	6.089	68.65	8.017
Total PCDF	9.166	28.10	250.9	26.28

NOTES
< Indicates below limit of detection (MDL)
* Chemical interference
** MPC (Maximum possible concentration)
- Total includes MDLs for homologues below the detection limit

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TABLE B-7

PCDD/PCDF CONCENTRATIONS IN STACK GAS
(ng/dscm corrected to 12% CO_2)

RUN #	DT-1S	DT-2S	DT-3S	DT-4S
DIOXINS				
2,3,7,8-TCDD	<0.188	<0.140	0.280	<0.168
Total TCDD	<1.732	<0.210	19.07	<0.157
1,2,3,7,8-PeCDD	<0.736	<0.400	1.159	<0.765
Total PeCDD	<1.126	1.949	32.90	<0.457
1,2,3,4,7,8-HxCDD	<1.732	<0.759	1.215	<0.429
1,2,3,6,7,8-HxCDD	<1.587	<0.809	2.056	<0.429
1,2,3,7,8,9-HxCDD	<1.443	<0.580	<1.028	<0.429
Total HxCDD	3.464	5.196	51.22	2.612
1,2,3,4,6,7,8-HpCDD	16.60	3.398	43.37	2.985
Total HpCDD	30.45	7.195	89.35	5.970
Total OCDD	32.04	9.993	94.40	12.31
Total PCDD	68.81	24.54	286.9	21.51
FURANS				
2,3,7,8-TCDF	<0.317	0.470	3.664	<0.448
Total TCDF	1.443	13.99	221.3	11.85
1,2,3,7,8-PeCDF	<0.548	2.099	15.6	1.716
2,3,4,7,8-PeCDF	<0.649	1.279	10.6	1.082
Total PeCDF	8.08	19.89	196.8	24.81
1,2,3,4,7,8-HxCDF	<1.443	2.458	13.3	<1.492
1,2,3,6,7,8-HxCDF	<1.429	1.399	13.8	<2.798
1,2,3,7,8,9-HxCDF	<3.031	0.530	4.673	<1.847
2,3,4,6,7,8-HxCDF	<4.762	0.500	14.2	<3.545
Total HxCDF	15.59	23.88	206.9	26.49
1,2,3,4,6,7,8-HpCDF	12.56	10.39	136.3	11.66
1,2,3,4,7,8,9-HpCDF	<0.476	2.199	28.4	2.500
Total HpCDF	12.56	20.99	252.9	24.81
Total OCDF	2.60	21.79	330.7	38.62
Total PCDF	40.3	100.5	1209	126.6

NOTES
< indicates below limit of detection (MDL)
* Chemical interference
** MPC (Maximum possible concentration)
- Total includes MDLs for homologues below the detection limit

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TABLE B-8

PCDD/PCDF CONCENTRATIONS IN STACK GAS
(ng/dscm)

RUN #	DT-1S	DT-2S	DT-3S	DT-4S
DIOXINS				
2,3,7,8-TCDD	<0.019	<0.015	0.026	<0.015
Total TCDD	<0.173	<0.023	1.748	<0.014
1,2,3,7,8-PeCDD	<0.074	<0.043	0.106	<0.070
Total PeCDD	<0.113	0.211	3.016	<0.042
1,2,3,4,7,8-HxCDD	<0.173	<0.082	0.111	<0.039
1,2,3,6,7,8-HxCDD	<0.159	<0.088	0.188	<0.039
1,2,3,7,8,9-HxCDD	<0.144	<0.063	<0.094	<0.039
Total HxCDD	0.346	0.563	4.695	0.239
1,2,3,4,6,7,8-HpCDD	1.660	0.368	3.975	0.274
Total HpCDD	3.045	0.779	8.19	0.547
Total OCDD	3.20	1.083	8.65	1.129
Total PCDD	6.88	2.659	26.30	1.97
FURANS				
2,3,7,8-TCDF	<0.031	0.050	0.335	<0.041
Total TCDF	0.144	1.515	20.28	1.085
1,2,3,7,8-PeCDF	<0.054	0.227	1.432	0.157
2,3,4,7,8-PeCDF	<0.064	0.138	0.971	0.099
Total PeCDF	0.808	2.154	18.03	2.274
1,2,3,4,7,8-HxCDF	<0.144	0.266	1.216	<0.136
1,2,3,6,7,8-HxCDF	<0.142	0.151	1.267	<0.256
1,2,3,7,8,9-HxCDF	<0.303	0.057	0.428	<0.169
2,3,4,6,7,8-HxCDF	<0.476	0.054	1.305	<0.324
Total HxCDF	1.558	2.587	18.96	2.428
1,2,3,4,6,7,8-HpCDF	1.255	1.125	12.49	1.068
1,2,3,4,7,8,9-HpCDF	<0.047	0.238	2.607	0.229
Total HpCDF	1.255	2.273	23.18	2.274
Total OCDF	0.259	2.360	30.31	3.539
Total PCDF	4.026	10.89	110.7	11.60

NOTES
< Indicates below limit of detection (MDL)
* Chemical interference
** MPC (Maximum possible concentration)
- Total includes MDLs for homologues below the detection limit

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TABLE B-9

PCDD/PCDF MASS EMISSION RATES IN STACK GAS
(ng/sec)

RUN # Sampling date	DT-1S 7-29-87	DT-2S 7-30-87	DT-3S 7-30-87
DIOXINS			
2,3,7,8-TCDD	0.24	< 0.11	0.140
Total TCDD	25.4	21.0	33.3
1,2,3,7,8-PeCDD	4.03	2.39	3.8
Total PeCDD	138	103	106
1,2,3,4,7,8-HxCDD	10.9	8.96	10.1
1,2,3,6,7,8-HxCDD	21.5	18.7	21.5
1,2,3,7,8,9-HxCDD	13.4	10.5	12.5
Total HxCDD	291	236	242
1,2,3,4,6,7,8-HpCDD	157	13.8	169
Total HpCDD	349	334	355
Total OCDD	237	265	269
Total PCDD	1041	959 **	1005
FURANS			
2,3,7,8-TCDF	6.51	4.86	6.05
Total TCDF	329	253	256
1,2,3,7,8-PeCDF	30.0	25.2	30.6
2,3,4,7,8-PeCDF	36.4	29.7	37.0
Total PeCDF	407	342	333
1,2,3,4,7,8-HxCDF	50.0	43.6	49.6
1,2,3,6,7,8-HxCDF	53.2	41.1	43.8
1,2,3,7,8,9-HxCDF	14.5	13.9	17.5
2,3,4,6,7,8-HxCDF	115	104	103
Total HxCDF	463	374	431
1,2,3,4,6,7,8-HpCDF	233	244	236
1,2,3,4,7,8,9-HpCDF	45.5	51.1	56.2
Total HpCDF	437	462	477
Total OCDF	381	404	396
Total PCDF	2016	1834	1893

NOTES
< indicates below limit of detection (MDL)
** - Total includes MDLs for homologues below the detection limit

TABLE B-10

PCDD/PCDF CONCENTRATIONS IN STACK GAS
(corrected to 12 percent CO2)

RUN # Sampling date	DT-1S 7-29-87	DT-2S 7-30-87	DT-3S 7-30-87
	(ng/dscm)	(ng/dscm)	(ng/dscm)
DIOXINS			
2,3,7,8-TCDD	0.56	< 0.22	0.29
Total TCDD	60.0	43.2	68.1
1,2,3,7,8-PeCDD	9.53	4.91	7.83
Total PeCDD	327	212	218
1,2,3,4,7,8-HxCDD	25.9	18.4	20.6
1,2,3,6,7,8-HxCDD	50.9	38.5	44.1
1,2,3,7,8,9-HxCDD	31.8	21.5	25.7
Total HxCDD	688	486	495
1,2,3,4,6,7,8-HpCDD	372	28	347
Total HpCDD	827	686	727
Total OCDD	560	545	551
Total PCDD	2462	1972 **	2059
FURANS			
2,3,7,8-TCDF	15.39	9.05	12.38
Total TCDF	779	520	525
1,2,3,7,8-PeCDF	71.0	51.8	62.7
2,3,4,7,8-PeCDF	86.2	61.1	75.8
Total PeCDF	962	702	681
1,2,3,4,7,8-HxCDF	118.2	89.6	101.6
1,2,3,6,7,8-HxCDF	125.8	84.4	89.7
1,2,3,7,8,9-HxCDF	34.3	28.6	35.8
2,3,4,6,7,8-HxCDF	273	213	211
Total HxCDF	1095	768	883
1,2,3,4,6,7,8-HpCDF	552	502	483
1,2,3,4,7,8,9-HpCDF	107.7	105.1	115.2
Total HpCDF	1033	950	976
Total OCDF	900	830	812
Total PCDF	4770	3770	3877

NOTES
dscm - dry standard cubic meter at 68 F and one atmosphere
< indicates below limit of detection (MDL)
** - Total includes MDLs for homologues below the detection limit

TABLE B-11

PCDD/PCDF CONCENTRATIONS IN STACK GAS

(ng/dscm)

RUN # Sampling date	DT-1S 7-29-87	DT-2S 7-30-87	DT-3S 7-30-87
DIOXINS			
2,3,7,8-TCDD	0.19	< 0.07	0.10
Total TCDD	20.0	14.4	22.7
1,2,3,7,8-PeCDD	3.18	1.64	2.61
Total PeCDD	109	70.5	72.6
1,2,3,4,7,8-HxCDD	8.63	6.14	6.86
1,2,3,6,7,8-HxCDD	17.0	12.8	14.7
1,2,3,7,8,9-HxCDD	10.6	7.17	8.57
Total HxCDD	229	162	165
1,2,3,4,6,7,8-HpCDD	124	9.48	116
Total HpCDD	276	229	242
Total OCDD	187	182	184
Total PCDD	821	657 **	886
FURANS			
2,3,7,8-TCDF	5.13	3.02	4.13
Total TCDF	260	173	175
1,2,3,7,8-PeCDF	23.7	17.3	21.9
2,3,4,7,8-PeCDF	28.7	20.4	25.3
Total PeCDF	321	234	227
1,2,3,4,7,8-HxCDF	39.4	29.9	33.9
1,2,3,6,7,8-HxCDF	41.9	28.1	29.9
1,2,3,7,8,9-HxCDF	11.4	9.55	11.9
2,3,4,6,7,8-HxCDF	91.1	71.0	70.2
Total HxCDF	365	256	294
1,2,3,4,6,7,8-HpCDF	184	167	161
1,2,3,4,7,8,9-HpCDF	35.9	35.0	33.4
Total HpCDF	344	317	325
Total OCDF	300	277	271
Total PCDF	1590	1257	1292

NOTES
dscm - dry standard cubic meter at 68 F and one atmosphere
< indicates below limit of detection (MDL)
** - Total includes MDLs for homologues below the detection limit

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TABLE B-12

MASS EMISSION RATES OF TRACE METALS IN STACK GAS

MASS EMISSION RATES, POUNDS/HOUR[a/]

RUN NO.	As.	Cd	Cr	Fe	Mn	Ni	Pb
M5-1S	0.45E-5	5.90E-4	9.84E-5	2.99E-3	1.14E-4	< 6.71E-5	7.65E-3
M5-2S	ND	1.86E-4	4.22E-5	3.12E-3	2.55E-5	< 6.09E-5	2.01E-3
M5-3S	ND	1.95E-4	5.20E-5	0.37E-3	1.67E-5	< 6.96E-5	2.97E-3
M5-4S	ND	2.07E-4	<4.87E-5	0.70E-3	0.31E-4	< 7.30E-5	2.34E-3
M5-5S	ND	6.68E-4	7.30E-5	1.52E-3	0.80E-4	< 9.13E-5	6.31E-3
M5-6S	0.11E-5	6.85E-4	1.16E-4	1.06E-2	2.55E-4	< 7.94E-5	1.23E-2

a/ Symbol (<) indicates below limit of detection.

ND Not Determined

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TABLE B-13

CONCENTRATIONS OF TRACE METALS IN STACK GAS, GRAINS/DRY STANDARD CUBIC FOOT[a/]

RUN NO.	As	Cd	Cr	Fe	Mn	Ni	Pb
M5-1S	1.65E-7	2.18E-5	3.63E-6	1.10E-4	4.22E-6	<2.47E-6	2.82E-4
M5-2S	ND	7.98E-6	1.81E-6	1.34E-4	1.05E-6	<2.61E-6	8.64E-5
M5-3S	ND	7.96E-6	2.12E-6	1.52E-5	0.68E-6	<2.84E-6	1.21E-4
M5-4S	ND	9.13E-6	<2.19E-6	3.13E-5	1.40E-6	<3.28E-6	1.05E-4
M5-5S	ND	2.65E-5	2.89E-6	0.60E-4	3.18E-6	<3.62E-6	2.50E-4
M5-6S	0.43E-7	2.81E-5	4.78E-6	4.33E-4	1.05E-5	<3.26E-6	5.05E-4

a/ Symbol (<) indicates below limit of detection

ND Not Determined

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TABLE B-14

MASS EMISSION RATES OF ARSENIC, CADMIUM CHROMIUM, IRON , MANGANESE, NICKEL AND LEAD IN STACK GAS

MASS EMISSION RATES, POUNDS/HOUR[a/]

RUN NO.	AS	Cd	Cr	Fe	Mn	Ni	Pb
M5-1S	1.5E-05	4.9E-04	< 1.4E-4	4.6E-03	1.7E-04	< 2.1E-4	4.1E-03
M5-2S	2.9E-05	1.1E-03	< 7.9E-5	5.6E-03	2.8E-04	< 1.2E-4	8.9E-03
M5-3S	1.7E-06	5.5E-05	< 6.5E-5	1.7E-03	9.1E-05	<1.0E-4	3.7E-03

a/ Symbol (<) indicates below limit of detection.

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TABLE B-15

CONCENTRATIONS OF ARSENIC, CADMIUM, CHROMIUM, IRON, MANGANESE, NICKEL AND LEAD IN STACK GAS

CONCENTRATIONS, GRAINS/DRY STANDARD CUBIC FOOT[a/]

RUN NO.	AS	Cd	Cr	Fe	Mn	Ni	Pb
M5-1S	3.6E-07	1.2E-05	< 3.3E-6	1.1E-04	4.1E-06	< 5.1E-6	9.8E-05
M5-2S	6.1E-07	2.3E-05	< 1.7E-6	1.2E-04	6.0E-06	< 2.6E-6	19.1E-05
M5-3S	1.7E-07	0.1E-05	< 1.6E-6	0.4E-04	2.2E-06	< 2.4E-6	9.0E-05

a/ Symbol (<) indicates below limit of detection.

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TABLE B-16

MASS EMISSION RATES OF SELECTED CHLORINATED AND AROMATIC ORGANIC COMPOUNDS BASED ON ANALYSIS OF RESIN SAMPLES, LB/HR

NO.	COMPOUND	SAMPLE ID / DATE	RT-1S 4-28-87	RT-2S 4-29-87	RT-3S 5-1-87
1.	DICHLOROFLUOROMETHANE		4.9e-5	1.2e-4	7.7e-5
2.	DICHLOROMETHANE		a/	3.9e-4	a/
3.	TRICHLOROFLUOROMETHANE		8.3e-5	3.6e-6	1.4e-4
4.	TRICHLOROMETHANE		a/	a/	a/
5.	1,2-DICHLOROETHANE		a/	a/	a/
6.	1,1,1-TRICHLOROETHANE		2.4e-4	1.5e-4	4.2e-4
7.	CARBON TETRACHLORIDE		a/	a/	a/
8.	1,1,2-TRICHLOROETHYLENE		5.4e-5	3.6e-5	9.5e-5
9.	1,2-DIBROMOETHANE		a/	a/	a/
10.	TETRACHLOROETHYLENE		8.4e-5	8.6e-5	6.7e-4
11.	TRICHLOROTRIFLUOROETHANE		1.9e-4	1.2e-4	8.0e-5
12.	BENZENE		3.4e-4	2.6e-4	1.3e-4
13.	TOLUENE		5.9e-4	5.9e-4	4.5e-4
14.	ETHYL BENZENE		1.4e-4	2.0e-4	1.1e-4
15.	P-XYLENE		1.1e-4	1.7e-4	8.7e-5
16.	M-XYLENE		2.7e-4	3.8e-4	1.9e-4
17.	CUMENE		a/	a/	a/
18.	O-XYLENE		1.5e-4	2.1e-4	1.1e-4
19.	MESITYLENE		5.1e-5	7.5e-5	3.7e-5
20.	NAPHTHALENE		7.7e-5	a/	5.0e-5
21.	METHYL ISOBUTYL KETONE		a/	a/	a/

a/ Below minimum detection level.

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TABLE B-17

PCDD/PCDF CONCENTRATIONS IN BOTTOM ASH SAMPLE
(ng/g)

RUN #	BA-1S
DIOXINS	
2,3,7,8-TCDD	<0.015
Total TCDD	<0.019
1,2,3,7,8-PeCDD	<0.046
Total PeCDD	0.018
1,2,3,4,7,8-HxCDD	< 0.11
1,2,3,6,7,8-HxCDD	< 0.11
1,2,3,7,8,9-HxCDD	< 0.11
Total HxCDD	0.24
1,2,3,4,6,7,8-HpCDD	< 0.17
Total HpCDD	< 0.17
Total OCDD	< 0.23
FURANS	
2,3,7,8-TCDF	< 0.12
Total TCDF	< 1.7
1,2,3,7,8-PeCDF	0.077
2,3,4,7,8-PeCDF	0.059
Total PeCDF	0.73
1,2,3,4,7,8-HxCDF	< 0.14
1,2,3,6,7,8-HxCDF	< 0.10
1,2,3,7,8,9-HxCDF	< 0.13
2,3,4,6,7,8-HxCDF	< 0.19
Total HxCDF	0.42
1,2,3,4,6,7,8-HpCDF	< 0.17
1,2,3,4,7,8,9-HpCDF	< 0.17
Total HpCDF	< 0.17
Total OCDF	< 0.24

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< indicates below the detection limit (MDL)

ARB/ML-88-026

Test Data for the Refuse Incinerator at Stanford University Environmental Safety Facility, Stanford, CA., California Air Resources Board Test Report, ARB/ML-88-025.

The staff of the California Air Resources board tested the air emissions from a dual chamber Ecolaire refuse incinerator located at the Stanford University Environmental Safety Facility in Stanford, CA. This refuse incinerator has a sodium hydroxide scrubber control system followed by a natural gas fired reheater. These test were conducted from June 29 through July 7, 1987 to determine the emissions from the Stanford refuse incinerator. Test were conducted before (inlet) and after (exhaust) the sodium hydroxide scrubbers. The results of these test are presented in the following tables:

TABLE B-18

DAILY AVERAGE OPERATING PARAMETERS

Date	Trash Rate, LB/HR	Natural[ab/] Gas Use, MM Btu/HR	Lower Chamber Temp., °F	Control Chamber Inlet Temp., °F	Control Chamber Outlet Temp., °F	Control Chamber Outlet Oxygen, Percent
6-30-87	550	4.3	1854	1930	1990	8.6
7-1-87	620	4.3	1964	1998	2059	8.0
7-2-87	725	4.6	1916	1993	2072	7.0
7-7-87	805	4.2	1776	1943	2000	8.8

a/ Natural gas heat, 1000 Btu/FT^3

b/ Includes reheater natural gas consumption, 1.2 MM Btu/HR

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TABLE B-19

DAILY AVERAGE CONCENTRATIONS OF OXYGEN, CARBON DIOXIDE, CARBON MONOXIDE, OXIDES OF NITROGEN, SULFUR DIOXIDE TOTAL HYDROCARBONS, PARTICULATE MATTER AND HYDROCHLORIC ACID IN THE STACK GAS

DATE	PM	O2 a/	CO2 a/	CO a/	NOX b/	SO2 b/	HC bc/	HCl b/
	GR/DSCF	PERCENT	PERCENT	PPMV	PPMV	PPMV	PPMV	PPMV
6-30-87	0.065	9.6	6.7	170	170	NA	160	2.78
7-1-87	0.028	10.6	5.5	<50	NA	NA	<1	0.52
7-2-87	0.029	11.5	6.0	<50	110	NA	2	1.86
7-7-87	-	9.5	7.0	200	100	NA	2	-

a/ THE O2, CO2 AND CO VALUES WERE USED TO DETERMINE THE MOLECULAR WEIGHT OF THE STACK GAS.

b/ NOX, SO2 AND HC DATA CORRECTED TO 3 PERCENT O2.

c/ TOTAL HYDROCARBON DATA REPORTED AS PROPANE.

SYMBOL (<) INDICATES BELOW DETECTABLE LIMIT.

NA/ ANALYZER INOPERATIVE.

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TABLE B-20

CONCENTRATIONS AND MASS EMISSION RATES OF PARTICULATE MATTER[a/]

	SCRUBBER INLET PM, gr/DSCF		STACK OUTLET PM, gr/DSCF	
	FRONT	BACK	FRONT	BACK
6-30-87	0.028	0.026	0.037	0.028
7-1-87	0.028	0.020	0.024	0.004
7-2-87	0.053	0.021	0.026	0.003

	SCRUBBER INLET PM, LB/HR		STACK OUTLET PM, LB/HR	
	FRONT	BACK	FRONT	BACK
6-30-87	0.421	0.393	0.679	0.512
7-1-87	0.475	0.339	0.442	0.079
7-2-87	0.962	0.377	0.495	0.064

a/ FRONT indicates the amount of particulate matter found in the Method 5 probe rinse and filter catch. BACK indicates the amount of particulate matter found in the Method 5 after-filter sample recovery.

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TABLE B-21

CONCENTRATIONS AND MASS EMISSION RATES HYDROCHLORIC ACID

	SCRUBBER INLET HCl, PPMV	STACK OUTLET HCl, PPMV
6-30-87	628	2.78
7-1-87	538	0.052
7-2-87	759	1.86

	SCRUBBER INLET HCl, LB/HR	STACK OUTLET HCl, LB/HR
6-30-87	6.19	0.034
7-1-87	6.01	0.006
7-2-87	9.14	0.024

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TABLE B-22

PCDD/PCDF MASS EMISSION RATES
(ng/sec)

RUN #	DT-1D Scrubber inlet	DT-1S Stack	DT-2D Scrubber inlet	DT-2S Stack
DIOXINS				
2,3,7,8-TCDD	<0.015	<0.029	0.081	<0.020
Total TCDD	0.142	<0.014	1.924	0.279
1,2,3,7,8-PeCDD	0.044	<0.040	0.366	<0.099
Total PeCDD	0.265	<0.068	4.452	1.330
1,2,3,4,7,8-HxCDD	0.092	<0.054	0.350	0.148
1,2,3,6,7,8-HxCDD	0.142	<0.050	0.445	<0.195
1,2,3,7,8,9-HxCDD	0.156	<0.081	0.525	<0.144
Total HxCDD	2.610	<0.080	6.519	3.003
1,2,3,4,6,7,8-HpCDD	3.866	0.179	4.690	1.716
Total HpCDD	7.966	0.318	10.65	4.227
Total OCDD	21.84	0.497	14.20	2.951
Total PCDD	32.82	0.976 **	37.75	11.79
FURANS				
2,3,7,8-TCDF	0.133 *	<0.030	0.816	0.214
Total TCDF	3.174	<0.037	20.57	4.933
1,2,3,7,8-PeCDF	0.546	<0.025	1.733	0.622
2,3,4,7,8-PeCDF	0.702	<0.022	1.779	0.751
Total PeCDF	12.30	<0.138	28.71	10.08
1,2,3,4,7,8-HxCDF	1.200	<0.023	1.933	0.987
1,2,3,6,7,8-HxCDF	1.232	<0.023	1.894	1.137
1,2,3,7,8,9-HxCDF	0.764	<0.028	0.779	0.343
2,3,4,6,7,8-HxCDF	3.243	<0.026	2.926	1.394
Total HxCDF	23.93	0.043	17.43	9.008
1,2,3,4,6,7,8-HpCDF	21.73	<0.032	13.37	4.719
1,2,3,4,7,8,9-HpCDF	2.401	<0.032	1.097	0.386
Total HpCDF	40.19	<0.032	21.08	7.228
Total OCDF	39.61	<0.057	13.14	1.501
Total PCDF	119	0.306 **	101	32.75

NOTES
< indicates below minimum detection limit (MDL)
* - Maximum possible emission rate
** - Total includes MDLs for homologues below the detection limit

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TABLE B-22

PCDD/PCDF MASS EMISSION RATES
(ng/sec)

RUN #	DT-3D Scrubber inlet	DT-3S Stack	DT-4D Scrubber inlet	DT-4S Stack
DIOXINS				
2,3,7,8-TCDD	<0.017	<0.010	0.081	<0.045
Total TCDD	0.975	0.176	0.940	<0.019
1,2,3,7,8-PeCDD	0.294	<0.026 *	0.517	<0.094
Total PeCDD	5.956	0.134	6.365	0.111
1,2,3,4,7,8-HxCDD	0.557	<0.038	0.705	<0.207
1,2,3,6,7,8-HxCDD	1.533	<0.040	1.488	<0.188
1,2,3,7,8,9-HxCDD	1.010	<0.033	2.066	<0.173
Total HxCDD	18.67	0.329	18.01	0.357
1,2,3,4,6,7,8-HpCDD	20.85	0.576	18.36	0.244
Total HpCDD	41.75	1.129	38.37	0.613
Total OCDD	75.53	2.986	59.67	0.902
Total PCDD	142.9	4.115	123.4	2.001 **
FURANS				
2,3,7,8-TCDF	0.434	0.026	0.798	<0.109 *
Total TCDF	16.18	0.470	22.18	1.296
1,2,3,7,8-PeCDF	1.376	<0.028	2.867	<0.096
2,3,4,7,8-PeCDF	1.637	0.047	3.987	<0.060
Total PeCDF	27.78	0.230	47.22	0.451
1,2,3,4,7,8-HxCDF	2.351	0.056	6.155	<0.244
1,2,3,6,7,8-HxCDF	2.299	<0.075	6.703	<0.225
1,2,3,7,8,9-HxCDF	1.550	<0.066	4.730	<0.319
2,3,4,6,7,8-HxCDF	4.702	<0.061	14.34	<0.301
Total HxCDF	51.95	0.193	84.32	1.018
1,2,3,4,6,7,8-HpCDF	64.96	0.329	84.28	0.789
1,2,3,4,7,8,9-HpCDF	4.789	<0.031	8.050	0.051
Total HpCDF	107.2	0.494	136.1	1.071
Total OCDF	93.18	0.174	125.9	0.490
Total PCDF	296.3	1.561	415.7	4.327

NOTES
< indicates below limit of detection (MDL)
* - Chemical interference
** - Total includes MDLs for homologues below the detection limit

TABLE B-23

PCDD/PCDF CONCENTRATIONS IN GAS
(ng/dscm corrected to 12% CO_2)

RUN #	DT-1D Scrubber inlet	DT-1S Stack	DT-2D Scrubber inlet	DT-2S Stack
DIOXINS				
2,3,7,8-TCDD	<0.034	<0.062	0.210	<0.042
Total TCDD	0.330	<0.029	4.973	0.589
1,2,3,7,8-PeCDD	0.102	<0.085	0.945	<0.208
Total PeCDD	0.616	<0.144	11.51	2.808
1,2,3,4,7,8-HxCDD	0.214	<0.115	0.904	0.313
1,2,3,6,7,8-HxCDD	0.330	<0.106	1.151	<0.412
1,2,3,7,8,9-HxCDD	0.363	<0.174	1.356	<0.303
Total HxCDD	6.070	<0.171	16.85	6.342
1,2,3,4,6,7,8-HpCDD	8.993	0.383	12.13	3.624
Total HpCDD	18.53	0.677	27.54	8.928
Total OCDD	50.80	1.060	36.71	6.233
Total PCDD	76.35	2.081 **	97.58	24.90
FURANS				
2,3,7,8-TCDF	0.308 *	<0.065	2.109	0.453
Total TCDF	7.383	<0.079	53.19	10.42
1,2,3,7,8-PeCDF	1.269	<0.053	4.480	1.314
2,3,4,7,8-PeCDF	1.632	<0.047	4.599	1.585
Total PeCDF	28.61	<0.294	74.23	21.29
1,2,3,4,7,8-HxCDF	2.792	<0.050	4.998	2.084
1,2,3,6,7,8-HxCDF	2.865	<0.050	4.895	2.401
1,2,3,7,8,9-HxCDF	1.777	<0.059	2.014	0.725
2,3,4,6,7,8-HxCDF	7.542	<0.056	7.563	2.944
Total HxCDF	55.66	0.091	45.05	19.02
1,2,3,4,6,7,8-HpCDF	50.55	<0.068	34.57	9.965
1,2,3,4,7,8,9-HpCDF	5.584	<0.068	2.836	0.815
Total HpCDF	93.48	<0.068	54.50	15.27
Total OCDF	92.14	<0.121	33.96	3.171
Total PCDF	277	0.653 **	261	69.17

NOTES
dscm - dry standard cubic meter at 68 F and one atmosphere
< indicates below minimum detection limit (MDL)
* - Maximum possible concentration
** - Total includes MDLs for homologues below the detection limit

TABLE B-23

PCDD/PCDF CONCENTRATIONS
(ng/dscm corrected to 12% CO_2)

RUN #	DT-3D Scrubber inlet	DT-3S Stack	DT-4D Scrubber inlet	DT-4S Stack
DIOXINS				
2,3,7,8-TCDD	<0.035	<0.018	0.161	<0.075
Total TCDD	2.092	0.323	1.860	<0.031
1,2,3,7,8-PeCDD	0.631	<0.047 *	1.023	<0.157
Total PeCDD	12.77	0.245	12.60	0.185
1,2,3,4,7,8-HxCDD	1.195	<0.069	1.395	<0.345
1,2,3,6,7,8-HxCDD	3.287	<0.073	2.945	<0.313
1,2,3,7,8,9-HxCDD	2.166	<0.060	4.090	<0.288
Total HxCDD	40.04	0.603	35.66	0.595
1,2,3,4,6,7,8-HpCDD	44.71	1.054	36.34	0.407
Total HpCDD	89.53	2.066	75.96	1.022
Total OCDD	162.0	5.466	118.1	1.504
Total PCDD	306.4	7.532	244.2	3.34 **
FURANS				
2,3,7,8-TCDF	0.930	0.047	1.581	<0.182 *
Total TCDF	34.70	0.861	43.91	2.16
1,2,3,7,8-PeCDF	2.951	<0.052	5.677	<0.160
2,3,4,7,8-PeCDF	3.511	0.086	7.894	<0.100
Total PeCDF	59.58	0.422	93.48	0.75
1,2,3,4,7,8-HxCDF	5.042	0.103	12.18	<0.407
1,2,3,6,7,8-HxCDF	4.930	<0.138	13.27	<0.376
1,2,3,7,8,9-HxCDF	3.324	<0.121	9.363	<0.533
2,3,4,6,7,8-HxCDF	10.08	<0.112	28.40	<0.501
Total HxCDF	111.4	0.353	166.9	1.70
1,2,3,4,6,7,8-HpCDF	139.3	0.603	166.8	1.316
1,2,3,4,7,8,9-HpCDF	10.27	<0.056	15.94	0.085
Total HpCDF	230.1	0.904	269.4	1.79
Total OCDF	199.8	0.318	249.3	0.818
Total PCDF	636	2.858	823	7.22

NOTES
dscm - dry standard cubic meter at 68 °F and one atmosphere
< indicates below limit of detection (MDL)
* - Chemical interference
** - Total includes MDLs for homologues below the detection limit

TABLE B-24

MASS EMISSION RATES OF SELECTED METALS IN THE STACK GAS

MASS EMISSION RATES, POUNDS/HOUR

RUN NO.	Cd	Cr	Fe	Mn	Ni	Pb	As	Cr^{+6}
M5-1S	4.24E-4	7.96E-5	12.04E-3	1.11E-4	<7.37E-5	1.51E-2	ND	-
2S	3.46E-4	8.30E-5	1.25E-3	0.51E-4	<7.88E-5	1.47E-2	ND	-
3S	6.71E-4	9.94E-5	3.49E-3	1.12E-4	<8.11E-5	1.78E-2	ND	-
1D	2.61E-4	6.86E-5	0.93E-3	0.53E-4	<5.41E-5	0.53E-2	ND	-
2D	6.74E-4	9.47E-5	1.16E-3	0.55E-4	<4.18E-5	1.55E-2	ND	-
3D	10.63E-4	16.29E-5	1.48E-3	1.27E-4	<4.78E-5	2.55E-2	ND	-
HCl-1S	-	-	-	-	-	-		2.24E-5
2S	-	-	-	-	-	-		10.47E-5
3S	-	-	-	-	-	-		12.23E-5
1D	-	-	-	-	-	-		7.69E-5
2D	-	-	-	-	-	-		<1.04E-5
3D	-	-	-	-	-	-		6.83E-5

a/ Symbol (<) indicates below limit of detection.

b/ ND indicates none detected.

TABLE B-25

CONCENTRATIONS OF SELECTED METALS
IN THE STACK GAS CONCENTRATIONS,
GRAINS/DRY STANDARD CUBIC FOOT[a/]

RUN NO.	Cd	Cr	Fe	Mn	Ni	Pb	As	Cr^{+6}
M5-1S	2.28E-5	4.28E-6	6.47E-4	5.97E-6	<3.96E-6	8.13E-4	ND	-
-2S	1.88E-5	4.52E-4	0.68E-4	2.80E-6	<4.29E-6	7.98E-4	ND	-
-3S	3.46E-5	5.13E-6	1.80E-4	5.79E-6	<4.18E-6	9.19E-4	ND	-
-1D	1.75E-5	4.61E-6	0.62E-4	3.59E-6	<3.64E-6	3.56E-4	ND	-
-2D	4.00E-5	5.62E-6	0.69E-4	3.27E-6	<2.48E-6	9.21E-4	ND	-
-3D	5.86E-5	8.98E-6	0.82E-4	7.01E-6	<2.59E-6	14.03E-4	ND	-
HCl-1S	-	-	-	-	-	-	-	1.35E-6
-2S	-	-	-	-	-	-	-	5.42E-6
-3S	-	-	-	-	-	-	-	6.05E-6
-1D	-	-	-	-	-	-	-	5.17E-6
-2D	-	-	-	-	-	-	-	<0.62E-6
-3D	-	-	-	-	-	-	-	3.76E-6

a/ Symbol (<) indicates below limit of detection.

b/ ND indicates none detected.

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TABLE B-26

MASS EMISSION RATES OF SELECTED CHLORINATED AND
AROMATIC ORGANIC COMPOUNDS BASED ON ANALYSIS OF RESIN SAMPLES (ug/sec)

STANFORD UNIVERSITY

SAMPLE ID / DATE	RT-1S 6-30-87	RT-2S 7-2-87	RT-3S 7-7-87	RT-1D 6-30-87	RT-2D 7-1-87	RT-3D 7-2-87
1. DICHLOROFLUOROMETHANE	1.80E+00	3.40E+00	9.68E-01	1.90E+00	1.07E+00	1.16E+00
2. DICHLOROMETHANE	3.24E+01	1.17E+01	1.07E+01	1.40E+01	3.30E+01	1.97E+01
3. TRICHLOROFLUOROMETHANE	< 4.83E-01	< 2.34E-01	1.94E-01	< 2.00E-01	< 1.91E-01	< 2.30E-01
4. TRICHLOROMETHANE	1.02E+01	5.16E+00	4.85E+00	8.99E-01	< 1.91E-01	1.51E+00
5. 1,2-DICHLOROETHANE	5.57E+01	3.29E+01	< 9.70E+00	< 9.99E+00	< 9.72E+00	< 1.16E+01
6. 1,1,1-TRICHLOROETHANE	1.80E+00	9.35E-01	1.45E+00	8.99E-01	1.90E+01	7.19E+00
7. CARBON TETRACHLORIDE	3.54E-01	< 2.34E-01	< 1.94E-01	< 2.00E-01	< 1.91E-01	1.04E+00
8. 1,1,2-TRICHLOROETHYLENE	3.54E-01	2.34E-01	2.88E-01	7.99E-01	3.11E+00	3.71E+00
9. 1,2-DIBROMOETHANE	< 3.54E-01	< 2.34E-01	< 1.94E-01	< 2.00E-01	1.91E-01	2.30E-01
10. TETRACHLOROETHENE	1.26E+00	8.18E-01	1.26E+00	6.99E-01	5.80E-01	3.24E+00
11. TRICHLOROTRIFLUOROETHANE	< 3.54E-01	< 2.34E-01	2.13E+00	6.99E-01	3.40E+00	1.04E+00
12. BENZENE	3.13E+02	6.69E+01	3.06E+01	3.84E+01	6.32E+02 *	2.27E+01
13. TOLUENE	2.10E+01	5.63E+00	1.86E+01	5.68E+00	4.66E+00	5.45E+00
14. ETHYLBENZENE	3.95E+00	2.46E+00	1.94E+00	1.50E+00	1.75E+00	< 1.16E+00
15. P-XYLENE	3.23E+00	1.29E+00	2.32E+00	1.90E+00	4.92E+01	9.43E+01
16. M-XYLENE	8.99E+00	2.23E+00	4.17E+00	1.86E+01	5.70E+01	1.74E+00
17. CUMENE	< 1.80E+00	1.17E+00	1.36E+00	9.19E+00	3.30E+00	4.06E+00
18. O-XYLENE	4.49E+00	2.23E+00	3.00E+00	4.39E+00	2.33E+00	1.62E+00
19. MESITYLENE	1.98E+00	< 1.17E+00	< 9.68E-01	5.00E+00	4.64E+01	4.52E+01
20. NAPHTHALENE	5.39E+00	1.10E+01	3.49E+00	5.29E+00	1.38E+01	5.56E+00
21. METHYLISOBUTYLKETONE	2.01E+01	7.51E+01	< 9.68E-01	**	**	**

* Possible coelution of another unknown compound
** Test results withheld pending confirmation by mass spectrometry
< less than

RT-1S First Sample in Stack
RT-2S Second Sample in Stack
RT-3S Third Sample in Stack
RT-1D First Sample at Inlet of Scrubber
RT-2D Second Sample at Inlet of Scrubber
RT-3D Third Sample at Inlet of Scrubber

TABLE B-27

PCDD/PCDF CONCENTRATIONS IN BOTTOM ASH AND SCRUBBER EFFLUENT

SAMPLE No. a/	B-1 ng/g	B-2 ng/g	B-3 ng/g	S-1 ng/L	S-2 ng/L	S-3 ng/L
DIOXINS						
2,3,7,8-TCDD	<0.015		<0.034			
Total TCDD	2.4	<0.074	0.25	< 0.57	< 4.0	< 0.70
1,2,3,7,8-PeCDD	<0.055 *		<0.045			
Total PeCDD	2.6	< 0.45	0.15	< 0.96	< 3.7	< 2.3
1,2,3,4,7,8-HxCDD	<0.076		<0.059			
1,2,3,6,7,8-HxCDD	<0.091		<0.059			
1,2,3,7,8,9-HxCDD	<0.060 *		<0.059			
Total HxCDD	0.27	< 0.41	0.16	< 1.3	< 1.6	< 2.0
1,2,3,4,6,7,8-HpCDD	0.61					
Total HpCDD	1.4	< 0.48	<0.095 *	< 1.3	< 6.3	< 3.2
Total OCDD	0.76	< 0.24	< 0.14	< 2.4	< 4.0	< 3.5
Total PCDD	7.43		0.56			
FURANS						
2,3,7,8-TCDF	0.20					
Total TCDF	2.5	< 0.18	< 0.14 *	< 0.92	< 1.7	< 0.68
1,2,3,7,8-PeCDF	0.23					
2,3,4,7,8-PeCDF	0.20					
Total PeCDF	2.3	< 0.27	<0.060 *	< 1.3	< 2.2	< 1.9
1,2,3,4,7,8-HxCDF	0.24					
1,2,3,6,7,8-HxCDF	0.20					
2,3,4,6,7,8-HxCDF	<0.077					
1,2,3,7,8,9-HxCDF	0.46					
Total HxCDF	3.1	< 0.24	<0.038 *	< 0.59	< 1.3	< 0.77
1,2,3,4,6,7,8-HpCDF	1.5					
1,2,3,4,7,8,9-HpCDF	< 0.16 *					
Total HpCDF	2.1	< 0.29	<0.081	< 0.96	< 4.4	< 3.4
Total OCDF	0.72	< 0.17	<0.068	< 2.3	< 5.6	< 3.7
Total PCDF	10.72					

Symbol (<) indicates below limit of detection
Symbol (*) indicates chemical interference
a/ B- indicates bottom ash sample
S- indicates scrubber effluent sample

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United States
Environmental Protection
Agency

Office of Air Quality
Planning and Standards
Research Triangle Park NC 27711

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Alternative Control Technology Document — Ethylene Oxide Sterilization/Fumigation Operations

EPA-450/3-89-007

Alternative Control Technology Document – Ethylene Oxide Sterilization/Fumigation Operations

Emissions Standards Division

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Air and Radiation
Office of Air Quality Planning and Standards
Research Triangle Park, North Carolina 27711
March 1989

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1.0 INTRODUCTION

The Clean Air Act (CAA) identified December 31, 1987, as the latest date for attainment of the national ambient air quality standard (NAAQS) for ozone. As of this writing, many areas of the country are not in attainment with the ozone NAAQS. The U. S. Environmental Protection Agency (EPA) has proposed to require States that have ozone nonattainment areas to submit revised State implementation plans (SIP's) that describe what steps will be taken to attain the standard (52 FR 45044, November 24, 1987).

Under the proposed rule (52 FR 45044), to demonstrate attainment of the NAAQS for ozone, emissions of volatile organic compounds (VOC's) must be reduced to a level that will produce ozone concentrations consistent with NAAQS as demonstrated by atmospheric dispersion modeling. Once the State has determined the VOC emission reduction required to meet the NAAQS, it must identify and select control measures that will produce the required reductions as expeditiously as practicable.

In 1985, EPA published a Federal Register notice titled "Assessment of Ethylene Oxide as a Potentially Hazardous Air Pollutant." The conclusion of that notice, based on the information available, was that EPA intended to list ethylene oxide (EO) under Section 112 of the CAA if emission standards were warranted. Therefore, a reduction in EO emissions (which also is a VOC) contributes to attainment of the NAAQS for ozone and reduces potential health risks from direct exposure to EO.

This report presents technical information that State and local agencies can use to develop strategies for reducing VOC (i.e., EO) emissions for sterilization/fumigation facilities. The information in this document will allow planners to (1) identify available control alternatives and (2) evaluate the VOC reduction and cost of implementing controls.

This document provides information on sterilization/fumigation processes, EO emissions, and emission reductions, and cost associated with the application of control units. Section 2.0 presents a summary of the findings of this study. Section 3.0 provides a description of sterilization/fumigation facility operations and emission sources.

Section 4.0 provides a description of alternative control techniques for the reduction of ethylene oxide emissions. Section 5.0 presents a cost analysis that includes a methodology for computing annualized equipment and operating costs.

A list of contacts at various Federal agencies who are knowledgeable about sterilization/fumigation processes is presented in Appendix A.

2.0 SUMMARY

Ethylene oxide (EO) is used as a sterilant/fumigant in the production of medical equipment supplies, in miscellaneous sterilization and fumigation operations, and at hospitals. Available information indicates that EO is used at over 200 commercial sterilization facilities in the U.S. and at approximately 7,000 hospitals. These facilities use EO as a sterilant for heat- or moisture-sensitive materials or as a fumigant to control microorganisms or insects. A variety of materials are sterilized or fumigated with EO, including medical equipment (e.g., syringes and surgical gloves), spices, cosmetics, and pharmaceuticals. These materials may be sterilized at the facility that produces or uses the product or by contract sterilizers (i.e., firms under contract to sterilize products manufactured by other companies). Libraries and museums use EO to fumigate books and other historical items. State departments of agriculture control diseases of bees by fumigating beehives with EO.

Practically all of the EO used in sterilization/fumigation processes is estimated to be emitted from three sources: (1) the sterilizer vent(s) (i.e., the vent from the vacuum pump gas/liquid separator), (2) the vacuum pump drain, and (3) the aeration room or chamber. Uncontrolled emissions from these sources are assumed to be 50 percent, 45 percent, and 5 percent of the EO use, respectively. The total amount of EO used by the 203 commercial sterilization facilities (i.e., not hospitals) represented in the EPA sterilization data base is 2,270 Megagrams per year (Mg/yr) (5 million lb/yr). Estimated emissions from these 203 facilities are 760 Mg/yr (1.7 million lb/yr) from sterilizer vents, 1,000 Mg/yr (2.2 million lb/yr) from vacuum pump drains, and 110 Mg/yr (0.25 million lb/yr) from aeration room vents. The sterilizer vent emissions are less than 50 percent of the EO use because several of these 203 facilities control EO emissions from the sterilizer vent. However, drain and aeration room emissions at these facilities are assumed to be uncontrolled. Based on approximately 80 responses to a 1986 information request to Federal hospitals and information in the 1988 American Hospital Association data base, EO use at hospitals is estimated to be approximately 1,000 Mg/yr. Because the majority of hospitals do not use

EO emission controls, EO emissions from hospitals are assumed to equal the EO use of approximately 1,000 Mg/yr.

Three primary techniques are applicable to the control of EO emissions from sterilization/fumigation processes: acid hydroysis (i.e., acid-water scrubbers), oxidation, and a gas/solid reactor system that chemically reacts EO and binds it to the solid reactor packing. Control efficiencies for those techniques range from 98.0 percent to 99.0 percent for sterilizer vent emissions. However, the control efficiencies of these devices have not been demonstrated for the low EO concentrations from aeration processes. Acid hydrolysis and thermal oxidation are applicable to the control of sterilizer vent emissions from the larger sterilizers (>2.8 m^3 [100 ft^3]) at commercial sterilization facilities. Several hospitals use catalytic oxidation or scaled-down acid-water scrubbers to control emissions from hospital sterilization chambers. Catalytic oxidation and the gas/solid reactor system are used by several hospitals and a few commercial sterilization facilities to control EO emissions from aeration rooms or aeration chambers. Closed-loop recirculating fluid vacuum pumps can virtually eliminate drain EO emissions by routing the gaseous phase exiting the gas/liquid separator to the sterilizer emission control device.

Federal regulations for stratospheric ozone-depleting chlorofluorocarbons (CFC's) have been developed under EPA's Stratospheric Ozone Protection Program (SOPP). The majority of commercial sterilization facilities and almost all hospitals use a sterilant gas mixture known as 12/88, which is 12 weight percent EO and 88 weight percent dichlorodifluorocarbon (CFC-12). The use of CFC's in sterilant gases is one of the source categories subject to the CFC regulations. However, the requirements of a CFC regulation would not affect the ability of a sterilization facility to control EO emissions.

The cost of controlling EO emissions from sterilizer vents at three of the commercial sterilization facilities represented in EPA's data base are presented in Table 2-1. Acid hydrolysis was chosen as the basis for the cost calculations because that control technique currently is practiced at many commercial facilities and has been demonstrated at both small and large commercial sterilization facilities. Detailed cost

TABLE 2-1. CONTROL COSTS FOR ACID HYDROLYSIS AT COMMERCIAL STERILIZATION FACILITIES[a] [b]

Model plant	Total sterilizer volume, m^3 (ft^3)	Annual EO use, Mg (lb/1,000)	Capital costs, $	Annualized costs, $	Annual emission reduction, Mg (lb/1,000)[c]
Small[d]	2.8 (100)	0.18 (0.39)	76,000	21,200	0.17 (0.37)
Medium[e]	28 (1,000)	3.9 (8.7)	160,000	40,800	3.7 (8.2)
Large[f]	168 (6,000)	109 (240)	291,000	117,000	102 (226)

[a]These cost estimates are not applicable to hospitals because the acid-water scrubbers costed are not designed for the low flowrates from the vacuum pumps on hospital sterilizers.
[b]See Chapter 5 and Appendix B for the methodology used to calculate these control costs.
[c]Calculated as (0.99)x(0.95)(EO use). Five percent of the EO use is assumed to be retained in the product after sterilization and emitted from the aeration room, which is assumed to be uncontrolled.
[d]The small model plant has one chamber and uses 12/88 (EO/CFC-12). Therefore, a model 100 scrubber (see Table 5-2) was chosen as the basis for the calculations.
[e]The medium model plant has one chamber and uses 12/88 gas. Therefore, a model 400 scrubber was chosen as the basis for the calculation.
[f]The large model plant has seven chambers and uses 100 percent EO. The sum of the volumes of the two largest chambers is 2,000 ft^3. Therefore, a model 500 scrubber (with explosion-proof valves) was chosen as the basis for the calculations.

estimates have not been developed for the control of EO emissions from hospitals or aeration processes. However, preliminary control cost estimates for hospitals have been developed by EPA's Office of Research and Development (see Chapter 5). Also, the Office of Air Quality Planning and Standards currently is developing control cost estimates for aeration rooms, which should be available by June 1989. (See Appendix C for preliminary aeration control costs.)

Possible alternatives to EO sterilization include radiation, chlorine dioxide, gas plasma, hydrogen peroxide, ozone, X-ray (a new, developing technology), deep freezing (museums and spice industry), and increased use of disposable medical items in hospitals. However, none of these alternatives can replace the use of EO in all applications.

3. ETHYLENE OXIDE STERILIZATION/FUMIGATION PROCESSES AND EMISSIONS

3.1 BACKGROUND INFORMATION

Ethylene oxide (EO) is used as a sterilant/fumigant in the production of medical equipment supplies, in miscellaneous sterilization and fumigation operations, and at hospitals. Available information indicates that EO is used at over 200 commercial sterilization facilities in the U.S. and at approximately 7000 hospitals.[1-3] These facilities use EO as a sterilant for heat- or moisture-sensitive materials or as a fumigant to control microorganisms or insects. A variety of materials are sterilized or fumigated with EO, including medical equipment (e.g., syringes and surgical gloves), spices, cosmetics, and pharmaceuticals. These materials may be sterilized at the facility that produces or uses the product or by contract sterilizers (i.e., firms under contract to sterilize products manufactured by other companies). Libraries and museums use EO to fumigate books and other historical items. State departments of agriculture control diseases of bees by fumigating beehives with EO.

Information about facilities that use EO as a sterilant/fumigant was obtained from three sources: (1) a survey of medical equipment suppliers conducted by the Health Industry Manufacturer's Association (HIMA) in 1985, (2) an information request submitted by EPA under Section 114 of the Clean Air Act to miscellaneous sterilizers and fumigators (identified during an extensive survey of potential users) in July 1986, and (3) an information request in January 1986 to Federal hospitals and nine of the largest non-Federal hospitals. A total of 203 commercial sterilization facilities (i.e., not hospitals) responded to the HIMA survey and the July 1986 EPA information request. Data from these responses comprise the EPA sterilization data base. Approximately 80 hospitals responded to the January 1986 information request.

As shown in Table 3-1, the facilities represented in the EPA commercial sterilization data base are located in 43 States and Puerto Rico. These facilities were grouped by Standard Industrial Classification (SIC) into the following categories:

TABLE 3-1. LOCATIONS OF COMMERCIAL STERILIZATION FACILITIES--EPA DATA BASE[1,2]

State	No. of facilities[a]		No. of facilities[a]
Arizona	3	Missouri	5
California	21	New Hampshire	2
Colorado	3	New Jersey	18
Connecticut	6	New York	14
Delaware	2	North Carolina	7
Florida	5	Ohio	2
Georgia	4	Pennsylvania	10
Illinois	8	Puerto Rico	14
Indiana	4	Rhode Island	2
Iowa	3	South Carolina	3
Maryland	5	Tennessee	3
Massachusetts	9	Texas	11
Michigan	8	Utah	2
Minnesota	6	Virginia	5
Mississippi	2	Washington	2
Subtotal	89	Subtotal	100

The EPA data base includes one facility located in each of the following States: Alabama, Alaska, Arkansas, Hawaii, Kentucky, Maine, Nebraska, Nevada, New Mexico, North Dakota, Oregon, South Dakota, Wisconsin, West Virginia.

Subtotal	14
Total No. of facilities	203

[a]Does not include hospitals.

1. medical equipment suppliers;
2. pharmaceuticals;
3. other health-related industries;
4. spice manufacturers;
5. contract sterilizers;
6. libraries, museums, and archives;
7. laboratories (research, testing, and animal breeding); and
8. State departments of agriculture.[4]

Table 3-2 shows the number of facilities in the EPA commercial sterilization data base for the eight categories listed above. Table 3-2 also shows the SIC codes represented by these industry categories.

3.2 PROCESS DESCRIPTION

There are two main types of EO sterilization processes: (1) bulk sterilization and (2) single-item sterilization. These processes are described below.

3.2.1 Bulk Sterilization

Bulk sterilization is the more commonly used EO sterilization process; 98 percent of the commercial sterilization facilities represented in the EPA data base use this process.[1,2] The products to be sterilized are placed in a sterilization chamber and are exposed to a sterilant gas at a predetermined temperature, humidity level, and pressure. The equipment, sterilant gases, and sterilization cycle used for bulk sterilization processes are described below.

3.2.1.1 Equipment. A schematic of a gas sterilizer is shown in Figure 3-1. The main components of the sterilizer are the chamber and vacuum pump. Chambers used by commercial sterilization facilities typically range in volume from 2.8 cubic meters (m^3) (100 cubic feet [ft^3]) to 28 m^3 (1,000 ft^3).[1,2] Table 3-3 presents size data for the chambers in the EPA commercial sterilization data base. Sterilization chambers at hospitals range from less than 0.3 to 2 m^3 (10 to 70 ft^3) but are typically about 0.6 to 0.8 m^3 (20 to 30 ft^3).[5]

A vacuum pump is used to remove air from the chamber before sterilization begins and to evacuate the sterilant gas after the sterilization cycle is complete. Typically, a once-through, water-ring vacuum pump is used. Oil-sealed vacuum pumps or vacuum pumps that use

TABLE 3-2. NUMBER OF FACILITIES AND STANDARD INDUSTRIAL CLASSIFICATION (SIC) PER INDUSTRY CATEGORY--EPA COMMERCIAL STERILIZATION DATA BASE[4]

Industry category	No. of facilities[a]	SIC
Medical equipment suppliers	64	3841, 3842
Pharmaceuticals	40	2834, 5122, 2831, 2833
Other health-related industries	25	3079, 3693, 5086, 2211, 2821, 2879, 3069, 3569, 3677, 3999
Spice manufacturers	25	2099, 5149, 2034, 2035, 2046
Contract sterilizers	17	7399, 7218, 8091
Libraries, museums, and archives	13	8411, 8231
Laboratories (research, testing, and animal breeding)	11	0279, 7391, 8071, 8922, 7397
State departments of agriculture	8	9641
Total	203	

[a]Does not include hospitals.

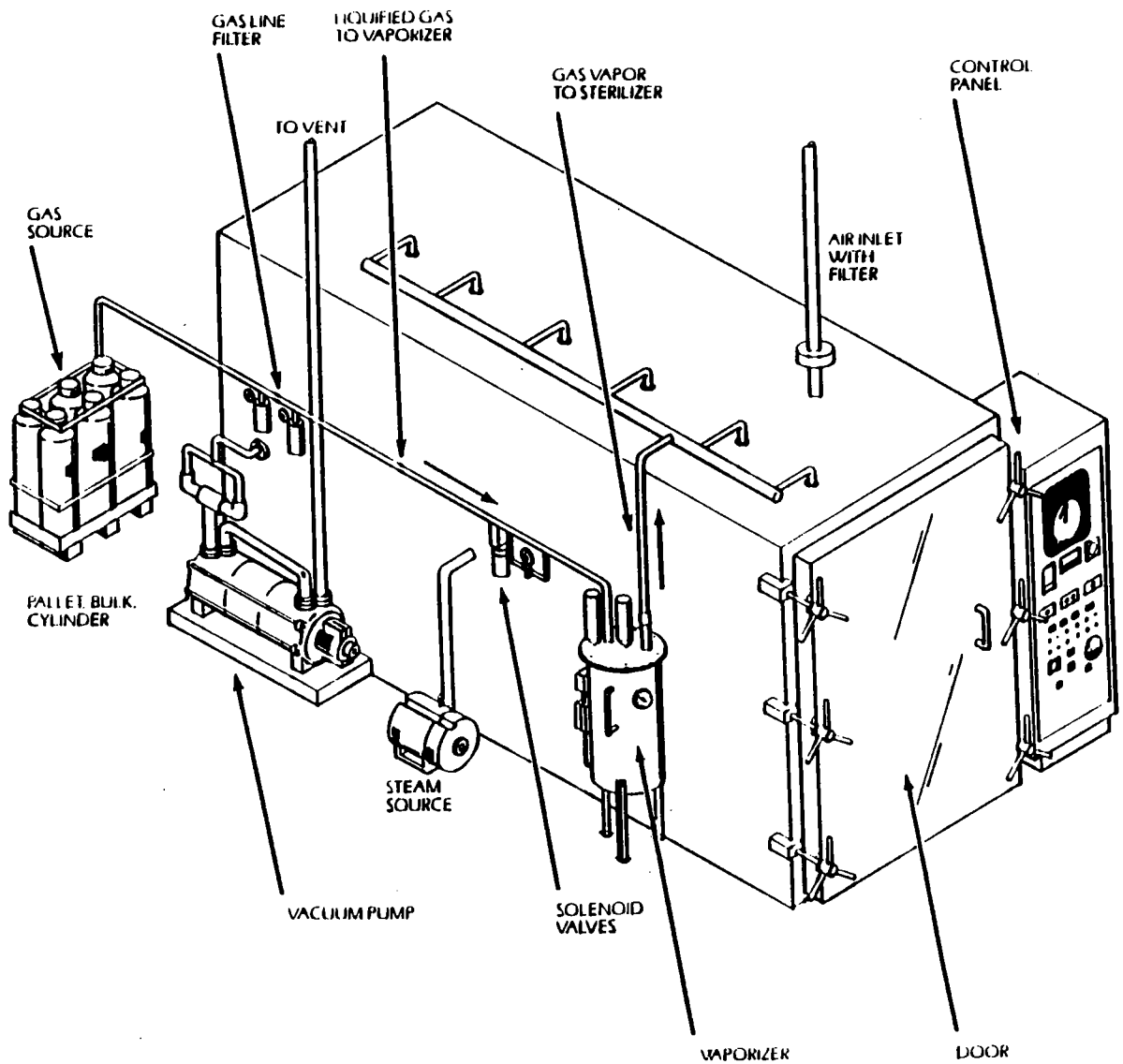

Figure 3-1. Schematic of a gas sterilizer. (Courtesy of Union Carbide Corporation, Linde Division.)[12]

TABLE 3-3. CHAMBER SIZES--EPA COMMERCIAL STERILIZATION DATA BASE[1,2]

Size range, m^3 (ft^3)	No. of chambers[a]	Percent	Cumulative No. of chambers	Cumulative, percent
≤1.4 (≤50)	87	20	87	20
1.5-2.8 (51-100)	29	7	116	27
2.9-14 (101-500)	111	26	227	53
15-28 (501-1,000)	130	29	357	84
29-57 (1,001-2,000)	60	14	417	98
≥58 (≥2,001)	10	2	427[b]	100

[a]Does not include hospitals.
[b]This number excludes four single-item sterilization units, one 55-gal drum user, and two facilities that did not report a chamber size.

recirculated water also are used. There are indications that some commercial sterilization facilities and hospitals are converting from once-through water-ring vacuum pumps to full sealant recovery vacuum pumps in order to meet the 1 part per million by volume (1 ppmv) Occupational Safety and Health Administration (OSHA) standard for EO and proposed State regulations.[6,7]

3.2.1.2 Sterilant Gases. Ethylene oxide is an extremely effective sterilant gas. The EO penetrates product packaging (e.g., cardboard shipping box, plastic shrink wrap, paper box, and final product wrapping) and destroys bacteria and viruses on the product. The product remains sterile until use because bacteria and viruses cannot penetrate the product wrapping.

The most widely used sterilant gas is a mixture of 12 percent by weight EO and 88 percent by weight dichlorodifluoromethane (CFC-12), referred to as 12/88. Two other commonly used sterilant gases are (1) pure EO (i.e., 100 percent EO) and (2) a mixture of 10 percent by weight EO and 90 percent by weight carbon dioxide (CO_2), referred to as 10/90. Other sterilant gas mixtures that are used include 20/80, 30/70, and 80/20 (weight percents EO/CO_2).[1,2] Gas mixtures that contain 20 percent or greater EO (by weight) are considered flammable. The 80/20 (EO/CO_2) mixture has the same flammability range as pure EO.[12] Physical and chemical properties of EO, CFC-12, and CO_2 are given in Table 3-4. Table 3-5 shows the number of commercial sterilization facilities represented in the EPA data base that use a particular gas type and the amount of EO used for each gas type. Since many commercial sterilization facilities operate more than one sterilization chamber, the gas usage rates in Table 3-5 also are presented on a chamber basis.[1,2] Seventy-five percent of the hospitals that responded to the 1986 information request use 12/88. The rest use pure EO in the form of ampules or single-use cartridges. At hospitals, pure EO is generally used only in very small ($<0.3m^3$ [$10ft^3$]) chambers.

The 12/88 mixture is the most popular sterilant gas for several reasons. Unlike pure EO, 12/88 is nonflammable and nonexplosive. Therefore, the use of 12/88 does not require explosion-proof rooms and additional safety precautions that are necessary when pure EO is used.

TABLE 3-4. PHYSICAL AND CHEMICAL PROPERTIES OF ETHYLENE OXIDE, DICHLORODIFLUOROMETHANE, AND CARBON DIOXIDE[8-11]

	Ethylene oxide	Dichlorodifluoromethane	Carbon dioxide
Other designations	1,2-epoxyethane, oxirane, dimethylene oxide	CFC-12, refrigerant 12, propellant 12	Carbonic acid gas, carbonic anhydride
Appearance	Colorless liquid or gas	Colorless gas, readily liquified under pressure and/or cooling	Colorless gas
Chemical formula	C_2H_4O	CCl_2F_2	CO_2
Molecular weight	44.0	120.9	44.0
Vapor pressure at 20°C (68°F)	146.0 kPa (21.2 psia)	567.6 kPa (82.3 psia)	5,731.0 kPa (831 psia)
Boiling point at 101.3 kPa (14.7 psi)	10.4°C (50.7°F)	-29.8°C (-21.6°F)	-78.5°C (-109.3°F)
Flammability limits in air	Lower 3 percent by volume Upper 80+ percent by volume[a]	Nonflammable	Nonflammable
Water solubility	Completely miscible	Low solubility	--
Heat of combustion, vapor at 25°C (77°F)	1,306 kJ/mol (12,760 Btu/lb)	111 kJ/mol (396 Btu/lb)	--
Threshold limit value (TLV) 8-h time weighted average (TWA)	1 ppmv	1,000 ppmv	5,000 ppmv

[a]Pure EO explodes by decomposition at 560°C (1040°F) with ignition.

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TABLE 3-5. STERILANT GAS TYPE USAGE--EPA COMMERCIAL STERILIZATION DATA BASE[1,2]

Sterilant gas	No. of facilities[a b]	Percent of facilities	No. of chambers[c]	Percent of chambers	EO use, Mg/yr[d]	Percent of total EO use
12/88 (EO/CFC-12)	154	76	295	68	720	30
Pure EO	44	22	122	28	1,350	60
10/90 (EO/CO_2)	14	7	19	4	4	<0.01
Other mixtures[e]	16	8	25	6	190	10

[a]Does not include hospitals.
[b]There are 203 commercial sterilization facilities in the EPA data base. Approximately 10 percent of these facilities use more than one type of sterilant gas.
[c]There are 434 operational sterilization "chambers" (the four single-item sterilization systems are counted as chambers) in the EPA commercial sterilization data base. More than one type of sterilant gas is used in 5 percent of these chambers.
[d]Amount of EO in the sterilant gas mixture.
[e]Includes mixtures of EO and CO_2 with a weight percent of EO ranging from 20 to 80 percent and custom mixes.

The 10/90 mixture also is nonflammable and nonexplosive.[12] But, because 10/90 is only 10 percent EO by volume whereas 12/88 is 27.3 percent EO by volume, 10/90 requires higher operating pressures to obtain an EO concentration that is sufficient for effective sterilization (approximately 304 kilopascals [kPa], or 44 pounds per square inch absolute [psia], for 10/90, as compared to 170 kPa [24.7 psia] for 12/88).[13] The chambers used for 10/90 sterilization must be ASME-rated pressure vessels, (i.e., manufactured in accordance with Section VIII, Division I, of the ASME Pressure Vessel Code) and are, therefore, more expensive to construct than the chambers used with 12/88. However, because of insurance requirements, many commercial sterilization facilities use chambers that meet requirements for ASME-rated pressure vessels when sterilizing with 12/88 or with explosive mixtures below ambient pressure.[14]

3.2.1.3 Sterilization Cycle. The typical sterilization cycle consists of five phases: (1) presterilization conditioning, (2) sterilization, (3) evacuation, (4) air wash, and (5) aeration. Figures 3-2 and 3-3 show pressure/time curves for the first four phases of the 12/88 sterilization cycle and the pure EO sterilization cycle, respectively. Steps 1 through 4 typically require about 8 hours at larger commercial sterilization facilities, and about 2 to 4 hours at hospitals.

3.2.1.3.1 Presterilization conditioning. After the products have been loaded into the chamber and the airtight door sealed, a partial vacuum is drawn inside the chamber. This initial vacuum, or drawdown, prevents dilution of the sterilant gas. Also, if flammable sterilant gases are used, the removal of air reduces the potential for ignition.[12] The chamber pressure is reduced to a pressure of about 6.9 to 69 kPa (1 to 10 psia) for 12/88 and 3 kPa (0.4 psia) for pure EO. The initial drawdown takes from about 5 to 45 minutes, depending on the product being sterilized. Certain products require a longer drawdown time because they are damaged by sudden pressure changes. The chamber temperature is then adjusted to between 38°C (100°F) and 54°C (130°F). A higher temperature will increase the diffusion rate of EO into the products and, thus, will reduce the time the products must be exposed to the sterilant gas to ensure proper sterilization. Finally, the relative humidity is raised to

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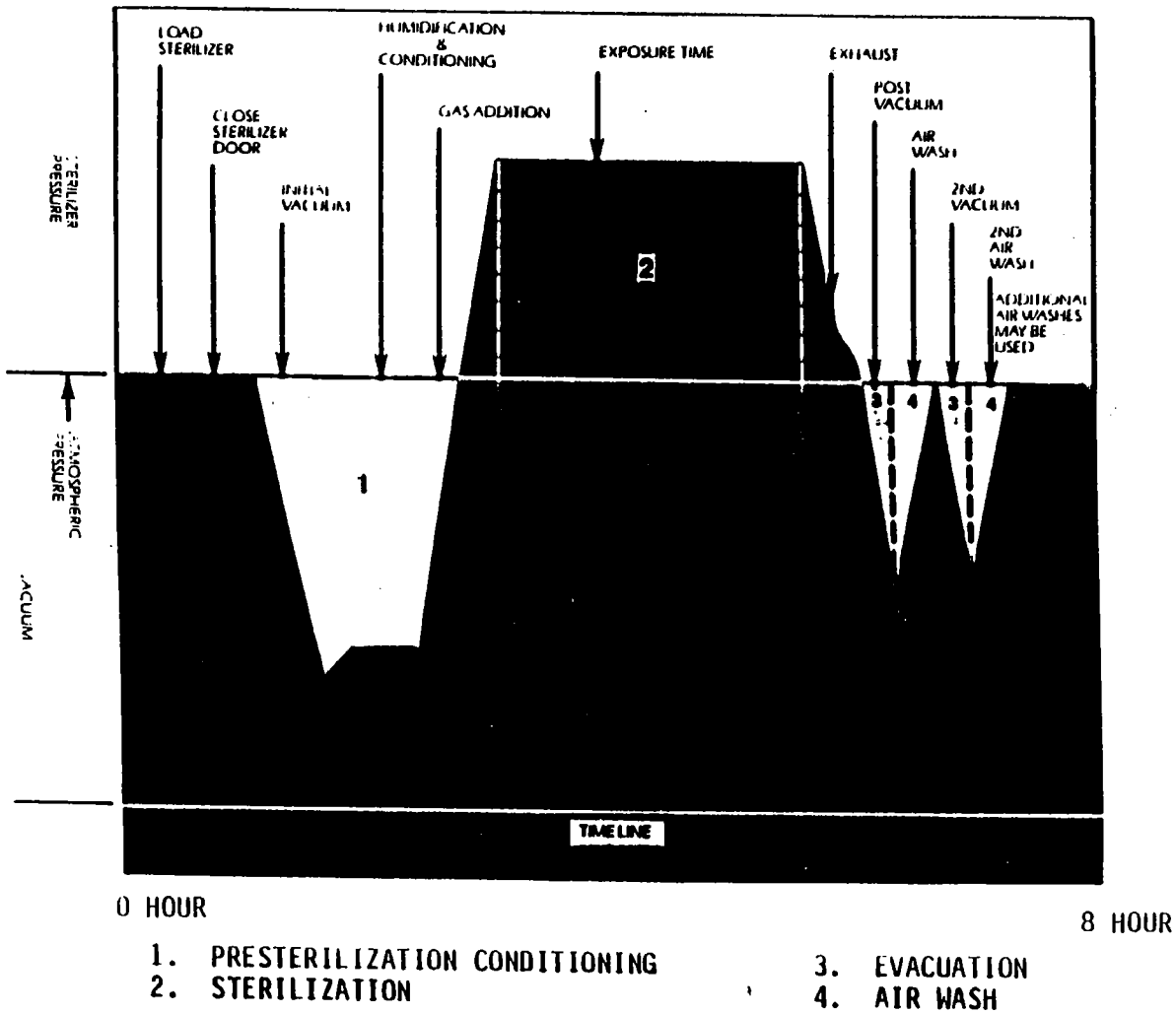

Figure 3-2. Sterilization cycle for 12/88. (Courtesy of Union Carbide Corporation, Linde Division.)[12]

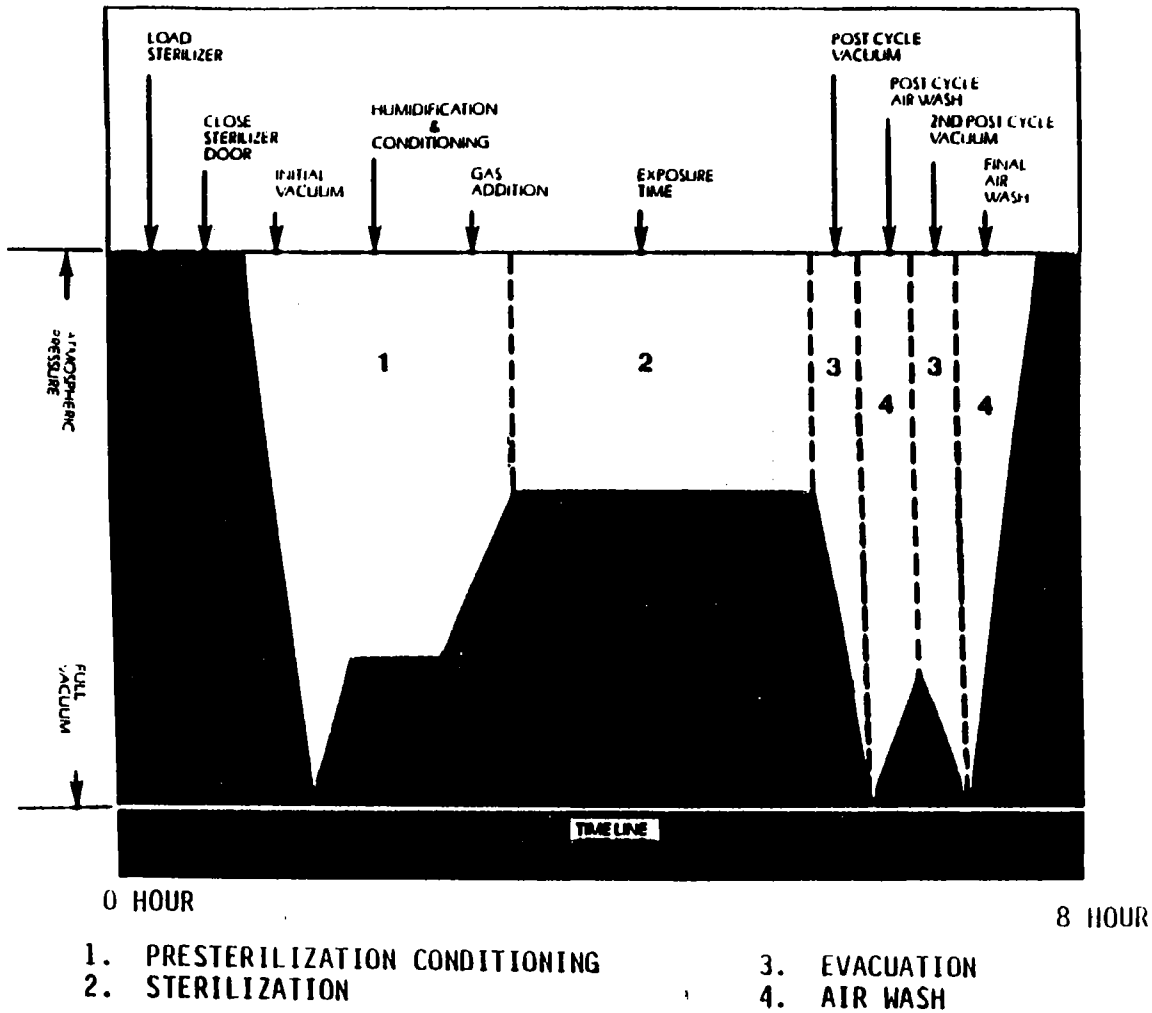

Figure 3-3. Sterilization cycle for pure EO. (Courtesy of Union Carbide Corporation, Linde Division.)[12]

about 45 percent by injecting steam. Proper humidification is important to the process because the susceptibility of microorganisms to the sterilant gas is increased under moist conditions.[12]

3.2.1.3.2 Sterilization. The sterilant, which is supplied as a liquid, is vaporized and introduced into the chamber to achieve the desired concentration of EO. The chamber pressure depends on the type of sterilant gas used. Pure EO is used under a slight vacuum at pressures of about 94 kPa (13.7 psia); the 12/88 mixture is used at pressures of about 170 kPa (24.7 psia). The pressure is held for about 4 to 6 hours. This exposure time is dependent on the temperature, pressure, humidity level, type of sterilant gas, and products being sterilized. For example, porous products require shorter exposures than nonporous products. Also, some bacteria are more resistant to EO and take longer to destroy.

3.2.1.3.3 Evacuation. Following sufficient exposure time, the sterilant gas is evacuated from the chamber with a vacuum pump. Typical evacuation pressures are 13 kPa (1.9 psia) for 12/88 gas and 3 kPa (0.4 psia) for pure EO. This postcycle vacuum phase lasts about 10 minutes.

3.2.1.3.4 Air wash. The pressure in the chamber is brought to atmospheric pressure by introducing air (when nonflammable sterilant gases are used) or either nitrogen or CO_2 (when flammable sterilant gases are used). The combination of evacuation and air wash phases is repeated from two to four times to remove as much of the EO from the product as possible. The air wash typically lasts 2 to 15 minutes.

The purpose of the air wash is to allow residual EO to diffuse from the product. Removal of EO from the product during the air wash helps meet Food and Drug Administration (FDA) guidelines on residual EO levels for medical devices, EPA residual tolerances for agricultural products, and the OSHA standard for exposure in the workplace.

3.2.1.3.5 Aeration. After the last air wash, the chamber doors are opened, and the sterile products are placed in an aeration room and kept there for several hours to days depending on the product. The purpose of aeration is to allow further diffusion of residual EO from the products prior to shipping to comply with the FDA and EPA residual EO guidelines. Ethylene oxide concentrations in the aeration room are maintained at

relatively low levels by ventilating the room at a rate of about 20 air changes per hour.

Recent information from industry contacts indicate that some commercial sterilization facilities are aerating some or all of the sterile products in heated enclosed aeration cells. In comparison to traditional warehouse-type aeration rooms, these cells are smaller in volume (<70m^3 [2500 ft^3]) with much lower ventilation rates. Consequently, the EO concentrations are usually higher than the 1 ppmv OSHA standard. However, worker exposure is reduced by not opening the door until the EO concentration drops and by limiting the frequency of opening the door. The main purpose of this type of aeration process is to increase the diffusion rate of EO out of the sterile product (by increasing the temperature) and, thus, reduce the aeration time.

Facilities that sterilize products infrequently may aerate in the sterilization chamber. Two basic chamber aeration processes are used. The first process involves cycling the chamber between atmospheric pressure and a slight vacuum pressure (i.e., a pressure of about 94 kPa [13.7 psia]) several times over a 12- to 24-hour period. The length of the cycles depends on the chamber size and vacuum pump capacity. The second process involves drawing an extreme vacuum (about 0.6 kPa [0.1 psia]) in the chamber and holding the vacuum for 24 to 48 hours.

Some hospitals and commercial sterilization facilities with smaller sterilizers (less than 1 m^3 [40 ft^3]) use aeration chambers (or cabinets), which are similar to the sterilization chambers in size and design. Sterile products at hospitals are aerated for about 24 hours.

3.2.2 Single-Item Sterilization System

Four of the 203 commercial sterilization facilities (2 percent) that responded to the HIMA survey or the July 1986 EPA information request reported the use of a single-item sterilization system.[1,2] Three of these facilities use the Sterijet® system manufactured by H. W. Andersen Products; one facility uses another patented system that is similar to the Sterijet® system.[2] In contrast to the bulk sterilization chambers used by most commercial sterilization facilities, these systems are designed to sterilize small individual items (such as medical equipment supplies) in sealed pouches. Marketing of these systems is primarily focused on hospital sterilization.[15]

The single-item sterilization systems consist of (1) a machine that delivers the sterilant gas through a nozzle, (2) flexible plastic pouches, and (3) an aeration cabinet. The process involves the following steps. The product to be sterilized is placed in a plastic pouch. With the open ends of the pouch sealed around the nozzle, a slight vacuum is drawn in the pouch followed by injection of a premeasured quantity of sterilant gas. The amount of sterilant gas injected depends on the size of the pouch. After the gas is injected, the nozzle is automatically withdrawn, and the pouch is heat sealed. The sealed pouches are placed directly into an aeration cabinet or temperature-controlled aeration room. The enclosed product is sterilized prior to the escape of the gas through the pouch, which is designed to retain the EO long enough to ensure proper sterilization. The products are sterilized for approximately 12 hours at about 50°C (122°F) and aerated for 36 hours.[15]

3.2.3 Beehive Fumigators

The process for beehive fumigators is essentially the same as bulk sterilization; however, a unique feature of the fumigators warrants a separate discussion. Whereas the sterilization processes described above are performed at one location, six of the eight State departments of agriculture represented in the EPA sterilization data base use portable chambers to fumigate beehives.[2] These fumigators are transported to and used at numerous and variable locations in each of the six States. The State departments of agriculture use an EO/CO_2 sterilant gas mixture. Typically, a garden hose is connected to the fumigation chamber and is placed along the ground for venting the sterilant gas during the evacuation phase of the sterilization cycle. After the evacuation, the beehive is removed from the chamber and aerated in the open air.

3.3 EMISSION SOURCES

The three principal sources of EO emissions from sterilization/fumigation processes are (1) the sterilizer vent(s) (i.e., the vent on the vacuum pump gas/liquid separator), (2) the sterilization chamber vacuum pump drain (assuming that a once-through, water-ring vacuum pump is used), and (3) the aeration room vent. A schematic of these emission sources is shown in Figure 3-4. Other potential emission sources are equipment leaks and storage and handling. For the purposes of developing emission

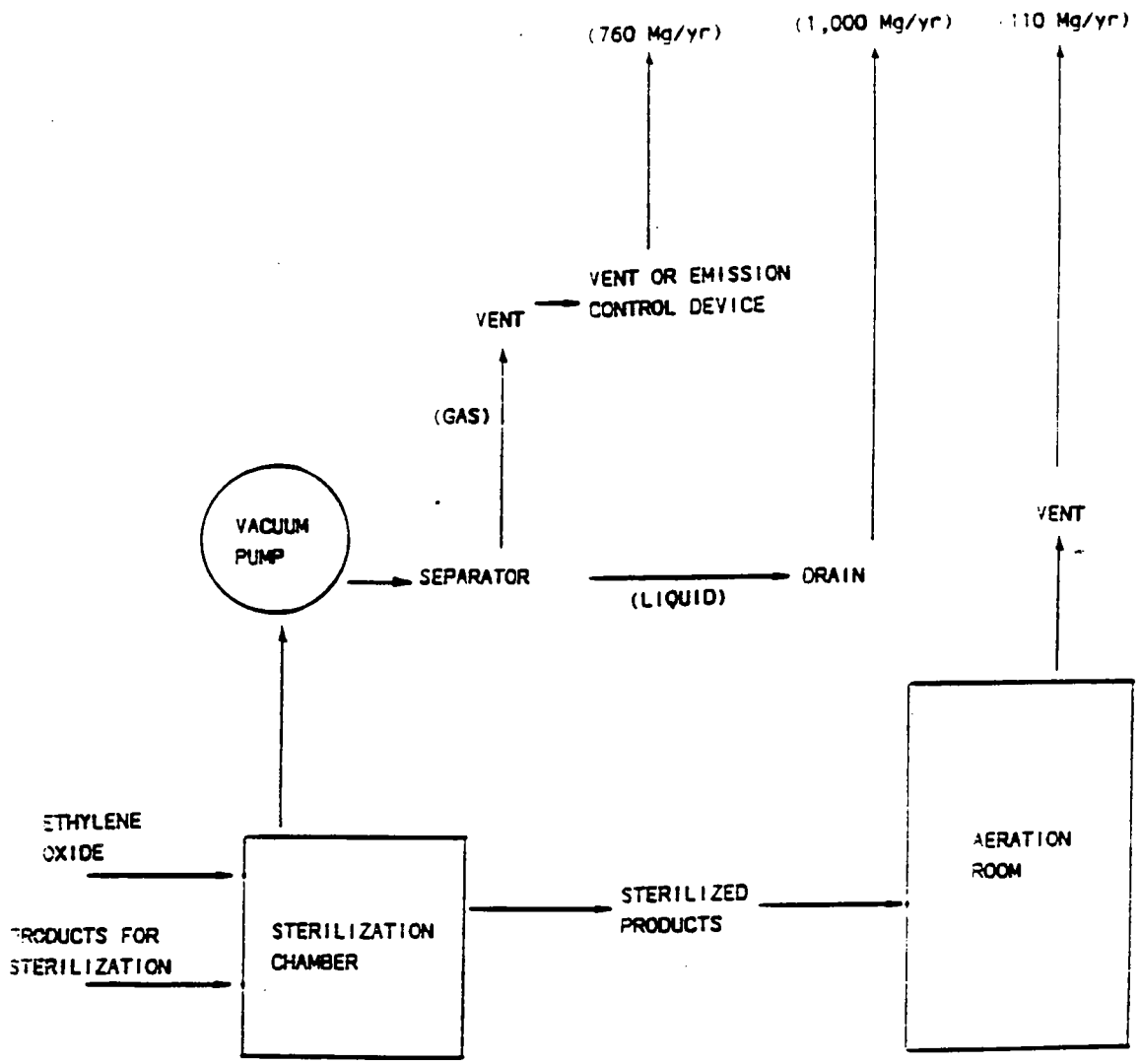

Figure 3-4. Schematic of emission sources at commercial sterilization facilities. (Does not include hospitals).

estimates and because bulk sterilization processes are the main source of emissions, emission sources were assumed to be the same for both sterilization processes (i.e., bulk and single-item).

3.3.1 Sterilization Chamber Vents

Sterilization chamber vent emissions are associated with the chamber vacuum pump. These vacuum pumps are typically once-through, liquid-ring designs that use water as the working fluid. During the evacuation phase of the sterilization cycle, a mixture of chamber gas and water is expelled from the pump to a centrifugal gas/liquid separator. In the separator, gas-phase EO is directed to a vent and emitted to the atmosphere. The liquids from the separator are directed to a sewer drain.

3.3.2 Sterilization Chamber Vacuum Pump Drains

Some of the EO that is released from the chamber during the evacuation phase enters the liquid-phase separator line with the vacuum pump water. Although some EO may be hydrolyzed to ethylene glycol, the conversion rate at ambient temperatures is extremely slow, requiring weeks for completion (see Figure 3-5).[8] Also, EO is rapidly released from an aqueous solution when agitated.[16] Therefore, virtually all of the EO that dissolves in the vacuum pump water is emitted from the water. The absorbed EO may be released at the 1-inch air break between the liquid pipe and drain (required by local plumbing codes) or may diffuse into other areas of the building as the water passes through the drain system. Any remaining EO would desorb into the head space of the sewer pipes (possibly creating flammable mixtures with air) and be emitted as it passes through the sewer or waste treatment systems.[6,8]

3.3.3 Aeration Room Vent

All emissions from residual EO in the product are referred to as aeration room vent emissions. As residual EO diffuses out of the sterile products in the aeration room or is emitted to the sterilization room when the chamber door is opened, it is emitted to the atmosphere via room ventilation. High ventilation airflow rates are used to maintain EO concentrations below the OSHA limit.

3.3.4 Equipment Leaks

Although equipment component counts (number of flanges, valves, etc.) were not obtained for the commercial sterilization facilities, observations

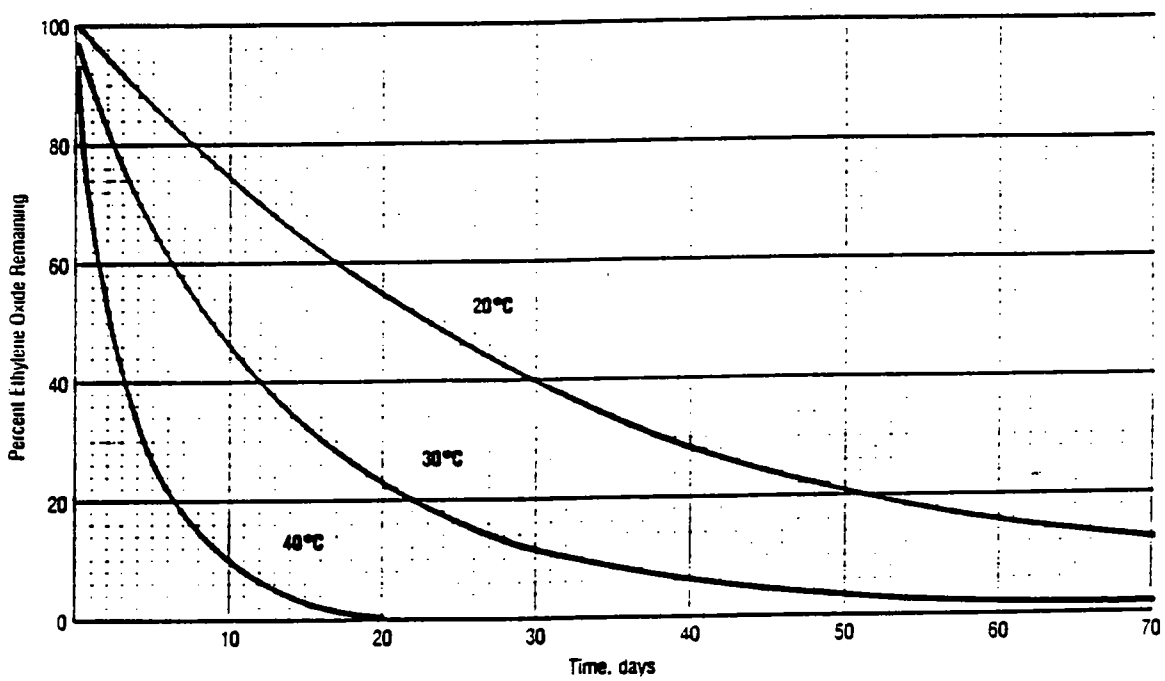

Figure 3-5. Hydrolysis rates of dilute, neutral aqueous solutions of ethylene oxide.
(Courtesy of Union Carbide Corporation, Ethylene Oxide/Glycol Division.)[8]

made during site visits indicated that the number of components is small. However, control of equipment leaks may be important to meet the 1 ppmv OSHA standard. For the purposes of this analysis, equipment leak emissions are assumed to be negligible.

3.3.5 Storage and Handling

Ethylene oxide at commercial sterilization facilities and hospitals is typically stored in pressurized cylinders rather than bulk containers. Therefore, material losses associated with loading and unloading bulk quantities of EO and storage tank breathing losses would not occur. Although bulk storage of sterilant gas at sterilization facilities is rare, at least one commercial sterilization facility stores bulk quantities of 12/88 in a pressure vessel. During transfer of the 12/88 from the tank truck to the pressure vessel, the vessel and the tank truck are vapor balanced. Therefore, emissions during transfer are expected to be negligible. Also, because the storage tank is a pressure vessel, no emissions should occur during routine operation. Consequently, commercial sterilization facilities and hospitals are likely to have negligible storage and handling emissions.

3.4 EMISSION ESTIMATES

3.4.1 Commercial Sterilization Facilities

The emission estimate for commercial sterilization facilities is based on the facility-specific annual EO usages and emission control levels reported in the 203 responses to the HIMA survey and the July 1986 EPA information request. Average EO emissions from these commercial sterilization facilities, based on total sterilizer volume, are presented in Table 3-6. The total amount of EO used by the 203 commercial sterilization facilities (i.e., not hospitals) represented in the EPA data base is 2,270 Mg/yr; approximately 16 percent (i.e., 370 Mg/yr) of this amount is controlled. Therefore, the EO emission estimate for the 203 facilities represented in the EPA commercial sterilization data base is 1,900 megagrams per year (Mg/yr).[1,2] Of this amount, it is estimated that 760 Mg/yr are emitted from sterilizer vents, 1,000 Mg/yr are emitted from sterilization chamber vacuum pump drains, and 110 Mg/yr are emitted from aeration room vents (see Figure 3-4). These estimates were developed using the HIMA survey, the July 1986 EPA information request responses, and the following assumptions:

TABLE 3-6. AVERAGE EMISSIONS FROM COMMERCIAL STERILIZATION FACILITIES--EPA DATA BASE[1,2]

Total chamber volume at facility, m^3 (ft^3)	No. of facilities[a]	Mean EO use, kg/yr (lb/yr)	Mean EO emissions, kg/yr (lb/yr)[b c]
<11 (<400)	88	660 (1,500)	640 (1,400)
11-56 (400-2,000)	77	7,600 (17,000)	6,800 (15,000)
>56 (>2,000)	38	43,000 (94,000)	34,000 (75,000)

[a]Does not include hospitals.
[b]Mean emissions are less than mean EO use because of existing controls.
[c]Emissions from all sources (i.e., sterilizer vent, vacuum pump drain, aeration).

1. All of the EO reported as used in the sterilization process is evacuated from the sterilization chamber or released from the product during aeration.

2. Within each facility, EO emissions are distributed among three emission points. The three emission points and the percentage of total EO emissions allocated to each are:

a. Sterilizer vent(s)--50 percent;

b. Sterilization chamber vacuum pump drain--45 percent; and

c. Aeration room vent(s)--5 percent.

This 50/45/5 percent split is based on industry estimates, limited test data, and engineering judgment.[17]

3. For the 355 sterilization chambers in the EPA commercial sterilization data base that are uncontrolled, all of the EO that enters the chamber vent(s) is released to the atmosphere. For the 79 sterilization chambers with emission control devices, the chamber vent emissions are controlled at the efficiencies reported on the HIMA survey and EPA information request responses.

4. At each facility, all of the EO that dissolves in the vacuum pump water and subsequently enters the drain is assumed to be emitted uncontrolled to the atmosphere at an outdoor ground-level drain near the facility. This assumption is consistent with test data that suggest EO is rapidly released from an aqueous solution when agitated.[16]

5. At each facility, all of the EO that enters the aeration room vent is released uncontrolled to the atmosphere.

3.4.2 Hospitals

The EO emission estimate for hospitals is based on data from the approximately 80 responses to the 1986 information request to hospitals and information in the 1988 American Hospital Association (AHA) hospital data base. Linear regression analyses of the 1986 data indicated that the annual EO use correlates better with the number of hospital beds (r^2 = 0.77) than with the number of surgical procedures (r^2 = 0.68).[18] A nationwide EO use rate of approximately 1,000 Mg/yr was obtained by extrapolating the 1986 data to the 1988 AHA data base, which contains hospital-specific information on the number of beds for 7064 hospitals.[19] Because the majority of hospitals do not use EO

emission controls, EO emissions from hospitals are assumed to equal the EO use of approximately 1,000 Mg/yr. Average EO emissions for hospitals, based on the number of hospital beds, is presented in Table 3-7.

3.5 CURRENT REGULATIONS

3.5.1 Occupational Safety and Health Administration Standard

In 1984, OSHA established a permissible exposure limit for occupational exposure to EO of 1 ppmv determined as an 8-hour time-weighted average (TWA) concentration. In addition, an action level of 0.5 ppmv as an 8-hour TWA was established as the level above which employers must monitor employee exposure.[20] In April 1988, OSHA established a short-term excursion limit (EL) for occupational exposure to EO emissions of 5 ppmv averaged over a 15-minute sampling period.[21]

3.5.2 State Regulations

Existing State regulations for EO are summarized in Table 3-8. Several States are currently regulating EO or developing air toxics programs.[22-28]

TABLE 3-7. AVERAGE EMISSIONS FROM HOSPITAL STERILIZERS[3,19]

Hospital size range	No. of hospitals	Mean EO use, kg/yr (lb/yr)[a]
Small (<200 beds)	4,907	70 (150)
Medium (200 to 500 beds)	1,645	200 (430)
Large (>500 beds)	512	790 (1,740)

[a]Because most hospitals do not control EO emissions, the EO emissions are assumed to equal the EO use.

TABLE 3-8. STATE REGULATIONS FOR ETHYLENE OXIDE EMISSIONS[22-28]

State	Regulatory description
California[a]	• Developing air toxics program but a regulation may not be proposed for 1 year. • South Coast--proposed rule for new (or modified) sources based on maximum 10^{-6} risk level, including aeration processes. • Bay Area--draft rule for new and existing sterilizers; no drain emissions; 99.5 percent control of vent emissions if EO_3use exceeds 250 lb/yr: exemptions--sterilizers smaller than 250 ft^3 and aeration processes.
Colorado	• Regulate as a volatile organic compound (VOC). • Reasonably available control technology (RACT) required for new sources.
Connecticut	• Best available control technology (BACT) required for all new or modified sources exceeding a maximum allowable stack concentration (MASC). • MASC is calculated using exhaust gas flow rate, stack height, and the distance from the discharge point to the property line. MASC would be exceeded for industrial sterilizers using typical sterilization cycles. Therefore, BACT required on new or modified sources. Existing sources exceeding the maximum allowable ambient concentration of 0.01 ppm have 3 years to comply with orders given by the Connecticut Department of Environmental Protection.
Florida[a]	• Maximum risk level of 10^{-6} for new or modified sources.
Michigan[a]	• BACT for all new sources. Requires emissions be indectable or subjected to risk analysis (maximum allowable risk level is 10^{-6}). For industrial sterilizers using typical sterilization cycles, a control efficiency based on a risk assessment analysis would be greater than 99 percent by weight.
Missouri	• Regulate as a VOC.
New Jersey	• Regulate as a VOC. • BACT required for new or modified sources.
New York[a]	• New or modified sources must receive 99 percent control or greater, or BACT (also at permit reviews) • Maximum annual impact must not exceed guideline Acceptable Ambient Level (AAL) of 6.67 $\mu g/m^3$ (a revised AAL of 0.019 $\mu g/m^3$ is anticipated for the next edition of Air Guide-1 [to be released by 01/90]. • Certificate of operation includes the following statement: "Should significant new scientific evidence from a recognized institution result in the decision by DEC that lower ambient levels must be established, it may be necessary to reduce emissions from this source prior to the expiration of this Certification of Operation."
Oklahoma	• Maximum ambient air concentration at property line is 1/100 of TLV.
Puerto Rico	• Regulate as a VOC. • Emission controls required for emissions greater than 3 lb/h or 15 lb/d.
Rhode Island[a]	• Maximum risk level of 10^{-6} for new and existing sources. • If BACT is used, may consider 10^{-5} risk level.
Tennessee	• Regulate under standards for process and nonprocess emissions.
Texas	• BACT required for all new sources.
Utah	• BACT required for all new or modified sources. BACT requirements to go into effect for existing sources. • Following the programs developed in New York.
Vermont	• Regulate as a VOC.
Virginia	• For any 24-hour concentration exceeding 1/100 of the TLV-TWA both existing and new facilities are required to control emissions as directed by the Virginia Air Pollution Control Board.
Wyoming	• BACT required for all new sources. • Controls must meet AAL at property line.

[a]Information obtained from State contacts in February 1989. All other information is from 1986 through 1987 data.

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4. EMISSION CONTROL TECHNIQUES

4.1 BULK STERILIZATION PROCESSES

The three principal sources of ethylene oxide (EO) emissions from bulk sterilization processes are:

1. The sterilizer vent(s) (i.e., the vent on the vacuum pump gas/liquid separator);
2. The sterilization chamber vacuum pump drain; and
3. The aeration room vent.

The following sections describe the techniques available to control EO emissions from these three sources. Table A-2 in Appendix A presents a list of the emission control devices and manufacturers.

4.1.1 Sterilization Chamber Vent Emissions

Three primary techniques are used to control EO emissions from sterilizer vents: hydrolysis, oxidation, and condensation. Ethylene oxide is catalytically hydrolyzed to form ethylene glycol; oxidation decomposes EO into carbon dioxide and water; and condensation allows the recovery of the sterilant gas mixture. A fourth control technique for sterilizer vents is a gas/solid reactor system that chemically reacts EO and binds it to the solid packing of the reactor.[1]

Table 4-1 shows the emission control techniques and devices used by the 203 commercial sterilization facilities (i.e., not hospitals) represented in the EPA data base (refer to Chapter 3 for a description of the contents and origin of the data base). Twenty-seven of these 203 commercial sterilization facilities (13 percent) reported the use of a control device for sterilizer vent emissions. Nineteen of these 27 facilities use one emission control device for multiple chambers by manifolding the chamber vents and staggering the evacuation of the sterilant gas from the chambers. The remaining eight facilities control emissions from single chambers.[2,3]

Nine additional commercial sterilization facilities reported the use of a neutral-water scrubber to control EO vent emissions. Neutral-water scrubbers reduce EO vent emissions by "washing" a portion of the EO to the drain (facilities reported 20 to 100 percent of the total EO emissions from the sterilizer chamber were "controlled" by a neutral-water

TABLE 4-1. ETHYLENE OXIDE EMISSION CONTROL DEVICES FOR STERILIZER VENTS--EPA COMMERCIAL STERILIZATION DATA BASE[2,3]

Emission control technique and device	Control efficiency, percent[a]	No. of facilities (percent)[b]	No. of chambers (percent)[b]	Chamber size, m^3 (ft^3)	EO usage/ facility, Mg/yr (lb/yr)
Hydrolysis					
Packed scrubber	99.0[c]	14 (7)	45 (10)	4-170 (140-6,000)	0.9-59 (2,000-130,000)
Reaction/detoxification tower	99.0	2 (1)	4 (1)	4-27 (140-960)	4 and 57 (9,500-126,000)
Caustic scrubber	30.0 and 95.0	1 (0.5)	2 (0.5)	32 and 60 (1,150 and 2,120)	44 (98,200)
Oxidation					
Flare	98.0[d]	2 (1)	5 (1)	2-77 (60-2,720)	34 and 80 (74,200 and 176,000)
Catalytic oxidizer	99.0	1 (0.5)	1 (0.2)	4 (130)	0.4 (1,000)
Condensation					
Condensation/reclamation system	50.0 - 88.0	7 (3)	20 (5)	5-45 (190-1,580)	7-46 (15,000-100,800)
TOTAL		27 (13)[e]	77 (18)[f]		790 (1,750,000)

[a]Control efficiencies are those reported by the 203 commercial sterilization facilities represented in the EPA data base, and are not necessarily supported by EPA-sponsored test data.
[b]Does not include hospitals.
[c]Although the 14 commercial sterilization facilities that use scrubbers reported control efficiencies ranging from 96.0 to 99.9 percent, a detailed review of the available test data for acid-water scrubbers indicates that 99.0 percent is the maximum removal efficiency that can be achieved on a continuous basis.[4]
[d]Although the two commercial sterilization facilities that use flares reported destruction efficiencies of 99.0 and 99.7 percent, the EPA's position is that flares operated within specified conditions of waste gas heat content and flare exit velocity will achive at least 98 percent destruction efficiency.[5]
[e]Total number of facilities = 203.
[f]Total number of chambers = 434.
[g]Represents 35 percent of the total EO used by the 203 commercial sterilization facilities represented in the EPA data base.

scrubber).[2,3] Some of the EO that is washed to the drain may be converted by hydrolysis to ethylene glycol; however, the conversion rate of EO to ethylene glycol in neutral water at ambient temperatures is extremely slow, requiring weeks for completion.[6] Since EO is rapidly released from an aqueous solution when agitated, the vast majority of the EO washed to the drain will off-gas uncontrolled from the air break in the drain line, sewer lines, or the waste treatment system.[6-8] Because the use of neutral-water scrubbers merely changes the EO emission source, they are not discussed here as a control technique.

The majority of hospitals do not control EO emissions from sterilizer vents. However, some hospitals use emission controls because of State and local regulations. Catalytic oxidation and the gas/solid reactor system are two techniques that are known to be used by hospitals to control EO emissions from sterilizer vents.[9-11]

4.1.1.1 Hydrolysis. Hydrolysis is the most common EO emission control technique used by commercial sterilization facilities.[2,3] This technique is applicable for both pure EO and EO/inert gas mixtures such as 12/88 (12 percent by weight EO and 88 percent by weight dichlorodifluoromethane [CFC-12]) and 10/90 (10 percent by weight EO and 90 percent by weight carbon dioxide). The majority of commercially available hydrolysis control devices are not designed for the low flow rates associated with chamber volumes less than 1.4 m^3 (50 ft^3) and are, therefore, not applicable to the control of most hospital sterilization chambers. However, two manufacturers have designed scaled-down acid-water scrubbers for flow rates less than 0.3 cubic meters per minute (m^3/min) [10 cubic feet per minute (ft^3/min.)].[11,12]

Ethylene oxide can be hydrolyzed under relatively mild conditions to ethylene glycol products (without affecting the inert gas) as shown in the following reaction:

$$C_2H_4O + H_2O \xrightarrow[H+ \text{ or } OH-]{} HOCH_2CH_2OH + HO(CH_2CH_2)_nOH$$

Ethylene oxide — Ethylene glycol — Polyethylene glycols

Ethylene oxide will hydrolyze in neutral water, but this reaction is very slow. (The half-life of EO in neutral water at ambient temperatures is approximately 14 days.)[8] The reaction rate is increased in an acidic or basic solution. The reaction is approximately two orders of magnitude faster under acidic conditions than under basic conditions, making acid hydrolysis the preferred method. Sixteen of the 203 commercial sterilization facilities represented in the EPA data base reported using acid-water scrubbers; one facility reported using caustic scrubbers to control EO emissions.[2,3]

4.1.1.1.1 Packed scrubbers. Figure 4-1 is a schematic of a packed scrubbing system used to control EO emissions. The system consists of a countercurrent packed tower, a reaction vessel, and a holding tank. In the countercurrent tower, the sterilant gas is contacted with an acidic water solution, generally aqueous sulfuric acid. Because EO is extremely water soluble, most of the EO is absorbed into the scrubber liquor. Next, the liquor is sent to the reactor vessel, which is a small storage tank operated at atmospheric pressure, to complete the hydrolysis of EO. After the reaction is complete, the liquor is sent to the storage vessel. The liquor in the storage vessel is recirculated to operate the tower until the concentration of the ethylene glycol in the liquor reaches a predetermined weight percentage, past which point the scrubber efficiency declines. Manufacturers of packed scrubbing systems suggest that the scrubbing liquor is spent when the solution is 30 to 40 percent by weight ethylene glycol.[13,14] Possible methods of determining when the liquor needs replacing include liquid level indicators or specific gravity detectors in the tank. (Both parameters increase as the amount of ethylene glycol increases.) Alternatively, the amount of EO charged to the sterilizer can be used to determine the liquor changeout point. The spent solution is neutralized and then disposed or sold. (See Section 4.1.1.1.3 for a more detailed discussion of waste disposal.) Generally, sodium hydroxide is used to neutralize the glycol solution; sodium carbonate also can be used.

Countercurrent packed scrubbers are used by commercial sterilization facilities with sterilizers ranging from 4.0 cubic meters (m^3) (140 cubic feet [ft^3]) to 170 m^3 (6,000 ft^3). Ethylene oxide use at these commercial

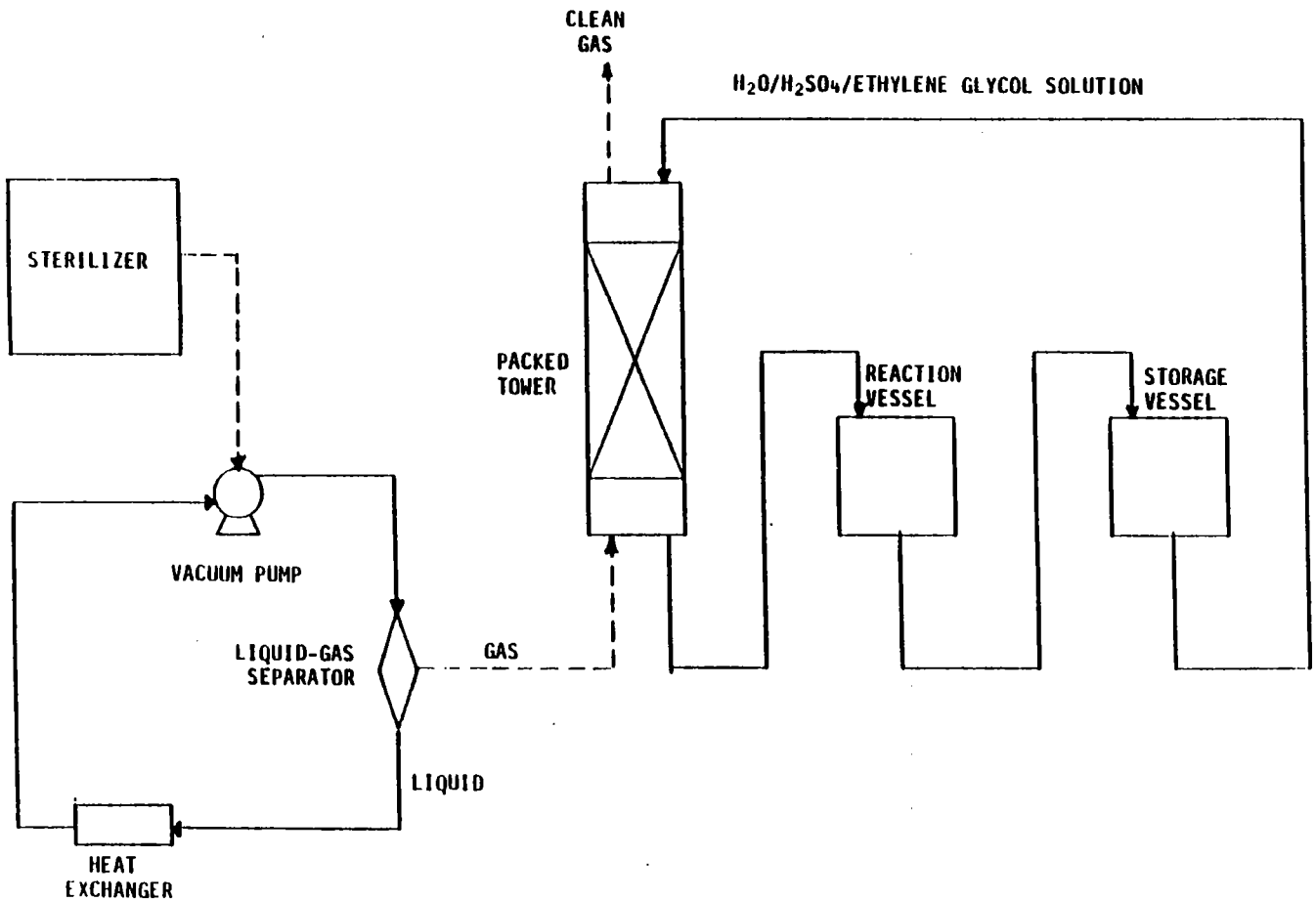

Figure 4-1. Countercurrent packed scrubbing system.

sterilization facilities ranges from 0.9 Mg/yr (2,000 lb/yr) to 59 Mg/yr (130,000 lb/yr).[2,3]

Manufacturers of countercurrent packed scrubbers designed to control EO emissions from sterilizer vents claim EO removal efficiencies greater than 99 percent.[1,13,15] For a 12/88 sterilant gas mixture, the average EO removal efficiency for three tests was 99.0 percent by weight (individual test results were 99.0, 98.7, and 99.4 percent).[16] These tests were conducted using a scrubber that was designed to achieve an EO removal efficiency of 99 percent. A representative of the manufacturer of the tested acid-water scrubber stated that the company can design scrubbers to achieve virtually any EO removal efficiency with any type of sterilant gas.[17] The results of an EPA-sponsored test on another acid-water scrubber designed by this company indicated an EO removal efficiency greater than 99.9 percent for 12/88.[18] For pure EO, the EO removal efficiency was greater than 99.98 percent for each of four tests performed at two facilities.[16,19] However, a detailed review of the available test data indicates that 99.0 percent is the highest EO removal efficiency that can be achieved on a continuous basis.[4]

4.1.1.1.2 Reaction/detoxification towers. Another acid hydrolysis scrubbing technique for EO emission control is a reaction, or detoxification, tower. A schematic of this system is shown in Figure 4-2. This system consists of a tank that holds the scrubbing liquor, which is a sulfuric acid solution at a pH of 0.5 to 2.5. The sterilant gas is bubbled upward through the liquor. The EO is absorbed into the liquor where it hydrolyzes to ethylene glycol. The gas stream then flows through the liquid surface and a demister. The demisting pad prevents acid mist from exiting with the scrubbed gas and provides a final hydrolysis reaction site for any EO remaining in the gas stream. Inert gases (i.e., CFC-12 and CO_2) are exhausted unreacted to the atmosphere. After ethylene glycol builds up in the stream to a maximum recommended level of 60 percent, the scrubber liquor is neutralized and disposed or sold.[20] (See Section 4.1.1.1.3 for a more detailed discussion of waste disposal.) Possible methods of determining the scrubbing liquor changeout point include (1) liquid level indicators, (2) specific gravity detectors, and (3) measuring the amount of EO charged to the sterilizer. Reaction

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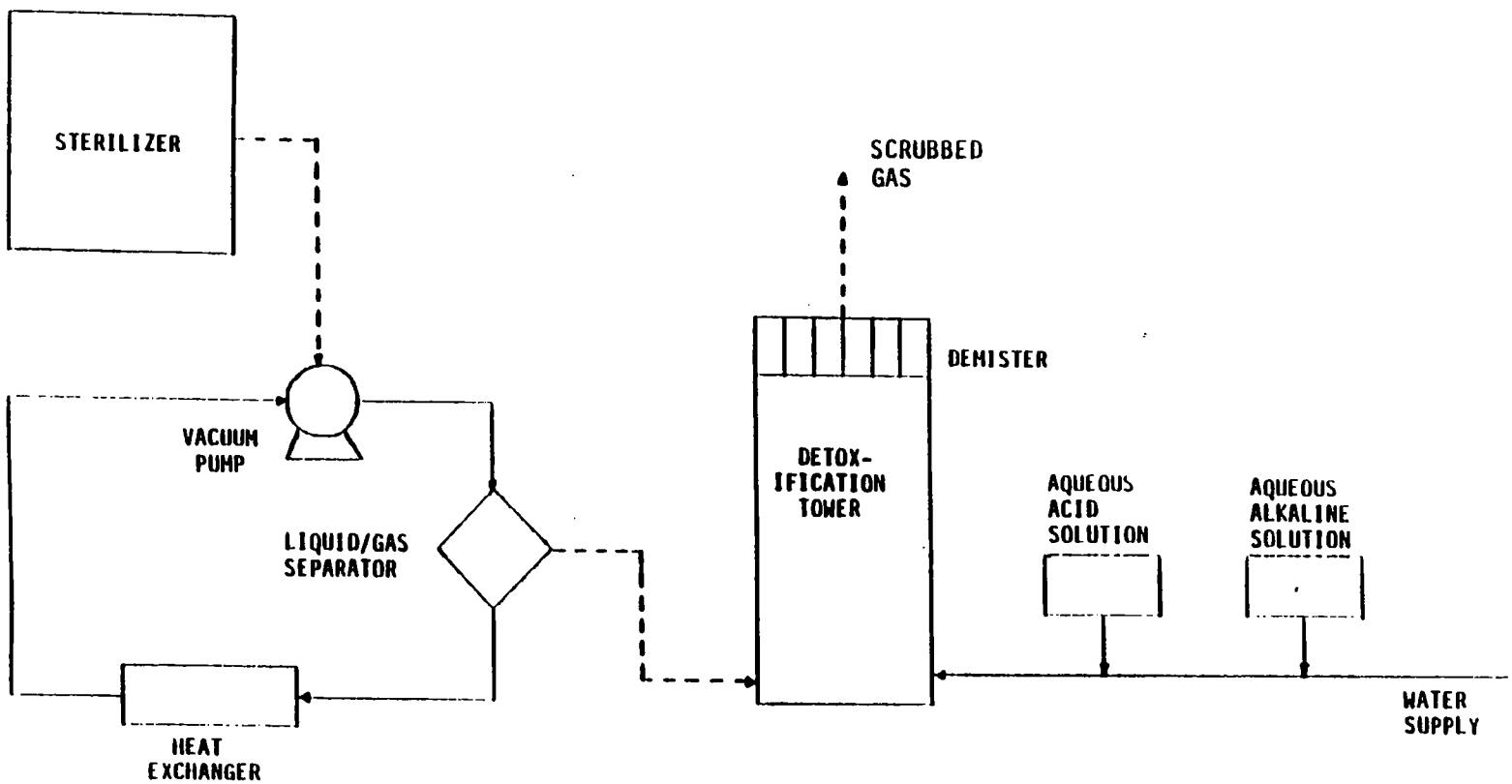

Figure 4-2. Detoxification tower control system.

towers are effective for chambers ranging from 1.4 m^3 (50 ft^3) to 45 m^3 (1,600 ft^3).[21,23] Two of the 203 commercial sterilization facilities represented in EPA's data base use reaction towers to control EO emissions from sterilizer vents. The sterilizers at these two facilities range in volume from 4 m^3 (140 ft^3) to 27 m^3 (960 ft^3). One of these facilities uses 4 Mg (9,500 lb) of EO per year; the other uses 57 Mg (126,000 lb) annually.[2,3]

Manufacturers of reaction/detoxification towers claim 99+ percent EO removal efficiency by weight.[21,22] Third-party laboratory test results indicate that EO emission reductions greater than 99.8 percent can be achieved with reaction towers.[23] However, a detailed review of the available test data indicates that 99.0 percent is the highest EO removal efficiency that can be achieved by acid hydrolysis techniques on a continuous basis.[4]

4.1.1.1.3 Waste disposal. The spent liquor from acid hydrolysis of EO is typically 40 to 60 weight percent ethylene glycol and has a pH of 0.5 to 2.0. Because of the low pH, the solution is considered a hazardous waste and, thus, requires special handling procedures for shipping if not neutralized. However, the spent liquor can easily be neutralized with sodium hydroxide (caustic) prior to disposal.

Two recovery companies have been identified that are willing to purchase the aqueous ethylene glycol solution.[24,25] One of these companies will pay $0.03 to $0.06 per gallon for neutralized scrubbing liquor that is at least 45 percent, by weight, ethylene glycol.[24] Both of these companies require that sodium hydroxide be used for neutralization and will pick up the solution at the sterilization facility. A third recovery company will accept the spent scrubbing solution on a no cost/no payment basis, except for shipping charges.[26] (See Table A-3 in Appendix A for the names and addresses of the above mentioned recovery companies.) The neutralized scrubbing solution also may be disposed to a landfill or incinerator.

4.1.1.2 Oxidation. Two methods of oxidizing EO are (1) thermal oxidation with flares and (2) catalytic oxidation with a solid-phase catalyst.

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4.1.1.2.1 Thermal oxidation. Ethylene oxide, which has a high heating value, a relatively low ignition temperature, and a very wide range of mixtures combustible in air (see Table 3-4), can be easily and efficiently destroyed by thermal oxidation using flares. Thermal oxidation of EO produces carbon dioxide and water as follows:

$$2\ C_2H_4O + 5\ O_2 \xrightarrow[\text{thermal oxidation}]{} 4\ CO_2 + 4\ H_2O$$

Two of the 203 commercial sterilization facilities represented in the EPA data base reported using flares to control EO emissions from the use of pure EO as a sterilant gas.[2] One of these facilities has one 76.7-m^3 (2,710-ft^3) chamber and uses 80 Mg (176,000 lb) of EO per year. The other facility has three chambers ranging in size from 75.2 to 76.9 m^3 (2,655 to 2,715 ft^3) and one smaller 1.7-m^3 (60-ft^3) chamber; this facility uses 98 Mg/yr (215,600 lb/yr) of EO.[2] Because of difficulties with sustaining combustion, commercially available flares are not applicable for facilities emitting only small amounts of EO.

A manufacturer of flare burners for the control of EO emissions claims greater than 99 percent control efficiency for pure EO but no data were provided to substantiate this claim.[27] The EPA's position is that flares operated within specified conditions of waste gas heat content and flare exit velocity will achieve at least 98 percent destruction efficiency.[5]

Flares can also be used with EO/CO_2 sterilant gas mixtures (e.g., 10/90) but are not designed for use with EO/CFC-12 mixtures (e.g., 12/88).[27,28] The EPA has not in the past and does not now recommend the use of flares to control emission streams containing halogenated compounds (e.g., CFC-12) because corrosive or toxic by-products may form. As shown below, thermal oxidation of CFC-12 may produce the following corrosive or toxic by-products at the high temperatures (400° to 800°C [800° to 1500°F]) associated with the use of flares:

$$CF_2Cl_2 + O_2 \xrightarrow[\text{thermal oxidation}]{} \begin{array}{ll} COCl_2 & \text{Phosgene} \\ COF_2 & \text{Carbonyl fluoride} \\ HCl & \text{Hydrogen chloride} \\ HF & \text{Hydrogen fluoride} \\ CF_4 & \text{Carbon tetrafluoride} \\ Cl_2 & \text{Chlorine} \\ CO & \text{Carbon monoxide} \end{array}$$

4.1.1.2.2 Catalytic oxidation. Catalytic oxidation of EO occurs in the presence of a solid-phase catalyst as follows:

$$2\ C_2H_4O + 5\ O_2 \xrightarrow[\text{catalytic oxidation}]{} 4\ CO_2 + 4\ H_2O$$

This control technique is applicable to pure EO, EO/CO_2 mixtures, and EO/CFC-12 mixtures. The CFC-12 does not react at the temperatures (150° to 180°C [300° to 350°F]) that occur during catalytic oxidation, and, therefore, the toxic CFC by-products that result from the higher temperatures associated with thermal oxidation are not produced. During an EPA-sponsored test of a catalytic oxidation unit, no CFC decomposition by-products were detected; the detection limit was 200 parts per billion (ppb) for the analyte chloride ion. The maximum operating temperature of the unit during testing was 155°C (311°F).[12]

A schematic of a catalytic oxidizer is shown in Figure 4-3. The spent sterilizer gas is first mixed with a large volume of air to reduce the control device inlet EO concentration to 5,000 ppmv or less. This dilution prevents excessive catalyst bed temperatures (which can damage the catalyst) from occurring during the oxidation of EO. The gas stream passes through a filter for dust removal and then is preheated to the reaction temperature with steam or electricity. The gas then enters the catalyst bed(s) where the EO is oxidized. Part of the exiting gas stream may be recycled for heat recovery before being vented to the atmosphere. One manufacturer also sells a catalytic oxidizer that uses excess catalyst, instead of diluent air, to absorb the heat of oxidation.[29] Because of cost considerations, the excess-catalyst system has been used, thus far, only for chambers less than 1 m^3 [40 ft^3]) in volume.[29]

Recent information indicates that the use of catalytic oxidation to control EO emissions is increasing, particularly for hospital sterilizers and other small chambers.[9,10] In general, the large amount of diluent air required for most catalytic oxidation systems has limited the use of this technique to smaller, hospital-size chambers. Also, some of the manufacturers of hospital sterilizers are developing sterilizers that are evacuated with air ejectors instead of a vacuum pump.[30] The emissions are then routed to a catalytic oxidizer.[30]

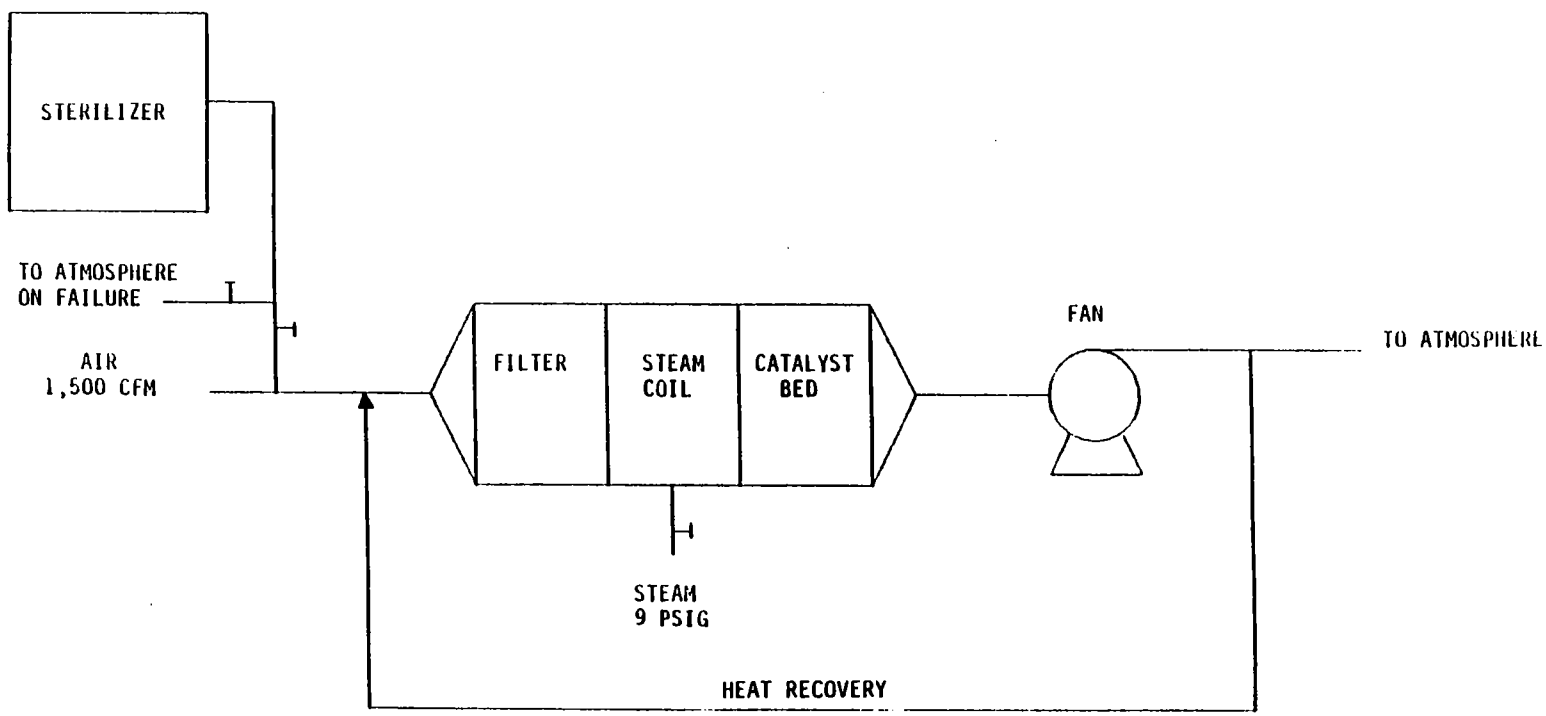

Figure 4-3. Catalytic oxidation system.

Only one of the 203 commercial sterilization facilities represented in the EPA data base reported the use of a catalytic oxidizer in 1986 to control EO emissions from the chamber vent.[2] This facility has one 4-m^3 (130-ft^3) chamber and uses 0.4 Mg/yr (1,000 lb/yr) of EO in an EO/CO_2 sterilant gas mixture.[2] However, data obtained in 1988 indicated that at least one additional commercial sterilization facility has installed a catalytic oxidation system to control EO emissions from a larger industrial-size sterilizer (17 m^3[600 ft^3]); the EO concentration to the control unit is regulated by throttles.[31]

Because catalytic oxidation is applicable to the control of low EO concentrations, many facilities manifold other EO emission sources (e.g., aeration chambers or room, sterilizer hood and door vent, and the gas cylinder room) to the control device. In addition, if the catalytic oxidizer requires diluent air, these low-concentration emission sources can provide part or all of the necessary diluent.

Manufacturers of catalytic oxidation units claim EO destruction efficiencies greater than 99.9 percent.[32,33] Third-party testing and an EPA-sponsored test support these claims for small (<30 ft^3) sterilizers.[12,32]

4.1.1.3 Condensation/Reclamation Systems. Recovery of sterilant gas mixtures is possible using a reclamation system. The sterilant gas mixtures will condense under conditions of reduced temperature and increased pressure, but precautions are necessary to avoid explosions.

Figure 4-4 is a schematic of a sterilization chamber room and a condensation/reclamation system for a 12/88 sterilant gas mixture. (See Table 3-4 for physical and chemical properties of CFC-12.) After each sterilization cycle, the 12/88 gas is withdrawn and passed through one of the two desiccant beds next to the chamber. (One of the desiccant beds is regenerated while the other is in use.) The dried 12/88 gas then passes to a compressor where it is compressed to 50 psig to improve condensation efficiency.[34] The compressed gas is piped to a separate explosion-proof room where it passes through a pressurized condenser that is chilled by ethylene glycol to about -18°C (0°F).[34] The liquid 12/88 mixture is collected in a pressurized, chilled holding tank. The noncondensed gas is recirculated to the chamber and back through the condenser. The liquid

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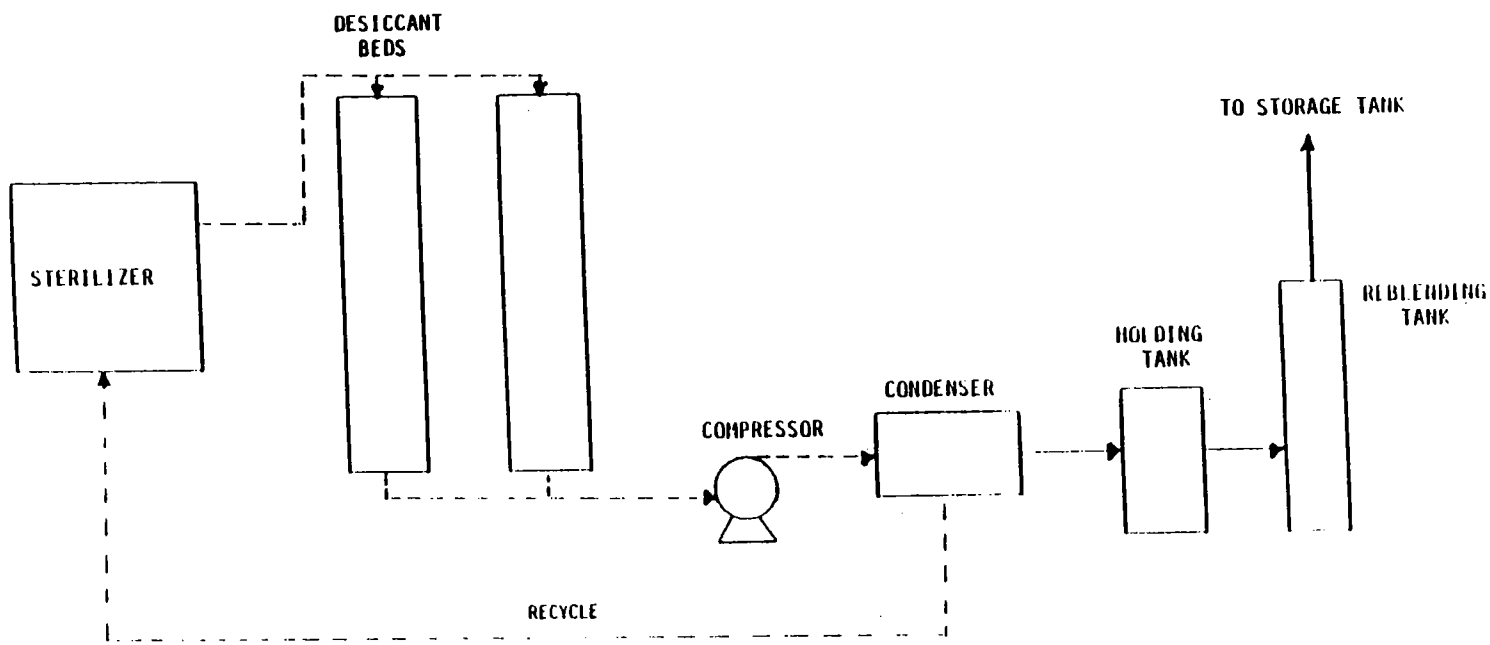

Figure 4-4. Condensation/reclamation system.

collected in the holding tank is transferred to a pressurized reblending tank where the liquid is mixed and its composition determined by infrared analysis. The liquid is then adjusted to the 12/88 (weight percent) ratio by adding the necessary amount of EO or CFC-12. When the correct ratio is obtained, the liquid is transferred to a pressurized storage tank in the chamber room.[34]

Although the reclamation cycle could be continued indefinitely, the amount of EO recovered declines to the point where it is not cost effective to continue the reclamation cycle after about three passes through the system (i.e., typically 60 to 90 minutes). The majority of the EO (80 to 85 percent) is recovered during this time. Also, increasing the reclamation time would require that products spend additional time in the sterilizer and could affect the plant's operating schedule. However, even if the reclamation time was increased, this system is not designed for low EO concentrations. Therefore, if this type of control system is used, add-on controls (e.g., catalytic oxidation or a small scrubber) need to be considered for the EO remaining in the chamber after the reclamation cycle is complete.

Seven of the 203 commercial sterilization facilities represented in the EPA data base reported the use of condensation/reclamation systems; three of these facilities reported an 85 percent EO recovery efficiency, three reported 80 percent, and one reported 50 percent.[2,3] These seven facilities recover EO/CO_2 and EO/CFC-12 sterilant gases. Six of these facilities each use over 23 Mg/yr (50,000 lb/yr) of EO. The seventh facility uses just over 6.8 Mg/yr (15,000 lb/yr).[2,3] The chamber sizes range from 5 to 45 m^3 (190 to 1,580 ft^3) at these seven facilities.[2,3]

The condensation/reclamation systems currently available are designed for the high volumetric flow rates of larger, industrial-size chambers. The systems are not technically or economically feasible for use with smaller chambers or at facilities that use small amounts of EO. In addition, the safety hazards (i.e., explosion potential) associated with this control technique preclude its use in hospitals.

4.1.1.4 Gas/Solid Reactor. A fourth control technique that is used by some hospitals to control vent emissions (after acid-water scrubbing) is a dry, solid-phase system that chemically converts EO and then binds the product to the solid packing.[1] The system operates at room temperature. There are no liquid waste streams produced; the vendor handles the disposal of the solid waste that is produced.[35] Although the gas/solid reactor can handle EO concentrations in the percent range (i.e., >100,000 ppmv) for brief periods of time, it is designed for low (ppm range) concentrations such as the exhaust from an acid-water scrubber. The manufacturer of this device markets a two-stage control system, which consists of an acid-water scrubber and the gas/solid reactor. (The company also sells the stages separately.) The majority of the EO is removed by the scrubber, which is specifically designed for the small sterilizers (<2 m^3 [70 ft^3]) used at hospitals. The gas/solid reactor removes the residual EO exiting the scrubber and, because it is designed for low EO concentrations, can also be manifolded to other emission sources (e.g., aeration chambers, sterilizer hood and door, and gas cylinder storage room).

The manufacturer of this system claims greater than 99.9 percent efficiency for the gas/solid reactor.[1] However, this efficiency is based on a test performed with an inlet EO concentration of 140,000 ppmv, which is much higher than the concentration of the scrubber outlet stream. In another test, no EO was detected (with a lower detection limit of 0.1 ppmv) in the gas/solid reactor outlet stream when the inlet stream (i.e., scrubber outlet stream) was 2 ppmv EO.[35] Because of the innate problems associated with measuring low EO concentrations, the actual efficiency of the system under normal operating conditions presently cannot be determined. (See Section 4.1.3 for a more detailed discussion of measuring low EO concentrations.) However, the maximum removal efficiency that the gas/solid reactor can achieve on a continuous basis is assumed to be 99.0 percent.

4.1.2 Sterilization Chamber Vacuum Pump Drain Emissions

Ethylene oxide drain emissions result from the use of vacuum pumps that use once-through water as the working fluid. (Some of the manufacturers of hospital sterilizers are developing sterilizers that are

evacuated by air ejectors instead of vacuum pumps.)[30] Ethylene oxide is infinitely soluble in water, and, therefore, a portion of the EO evacuated from the chamber enters the drain with the vacuum pump water (see Figure 4-5a). The EO that enters the drain with the vacuum pump water is subsequently released uncontrolled from the air break in the drain line, sewer lines, or the waste treatment plant.[6-8]

The EO drain emissions can be controlled by replacing the existing once-through vacuum pump with a closed-loop (recirculating) vacuum pump. The recirculating fluid (sealant) can be water, oil or ethylene glycol.[36] In this closed-loop system, the water or liquid from the liquid-gas separator is cooled in a heat exchanger and recirculated through the vacuum pump (see Figure 4-5b). Because ethylene oxide is not soluble in oil or ethylene glycol and will off-gas from water as it is recirculated, nearly all of the EO will be emitted through the liquid-gas separator (chamber) vent. (Techniques for control of chamber vent emissions are discussed above.) In addition, mechanical seals are used to eliminate leakage (and, thus, any EO emissions) from the pump.[37]

Because the sterilization cycle operates under humid conditions, some water will be condensed in the liquid-gas separator and, thus, mix with the liquid sealant in the pump. An overflow collection tank is used to maintain a constant amount of sealant recirculating in the pump.[37] If ethylene glycol is used as the sealant, the contaminated glycol will eventually need to be disposed and replaced with a fresh charge.[36] However, if oil is used as the sealant, the condensed water can be drained off the bottom with minimal oil loss because of the immiscibility of oil and water.[36]

4.1.3 Aeration Room Vent Emissions

4.1.3.1 Aeration Rooms. Most commercial sterilization facilities aerate the sterile products in large, warehouse-type aeration rooms that are typically 280 to 2,800 m^3 (10,000 to 100,000 ft^3) in volume but may be larger than 14,000 m^3 (500,000 ft^3).[31] The ventilation rates are, generally, in the range of 112 to 560 m^3/min (4,000 to 20,000 ft^3/min) but may be as high as 1,680 m^3/min (60,000 ft^3/min).[31] These large flow rates are necessary to maintain a low EO concentration in the room to comply with the Occupational Safety and Health Association (OSHA) standards (see

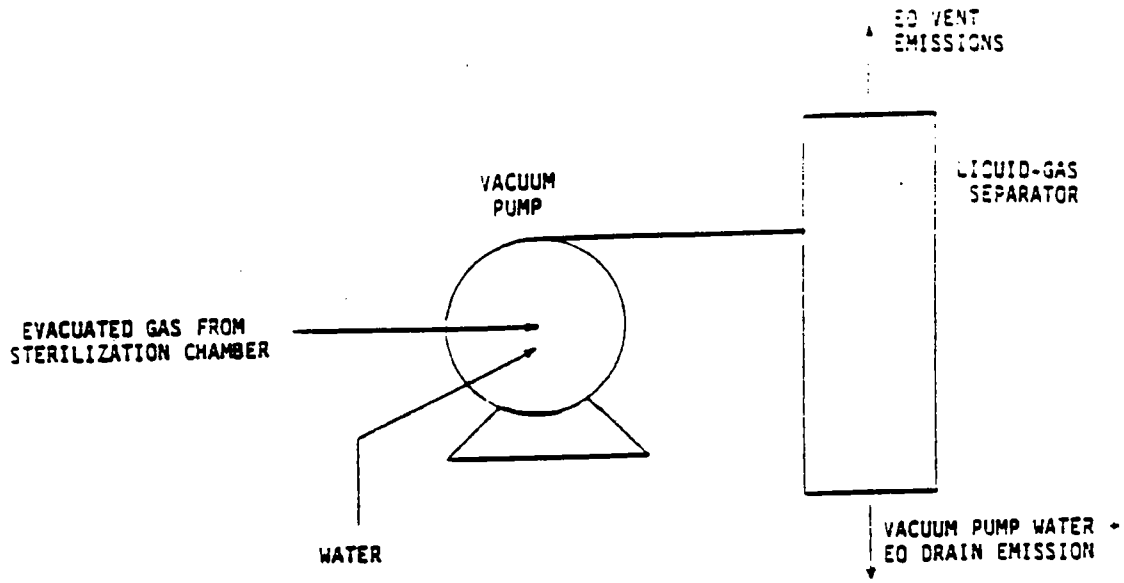

Figure 4-5a. Once-through liquid-ring vacuum pump.

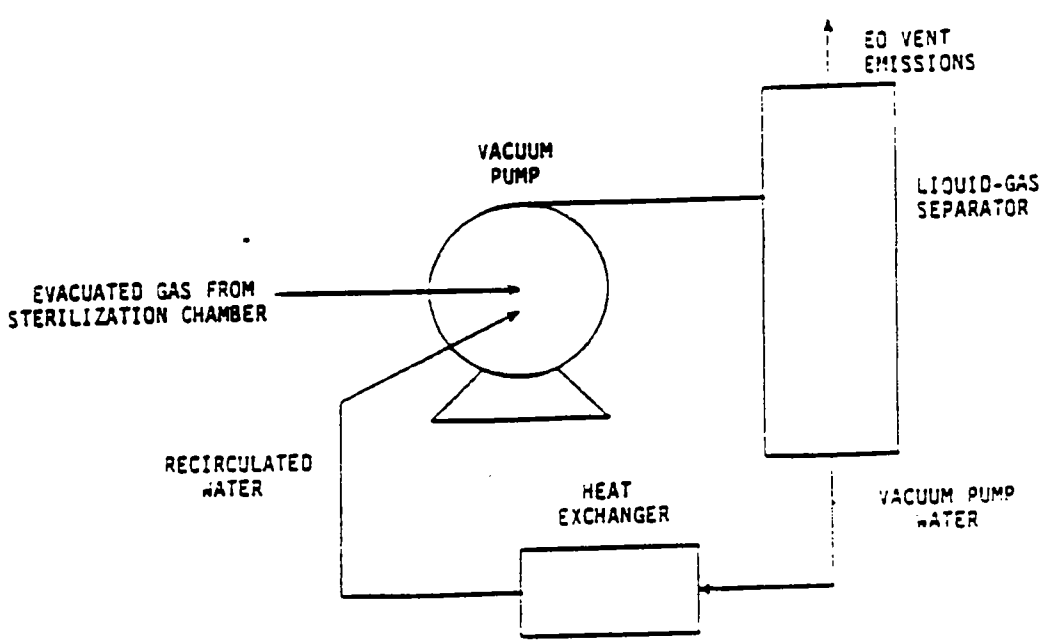

Figure 4-5b. Recirculating liquid-ring vacuum pump.

Section 3.5). Data from a cross-sectional survey (44 facilities) of the 203 commercial sterilization facilities represented in EPA's data base indicated an average 8-hour time-weighted average (TWA) EO concentration of 2.5 to 3 ppmv in aeration rooms.[31]

Two issues of concern regarding the control of aeration room emissions are: (1) most EO emission control devices are impracticable for the low-concentration, high-flow-rate exhaust streams from aeration rooms; and (2) the lower detection limit of most analytical methods makes it impossible to determine the true control efficiency of the low EO concentrations (<1 ppmv) found in most aeration rooms. Hydrolysis, thermal oxidation, and condensation/reclamation presently have not been demonstrated to be practicable control techniques for low-concentration, high-flow-rate gas streams. However, catalytic oxidation and the gas/solid reactor system have the potential to control aeration room emissions. Catalytic oxidation units are commercially available to handle flow rates from less than 1 m^3/min (40 ft^3/min) to approximately 340 m^3/min (12,000 ft^3/min).[9,38] The catalytic oxidizers are modular, and systems can be designed to handle higher flow rates; however, the increased size of the system for high flow rates can restrict its practical use. Gas/solid reactors are being used for flow rates up to 42 m^3/min (1,500 ft^3/min), and systems can be designed to handle any flow rate; however, as with catalytic oxidation, the system size can become impractical.[39]

The manufacturers of the catalytic oxidizers and of the gas/solid reactor claim EO destruction efficiencies greater than 99.9 percent and offer the results of third-party tests to support these claims.[35,40,41] However, test data on the efficiencies of the control units operating under conditions (i.e., low concentrations and high flow rates) that are typical of aeration room exhaust streams are not available.

Generally, the control units are tested by sending the control device a stream of EO with a much higher concentration (e.g., 100 to 140,000 ppmv) than that associated with normal operating conditions.[35,40,41] The results of these tests are the efficiencies reported by the manufacturers. However, these test results are inconclusive because (1) it has not been demonstrated whether the control

units perform at the same efficiencies under normal operating conditions (i.e., very low inlet concentrations) as during test conditions (i.e., controlled flow, high concentration); (2) EPA has not verified the available test data; (3) there has not been an EPA-sponsored test of these control devices with aeration room emissions; and (4) a test reference method has not been developed (but is being developed) to evaluate the efficiencies of these control devices with aeration room emissions.

The lower detection limits of most analytical procedures that are used to measure EO concentrations are approximately 0.5 ppmv to 1 ppmv, which is equal to or greater than the EO concentrations in many aeration rooms. Although one testing laboratory reportedly used a method with a detection limit less than 0.1 ppmv, the test data have not been verified by EPA, and it is unknown whether this method can be applied to high flow rates. (The flow rate tested was 14 m^3/min [500 ft^3/min].)[41] Also, because of the reactivity of EO, the validity of detection limits below 1 ppmv, and particularly below 0.5 ppmv, is questionable.[42] Because the detection limits of the analytical methods (in ppmv) are so close to the room concentrations, testing under normal operating conditions may yield an efficiency that only can be calculated to be equal to 50 percent or less.

Three possible techniques for reducing EO emissions from aeration rooms are (1) recirculate the air from the aeration room control device to the aeration room, (2) replace the warehouse-type aeration rooms with smaller, heated aeration cells, or (3) modify the evacuation and air wash phase of the sterilization cycle. The first two techniques increase the EO concentration in the aeration room and lower the flow rate, which makes both control of the emissions and testing of the control efficiency more practical. The third alternative lowers the EO emissions from the aeration room by decreasing the residual EO in the product prior to aeration. These techniques are discussed in more detail below.

The first alternative refers to routing the aeration room air through an emission control device and back to the aeration room. A small amount of makeup air is added to the control device exit stream to regulate the room temperature. This practice increases the room temperature and, therefore, increases the diffusion rate of EO from the product, producing

a higher EO concentration in the room. (Worker exposure and compliance with the OSHA standards will need to be considered if frequent worker access to the room is required.) Catalytic oxidation and the gas/solid reactor are more applicable to the increased EO concentrations and decreased flow rates associated with this process than to typical aeration room emissions. (In addition, increasing the room temperature reduces the energy costs of preheating the inlet stream to the catalytic oxidizer.) Hydrolysis, thermal oxidation, and condensation/reclamation are not applicable because the EO concentrations are too low (<20 ppmv) for these techniques to be practicable. Because the room air is recirculated and not vented to the atmosphere, this technique eliminates practically all aeration room emissions; only a small amount of the emissions from the control device are vented to allow fresh makeup air to enter the room. This practice of recirculating the aeration room air is used by two of the 203 commercial sterilization facilities represented in the EPA data base.[3] The aeration rooms at these two commercial facilities are each approximately 140 m^3 (5,000 ft^3) in volume.[31] These 2 facilities manufacture synthetic rubber products, which retain a large amount of residual EO and, therefore, require a longer aeration period than the majority of products that are sterilized with EO. The facilities installed the recirculating system to decrease the aeration time and the residual EO concentrations in the products.[43] A catalytic oxidation system is used to control the EO emissions and to provide hot air to heat the room.[43]

Another alternative is to replace the large, warehouse-type aeration rooms with smaller (70 m^3 [2,500 ft^3] or less), heated aeration cells and control the emissions from the cell. In this process, instead of storing the sterile products in a warehouse and aerating at normal room temperatures, the products are aerated in heated (>43°C [110°F]) insulated cellular units. The emissions from these cells can be controlled by catalytic oxidation or the gas/solid reactor system. Emissions from the control unit can be recirculated to the aeration cell or vented to the atmosphere. The cells can be filled approximately 40 to 75 percent full and still allow sufficient air space for off-gassing.[29,44] The cell is heated either with supplemental heat or hot air from the control device if

catalytic oxidation is used. Several commercial sterilization facilities, particularly contractors, are aerating at least part of the sterile products in heated, cellular units.[31,38] Structures used for aeration include insulated shipping containers, modified walk-in coolers (which are heated instead of cooled), and manufactured units designed specifically for the heated aeration process.[45-47] Most of these facilities have installed these units to reduce the aeration time or the residual EO concentration in the products. The heated cells are similar to the first technique described above (i.e., the practice of recirculating the aeration room air) in that the EO concentration in the cell will increase due to elevated temperature.

Another strategy for reducing aeration room emissions is modifying the evacuation/air wash phase of the sterilization cycle. Residual EO in the product can be reduced by performing additional sterilization chamber purges. However, this procedure does require additional time in the sterilizer and could affect plant operating schedules. The potential reduction in residual EO with evacuation-phase modifications is product dependent. Results from tests performed at one facility that fumigates spices showed an average reduction in residual EO of 26 percent for four different spices following evacuation-phase modifications.[19] Some facilities aerate in the sterilizer, with or without cycle modifications.[31] Aeration emissions from the sterilizer can be sent to the sterilizer control device. However, the removal efficiencies of the hydrolysis techniques have not been determined for the low inlet concentrations associated with aeration emissions. Also, condensation/reclamation would not be practicable for controlling these low concentrations.

4.1.3.2 Aeration Chambers. Many hospitals and some commercial sterilization facilities use aeration chambers instead of aeration rooms. These chambers are similar in appearance and size (<1 m^3 [40 ft^3]) to the sterilization chambers used at hospitals. However, the flow rate is much lower from the chambers than from aeration rooms. Therefore, catalytic oxidation and the gas/solid reactor are applicable to the control of EO emissions from aeration chambers. Several hospitals and small commercial sterilization facilities use catalytic oxidation or the

gas/solid reactor system to control aeration chamber emissions, and at least one commercial sterilization facility uses an acid-water scrubber to control these emissions.[9,10,31] However, as stated in Section 4.1.3.1, the control efficiencies of these techniques have not been determined for the low concentrations from aeration processes.

4.2 OTHER STERILIZATION PROCESSES

There are no demonstrated EO emission control devices for single-item sterilization processes or for portable fumigation units. The problems associated with controlling EO emissions from these sources are discussed below.

4.2.1 Single-Item Sterilization

Single-item sterilization systems do not use a chamber evacuated with a vacuum pump. (See Section 3.2.2 for a description of single-item sterilization.) Instead, the EO is allowed to diffuse from products while they are inside an aeration room or cabinet. The EO from facilities using single-item sterilization systems is, therefore, emitted from one major source, the aeration room/cabinet vent. Because there is no evacuation phase, the EO concentration in the gas stream from single-item sterilization systems is higher than the concentration of EO in aeration rooms. However, the concentration is sufficiently low such that catalytic oxidation or the gas/solid reactor system may be viable control options.

4.2.2 Fumigation with Portable Units

Because of problems with transporting an emission control device, there are no practical controls of EO emissions from the portable units operated by State departments of agriculture to fumigate beehives. However, one State Department of Agriculture is working on the development of an acid-water scrubber for portable fumigation units.[3]

4.3 ALTERNATIVES TO EO STERILIZATION

In some cases, radiation sterilization can replace EO sterilization. Radiation sterilization is used for about half of the products sterilized in the U.S.[48] However, not all products can be sterilized with radiation; plastics can become broken, discolored, or malodorous, and Teflon® and acetyl delrin are damaged by radiation.[48,49] According to industry representatives, most of the commonly used plastics have been or are in the process of being reformulated to withstand radiation.[50,51] Therefore, the potential use of this alternative will probably increase.

There are several chemical alternatives to EO sterilization (e.g., chlorine dioxide, gas plasma, hydrogen peroxide, and ozone). However, these chemicals do not necessarily offer environmental improvements over EO. Other alternatives include X-ray (a new, developing technology), deep freezing (museum and spice industry), and increased use of disposable medical items in hospitals. However, none of these alternatives can replace the use of EO in all applications.

4.4 RETROFIT CONSIDERATIONS

All of the control devices discussed above can be retrofitted to existing EO bulk sterilization chambers. However, the use of flares in urban areas is prohibited because of safety hazards. There are no retrofit problems associated with the replacement of once-through vacuum pumps with closed-loop recirculating vacuum pumps for control of drain emissions.

4.5 IMPACTS OF A CFC REGULATION ON EO EMISSION CONTROLS

Federal regulations for stratospheric ozone-depleting chlorofluorocarbons (CFC's) have been developed under EPA's Stratospheric Ozone Protection Program (SOPP). The use of CFC's in sterilant gases is one of the source categories subject to these regulations. The most popular sterilant gas mixture, 12/88, contains 88 percent by weight dichlorodifluoromethane (CFC-12), which is an ozone-depleting CFC. Nearly all hospitals and 75 percent of the 203 commercial sterilization facilities represented in the EPA data base use 12/88 at least part of the time.[2,3] The requirements of a CFC regulation would not affect the ability of a sterilization facility to control EO emissions. The explosion-proof condensation/reclamation system discussed above recovers CFC-12 emissions in addition to EO emissions. However, if this control device is used, add-on controls (e.g., catalytic oxidation or a small scrubber) need to be considered for the EO remaining in the chamber after the reclamation cycle is complete. Also, a nonexplosion-proof condensation/reclamation system that recovers only CFC-12 could follow the acid-water scrubbing of EO to ethylene glycol.[52] Some facilities may switch to sterilant gases that do not contain CFC-12 (such as 10/90 and pure EO), in which case, the EO control techniques discussed above still would be applicable.

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5. EMISSION CONTROL COSTS

5.1 INTRODUCTION

This chapter presents a summary of the methodology to develop emission control cost estimates. Costs presented in this chapter are in December 1984 dollars. A method for estimating EO emission control costs at commercial sterilization facilities is presented in Section 5.2. Limited cost information has been obtained about emission controls for hospital sterilizers, single-item sterilization systems, and aeration rooms; these costs are discussed in Sections 5.3 through 5.5, respectively.

5.2 CONTROL COSTS FOR COMMERCIAL STERILIZATION FACILITIES

This section describes a method for estimating emission control costs for sterilizer vent(s) and the vacuum pump drain at commercial sterilization facilities. Acid hydrolysis (i.e., acid-water scrubbing) was chosen as the basis for the costing procedure because that control technique currently is practiced at several commercial sterilization facilities and has been demonstrated at both small and large commercial facilities. A detailed review of the available test data indicated that 99.0 percent is the maximum EO removal efficiency that acid hydrolysis techniques can achieve on a continuous basis.[1] Therefore, 99.0 percent was used to calculate the emission reductions.

The costing procedure presented in this section has been used to develop emissions control costs for the 203 commercial sterilization facilities represented in the EPA data base.[2] (See Section 3.1 of this report for a description of how the data base was developed.) The results of this cost analysis for three actual commercial sterilization facilities are presented in Table 5-1. Detailed sample calculations for another commercial sterilization facility are given in Appendix B.

5.2.1 Description of Components Costed

The following components were costed: (1) an acid-water scrubber, (2) a water-sealed vacuum pump with closed-loop recirculation for each sterilizer, (3) piping for manifolding all chambers at a facility to one scrubber, (4) operating materials (i.e., chemicals and chlorine filters), (5) scrubber waste disposal, and (6) labor.

Scrubber prices are listed in Table 5-2. The capital costs of the piping system for manifolding and the installed cost of the vacuum pump are presented in Tables 5-3 and 5-4. The costs of operating materials, as well as the shipping charges used for computing disposal costs for the spent scrubber solution, are presented in Table 5-5.[2]

Costs reported in Tables 5-2 through 5-5 are in fourth quarter 1984 dollars. The prices for the scrubbers, vacuum pump, chlorine filters, and chemicals were obtained from the manufacturer and suppliers and were originally in 1986 dollars. These prices were converted to fourth quarter 1984 dollars using the CE Plant Cost Index (for the equipment) and the Current Business Indicators (for the chemicals) in Chemical Engineering.[3,4] The labor costs were calculated from the Economics Assessment Branch (EAB/EPA) control cost manual and from the CE Plant Cost Index.[4,5] The indices used and the conversion factors obtained are reported in Appendix B.

5.2.2 General Assumptions

Chamber volume was used as the basis for scrubber sizing. The relationship of chamber volume to scrubber size is presented in Table 5-2.[2]

If a facility has three or more sterilization chambers, the scrubber costed was chosen based on the sum of the volumes of the two largest chambers at that facility. This methodology simulates the cost of controlling emissions from a facility if two chambers at that facility were to be evacuated simultaneously. If a facility has two chambers, the scrubber was selected based on the volume of the larger chamber. For facilities with two chambers, it was assumed that the sterilization cycles could be staggered so that the chambers would not be evacuated simultaneously.[2]

For the purposes of this cost analysis, it was assumed that the ethylene glycol would be accepted by a recovery facility on a no cost/no credit basis, except for shipping charges. Therefore, the disposal cost for the aqueous ethylene glycol solution produced by the acid-water scrubbers was computed as the cost to ship the solution, either in 55-gallon drums or in a tank truck, depending on quantity, to a recovery facility. Transportation costs were calculated by assuming that commercial sterilization facilities are within 1,000 miles of one of the three known

recovery facilities.[2] However, these disposal costs may not be applicable to all sterilization facilities. If a recovery facility is not available to accept the liquor, it may be necessary to neutralize the scrubbing liquor and then have it hauled to a landfill or incinerator, which may increase the waste disposal costs.

5.2.3 Capital Costs

The fixed capital costs for a particular facility represent the initial investment and installation charges for control equipment. The cost data presented in Table 5-6 were used to calculate capital cost estimates for each of the facilities.[2]

5.2.4 Annualized Costs

Annualized costs for a particular facility represent direct operating costs such as labor costs, cost of materials, and disposal costs, as well as indirect operating costs such as overhead charges, tax/insurance charges, and capital recovery costs. The cost data presented in Table 5-7 were used to estimate plant-specific annualized costs.[2]

5.3 CONTROL COSTS FOR HOSPITAL STERILIZATION CHAMBERS

Detailed cost estimates have not been developed for EO emission controls at hospitals. Only a small percentage of hospitals control EO emissions to the atmosphere. Emission controls used at hospitals include acid-water hydrolysis, catalytic oxidation, and the gas/solid reactor system discussed in Section 4.1.1.4 of this report.[6-9]

Because only a few control devices are in place at hospitals, the cost data available are limited and, therefore, should be used cautiously. Table 5-8 presents a range of the approximate costs of using catalytic oxidation to control EO emissions from hospitals. The capital costs and annual operating costs for catalytic oxidation were obtained from two hospitals.[10] Additional control cost estimates for hospitals have been obtained from vendors and are given in Appendix C.

5.4 CONTROL COSTS FOR OTHER STERILIZATION SYSTEMS

There are no demonstrated EO emission control devices for single-item sterilization processes or for portable fumigation units. Therefore, emission cost estimates have not been developed for these processes. However, the EO concentration and flow rate from single-item sterilization units is low enough that catalytic oxidation or the gas/solid reactor system

may be viable control options. See Appendix C for vendor-supplied cost estimates for these control devices.

5.5 CONTROL COSTS FOR AERATION ROOMS

The potential control of aeration emissions is being evaluated by EPA, and the preliminary cost analysis should be available by June 1989. Catalytic oxidation and the gas/solid reactor system may be applicable to the control of aeration emissions particularly from aeration chambers and the heated, cellular structures to which some facilities are switching. See Appendix C for vendor-supplied cost estimates for catalytic oxidation and the gas/solid reactor system.

TABLE 5-1. CONTROL COSTS FOR ACID HYDROLYSIS[a] [b]

Model plant	Total sterilizer volume, m^3 (ft^3)	Annual EO use, Mg (lb/1,000)	Capital costs, $	Annualized costs, $	Annual emission reduction, Mg (lb/1,000)[c]
Small[d]	2.8 (100)	0.18 (0.39)	76,000	21,200	0.17 (0.37)
Medium[e]	28 (1,000)	3.9 (8.7)	160,000	40,800	3.7 (8.2)
Large[f]	168 (6,000)	109 (240)	291,000	117,000	102 (226)

[a]These cost estimates are not applicable to hospitals because the acid-water scrubbers costed are not designed for the low flowrates from the vacuum pumps on hospital sterilizers.
[b]See Appendix B for the methodology used to calculate these control costs.
[c]Calculated as (0.99)x(0.95)(EO use). Five percent of the EO use is assumed to be retained in the product after sterilization and emitted from the aeration room, which is assumed to be uncontrolled.
[d]The small model plant has one chamber and uses 12/88 (EO/CFC-12). Therefore, a model 100 scrubber (see Table 5-2) was chosen as the basis for the calculations.
[e]The medium model plant has one chamber and uses 12/88 gas. Therefore, a model 400 scrubber was chosen as the basis for the calculations.
[f]The large model plant has seven chambers and uses 100 percent EO. The sum of the volumes of the two largest chambers is 2,000 ft^3. Therefore, a model 500 scrubber (with explosion-proof valves) was chosen as the basis for the calculations.

TABLE 5-2. COST OF DAMAS SCRUBBER MODELS (F.O.B.)[1]
(4th Quarter 1984 Dollars)

Model No.	Chamber size, m^3 (ft^3)[a]	Conversion capacity of scrubber, kg (lb) of EO	Automated scrubber cost, $	Cost of explosion-proof valves for scrubber, $[b]
100	<11.3 (<400)	908 (2,000)	47,250	12,180
200	11.3 to 17.0 (400 to 600)	1,816 (4,000)	68,250	13,195
300	17.0 to 22.7 (600 to 800)	2,724 (6,000)	89,250	14,210
400	22.7 to 45.3 (800 to 1,600)	3,632 (8,000)	99,750	15,225
500	45.3 to 56.6 (1,600 to 2,000)	4,540 (10,000)	141,750	17,255
600	>56.6 (>2,000)	5,448 (12,000)	157,500	18,270

[a]The size of sterilization chamber that can be served by the model number, assuming the smallest appropriate vacuum pump is used.
[b]Explosion-proof valves are necessary if the sterilization chamber that is vented to the scrubber uses a gas mixture greater than 20 percent by weight EO.

TABLE 5-3. INCREMENTAL CAPITAL COSTS OF MANIFOLDING STERILIZATION CHAMBERS[1]

Item	Cost, 1984 $
Opening in explosion-proof wall[a]	
Adjustable sheetmetal sleeve	2[b]
Labor costs at $18.05/hour	93
Overhead costs at $8.35/hour	43
Drill holes for pipe hangers[c]	
Labor costs at $19.40/hour	146
Overhead costs at $15.06/hour	113
Piping[d]	
100 ft, 2 in. diameter, 40 standard carbon steel pipe	240[b]
90° elbows, 3 at $4.19	13[b]
Tee with full-size outlet	14[b]
Swing check valve	350[b]
Bolts and gaskets, two sets at $6.76	14[b]
Pipe hangers, 1 carton of 50 hangers	140[b]
Labor costs at $20.50/hour	576
Overhead costs at $12.71/hour	357
Total installed cost for piping system	
Total direct costs[e]	1,588
Total indirect costs:	
Overhead costs[f]	513
Administration[g]	159
Taxes[h]	39
Total installed cost[i]	2,299
Total installed cost for recirculating vacuum pump	4,935
TOTAL CAPITAL COST	7,234

[a]Requires 5.15 labor-hours.
[b]Equipment cost.
[c]Requires 7.5 labor-hours.
[d]Requires 28 labor-hours.
[e]Sum of all labor and equipment costs.
[f]Sum of all overhead costs.
[g]Ten percent of total direct costs.
[h]Five percent of total equipment costs.
[i](Total direct costs)+(total indirect costs).

TABLE 5-4. CAPITAL COST OF CHECK VALVE FOR CHAMBER[1]

Cost item	Cost, 1984 $
Swing check valve	350[a]
Installation costs[b]	
Labor costs at $20.50/hour	23
Overhead costs at $12.71/hour	14
Total direct costs[c]	373
Administration: 10 percent of total direct costs	37
Taxes: 5 percent of equipment cost	18
Total indirect costs[d]	69
Total installed cost[e]	442
Annualized capital recovery cost[f]	74

[a]Equipment cost.
[b]Requires 1.1 labor hours to install.
[c]Sum of all labor and equipment costs.
[d]Sum of overhead costs, taxes, and administration.
[e](Total direct costs)+(total indirect costs).
[f]Calculated as 0.16275x(total installed cost), for an interest rate of 10 percent and a 10-year recovery period.

TABLE 5-5. MISCELLANEOUS OPERATING COSTS[1]

Item description	Cost, 1984 $
Operating materials	
1. 50 percent H_2SO_4, electrolyte-grade	0.069/lb
2. 50 percent NaOH, industrial grade:	
<2 drums	0.108/lb
3-9 drums	0.0787/lb
>9 drums	0.0738/lb
3. Chlorine filters:	
Filter housing	41.50 each
Filter	15.00 each
Installation	20.00 each
Shipping charges for waste disposal	
Weight of solution for disposal:	
<42,000 lb (drums)	0.096/lb
≥42,000 lb (bulk)	0.059/lb

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TABLE 5-6. DATA USED TO CALCULATE CONTROL EQUIPMENT CAPITAL COSTS[1]
(4th Quarter 1984 Dollars)

Item	Cost factor
Automated scrubber	--[a]
Explosion-proof valves for scrubber	--[a b]
Chlorine filter house	($41.50 each)x(No. of tanks)[c]
Scrubber installation	50 percent of scrubber cost
Chlorine filter installation	($20.00)x(No. of tanks)[c]
Taxes	5 percent of total equipment cost
Freight	5 percent of total equipment cost
Vacuum pump(s)	$4,935 per pump
Manifolding of chambers (includes check valve)	--[d]

[a]Function of chamber size (see Table 5-2).
[b]Explosion-proof valves are necessary if the chamber that is vented to the scrubber uses a gas mixture greater than 20 percent (by weight) EO.
[c]Number of scrubber tanks required = scrubber conversion capacity divided by the conversion capacity of one tank (2,000 pounds of EO).
[d]See Tables 5-3 and 5-4.

TABLE 5-7. DATA USED TO CALCULATE CONTROL DEVICE ANNUALIZED COSTS[1]
(4th Quarter 1984 Dollars)

Item	Cost factor
Direct operating costs	
Labor	\$3,177+(\$11.60)x(16 person-hours)x(No. of scrubber regenerations)[a b]
Materials:	
50 percent H_2SO_4	(\$0.069/lb)x(594 lb/drum)x(No. of drums required)[c d]
50 percent NaOH	(Cost/lb)x(700 lb/drum)x(No. of drums required)[c, e, f]
Chlorine filters	(\$15/filter)x(No. of tank regenerations)[c g]
Taxes	5 percent of materials cost
Freight	5 percent of materials cost
Compressed air	0[h]
Disposal of ethylene glycol	--[i]
Indirect operating costs	
Overhead	(0.8)x(labor costs)
Property tax, insurance, and administration	4 percent of total capital costs
Capital recovery costs	(0.16275)x(total capital costs)[j]

(continued)

TABLE 5-7. (continued)

[a]Number of scrubber regenerations = amount of EO to be treated divided by the conversion capacity of the scrubber (See Table 5-2).
[b]The $3,177 is for visual inspection of the system 15 minutes per shift, 3 shifts per day, 365 days per year at $11.60/person-hour. It was assumed that each regeneration of the scrubber solution would require two people at 8 person-hours each, independent of scrubber size.
[c]Number of scrubber tanks = scrubber conversion capacity divided by the conversion capacity of one tank (2,000 pounds of EO). Number of tank regenerations = number of scrubber regenerations multiplied by the number of scrubber tanks.
[d]Each tank regeneration requires one 55-gallon drum of 50 percent H_2SO_4.
[e]Each tank regeneration requires 250 pounds of NaOH for neutralization.
[f]Cost basis for 50 percent NaOH (350 pounds NaOH per drum):
If No. of drums >9, cost/lb = $0.0738
If No. of drums = 3 to 9, cost/lb = $0.0787
If No. of drums <2, cost/lb = $0.108
[g]Each chlorine filter can dechlorinate approximately 200 gallons (one tank) of H_2O; replace filter at each tank regeneration.
[h]The cost of 10 seconds of in-house compressed air per cycle is considered negligible.
[i]Unit cost of disposal was calculated by multiplying the total number of tank regenerations by the weight of a tank at regeneration, approximately 4,845 lb (see Example Calculation No. 3 in Appendix B [page B-3]).
If the total weight <42,000 lb, disposal cost = (weight)x($0.096/lb).
If the total weight ≥42,000 lb, disposal cost = (weight)x($0.059/lb).
[j]Assumes an interest rate of 10 percent and a 10-year recovery period.

TABLE 5-8. HOSPITAL EMISSION CONTROL COSTS[10]

Control device	Capital costs, $[a]	Annual operating costs, $[b]
Catalytic oxidation	30,000-50,000	6,000-16,000

[a]Total installed capital costs. (Does not include modifying vacuum pump)
[b]Direct operating cost and annualized catalyst and prefilter replacement.

5.6 REFERENCES FOR CHAPTER 5

1. Memorandum. Srebro, S., MRI, to Markwordt, D., EPA/CPB. Examination of Ethylene Oxide Control Efficiencies. Attachment to Effect on the Maximum Individual Risk from an Increase in the Ethylene Oxide Removal Efficiencies. October 5, 1988.

2. Memorandum. Srebro, S., MRI, to Markwordt, D., EPA/CPB. Capital cost, annualized cost, and cost effectiveness of reducing ethylene oxide emissions at commercial sterilization facilities. March 20, 1987. 80 p.

3. Chemical Engineering. Economic Indicators. February 18, 1985. p. 7.

4. Chemical Engineering. Economic Indicators. June 23, 1986. p. 7.

5. Neveril, R., Capital and Operating Costs of Selected Air Pollution Control Systems. GARD, Inc. Niles, Illinois. Publication No. EPA-450/5-80-002. December 1978. p. 3-11, 12, 16.

6. Responses to July 1988 EPA information request regarding chamber operating parameters, vacuum pumps, current controls, and aeration rooms.

7. Telecon. Nicholson, R., MRI, with Olson, C., Donaldson Company, Inc. May 12, 1988 and June 13, 1988. Discussion about applicability of catalytic oxidation to large aeration rooms and location of facilities using EtO Abators™.

8. Contact report. Srebro, S., MRI, with Meo, D., DM3, Incorporated. December 9, 1988.

9. Telecon. Nicholson, R., MRI, with Kruse, R., Advanced Air Technologies, Inc. June 14, 1988. Discussion about Safe-Cell™ gas/solid reactor.

10. Ethylene Oxide Control Technology Development for Hospital Sterilizers. Meiners, A., MRI. EPA 600/2-88-028. May 1988.

APPENDIX A.

FEDERAL AGENCY CONTACTS, CONTROL DEVICE VENDORS, AND ETHYLENE GLYCOL RECOVERY COMPANIES

TABLE A-1. CONTACTS AT FEDERAL AGENCIES

Agency name and address	Item of concern	Contact name	Phone
Food and Drug Administration Division of Compliance 8757 Georgia Avenue Silver Spring, Md. 20910	Sterility compliance (e.g., switching sterilants)	Virginia Chamberlain	(301) 427-7194
Occupational Safety and Health Administration 200 Constitution Avenue Washington, D.C. 20210	Worker exposure (e.g., aeration rooms)	Melody Sands	(202) 523-9308
U. S. Environmental Protection Agency	Sterilant registration (e.g., switching sterilants)	John Lee	(703) 557-5339
U. S. Environmental Protection Agency Global Change Program 401 M Street, S.W. Washington, D.C. 20460	Chlorofluorocarbon regulations	Karla Perri	(202) 475-7496
U. S. Environmental Protection Agency Office of Air Quality Planning and Standards Research Triangle Park, N.C. 27711	Economics	Tom Walton	(919) 541-5311
	Emission test method	John Margeson (Office of Research and Development	(919) 541-2848
	Health risk assessment	Nancy Pate	(919) 541-5347
	Standards development (EPA Lead Engineer)	David Markwordt	(919) 541-0837

TABLE A-2. CONTROL DEVICE MANUFACTURERS[a]

Company name and address	Control types	Emission source applicability
Advanced Air Technologies, Inc. 710 S. McMillan Street Owosso, Michigan 48867 (517) 723-2171	Scrubber Gas/solid reactor	Scrubber--vent (small and large chambers) Gas/solid reactor--vent (after scrubbing); aeration chamber or room; sterilizer door; hood; single-item sterilization units
Chemrox, Incorporated 217 Long Hill Crossroads Shelton, Connecticut 06484 (203) 926-9081	Scrubber CFC reclamation system (after EO removed)	Vent
Croll-Reynolds Post Office Box 668 Westfield, New Jersey 07091 (201) 232-4200	Scrubber	Vent
Damas Corporation 8 Romanelli Avenue S. Hackensack, New Jersey 07606 (201) 489-0525	Scrubber	Vent
DM3, Incorporated 1530 E. Edinger Avenue Santa Ana, California 92705 (714) 543-1312	Catalytic oxidation	Vent (low flows, small chambers) Aeration chamber or room Single-item sterilization units
Donaldson Company, Inc. Post Office Box 1299 Minneapolis, Minnesota 55440 (612) 887-3155	Catalytic oxidation	Vent (low flows, small chambers) Aeration chamber or room Single-item sterilization units
John Zink 4401 South Peoria Avenue Post Office Box 702220 Tulsa, Oklahoma 74170 (918) 747-1371	Flare	Vent (large chambers; pure EO)
Environmental Tectonics, Inc. County Line Industrial Park Southampton, Pennsylvania 18966 (215) 355-9100	Scrubber	Vent
Vacudyne, Inc. 375 E. Joe Orr Road Chicago Heights, Illinois 60411 (312) 757-5200	EO reclamation system (for use with 12/88)	Vent (large chambers)

[a]This information is provided for the convenience of the reader and does not imply product endorsement by EPA.

TABLE A-3. ETHYLENE GLYCOL RECOVERY COMPANIES[a]

Mr. Jerry Duvow
Chemstreams
3501 River Road
Matthews, North Carolina 28106
(704) 821-6727

Mr. Keven Dalton
High Valley Chemicals
1151 S. Redwood Road
Suite 105
Salt Lake City, Utah 74104
(801) 973-7966

Mr. John Hoffman
Med-Chem Reclamation, Inc. (formerly B&D Industries)
7900 N. Kolmar
Skokie, Illinois 60076
(312) 673-1441

[a]This information is provided for the convenience of the reader and does not imply product endorsement by EPA.

APPENDIX B.

COST INDICES AND

SAMPLE COST CALCULATIONS

COST INDICES AND CONVERSION FACTORS

The prices for the scrubbers, vacuum pump, chlorine filters, and chemicals were obtained from the manufacturers and suppliers and were originally in 1986 dollars. These prices were converted to 4th quarter 1984 dollars using the following indices from Chemical Engineering:

	February 1986[1]	October 1984[2]	Conversion factor
CE Plant Cost Index			
Scrubber	319.2	335.1	1.05
Vacuum pump	418.6	413.1	0.987
Explosion-proof valves	377.1	382.9	1.015
Chlorine filters	344.1	334.7	0.98
Current Business Indicators			
Industrial chemicals	340.0	334.7	0.98

The labor costs were calculated using the Economics Assessment Branch (OAQPS/EAB) Control Cost Manual and the annual CE Plant Cost Indices in Chemical Engineering:

CE Plant Cost Index[1]	
1978	218.8
1984	322.7
Conversion factor	1.47
EAB Conrol Cost Manual[3]	$7.87/person-hour
Labor for calculations	$11.60/person-hour

EXAMPLE CALCULATIONS FOR CONTROL COSTS[4]

	Sterilization chambers at the facility				
	No. 1	No. 2	No. 3	No. 4	No. 5
Size, ft^3	667	667	1,200	1,334	1,334
Gas type	100	100	12/88	100	100
EO USE, lb	28,000	28,000	1,200	46,000	46,000
EO-EMIT, lb	26,600	26,600	1,140	43,700	43,700
MEO-EMIT, Mg	12.07	12.07	0.52	19.82	19.82
EO-FAC, lb	141,740				
MEO-FAC, Mg	64.30				
EO-TOT, lb	149,200				
MEO-TOT, Mg	67.7				
CON-EM, Mg	0.64				
REDUCE, Mg	63.66				

1. The size, gas type, and EO use are those for an actual commercial sterilization facility represented in the EPA data base. (See Section 3.1 of this report for a description of how this data base was developed.) The other values were calculated using the following assumptions:

a. EO-EMIT (lb) = EO (lb) emitted annually from an individual sterilization chamber to the vacuum pump drain and to the atmosphere. Sterilizer vent emissions and vacuum pump drain emissions were assumed to be 50 percent and 45 percent of EO use (lb), respectively. Residual EO in the sterilized product prior to aeration was assumed to be 5 percent of EO-USE (lb). This 5 percent of the EO use is not included as part of EO-EMIT (lb).

b. MEO-EMIT (Mg EO) = EO-EMIT (lb)/2,204.6

c. EO-FAC (lb) and MEO-FAC (Mg) are the amount of EO released annually by the facility to the vacuum pump drain and to the atmosphere, i.e., the sum of EO-EMIT and the sum of MEO-EMIT, respectively.

d. EO-TOT (lb) is the total amount of EO (lb) used annually by the facility, i.e., the sum of EO use. MEO-TOT (Mg) = EO-TOT (lb)/2,204.6.

e. CON-EM (Mg) is the amount of EO that would be released annually after control, i.e., MEO-TOT*(1-0.99)*0.95. Note that the 5 percent residual EO in the sterilized product, which is later released from the aeration room vent, is excluded from this calculated emission estimate.

f. REDUCE (Mg) is the incremental amount of EO that would be reduced if controls are implemented, i.e., (MEO-FAC)-(CON-EM).

2. For all calculations, a conversion efficiency of 99.0 percent was assumed for the scrubber.

3. Each tank of the scrubber initially holds 198 gal H_2O and 19.8 gal H_2SO_4. The manufacturer recommends that the tank be regenerated (i.e., drained, rinsed, and refilled) after 2,000 lb EO have been treated.

a. 19.8 gal H_2SO_4 = 1.42 kg-mole H_2SO_4 (ρ = 1.834; MW = 98.08) $2NaOH+H_2SO_4 \rightarrow Na_2SO_4+2H_2O$; 1.42 kg-mole H_2SO_4 requires 2.84 kg mole NaOH to neutralize. Neutralization will produce 2.84 kg-moles H_2O and 1.42 kg mole Na_2SO_4. Use 50 percent (w/w) NaOH to neutralize; each 55-gal drum of 50 percent NaOH weighs 700 lb, i.e., 350 lb NaOH (MW = 40); need 2.84 kg-moles or 250 lb NaOH to neutralize.

b. C_2H_4O (EO)$+H_2O \rightarrow C_2H_4(OH)_2$ (ethylene glycol); 2,000 lb EO = 20.51 kg-moles EO (MW = 44.1).

c. At 99 percent conversion, yield is 20.365 kg-moles or 301 gal ethylene glycol (EG) (MW = 62.07; ρ = 1.1088).

d. At 99 percent conversion, 20.365 kg-moles H_2O have reacted. 41.64 kg moles H_2O originally available (MW = 18; ρ = 1); 21.275 kg-moles or 100 gal H_2O remain unreacted.

e. Weight of neutralized solution per tank: 1.42-kg mole Na_2SO_4 = 202 kg Na_2SO_4 (MW = 142.04); 2.84 kg-moles H_2O (from neutralization) = 51 kg H_2O; 250 lb (113 kg) H_2O = from 50 percent NaOH solution; 100 gal unreacted H_2O = 378 kg H_2O; 301 gal EG = 1,264 kg EG; total wt = 2,008 kg = 4,427 lb.

f. Solution is 63 percent (w/w) EG. Add about 50 gal rinse water for each tank = 189 kg; total wt (+rinse H_2O) = 4,844 lb; total gal (+rinse H_2O) = 495 gal = nine 55-gal drums; wt per 55-gal drum = 538 lb.

4. Find scrubber model and cost from Table 5-2, based on the sum of the volumes of the two largest chambers at the facility:

Chambers 4 and 5	2,668 ft^3	Model 600	$157,500

5. Because at least one chamber uses 100 percent EO, explosion-proof valves are necessary.

6. Find number of regenerations of scrubber required per year:

a. Number of scrubber tanks = scrubber model/100 = 6 (scrubber consists of modular tanks).

b. Conversion capacity of scrubber = (no. of tanks)x2,000 lb = 12,000 lb

c. Number of scrubber regenerations = EO-FAC (lb)/12,000, i.e., the amount of EO (lb) to be treated per year divided by the conversion capacity of the scrubber.

141,700/12,000 = 11.81 scrubber regenerations/yr

d. Number of tank regenerations = (No. of scrubber regenerations)x(No. of tanks per scrubber) = (11.81)x(6) = 70.87.

7. Cost of chlorine filter housing = (41.50)x(no. of tanks) = $(41.50)x(6) = $249.

8. Installation costs:

a. Scrubber installation = (0.5)x(cost of scrubber) = $78,750

b. Chlorine filter housing installation = (20)x(no. of tanks) = $120

9. The incremental capital costs of manifolding are presented in Table 5-3 of this report.

10. Vacuum pumps. A closed-loop recirculating water vacuum pump is required on each of the five chambers. The cost of modifying the first vacuum pump is included in the cost of the scrubber; the cost of modifying the other four vacuum pumps is $4,935 each.

11. Calculate direct operating costs:

a. Labor = 3,177+(11.60)x(16)x(no. of regenerations). The $3,177 is for general inspection of the system 15 minutes/shift, 3 shifts/day, 365 days/yr at $11.60/person-hour. For the purposes of these cost analyses, it was assumed that each regeneration of the scrubber would require 2 people at 8 person-hours each, independent of scrubber size. System inspection was also assumed to be independent of scrubber size.

b. Sulfuric acid (50 percent H_2SO_4-electrolyte grade). Assumed: 1 55-gal drum of 50 percent H_2SO_4, i.e., 19.4 gal H_2SO_4, per scrubber tank.

No. of drums required = No. of tank regenerations = (No. of scrubber regenerations)x(No. of tanks per scrubber) = 70.87

Cost of acid = (no. of drums)x(594 lb/drum)x($0.069/lb)

c. Caustic (50 percent NaOH-industrial grade). First, the unit cost of NaOH was calculated.

NaOH required per year = [No. of tank regenerations]x[NaOH (lb) required per tank] = 70.87x250 = 17,718 lb/yr

Total drums/yr required by facility = total NaOH (lb)/350 lb per drum; total drums = 50.6

If total drums >9, cost/lb = 0.0738

If total drums = 3 to 9, cost/lb = 0.0787

If total drums = <2, cost/lb = 0.108

Cost of caustic = (No. of drums)x(cost/lb)x(700 lb/drum)

d. Cost of chlorine filters. Each filter can dechlorinate ~200 gal H_2O (or 1 scrubber tank); replace at each scrubber regeneration.

Cost = (No. of scrubber regenerations)x(No. of tanks)x($15/filter)

e. Disposal. Unit cost of disposal was calculated by multiplying the total number of tank regenerations by the weight of a tank at the time of regeneration, including rinse water (see 3.f).

Total wt = 70.87x4,844 lb/tank = 343,943 lb/yr

If total wt <42,000 lb, disposal cost = wt (lb)x($0.096/lb)

If total wt ≥42,000 lb, disposal cost = wt (lb)x($0.059/lb)

f. Compressed air. The cost of 10 seconds of in-house air per cycle was considered negligible and was not computed for these cost analyses.

12. The capital and annualized costs are reported in Table B-1.

TABLE B-1. CAPITAL AND ANNUALIZED COSTS OF INSTALLING SCRUBBER[1]
(4th Quarter 1984 Dollars)

Item	Cost
I. CAPITAL COSTS[a]	
Installed equipment costs, 1984, $	
Automated scrubber[b]	158,000
Explosion-proof valves for scrubber[c]	18,300
Chlorine filter house[d]	249
Installation of scrubber[e]	79,000
Installation of chlorine filters	120
Taxes: 5 percent of equipment cost	8,850
Freight: 5 percent of equipment cost	8,850
Vacuum pump[f]	19,700
Manifolding of chambers (includes check valve)[g]	9,560
Total capital costs, 1984, $	303,000
II. ANNUALIZED COSTS[a]	
Direct operating costs, 1984, $	
Labor[h]	5,370
Materials	
50 percent H_2SO_4[i]	2,900
50 percent NaOH[j]	2,620
Chlorine filters[k]	1,060
Taxes: 5 percent of materials cost	329
Freight: 5 percent of materials cost	329
Compressed air[l]	0
Disposal of ethylene glycol[m]	20,300
Indirect operating costs, 1984, $	
Overhead: 0.80 x labor	4,300
Property tax, insurance, and administration[n]	12,100
Capital recovery costs[o]	49,300
TOTAL ANNUALIZED COSTS, 1984, $	98,600
III. COST EFFECTIVENESS	
Reduce, Mg EO yr	63.66
Cost effectiveness, 1984, $/Mg EO	1,500

(continued)

TABLE B-1. (continued)

[a]Costs rounded to three significant figures.
[b]Based on total volume of two largest chambers.
[c]One set per scrubber at $18,300 each.
[d]One per tank; six tanks; $41.50 each.
[e]Fifty percent of scrubber cost.
[f]The cost of the first vacuum pump is included in the installation cost of the scrubber; therefore, cost is for remaining four pumps at $4,935 each.
[g]See Table 5-4 of this report. Manifold four chambers at $2,300 each plus $355 for a check valve for the first chamber.
[h]Labor was calculated for 0.25 person-hours/shift, 3 shifts/day, 365 days/year for system inspection and 16 person-hours for each regeneration of the scrubber at $11.60/person-hour. No. of scrubber regenerations = (annual EO use at facility)÷(2,000)x(No. of tanks in scrubber).
[i]The cost of acid is calculated, (annual EO use at facility)÷(2,000)x(594)x($0.069).
[j]The cost of caustic is calculated, No. drum = (EO use/yr at facility)÷(2,000)x(250)÷(350). No. drum = 50.62; therefore, unit cost = $0.0738. Total cost = (No.drums)x(700)x(0.0738).
[k]Chlorine filter cost is (annual EO use at facility)x(15)÷(2,000).
[l]The cost of 10 seconds of house-supplied compressed air per cycle was considered negligible.
[m]Disposal cost is (annual EO use at facility)÷(2,000)x(4,845)x(0.059).
[n]Calculated as 4 percent of total capital costs.
[o]Calculated as (0.16275)x(total capital costs) for an interest rate of 10 percent and a 10-year recovery period.

REFERENCES FOR APPENDIX B

1. Chemical Engineering. Economic Indicators. June 23, 1986. p. 7.

2. Chemical Engineering. Economic Indicators. February 18, 1985. p. 7.

3. Neveril, R., Capital and Operating Costs of Selected Air Pollution Control Systems. GARD, Inc. Niles, Illinois. Publication No. EPA-450/5-80-002. December 1978. p. 3-11, 12, 16.

4. Memorandum from Srebro, S., MRI, to Markwordt, D., EPA/CPB. March 20, 1987. Capital cost, annualized cost, and cost effectiveness of reducing ethylene oxide emissions at commercial sterilization facilities.

APPENDIX C.

CONTROL DEVICE COSTS

(CATALYTIC OXIDATION AND GAS/SOLID REACTOR SYSTEM)

TABLE C-1. CATALYTIC OXIDATION[1]

Flow rate, m^3/min[a] (ft^3/min)	Cost, $[b c]
1.4 (50)	15,000
3.5 (125)	23,000
14 (500)	37,000
28 (1,000)	60,000
84 (3,000)	97,000
168 (6,000)	140,000
252 (9,000)	192,000
336 (12,000)	240,000

[a]The catalytic oxidation units are modular. The sizes listed are available currently. Larger sizes can be designed.
[b]These costs are for catalytic oxidation systems capable of handling sterilizer and aeration emissions simultaneously. Costs were not provided for a system to handle only aeration emissions.
[c]Cost includes heat exchanger (70 percent heat recovery), preheater, and prewiring. Installation and ducting costs are facility-specific and were not provided.

TABLE C-2. ACID-WATER SCRUBBER AND GAS/SOLID REACTOR SYSTEM[2]

Sterilizer volume	Cost, $[a b]
$\leq$0.6 m^3 (20 ft^3)	30,000 to 35,000
0.6 to 1.2 m^3 (20 to 40 ft^3)	40,000 to 45,000
Two 0.8 m^3 (30 ft^3) sterilizers	45,000 to 50,000
One 2 m^3 (72 ft^3) sterilizer	50,000 to 55,000

[a]These are "budget" costs for a complete two-stage system (i.e., acid-water scrubber and the gas/solid reactor). Costs were not provided for the gas/solid reactor separately.
[b]Includes installation costs, wiring, and ductwork.

REFERENCES FOR APPENDIX C

1. Telecon. Nicholson, R., MRI, with Olson, C., Donaldson Company, Inc. May 12, 1988, and June 13, 1988. Discussion regarding the EtO Abator™ catalytic oxidation system.

2. Letter from Kruse, R., Advanced Air Technologies, Inc., to Nicholson, R., MRI. June 13, 1988. Transmitting information about the Safe-Cell™ two-stage system.

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Please read Instructions on the reverse before completing)

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15. SUPPLEMENTARY NOTES

ESD Work Assignment Managers: David Markwordt (MD-13) (919) 541-0837

16. ABSTRACT

This document contains the data and methodology which EPA believes most accurately describes alternative control technologies for ethylene oxide emissions from sterilization facilities.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Ethylene Oxide Ethylene Oxide Sterilization Sterilization Chlorofluorocarbons Volatile Organic Compound (VOC) Emissions		

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Hospital Incinerator Operator Training Course: Volume I

Student Handbook

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HOSPITAL INCINERATOR OPERATOR TRAINING COURSE:

VOLUME I

STUDENT HANDBOOK

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HOSPITAL INCINERATOR OPERATOR TRAINING COURSE:
VOLUME I
STUDENT HANDBOOK

EPA Contract No. 68-02-4395
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NOTICE

This training course is intended to provide the operator with a basic understanding of the principles of incineration and air pollution control. This training course is not a substitute for site-specific hands-on training of the operator with the specific equipment to be operated.

DISCLAIMER

This document generally describes the proper operation of a hospital waste incinerator. It is based on EPA's review and assessment of various scientific and technical sources. The EPA does not represent that this document comprehensively sets forth procedures for incinerator operation, or that it describes applicable legal requirements, which vary according to an incinerator's location. Proper operation of an incinerator is the responsibility of the owner and operator.

Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

ACKNOWLEDGEMENT

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PREFACE

The program for development of a training course for operators of hospital medical waste incinerators was funded as a project of EPA's Control Technology Center (CTC).

The CTC was established by EPA's Office of Research and Development (ORD) and Office of Air Quality Planning and Standards (OAQPS) to provide technical assistance to State and local air pollution control agencies. Three levels of assistance can be accessed through the CTC. First, a CTC HOTLINE has been established to provide telephone assistance on matters relating to air pollution control technology. Second, more in-depth engineering assistance can be provided when appropriate. Third, the CTC can provide technical guidance through publication of technical guidance documents, development of personal computer software, and presentation of workshops on control technology matters. The technical guidance projects, such as this one to develop training materials for hospital waste incinerator operators, focus on topics of national or regional interest that are identified through contact with State and local agencies.

The CTC became interested in developing a basic training course for operators of hospital waste incinerators with the idea that properly trained operators can improve operating and maintenance procedures and, consequently, minimize air emissions. This training course was prepared to provide the operator with a basic understanding of the principles of incineration and air pollution control and to identify, in a general sense, good operating practices. The course is <u>not</u> intended as a substitute for site-specific hands-on training of the operator with the specific equipment to be operated.

The course consists of three volumes:

Volume I--Student Handbook
Volume II Course--Presentation Slides
Volume III--Instructor Handbook

This volume is a student handbook which includes 11 separate sessions. The handbook sessions cover, in more detail, the same topics your instructor will cover during the course. The handbook also includes a glossary of terms and a list of suggested documents from which further information can be obtained. The student handbook is narrative in style and is for your use not only during the course but also afterwards as a valuable reference when you go back to work.

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INTRODUCTION

DESCRIPTION

This course is designed for hospital waste incinerator operators. It focuses on the basic principles of combustion; the proper design, operation, and maintenance of hospital waste incineration systems and their associated air pollution control systems; and the operator's role in reducing air pollution and complying with applicable regulations.

COURSE GOALS AND OBJECTIVES

COURSE GOALS

1. To provide you with the knowledge of the basic principles of incineration and proper operation and maintenance practices for hospital waste incinerators and air pollution control systems.
2. To help you understand your role in protecting the environment by reducing air pollution and disposing of ash properly.
3. To increase your awareness of regulatory requirements and safety concerns.

COURSE OBJECTIVES

At the conclusion of this course you will:

1. Understand the air pollution problems associated with hospital waste incinerators and how to minimize them.
2. Be aware of common operational problems and safety hazards and their causes.

3. Know how to use monitoring and recordkeeping to improve operation and maintenance and to aid in compliance with regulatory requirements.

USING THE HANDBOOK

The material in the handbook covers the same topics your instructor will cover. Your handbook is for your use not only during the course but also afterwords as a valuable reference when you go back to work.

There are one or more review exercises in each session. To complete an exercise, place a piece of paper across the page, covering the questions below the one you are answering. After writing your answer on a separate piece of paper (not in the book), slide the paper down to uncover the next question. The answer for the first question will be given on the right side of the page, separated by a line from the second question, as shown on the next page. All answers to review questions will appear below and to the right of their respective questions. The answer will be numbered to match the question. Complete each review exercise in the book. If you are unsure about a question or answer, review the material in the session.

A list of references used during preparation of the course is provided at the end of each session. A list of documents which may be particularly helpful to students wishing to learn more about particular topics is presented at the end of the handbook.

SESSION 1.
PROTECTING THE ENVIRONMENT - YOUR RESPONSIBILITY

SESSION 1. PROTECTING THE ENVIRONMENT - YOUR RESPONSIBILITY

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SESSION 1.
PROTECTING THE ENVIRONMENT - YOUR RESPONSIBILITY

SESSION GOAL AND OBJECTIVES

GOAL

To familiarize you with
- Why hospital waste is incinerated;
- What the environmental concerns are related to incineration; and
- What air pollutants are important.

OBJECTIVES

Upon completing this session, you should be able to:

1. Name the primary reasons that hospital wastes are incinerated;
2. Identify environmental concerns related to incineration;
3. List the types of air pollutants of concern that could be emitted to the atmosphere from hospital waste incinerators; and
4. Recognize your role in preventing air pollution and improper ash disposal.

WHY INCINERATION

Hospitals generate large quantities of waste. Some of the types of wastes that are generated are infectious wastes, spent alcohols or other solvent materials, plastic containers, and general rubbish. Historically, much of this waste has been disposed of in landfills. However, as many landfills reach capacity and people become more concerned with environmental problems caused by improper disposal of waste materials, incineration has become an attractive option for handling wastes. Incineration does not eliminate the need to landfill waste, but it does reduce the amount of waste that must be placed in landfills. It also generates a waste for landfills that is more acceptable than recognizable hospital wastes to the general public.

The primary advantages of incineration are:

- It greatly reduces the weight and volume of waste material that must be disposed of in landfills.
- It destroys organic materials that may be harmful or that may be degradable to harmful materials in landfills.
- The incinerator sterilizes the waste. That is, the high temperatures in incinerators can destroy any pathogens that may be in infectious waste materials.
- The incinerator destroys animal or human pathological wastes or other hospital waste materials that the general public finds objectionable to handle or see.

ENVIRONMENTAL CONCERNS

The general public will not accept incineration as an option for treating hospital wastes if they do not believe that it is safe environmentally. The primary concerns are that the pathogens are destroyed in the incinerator, that the ash residue is of acceptable quality, and that harmful air pollutants are not emitted from the incinerator. This section will present some of the terminology that is important to understanding these concerns. The remainder of the course will describe how an incineration system can be operated and maintained in a way that keeps environmental releases at an acceptable level.

PATHOGEN DESTRUCTION

The primary objective of hospital waste incineration is the destruction of pathogens in infectious wastes. Pathogens are those biological components of the waste that can cause an infectious disease.

The pathogens in infectious waste can be destroyed by the high temperatures achieved in hospital waste incinerators. Almost no information is available on the incinerator conditions required to destroy all pathogens, but temperature and time of exposure are known to be important. Emissions of pathogens from the incinerator could be attributed to insufficient retention time and temperature as a result of the following conditions:

1. Initial charging of the incinerator before operating temperatures are achieved;
2. Failure to preheat the refractory lining;
3. Temperature fluctuations caused by intermittent use;
4. Exceeding design airflow rates, thereby reducing the retention time;
5. Charging beyond incinerator capacity; and
6. Excessive moisture content of the waste.

Other factors such as the type of refractory lining, the positioning and number of burners, and the precision of temperature controlling devices also can affect pathogen destruction. The destruction of pathogens in the incinerator ash also depends on temperature and time of exposure.

AIR POLLUTANTS OF CONCERN

Figure 1-1 shows an incinerator and the main pollutants of concern. These pollutants are:

- Particulate matter;
- Hydrochloric acid gas;
- Toxic metals;
- Organic compounds; and
- Carbon monoxide.

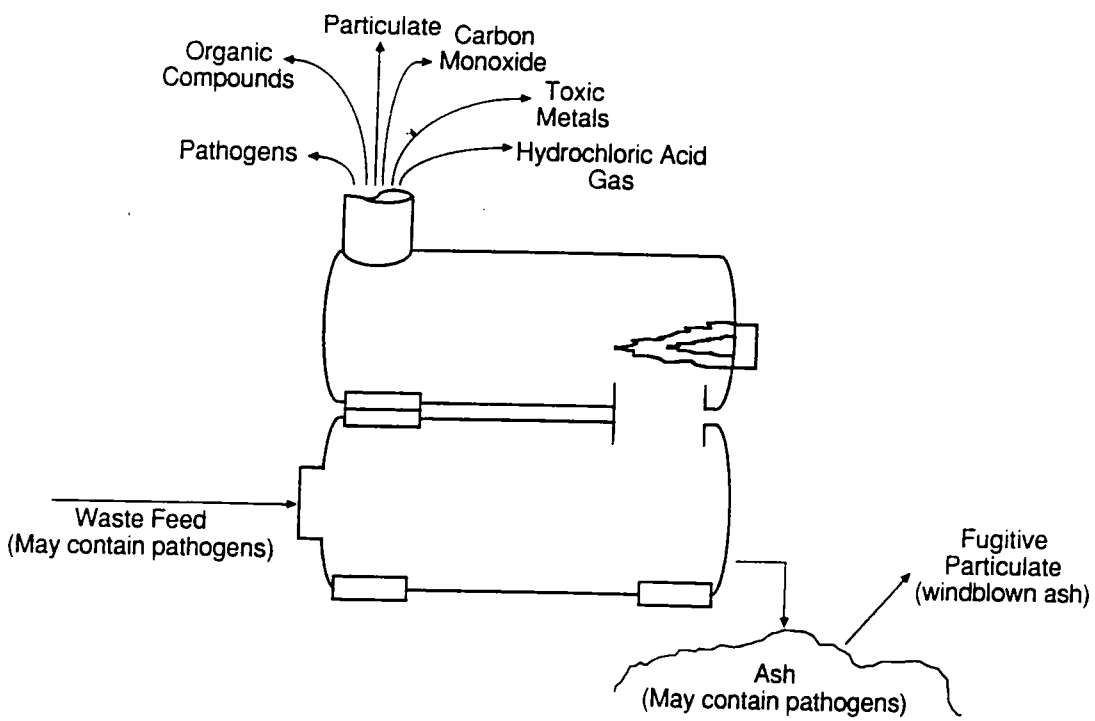

Figure 1-1. Schematic of incinerator showing sources of pollutants of concern.

Particulate matter may be defined as fine liquid or solid matter such as dust, smoke, mist, or fumes found in the gaseous emissions from the incinerator. Particulate matter emissions may have a dark or light color. Particulate matter emissions can be described in terms of opacity. Opacity is the degree to which light is obscured by a polluted gas--a clear window has 0 percent opacity while black paper has 100 percent opacity. Opacity may be measured with the naked eye or using a transmissometer (opacity monitor). Particulate matter is a problem because it can cause or aggravate respiratory problems in humans. It also creates aesthetic problems since it is readily noticed and is a nuisance because of soiling of exposed surfaces on houses and cars.

Hydrochloric (HCl) acid is generated when polyvinyl chloride (PVC) plastic (usually clear plastic) material is burned in the incinerator. The appearance of a white plume or cloud a short distance above the stack indicates that HCl is condensing. The major concerns about HCl are that it causes respiratory problems in humans, contributes to acid rain problems, and causes material damage to metals and concrete.

Toxic metals include cadmium, arsenic, beryllium, chromium, nickel, lead, and mercury. These metals may be found in hospital wastes. These metals are known to be hazardous to human health.

Organic compounds are compounds that contain primarily carbon and hydrogen and may also contain other elements such as oxygen, nitrogen, and chlorine in smaller amounts. Some organic compounds are known to cause or are suspected of causing cancer and are considered hazardous air pollutants. The public's primary concern is related to dioxin and furan emissions, but other organic compounds such as benzene and vinyl chloride may be emitted.

Carbon Monoxide (CO) also is generated during combustion if the combustor is not operated properly. (Your automobile generates some amount of CO.) CO is toxic to humans if concentrations are high enough, and it also is an indicator of combustion quality.

SOLID WASTE ASH QUALITY

One of the major objectives of incineration is to generate a high quality ash for land disposal. All pathogens should be destroyed, and almost all organic material should be completely burned. Ideally, no large chunks of unburned waste material (other than metals or glass) should remain in the waste. Attempting to dispose of hospital waste that is incompletely burned may result in monetary fines, or the landfill may refuse to accept the waste. From an aesthetic standpoint, large pieces of medical waste that have not been burned may be of concern to the public. A measure of ash quality is "burnout," which is the percentage of organic material remaining in the waste. For example, a burnout of 95 percent means that the ash can contain only 5 percent organics.

Adequately burned and quenched ash may be disposed of in a sanitary (municipal) landfill. The ash should be stored in covered containers or

kept wet prior to transport to the landfill to prevent fugitive emissions. Individual landfills may have requirements that must be followed in order for your waste to be accepted. You should familiarize yourself with these requirements to prevent refusal of the waste.

THE OPERATOR - YOUR ROLE

It is the operator's role and responsibility to protect the environment by:

1. Complying with all emission limits and operating practices specified in the permit to operate.
2. Minimizing emissions of particulate matter, HCl, toxic metals, carbon monoxide, and organic compounds through proper incinerator and air pollution control device operation;
3. Operating the incinerator to generate high quality ash that is sterile and can be disposed of in landfills;
4. Minimizing particulate matter emissions from ash handling;
5. Disposing of ash properly by sending it to appropriate disposal sites; and
6. Performing the regular maintenance inspections (described in Session 8) to catch any operational problems early.

The rest of this document will provide you with information to help you meet this responsibility.

REVIEW EXERCISE

1. List three advantages of hospital waste incineration

2. List the main pollutants of concern.

3. Emissions of hydrochloric acid gas occur because of the presence of _____ in the feed material.

4. Waste ash that does not meet landfill requirements can be refused by the landfill, and monetary fines may be imposed for improper ash disposal. True or false.

5. To minimize environmental problems, you should properly:
   a) _____
   and
   b) _____

6. You should perform regular _____ inspections to catch any problems early.

1. Reduces volume and weight of waste
   Destroys pathogens (sterilizes waste)
   Destroys organics
   Destroys objectional waste materials

2. Particulate matter
   Hydrochloric acid gas
   Toxic metals
   Hazardous organics
   Carbon monoxide

3. Polyvinyl chloride plastic

4. True

5. a) operate your incinerator

   b) handle and dispose of the ash.

6. Maintenance

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SESSION 2.
BASIC COMBUSTION PRINCIPLES

SESSION 2. BASIC COMBUSTION PRINCIPLES

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SESSION 2.
BASIC COMBUSTION PRINCIPLES

GOAL AND OBJECTIVES

GOAL

To familiarize you with:

- Basic combustion terminology that will be used in the remainder of the course;
- How the combustion process works and how you affect the process;
- Indicators of good combustion and poor combustion; and
- How the combustion process affects air emissions.

OBJECTIVES

Upon completing this session, you should be able to:

1. List the three factors that are needed for combustion to occur;
2. List the combustion products generated under good combustion and poor combustion conditions;
3. Describe the relationship among fuel, air, and waste control;
4. Describe how combustion air requirements are affected by waste characteristics;
5. Describe what happens when you have too much or too little combustion air;
6. Estimate the heating value of different waste types;
7. Describe how the combustion gas oxygen level is related to combustion air;
8. Define opacity and describe what happens to opacity under poor combustion conditions; and
9. Recognize the definitions of these terms:

   - Heating value;
   - Stoichiometric (theoretical) air;
   - Excess air;
   - Starved air; and
   - Products of incomplete combustion.

THE COMBUSTION REACTION

Combustion of hospital wastes is a chemical reaction. In the incinerator, organic materials and oxygen react rapidly and violently to produce combustion gases and energy in the form of heat and light. The reaction works like this:

$$\text{Organic Material} + \text{Oxygen} \xrightarrow[\text{Heat}]{} \text{Combustion Gas} + \text{Solid Residue} + \text{Energy(Heat)}$$

For the reaction to begin and to keep going, all three elements--organic material, oxygen, and heat--must be present.

The organic material used in the reaction comes from two sources, waste and auxiliary fuel. Some organic material is contained in most hospital waste. Depending on the fraction of organics and the specific organic composition, the waste may be adequate to sustain combustion. The other source of organic material is auxiliary fuel. Auxiliary fuel is always used to preheat the incinerator and to start combustion; auxiliary fuel may be used to maintain combustion if the waste material does not contain enough organic material to maintain high temperatures.

The oxygen needed for the combustion reaction is supplied by the ambient combustion air. Combustion air is supplied to the combustion chambers through air ports by a forced draft fan, by an induced draft fan, or by natural draft. In general, this air contains about 21 percent oxygen (O_2) and 79 percent nitrogen (N_2), so about 21 percent of the total combustion air fed to the incinerator is oxygen that is available to react with the organic material in the waste and fuel.

The combustion reaction between the organic material and oxygen that causes the organics to burn will occur only after the temperature of the organic material is raised to the point that combustion can begin. Each specific organic compound has its own temperature at which the reaction occurs, but temperatures in the range of 1000° to 1800°F generally are considered to provide "good combustion conditions." Energy in the form of heat is required to raise the temperatures of the incinerator chamber and organic material and O_2. Initially, this energy usually is supplied by the pilot and auxiliary fuel burners. After the system is in full operation, the energy released from the burning waste often is adequate to maintain these high temperatures.

Hospital wastes contain two types of organic materials--volatile matter and fixed carbon. These two types of materials are involved in distinct types of combustion reactions, and the operating variables that control the two types of reaction are different.

Volatile matter is that portion of the waste that is vaporized (or evaporated) when the waste is heated. Combustion occurs after the material becomes a gas. The combustion variables that influence this reaction are gas temperature, residence time, and mixing. A minimum temperature is needed to start and sustain the chemical reaction. Residence time is the length of time, generally measured in seconds, that the combustion gas spends in the high temperature combustion chamber. The residence time must be long enough for the reaction to be completed before it leaves the high temperature zone. Turbulent mixing of the volatile matter and combustion air is required to ensure that the organic material and oxygen are well mixed.

Fixed carbon is the nonvolatile organic portion of the waste. For fixed carbon, the combustion reaction is a solid-phase reaction that occurs primarily in the waste bed (although some materials may burn in

suspension). Key operating parameters are bed temperature, solids retention time, and mechanical turbulence in the bed. The solids retention time is the length of time that the waste bed remains in the primary chamber. Mechanical turbulence of the bed is needed to expose all the solid waste to oxygen for complete burnout. Without mechanical turbulence, the ash formed during combustion can cover the unburned waste and prevent the oxygen necessary for combustion from contacting the waste.

OPERATING FACTORS RELATED TO COMBUSTION

The three operating factors that have the greatest effects on the combustion reaction are combustion air flow rate and distribution, operating temperatures, and waste feed rate and characteristics. These three factors are all related, and the combustion reaction is controlled by controlling them.

The two key questions about combustion air that we will address are:

- How much combustion air is needed to sustain the combustion reaction?
- What happens if there is too much or too little combustion air?

COMBUSTION AIR

In the chemical reaction between organic materials and oxygen, the amount of oxygen required under ideal or "perfect" conditions to burn all of the organic materials with no oxygen left over is called the stoichiometric (or theoretical) oxygen level. The amount of combustion air associated with that oxygen level is called the stoichiometric air level. Air flows greater than those required at stoichiometric levels are called excess air levels, and airflows less than those required at stoichiometric levels are called deficient air or substoichiometric starved air levels. Typically a hospital incinerator operates with an overall 140 to 200 percent excess air level. That is, the incinerator operates with about one and one-half to two times more air than required at stoichiometric levels. Excess air is used to assure that enough oxygen is available for complete combustion.

Computation of exact stoichiometric air requirements for a waste incinerator is difficult because it depends on the chemical composition of the waste and fuel. However, stoichiometric air requirements can be estimated on the basis of the energy input (or heat input) to the incinerator. Heat input is a measure of the energy released when the waste and fuel are burned. It is measured in British thermal units (Btu's). Generally about 1 standard cubic foot of combustion air is required per 100 Btu's of heat input to the incinerator.

Maximum combustion temperatures are always attained at stoichiometric conditions. As the amount of excess air is increased above the stoichiometric point, the temperature in the incinerator drops because energy is used to heat the combustion air. If the amount of combustion air is too great, the temperature can drop below "good combustion

temperature," and undesirable combustion products are generated as a result of incomplete combustion. As the amount of excess air is decreased, the combustion temperature increases until it becomes maximum at the stoichiometric point. Below the stoichiometric point, the temperature decreases because complete combustion has not occurred. A graphical representation of the relationship between combustion temperature and excess air level is shown in Figure 2-1. At air levels below the stoichiometric point, some of the organics are not reacted, and pollutants are emitted as a result of incomplete combustion..

If an incinerator operates with excess air, some of the oxygen in the combustion air does not react. Increases in excess air levels result in increases in combustion gas oxygen levels. The oxygen concentration of the effluent gas stream is a useful indicator of the combustion excess air levels and is useful for monitoring the combustion process.

COMBUSTION TEMPERATURE

Temperature also plays an important role in the combustion of hospital wastes. Temperatures should be maintained at levels above design temperatures to ensure pathogen destruction and to sustain the combustion reaction. However, temperatures that are too high also cause problems. Continuous exposure of the combustor refractory to high temperatures is generally not desirable because it can cause the ash to fuse and can cause thermal damage to the refractory. The lower and upper limits for "proper" temperature ranges are discussed in later sessions of this course.

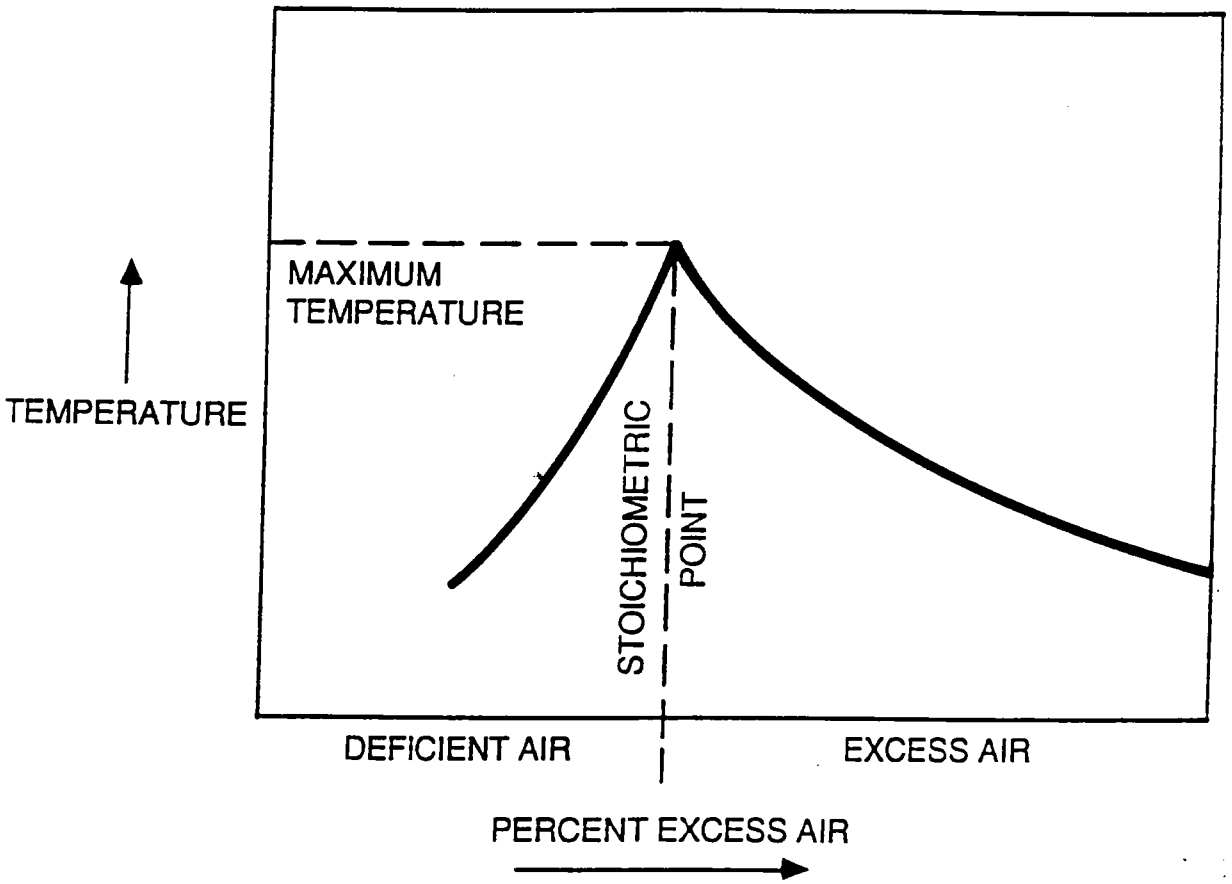
WASTE CHARACTERISTICS

The primary characteristics of the waste that affect the combustion reaction are the heating value, the moisture content, and the chlorine content. Typical heating values and moisture contents of some waste materials typically fired to hospital waste incinerators are shown in Table 2-1.

The heating value of a waste is a measure of the energy released when the waste is burned. It is measured in units of Btu/lb (J/kg). A heating value of about 5,000 Btu/lb (11.6×10^6 J/kg) or greater is needed to sustain combustion. Wastes with lower heating values can be burned, but they will not maintain adequate temperature without the addition of auxiliary fuel. The heating value of the waste also is needed to calculate total heat input to the incinerator where:

Heat Input (Btu/h) = Feed Rate (lb/h) x Heating Value (Btu/lb)

Moisture is evaporated from the waste as the temperature of the waste is raised in the combustion chamber; it passes through the incinerator, unchanged, as water vapor. This evaporation of moisture uses energy and reduces the temperature in the combustion chamber. The water vapor also increases the combustion gas flow rate, which reduces combustion gas residence time.



CONTROL OF TEMPERATURE AS A FUNCTION OF EXCESS AIR[1]

Figure 2-1. Relationship of temperature to excess air.[1]

TABLE 2-1. CHARACTERIZATION OF HOSPITAL WASTE[3]

Component description	HHV dry basis, kJ/kg	Bulk density as fired, kg/m^3	Moisture content of component, weight %	Heat value as fired, kJ/g
Human anatomical	18,600-27,900	800-1,200	70-90	1,860-8,370
Plastics	32,500-46,500	80-2,300	0-1	32,300-46,500
Swabs, absorbants	18,600-27,900	80-1,000	0-30	13,000-27,900
Alcohol, disinfectants	25,500-32,500	800-1,000	0-0.2	25,500-32,500
Animal infected anatomical	20,900-37,100	500-1,300	60-90	2,090-14,900
Glass	0	2,800-3,600	0	0
Beddings, shavings, paper, fecal matter	18,600-20,900	320-730	10-50	9,300-18,800
Gauze, pads, swabs, garments, paper, cellulose	18,600-27,900	80-1,000	0-30	13,000-27,900
Plastics, PVC, syringes	22,500-46,500	80-2,300	0-1	22,300-46,500
Sharps, needles	140	7,200-8,000	0-1	140
Fluids, residuals	0-23,200	990-1,010	80-100	0-4,640

Component description	HHV dry basis, Btu/lb	Bulk density as fired, lb/ft^3	Moisture content of component, weight %	Heat value as fired, Btu/lb
Human anatomical	8,000-12,000	50-75	70-90	800-3,600
Plastics	14,000-20,000	5-144	0-1	13,900-20,000
Swabs, absorbants	8,000-12,000	5-62	0-30	5,600-12,000
Alcohol, disinfectants	11,000-14,000	48-62	0-0.2	11,000-14,000
Animal infected anatomical	9,000-16,000	30-80	60-90	900-6,400
Glass	0	175-225	0	0
Beddings, shavings, paper, fecal matter	8,000-9,000	20-45	10-50	4,000-8,100
Gauze, pads, swabs, garments, paper, cellulose	8,000-12,000	5-62	0-30	5,600-12,000
Plastics, PVC, syringes	9,700-20,000	5-144	0-1	9,600-20,000
Sharps, needles	60	450-500	0-1	60
Fluids, residuals	0-10,000	62-63	80-100	0-2,000

Most chlorine in plastics or solvents in the waste feed will react to form hydrochloric acid (HCl). This HCl is an emission problem, and it can create corrosion problems downstream from the incinerator.

PRODUCTS OF THE COMBUSTION REACTION

The primary products of hospital waste incineration are combustion gases, solid residue (ash), and energy. The primary objectives of the combustion process are to generate an ash residue that is sterile (free of pathogens) and does not contain unburned, recognizable medical wastes; and to minimize air pollutants in the combustion gas stream.

The organic materials that enter the incinerator with the waste and fuel are primarily made up of carbon, hydrogen, and oxygen. Ideally, these organic materials react with oxygen in the combustion gas to form carbon dioxide (CO_2) and water vapor (H_2O). The chemical reaction for this ideal situation is

$$\underset{(C,\ H,\ O)}{\text{Organics}} + O_2 \rightarrow CO_2 + H_2O + \text{Heat}$$

This ideal reaction represents <u>complete combustion</u>.

However, this ideal reaction does not occur in operating waste combustion systems. Factors that lead to a less than ideal reaction are poor mixing, too little combustion air, and low temperatures. Under those conditions <u>products of incomplete combustion</u> are emitted with the stack gases. The most common product of incomplete combustion is CO. Concentrations of CO in the stack gas generally will increase under any of the poor combustion conditions described above. A product of incomplete combustion that often is emitted under poor mixing conditions or high temperature, low excess air conditions, is elemental carbon (or soot). The soot particles are very fine and generally result in high opacity at the combustion stack. Other products of incomplete combustion that cause concern because of their health impacts are benzene, dioxins and furans, and other hazardous organic compounds.

The waste feed also includes inorganic materials. Generally, they are not involved in the combustion reaction. The inorganic materials in the waste feed are either retained in the ash or are emitted as particulate matter in the combustion gas. Air velocities in the combustion bed are controlled to reduce the amount of inorganic material entrained (picked up by) the combustion gas and emitted with the combustion gas.

COMBUSTION INDICATORS

The information presented in the above section suggests that the following indicators can be used to monitor combustion quality.

OPACITY

The opacity of the combustion gas stream is a measure of the degree to which the stack gas plume blocks light. Opacity is primarily caused by noncombustible ash or uncombusted carbon (soot) in the flue gas. High opacities can indicate poor mixing or low levels of combustion air. High opacities also may be generated by high levels of HCl emissions or poor burner operation in the secondary chamber. If a large amount of water vapor is present in the combustion gas, the water can condense when it cools as it leaves the stack forming a dense white "steam plume." This is not an indicator of poor combustion and should not be confused with a black or white smoke plume caused by soot or acid gases.

STACK GAS O_2 CONCENTRATION

The stack gas O_2 concentration provides a measure of excess air. Hospital waste incinerators typically operate at 140 to 200 percent excess air, which roughly corresponds to 12 to 14 percent O_2 in the stack gas.

STACK GAS CO CONCENTRATION

Each combustion system has a "typical operating range" for CO. If the stack gas CO concentration goes above this typical range, combustion problems are likely.

COMBUSTION TEMPERATURE

Rapid increases or decreases in combustion gas temperature indicate potential combustion problems. Rising temperatures indicate that the heat input is increasing and/or airflow is decreasing which can lead to insufficient air for complete combustion. Falling temperatures indicate problems in sustaining combustion.

ASH COMBUSTIBLES

If an incinerator is operating properly, little organic material will remain in the ash. The extent of organics combustion is measured by the quantity of combustible materials remaining in the ash. Increases in ash combustibles indicate that bed temperatures are too low, that combustion air is not being distributed properly in the bed, or that waste retention time is too short.

REVIEW EXERCISE

1. List the three factors required for combustion.

2. Which of the following are products of complete combustion?
   Dioxins
   H_2O
   CO
   CO_2

3. The heating value of a waste required to sustain combustion without auxiliary fuel is about _____ Btu/lb.

4. List two combustion conditions that can cause high stack gas CO concentrations.

5. When the combustion air level is below stoichiometric, it is called a substoichiometric or _____-air condition.

6. All inorganic material is removed with the ash. True or False?

7. As excess air levels increase beyond stoichiometric levels, temperatures ___.

8. About 1 scf of combustion air is needed for every _____ Btu of heat input.

9. Heat input (Btu/h) = heating value (Btu/lb) x _____ _____.

10. Describe the combustion conditions that result in high opacity.

11. The most common product of incomplete combustion is _____.

1. Organic material
   Oxygen
   Heat

2. H_2O
   CO_2

3. 5,000

4. Poor mixing
   Low temperature
   Insufficient air

5. starved

6. False. Some may be emitted as particulate matter in the combustion gases.

7. decrease

8. 100

9. feed rate, lb/h

10. Poor mixing or low excess air which causes soot formation.

11. CO

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SESSION 3.
BASIC INCINERATOR DESIGN

SESSION 3. BASIC INCINERATOR DESIGN
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SESSION 3.
BASIC INCINERATOR DESIGN

SESSION GOAL AND OBJECTIVES

GOAL

To familiarize you with

- The key components of an incinerator system;
- The different types of incineration systems; and
- The operating principles of multiple chamber excess-air and controlled (starved)-air incinerators.

OBJECTIVES

Upon completing this session, you should be able to:

1. Understand the difference between multiple chamber, controlled-air and rotary kiln incinerators;
2. Identify the type of incinerator you operate--multiple chamber, controlled air or rotary kiln;
3. Identify the type of waste charging system you use; and
4. Identify the type of ash removal system you use.

INTRODUCTION

During this session we will discuss:

1. The major components of an incineration system:

   - Waste handling and charging system;
   - Incinerator;
   - Ash removal system;
   - Auxiliary components; and
   - Control/monitoring system.

2. The three major types of incinerators used for hospital wastes and their principle of operation:

   - Multiple chamber;
   - Controlled-air; and
   - Rotary kiln.

MAJOR PARTS OF AN INCINERATION SYSTEM

Figure 3-1 depicts the major parts of an incineration system that will be discussed in this session. These are the waste charging system, the incinerator, and the ash removal system. Control and monitoring systems are discussed separately in Session 5. Add-on air pollution control systems are discussed in Session 4.

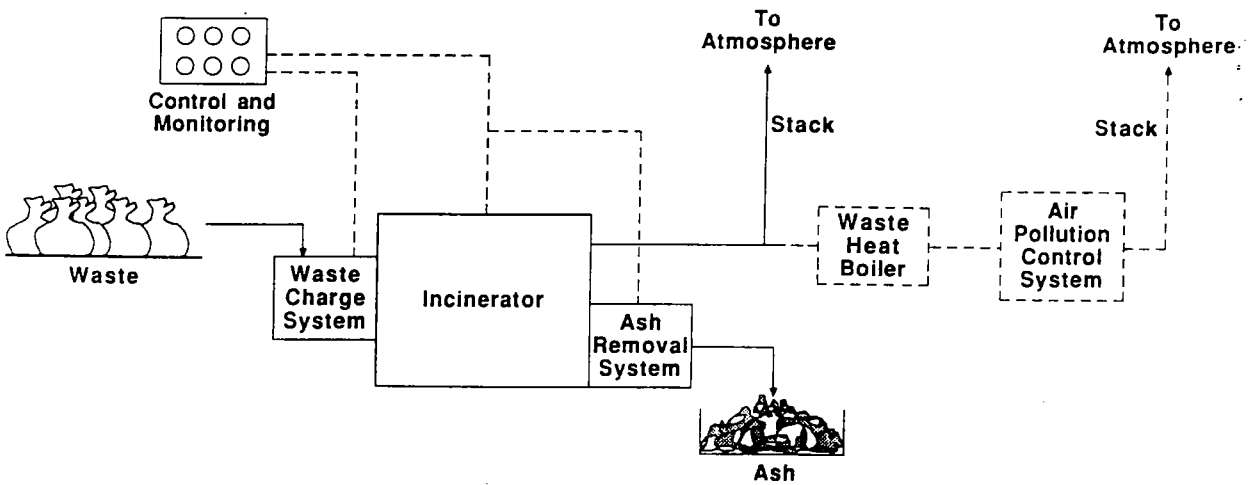

Figure 3-1. Major components of an incineration system.

It is important to think of the incinerator as a system because the design, operation, and maintenance of each part of the system affects the performance of the other parts.

For example, let's consider the waste charging system:

-- The design of the waste charging system will affect how the incinerator can be operated. If the charging system is a mechanical system with automatic controls and interlocks, then the charging rate can be automatically controlled by a timer system.
-- The operation of the waste charging system affects the performance of the incinerator; if waste is fed to the incinerator too fast, incomplete combustion and air pollution may result.
-- The maintenance of the waste charging system affects the operation of the incinerator; if the charging system breaks down, the incinerator cannot be operated.

Throughout this course, and when you operate your incinerator, you should think about all the system parts and how operation of each part affects operation and performance of the entire system.

The "heart" of the system is the incinerator, and there are three basic types of incinerators used for medical wastes:

- Multiple chamber;
- Controlled air; and
- Rotary kilns.

The following sections briefly discuss the principle of operation for each type incinerator and identify key components.

Following the sections on the major types of incinerators used for hospital waste, there is a discussion of the waste handling and charging systems, ash handling systems, and combustion air/gas handling systems typically used for the incinerators.

MULTIPLE-CHAMBER INCINERATORS

INTRODUCTION

Multiple-chamber incinerators consist of two or more combustion chambers; the primary chamber for solid phase combustion and the secondary chamber for gas phase combustion. These incinerators are often referred to as excess-air incinerators because they operate with excess air levels well above stoichiometric in both the primary and secondary combustion chambers.

The traditional designs that are used for multiple-chamber incinerators are:

the "in-line" hearth, and
the "retort" hearth.

Figure 3-2 depicts the in-line hearth design. For the in-line hearth, flow of the combustion gases is straight through the incinerator with turns in the vertical direction only (as depicted by the arrows in Figure 3-2). Figure 3-3 depicts the retort design. In the retort incinerator, the combustion gases turn in the vertical direction (upward and downward) as in the in-line incinerator, but also turn sideways as they flow through the incinerator. Because the secondary chamber is adjacent to the primary chamber (they share a wall) and the gases turn in the shape of a U, the design of the incinerator is more compact. In-line incinerators perform better in the capacity range greater than 750 lb/h (340 kg/h). The retort design performs more efficiently than the in-line design in the capacity range of less than 750 lb/h (340 kg/h). The retort design is more typically used in hospital waste applications. Multiple-chamber incinerators are frequently designed and used specifically for incinerating pathological wastes.

PRINCIPLE OF MULTIPLE CHAMBER "EXCESS-AIR" INCINERATION

The combustion process involves two chambers. Both the primary and secondary combustion chambers are operated above stoichiometric oxygen levels.

- In the primary chamber, the waste is ignited using the primary burner. Once the waste has started burning, the burner usually shuts off because it is no longer needed.
- Moisture and the volatile part of the waste are vaporized.
- As the burning proceeds, combustion of the nonvolatile portion (fixed carbon) of the waste occurs in the primary chamber. The incinerator is designed for surface combustion of the waste. Surface combustion requires mostly overfire combustion air, rather than underfire air.
- The combustion products and vaporized gases pass from the primary chamber through the flame port to the mixing chamber.
- Secondary combustion air is added in the flame port. The design of the flame port and mixing chamber, as well as the addition of secondary air, promotes mixing.
- A secondary burner located in the mixing chamber provides additional heat to maintain sufficient combustion temperatures.
- The combustion of the gases begun in the mixing chamber continues as the gases pass through a port in the wall to the secondary or "combustion" chamber.

COMPONENTS OF MULTIPLE-CHAMBER INCINERATORS

The key components of a multiple-chamber retort incinerator are identified in Figure 3-3.

Primary Chamber. The chamber where the waste is fed and combustion begins. The chamber is operated in an "excess-air" atmosphere.

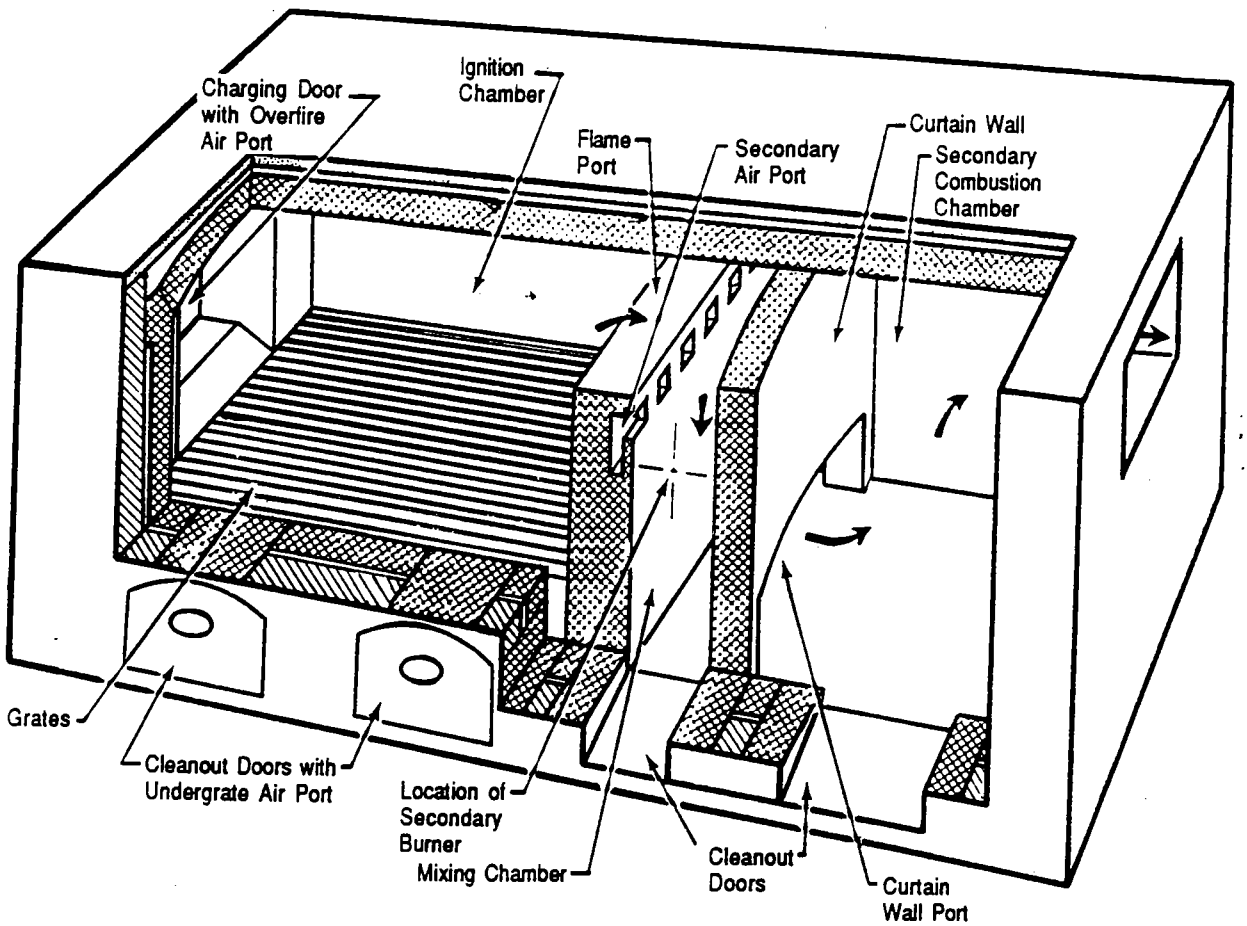

Figure 3-2. In-line multiple-chamber, excess-air incinerator.[1]

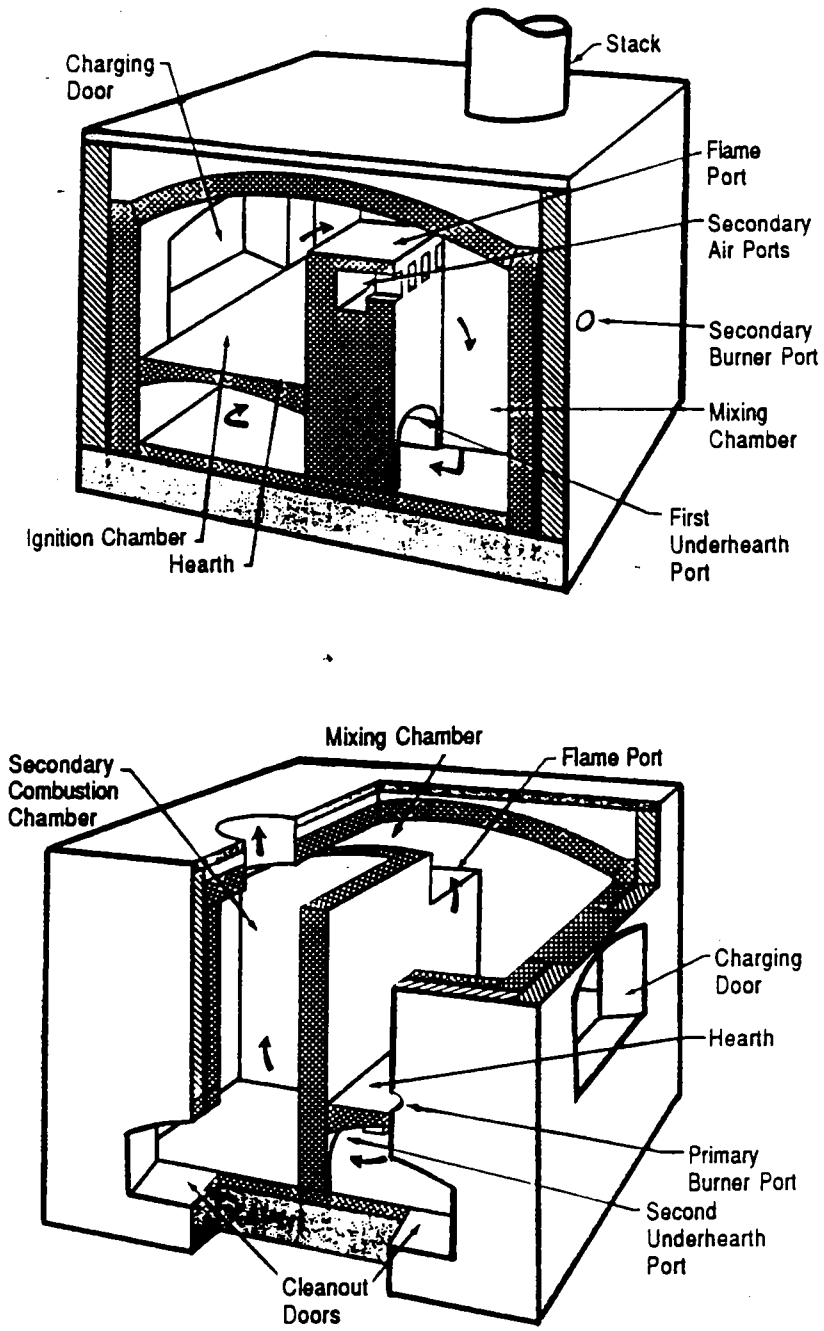

Figure 3-3. Retort multiple-chamber, excess-air incinerator.[1]

Hearth. The hearth is the surface on which the waste is placed. The hearth on a multiple-chamber incinerator is either a metal grate (Figure 3-3) or solid refractory hearth. When a grate is used, ash falls through the grate into the ash pit. Note: A grate will allow liquids and small solid objects (such as needles) to fall through to the ash pit; consequently, multiple-chamber incinerators designed with a grate hearth are not recommended for burning infectious wastes. Incinerators designed specifically for burning pathological wastes such as body parts and animals, i.e., "pathological incinerators," are always designed with solid hearths.

Ignition Burner. Fuel burner for igniting the waste.

Charging Door. Door through which waste is loaded.

Overfire Air Port. Adjustable natural draft opening which allows overfire combustion air to enter the primary chamber. A forced draft combustion air blower also may be used to provide overfire air.

Cleanout Door(s). Door(s) for removal of ash from the primary and secondary chambers.

Mixing Chamber. Chamber located between the primary and secondary combustion chamber in which the combustion gases and secondary combustion air are mixed and burning is initiated.

Flame Port. Opening between the primary chamber and mixing chamber through which the combustion gases pass.

Secondary Air Port. Natural draft opening through which the secondary combustion air enters the mixing chamber. A forced air blower also may be used to provide combustion air to the secondary chamber.

Secondary Burner. Auxiliary fuel burner for maintaining high gas temperature sufficient for complete combustion.

Secondary Combustion Chamber. Chamber where combustion of gases is completed.

Stack. Duct for venting combustion gases to atmosphere.

Multiple-chamber incinerators designed specifically for pathological wastes incorporate the following two design features:

1. The hearth in the primary chamber is solid instead of a grate; and
2. The auxiliary burners in the primary chamber are intended for continuous operation.

Pathological waste is moist and contains liquids. To assure that fluids are retained in the incineration chamber, a solid hearth is used. A raised "lip" at the door often is designed into the hearth to prevent liquids from spilling out the door during charging. Because the heating

value of pathological waste is low and is not sufficient to sustain combustion, additional auxiliary burners are provided in the primary chamber to provide the heat necessary for incineration.

CONTROLLED-AIR INCINERATION

The terms used to describe various types of incinerators are quite varied. Multiple names have been used to describe the same type of incinerator. We will use the term "controlled-air" incinerator to describe one particular type of incinerator. In a controlled-air incinerator the amount and distribution of air to each combustion chamber is controlled. This type incinerator is often referred to as a "starved-air" incinerator. The term "starved-air" is derived from the principle of combustion most frequently used in this type of incinerator. The combustion air to the chamber into which the waste is fed is strictly controlled so that the amount of air present is less than that needed for complete combustion, i.e., the chamber is "starved" for air.

Controlled-air incinerators come in all sizes and shapes. Incinerators are available with design capacities ranging from 50 lb/h (23 kg/h) to 4,000 lb/h (1,800 kg/h). Some are manually controlled, and others are automatically controlled. Some use manual waste loading and ash removal, and others are fully automated.

This section presents the operating principle of controlled-air incineration and identifies the major components of a controlled-air incinerator.

PRINCIPLE OF CONTROLLED-AIR INCINERATION

Figure 3-4 is a simplified drawing of an incinerator that operates using the controlled-air principle. The principle of controlled-air combustion is summarized as follows:

- The system consists of two combustion chambers:
  - -- the primary chamber (also referred to as the ignition chamber); and
  - -- the secondary chamber (also referred to as the combustion chamber).
- The primary chamber accepts the waste, and the combustion process begins. A burner is used to ignite the waste. Once the waste has started burning, the burner usually shuts off because it is no longer needed (unless pathological wastes are being incinerated).
- The air distributed to the primary chamber is controlled so that the chamber is starved for oxygen, in other words, the chamber is operated below stoichiometric levels.
- The combustion air usually is fed to the primary chamber as underfire air--underfire air is directed "under" or through the waste bed through air inlets located near the floor or hearth of the primary chamber.

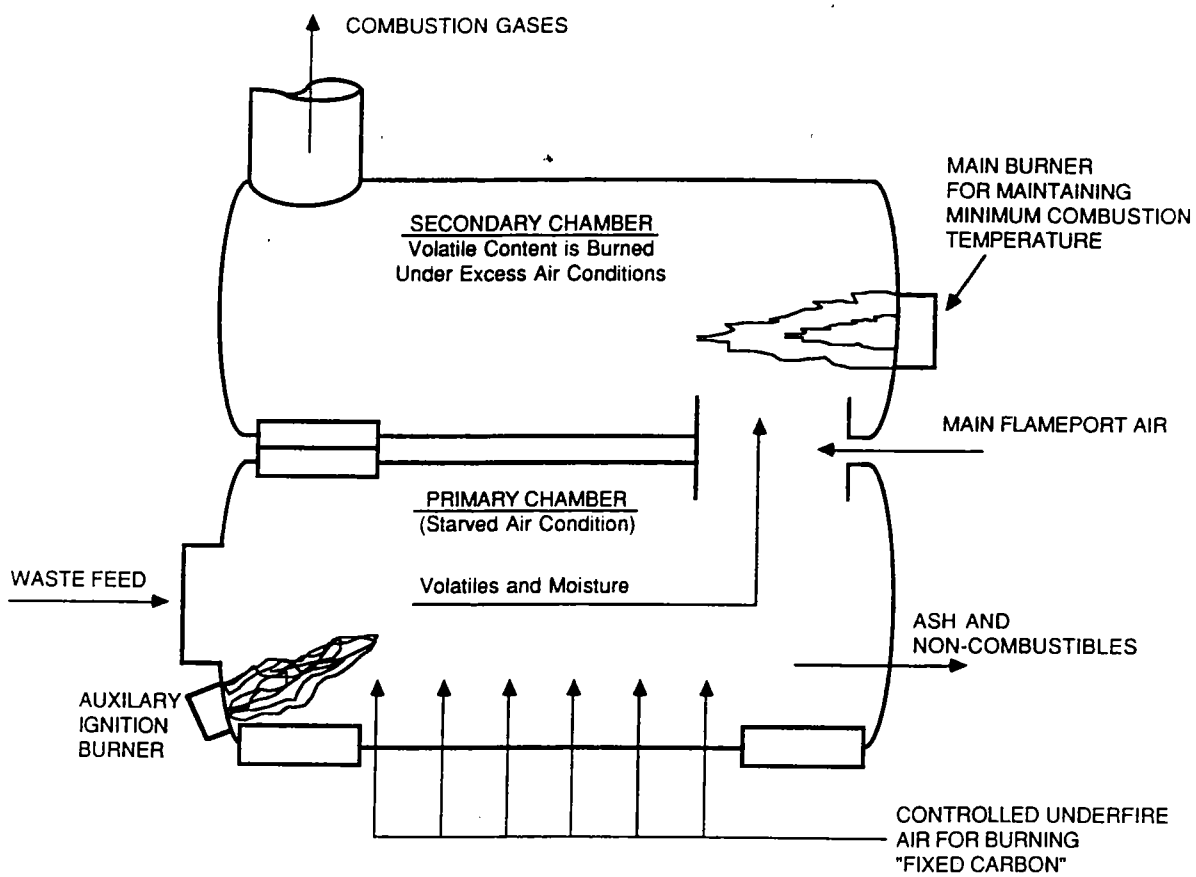

Figure 3-4. Principle of controlled-air incineration.[2]

- Three processes occur in the primary chamber.
  - -- First - the moisture in the waste is vaporized; boiling a pot of water on the stove is an example of the vaporization of water.
  - -- Second - the volatile fraction of the waste is vaporized; when an open can of gasoline sits in the sun, the gasoline vaporizes.
  - -- Third - the fixed carbon remaining in the waste is burned. Fixed carbon is the nonvolatile portion of the waste. To achieve complete combustion, the fixed carbon must be burned in the primary chamber at higher temperatures and for longer times then the volatile fraction. Charcoal briquettes burning in your charcoal grill are an example of fixed carbon burning.
- The combustion gases containing the moisture and the volatile combustible materials from the primary chamber are directed to the secondary chamber.
- As the gases enter the secondary combustion chamber more air--the secondary combustion air--is added. The air is added with enough force to cause mixing of the air and the combustion gases.
- Enough air is added to the secondary chamber so that an "excess" of oxygen is available for the combustion process.
- The gas/air mixture is burned in the secondary chamber at high temperatures 1800° to 2200°F (980° to 1200°C) to promote complete combustion.
- A fuel burner is used in the secondary chamber to ensure that the high temperature is maintained.

Control of the Incinerator. The amount of air supplied to each chamber of the incinerator is used to control the combustion chamber temperature. Figure 3-5 illustrates this principle.

- The primary chamber operates in a starved-air condition. Adding more air allows more combustion and therefore increases the temperature (up to the point of maximum temperature at the stoichiometric air level).
- The secondary chamber operates in an excess-air condition. Adding more excess air (which is cold) dilutes and cools the gases and decreases the temperature.

Thus:

- The amount of air supplied to the primary chamber controls the combustion rate of the waste and the temperature of this chamber; and
- The amount of air supplied to the secondary chamber controls the temperature of this chamber and the combustion rate of the combustion gases from the primary chamber.

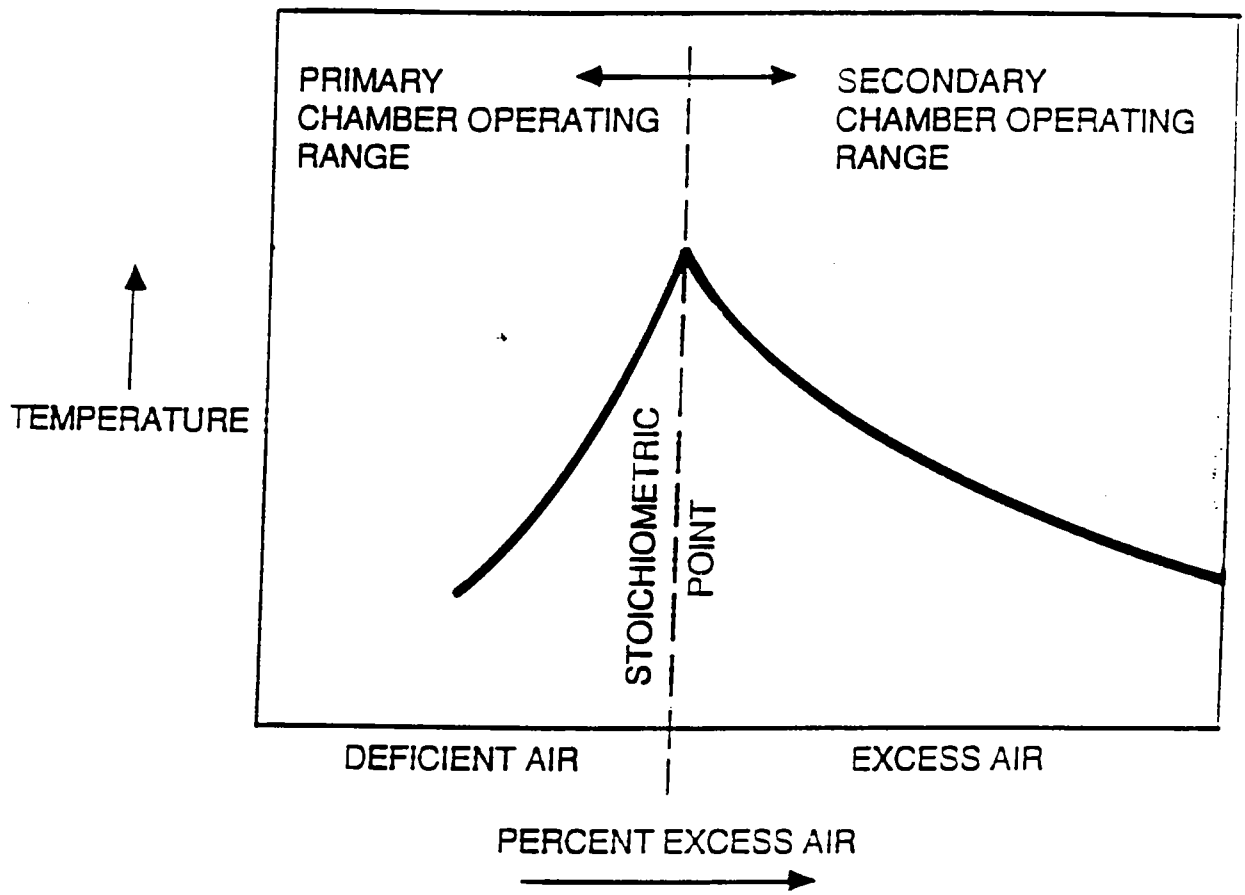

Figure 3-5. Control of temperature as a function of excess air.[3]

The control system for a controlled-air incinerator is based upon the air levels and temperatures in each chamber. Control systems are discussed in Session 5.

COMPONENTS OF A CONTROLLED-AIR INCINERATOR

Figure 3-6 presents a schematic of a controlled-air incinerator. The major components identified are:

1. Primary Chamber. The chamber where the waste is fed and combustion begins. The primary chamber operates with a "starved-air" atmosphere.
2. Primary Chamber - Combustion Air Blower. Forced air blower for providing underfire combustion air to the primary chamber.
3. Primary (Ignition) Burner. Fuel burner for preheating combustion chamber, igniting waste, and maintaining temperature in the primary chamber.
4. Charge Door. Door through which waste is loaded.
5. Ash Removal Door. Door through which ash is removed from the primary chamber.
6. Secondary Combustion Chamber. Chamber where combustion of volatile gases is completed. The secondary chamber operates with an excess-air atmosphere.
7. Secondary Combustion Air Blower. Forced air blower for providing combustion air to the secondary chamber.
8. Secondary Combustion Chamber Air Port. Port through which combustion air enters chamber and causes mixing.
9. Secondary Combustion Chamber Burner. Auxiliary fuel burner for maintaining high temperature in secondary chamber.
10. Cleanout/Inspection Doors. Doors in the secondary and primary chambers which can be opened when the incinerator is shut down to remove ash and inspect the refractory.
11. Primary Chamber Water Spray. Some manufacturers include a spray system to inject a fine water spray (mist) into the primary chamber to assist in temperature control.
12. Primary Chamber Underfire Steam Injection. Some manufacturers include systems for injecting steam into the ash.
13. Stack. Natural draft stack for venting combustion gases to the atmosphere. Because gases are hot, they rise up the stack causing a "draft" (pulling air) through the system.
14. Thermocouples. Two thermocouples located at the exit to each chamber to measure the temperature of the combustion gases.
15. View Ports. Sealed glass view ports for observing the combustion chamber during operation.
16. Control Panel. Instrument panel where the controls and the instruments for controlling and monitoring the operation are located.

The incinerator, as shown in Figure 3-6, has a hopper/ram assembly for automatically feeding the waste to the incinerator but no mechanical device for continuously removing the ash from the system. Waste feed charging systems and ash removal systems are discussed later in this section.

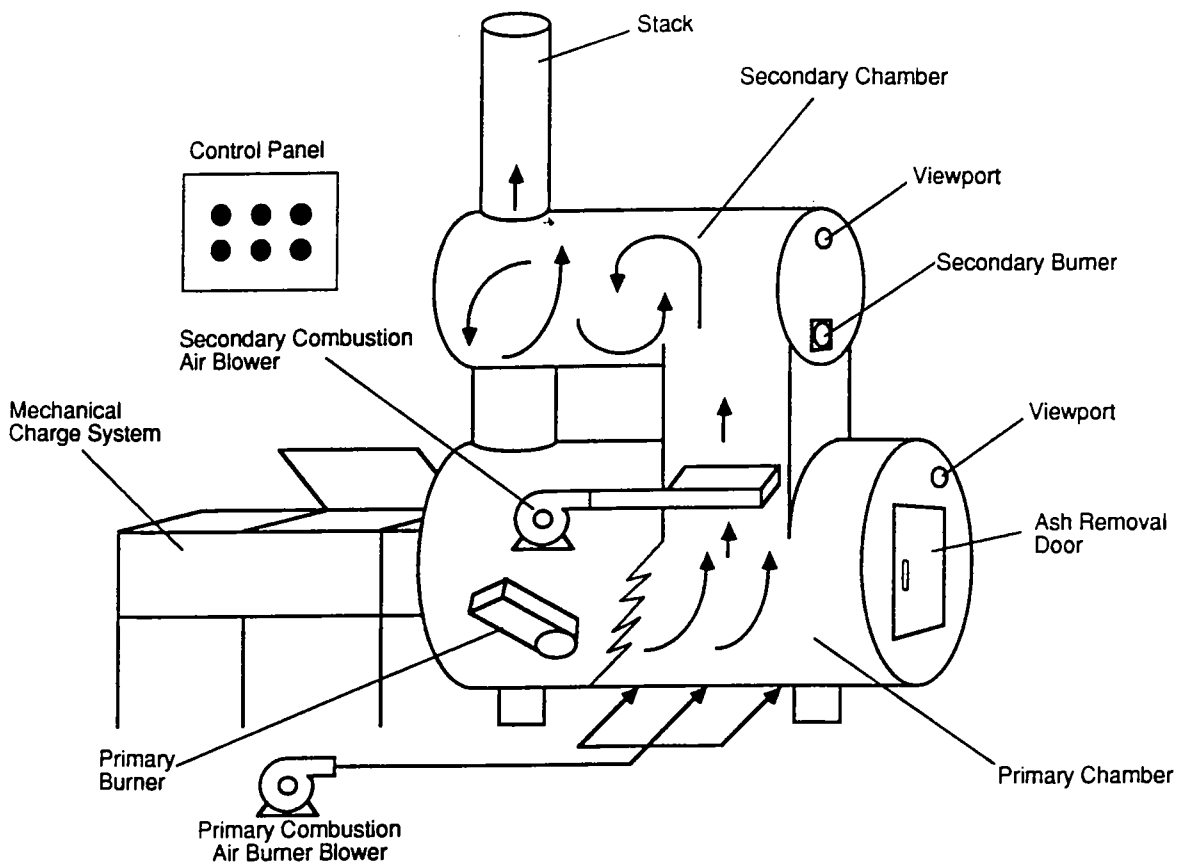

Figure 3-6. Major components of a controlled-air incinerator.

ROTARY KILN

INTRODUCTION

Figure 3-7 is a schematic of a rotary kiln. A rotary kiln also uses the concept of two stage combustion and has two combustion chambers. The primary chamber is a horizontal cylindrical chamber which is slightly inclined and rotates, hence the name "rotary kiln." The secondary chamber is usually cylindrical in shape--much like the secondary chambers described for controlled-air incinerators--or is box-like as depicted in Figure 3-7.

PRINCIPLE OF OPERATION

A rotary kiln is designed to operate continuously. The incinerator must include a system for continuous waste feed to the kiln and continuous ash removal. The principle of operation of a kiln is summarized as follows:

- The rotating kiln is inclined. Waste is fed into the higher end of the kiln by the mechanical feed system.
- Inside the kiln, moisture and volatiles are vaporized from the waste, and the waste is ignited. The volatile gases pass into the secondary chamber.
- Air and heat are added in the secondary chamber to promote complete combustion.
- As the kiln rotates, the solids are tumbled within the kiln and slowly move down the incline toward the discharge end. Tumbling of the waste within the kiln provides exposure of the waste to the air. Combustion of the solids occurs within the kiln, and the ash is discharged into the ash removal system.
- The residence time of the solids within the kiln can be controlled by the kiln's speed of rotation (revolutions per minute [rpm]). The faster the kiln rotates, the faster the solids will move through the kiln.

COMPONENTS OF A ROTARY KILN

The key parts of a rotary kiln are shown in Figure 3-7:

Charging System. Mechanical waste feed charging system for continuously feeding waste to the kiln.

Kiln. The rotating kiln is the primary combustion chamber. The waste is fed into this kiln and ignited. Traditionally, the kiln operates with an excess-air atmosphere. However, some manufacturers now have rotary kilns designed to operate with a substoichiometric atmosphere in the kiln; these kilns use special seals and air injection schemes.

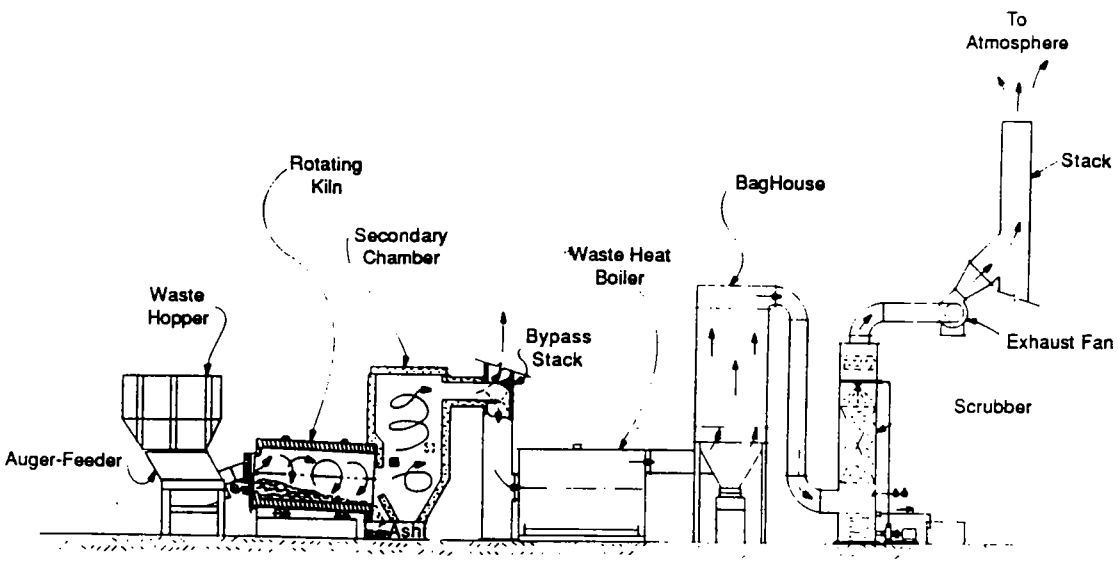

Figure 3-7. Rotary kiln with auger feed.[4]

Kiln Drive. The kiln is rotated by a drive motor and gear system.

Primary Burner. The primary burner ignites the waste and provides additional heat input to the primary chamber, as necessary.

Primary Combustion Air Blower. Provides combustion air for the primary chamber.

Kiln Seals. Sealing rings to minimize air in-leakage between the rotating kiln and the kiln end plates.

Secondary Chamber. Chamber where final combustion of gases occurs.

Secondary Burner. Auxiliary fuel burner to maintain temperature of the secondary combustion chamber.

Secondary Combustion Air Blower. Provides combustion air for the secondary chamber.

Ash Container. Container for collecting ash exiting the lower end of the kiln.

Stack. Vent for discharge of combustion gases to the atmosphere.

MODE OF INCINERATOR OPERATION

The design of the incinerator and associated equipment--such as waste feed charging and ash removal systems--must be consistent with how the incinerator will be operated. The opposite also is true--how you operate your incinerator must be consistent with the design features. For the purposes of discussion, we can define three basic modes of incinerator operation.

1. Single batch;
2. Intermittent duty; and
3. Continuous duty.

SINGLE BATCH OPERATION

Single batch operation means the incinerator is loaded with a batch of waste, sealed, and turned on. After combustion is completed, the incinerator is allowed to cool and the ash is removed. Usually, ash is not removed until the next day.

INTERMITTENT DUTY

Intermittent duty means that the incinerator is intermittently loaded with batches of waste, one after another, over a period of time, usually one to two work shifts. The batches might be fed at routine intervals--such as every 5 minutes for 8 hours or might be fed at uneven intervals,

whenever waste is available. In any event, the incinerator must be shut down to remove ash from the system; thus, its operation is intermittent.

CONTINUOUS DUTY

Continuous duty means the incinerator can be continuously operated 24 hours per day. The system is designed so that ash is removed while the incinerator is in operation and the incinerator does not have to be shut down. The waste feed charging system and ash removal system are very important parts of this incineration system.

WASTE FEED CHARGING AND ASH HANDLING SYSTEMS

WASTE FEED CHARGING SYSTEMS

There are many different ways to "feed" the incinerator. The incinerator should be fitted with a waste feed charging system that is consistent with its mode of operation and capacity. Manual and mechanical waste feed systems will be discussed.

Manual Feed. This means you load the waste directly into the incinerator. This approach is applicable only for single batch units or smaller intermittent feed units. A safety hazard exists when waste is fed manually into an operating incinerator.

Mechanical Feed. When mechanical feed is employed, some type of mechanical device is used to charge the waste to the incinerator. The most common mechanical feed system is the hopper ram assembly, which frequently is called a ram feed system. Figure 3-8 shows a hopper/ram system. In a mechanical hopper/ram feed system:

- Waste is manually placed into a charging hopper, and the hopper cover is closed.
- A fire door isolating the hopper from the incinerator opens.
- The ram moves forward to push the waste into the incinerator.
- The ram reverses to a location behind the fire door.
- After the fire door closes, a water spray cools the ram, and the ram retracts to the starting position.
- The system is ready to accept another charge.

Figure 3-9 depicts this sequence. The entire hopper/ram charging sequence normally is timed and controlled by an automatic sequence. The sequence can be activated by the operator (push start button) or for larger, fully automated incinerators may be activated at preset intervals by an automatic timer.

The simplest hopper ram assembly requires the operator to manually load the waste into the hopper. However, some systems are designed to make loading the hopper easier. An example of a way to make hopper loading easier is a system where the hopper is located low enough so that all the operator has to do is tilt a cart containing the waste so that the waste falls into the hopper. One fully automated system uses a "cart

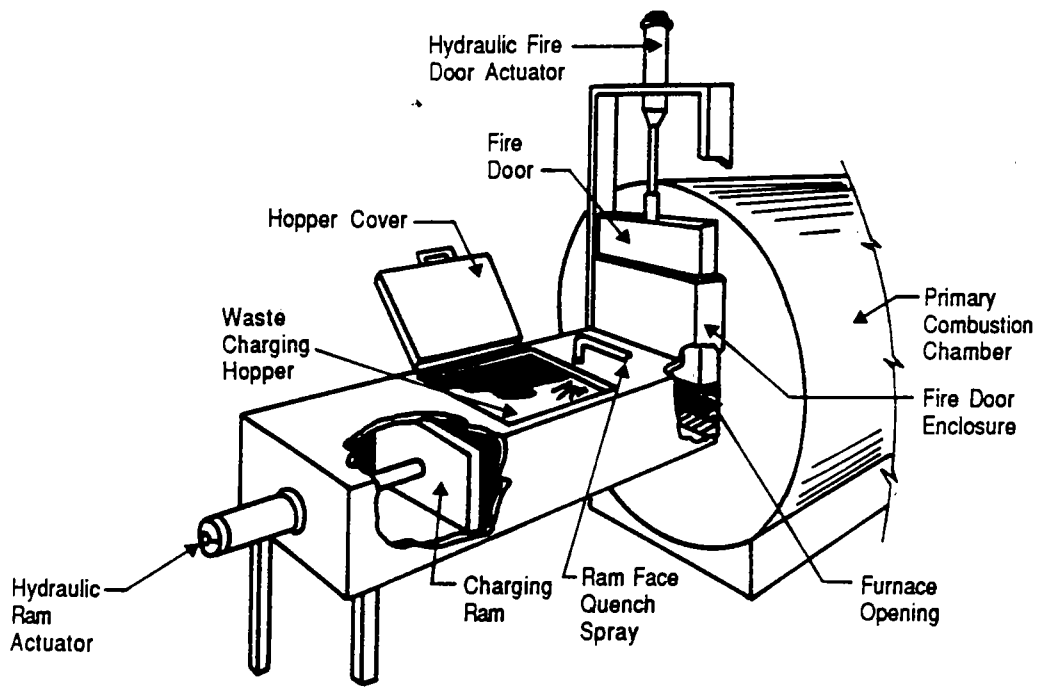

Figure 3-8. Hopper/ram mechanical waste feed system.[5]

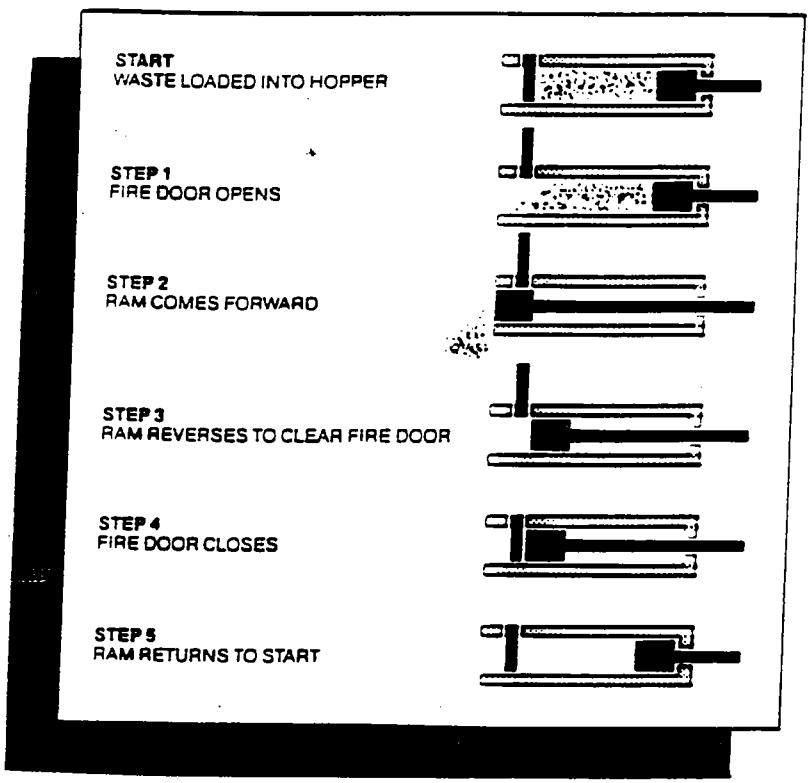

Figure 3-9. Hopper ram charging sequence.[6]

dumper" which automatically picks up a cart full of waste and dumps the waste into the hopper.

Another type of mechanical feed system which has been used for rotary kilns is an auger-feeder. The auger-feeder utilizes an auger (screw-type device) at the bottom of the waste hopper to continuously feed the waste into the kiln. However, these systems may cause problems with medical wastes because red bags can break. Breaks may result in liquids leaking from the feed system or in fugitive emissions of volatile organic materials.

Mechanical charging systems have several advantages over manual handling and charging:

- They provide added safety to the operating personnel by preventing heat, flames, and combustion products from escaping the incinerator during charging.
- They limit ambient air infiltration when charging a controlled-air incinerator, thus, there is little impact on the combustion rate.
- They enable incinerators to be automatically charged with smaller batches of waste at regulated time intervals; this improves operation and combustion efficiency.

ASH REMOVAL SYSTEMS

The ash remaining from the combustion process must be removed from the incinerator and disposed of in an acceptable manner. The ash is removed either manually or mechanically.

- Manual removal is typical for smaller units.
- Manual or mechanical removal is practiced for medium-sized, intermittent-duty incinerators.
- Mechanical semicontinuous removal of ash is necessary for continuous-duty incinerators.

Manual Ash Removal. Manual ash removal means that you remove the ash from the incinerator using a rake or shovel.

Mechanical Ash Removal. Continuous operation of an incinerator requires some type of mechanical system for removing the ash while the incinerator is operating. The mechanical system includes three major components:

1. A means of moving the ash to the end of the incinerator hearth--usually an ash transfer ram or series of transfer rams;
2. A collection device or container for the ash as it is discharged from the hearth; and
3. A transfer system to move the ash from the collection point.

Manual ash removal is used for most multiple-chamber incinerators. For controlled-air incinerators using mechanical ash removal, the ram used

for waste charging often is used for pushing the ash to the discharge end of the hearth. As each new waste charge is pushed into the incinerator, it pushes the waste bed on the hearth forward towards the discharge end. Each repetitive charge continues to push a portion of the waste bed towards the discharge end where it falls into a drop chute or water quench pit.

Figure 3-10 depicts an incinerator that has stepped hearths and several individual ash transfer rams. This system is often used in larger incinerators. Each hearth has its own ash ram and the waste is pushed from one hearth to the other by activating each ram in series, starting at the discharge end of the hearth. In other words:

- The ash on the last hearth (3) is discharged by ram No. 3.
- Ram No. 2 activates and pushes the waste on hearth No. 2 to hearth No. 3.
- Ash ram No. 1 activates and pushes the waste on hearth No. 1 to hearth No. 2.
- Finally, a new charge is added to hearth No. 1.

A major advantage to this type of system is that when the waste is pushed from one hearth to the next, the waste bed is mildly disturbed and redistributed which provides some degree of "mixing" of the waste and promotes more complete combustion. Another advantage is that the underfire air to each hearth usually can be controlled separately, which allows for greater combustion control.

After the ash drops from the hearth, some means of collecting and transporting the ash is required. One type of collection system uses an ash bin sealed directly to the discharge chute or positioned within an air-sealed chamber below the hearth. A door or gate which seals the chute is opened at regular intervals to allow the ash to drop into the collection bin. When the bin is filled, the seal-gate is closed and the bin is removed and replaced with an empty bin. In the second method, the ash is discharged into a water pit. The ash discharge chute is extended into the water pit so that an air seal is maintained. The water bath quenches the ash as the ash is collected. A mechanical device, either a rake or drag conveyor system, is used to intermittently or continuously remove the ash from the quench pit. The excess water is allowed to drain from the ash as it is removed from the pit, and the wetted ash is discharged into a collection container.

COMBUSTION GAS HANDLING SYSTEM

All incinerators must have a system for moving combustion air and combustion gases through the incinerator system and for controlling the air flow. Three basic types of systems are typically used for hospital waste incinerators. These are:

- natural draft;
- induced draft; and

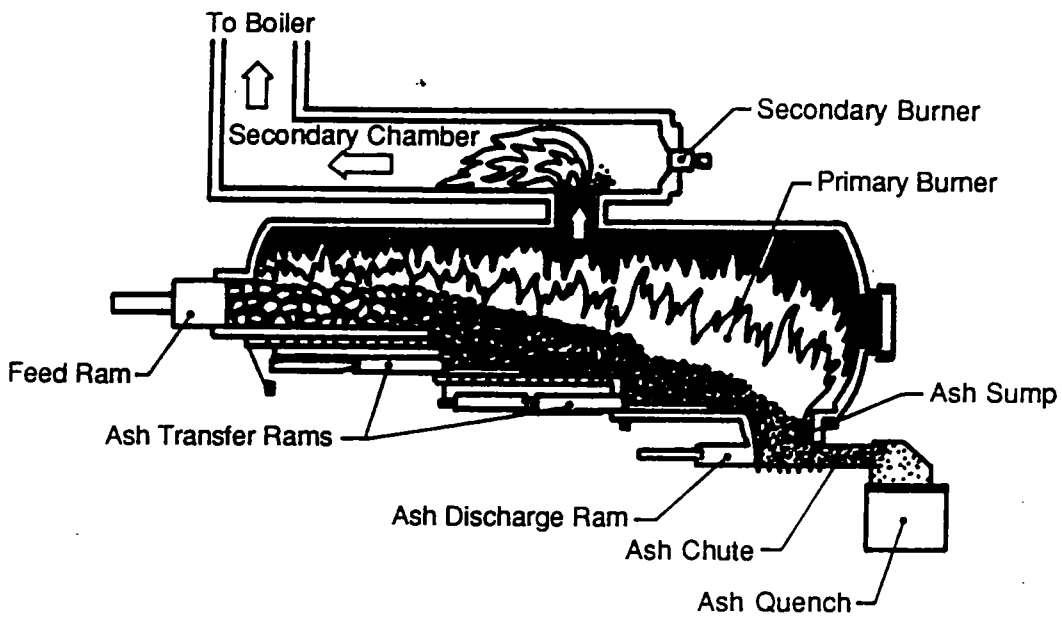

Figure 3-10. Incinerator with staged hearth and automatic ash removal.[7]

- balanced draft (a combination of induced draft and forced draft)

Draft is the difference between the pressure within the incinerator and the pressure in the atmosphere. When the pressure inside the incinerator is lower than the outside air pressure (i.e., negative pressure), air tends to flow into the incinerator. Incinerators are equipped with stacks to produce the "draft" necessary to move combustion air into the incinerator and to discharge the combustion gases to the atmosphere. The height of the stack and the difference in temperature between the combustion gases and the outside air creates a natural draft. Because the incinerator is at a lower pressure than the outside air, combustion air is pulled into the incinerator.

Incinerators that have heat recovery boilers or air pollution control (APC) systems usually use an induced draft system. When a boiler or APC system is added to the incinerator, the resistance to airflow is increased (that is, airflow is "blocked") and natural draft is no longer sufficient to move air through the system. A fan is added at the end of the system to "induce" a draft, or pull the gases through the system.

Many incinerators use forced draft fans or "combustion air blowers" to push the combustion air into the incinerator. In a balanced draft system, a forced draft fan is used to push (or blow) combustion air into the incinerator and an induced draft fan (or the natural draft stack) is used to pull the combustion gas through the incinerator and exit from the stack. The draft is balanced so that the incinerator is maintained at a slightly negative pressure. This negative pressure presents emissions from leaking from the combustion chamber.

Mechanisms for controlling incinerator draft are discussed in Session 5.

BURNERS

The burners on a hospital waste incinerator provide the heat needed to ignite the waste initially and to sustain combustion of the waste charged. The burners may be either oil-fired or gas-fired (natural gas or propane) and are designed to provide a rated heat input expressed in BTU/h. The heat input rate for the burners on your incinerator will depend on the type of incinerator at your facility, the number of burners, and the heating value of the waste burned. Most incinerators have a single burner in the secondary chamber that burns the combustion gases from the primary chambers. However, the primary chamber may have more than one burner, especially if the incinerator has been designed to burn pathological waste only.

The components of a burner system include a forced-air blower, a fuel train, pilot and main burners, and most importantly a flame safeguard system. The following paragraphs give a brief description of these components.

FORCED AIR BLOWER

The forced-air blower provides the combustion air needed to burn the oil or gas fuel and, if oil is used, the atomizing air. A single forced-air blower in conjunction with regulatory values may be used to supply air to the different burners or each burner may have a separate air blower. When the burner is first turned on, the blower comes on and purges the burner of any volatile gas or oil residues that may have built up since the last burn. This is a safety feature.

FUEL TRAIN

The fuel train is the series of components that controls the flow of fuel to the burner. The fuel train set up for gas and oil burners is basically the same. Each fuel train has a pressure gauge, a manual shutoff valve, and a solenoid shut-off valve. The only difference between the gas and oil fuel trains is the device used to control fuel flow; the oil fuel train utilizes a needle flow valve while the gas fuel train utilizes a gas orifice union. The manual shut-off valves must be open before the burners are turned on. The solenoid valves are safety valves which close off the fuel supply if the burners do not light or if the air supply for combustion is lost.

PILOT AND MAIN BURNERS

Each burner is equipped with both a pilot and main burner. The pilot is lit first, and, once a flame is detected, the fuel supply to the main burner is opened allowing the pilot to light the main burner. Proper operation of the burners is best achieved by looking at the burner flame pattern through the viewports in the incinerator wall or in the burner itself. Some burners are equipped with an observation port to view the main flame and another to view the pilot flame. Gas-fired burners have a blue flame while oil-fired burners have a luminous yellow flame. The flame pattern will likely vary with the type of burner. However, the length of the flame should be such that the flame touches the waste but does not impinge directly on the refractory floor or wall.

FLAME SAFEGUARD

The device which controls the burner ignition process is called the flame safeguard. When the burner is first started, the burner blower starts and when it reaches full speed, a purge timer starts. When the purge timer times out, the flame safeguard energizes the pilot relay that opens the pilot fuel supply and ignitor. When the pilot lights, a flame detector (either an ultraviolet scanner [gas or oil] or flame rod circuit [gas only]) detects the pilot flame and causes the main flame relay to activate the fuel supply to the main burner. The pilot then ignites the main burner. The flame detector continues to operate and shuts the burner down if the main burner fails. Additionally, if the air supply is lost, both pilot and flame relays shut off the fuel supply. The pilot usually is ignited for no more than 15 seconds (interrupted pilot). If the main burner does not ignite during the pilot ignition period, the flame

safeguard system shuts the entire system down by closing the solenoid shut-off valve and turning off the burner blower.

WASTE HEAT BOILERS

The heat generated during incineration can be recovered and used to generate hot water or steam in a waste heat boiler. Addition of a waste heat boiler to an incinerator has several impacts on the incineration system. One impact of adding a boiler to the system is that fan induced draft fan must be added to the system in order to move air through the system. An emergency bypass stack is another feature that normally would be added to an incinerator when a waste heat boiler (or air pollution control system) is added to the incinerator system. Since the boiler causes a resistance (blockage to airflow) in the system if the induced draft fan stops, pressure will build up in the incinerator because the hot gases cannot escape quickly enough. The bypass stack is added to allow a route for the hot gases to escape should the fan fail. In other words, it allows the incinerator to go back to a natural draft system. The bypass stack also is used in cases where the boiler must be bypassed for some reason (for example, loss of water flow to the boiler causing heat buildup). The bypass stack usually contains a damper valve in the stack to control direction of the gas flow or a cap on top of the stack to prevent air from being pulled into the system when the fan is operating. When the "bypass" must be activated, the damper, or cap, is opened. The bypass is usually activated automatically by some type of sensor; for example, if the fan speed falls below a preset level, the bypass opens. Figure 3-11 is a schematic of an incinerator with a waste heat boiler, induced draft fan, and emergency bypass stack.

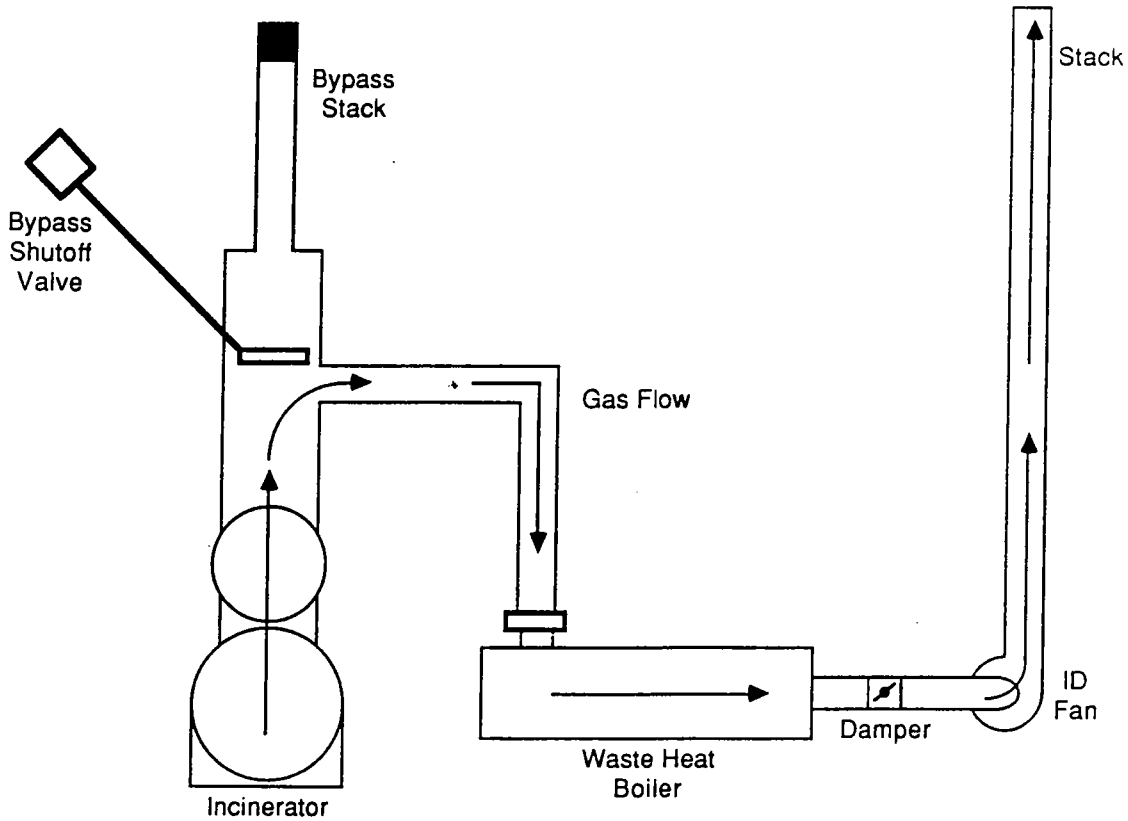

Figure 3-11. Incinerator with waste heat boiler and bypass stack.[2]

REVIEW EXERCISE

1. Which type of incinerators listed below use combustion in two chambers?

   a. Controlled-air incinerators
   b. Multiple-chamber incinerators
   c. Rotary kilns
   d. All of the above
   e. a and b

2. The unique feature of the controlled-air incineration principle is:
   a. Large incinerators can be built
   b. Combustion is controlled by limiting the air in the primary chamber to below stoichiometric; combustion occurs in two stages
   c. The combustion chambers are shaped like cylinders

3. Continuous-duty incinerators <u>must</u> include which of the following important features not normally included in intermittent-duty incinerators?

   a. Automatic waste feed
   b. Continuous ash removal
   c. Temperature monitors

4. An incineration <u>system</u> includes which of the following:

   a. Waste feed charging system
   b. Incinerator
   c. Ash removal system
   d. Control and monitoring system
   e. All of the above
   f. b and d

1. d. All of the above

2. b. The primary chamber operates with starved air and combustion occurs in two stages.

3. b. Continuous ash removal

4. e. All of the above

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SESSION 4.
AIR POLLUTION CONTROL EQUIPMENT DESIGN AND FUNCTIONS

SESSION 4. AIR POLLUTION CONTROL EQUIPMENT DESIGN AND FUNCTIONS

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SESSION 4. AIR POLLUTION CONTROL EQUIPMENT DESIGN AND FUNCTIONS

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SESSION 4.
AIR POLLUTION CONTROL EQUIPMENT DESIGN AND FUNCTIONS

SESSION GOAL AND OBJECTIVES

GOAL

To familiarize you with the components and the functions of the various types of air pollution control systems that are found on hospital incinerators.

OBJECTIVES

Upon completing this session, you should be able to:

1. Identify the type of air pollution control system used on your incinerator;
2. Name the air pollutants that your air pollution control system is intended to control;
3. Understand the basic principles that account for pollutant collection and removal;
4. Identify the major components of your air pollution control system; and
5. List the functions of each major component.

INTRODUCTION

During this session we will discuss the various types of APCS usually used or expected to be extensively used in the future on hospital waste incinerators. The APCS to be discussed are listed below.

- Wet scrubbers
  - -- Packed-bed scrubbers
  - -- Venturi scrubbers
  - -- Spray towers
- Fabric filters
- Dry scrubbers
  - -- Spray dryers
  - -- Dry injection
- Electrostatic precipitators

WET SCRUBBERS - GENERAL

POLLUTANTS CONTROLLED

The pollutants controlled by wet scrubbers include particulate matter and the acid gases (HCl and SO_2). Because of the variations in design some units are more effective for particulate matter while others are primarily intended for acid gas control.

POLLUTANT COLLECTION PRINCIPLES

- Particulate matter - collection mechanism is primarily impaction on wetted surfaces or in liquid droplets. Figure 4-1 shows impaction.
- Gases - gaseous collection is through diffusion and absorption. Figure 4-2 shows absorption.
- After capture of the pollutants in the liquid, the liquid droplets must be separated from the clean gas stream.

TYPES OF WET SCRUBBERS USED ON HOSPITAL INCINERATORS

- Packed-bed scrubbers
- Venturi scrubbers
- Spray towers

PACKED-BED SCRUBBERS

Figure 4-3 shows a packed-bed scrubber.

POLLUTANTS CONTROLLED

- Packed-bed scrubbers are used primarily for acid gas control.
- While packed-bed scrubbers remove some particulate matter, they have a low collection efficiency for fine particulates.

DESCRIPTION OF PACKED-BED SCRUBBER

Packed-bed scrubbers consist of:

- A cylindrical shell to house the scrubbing media;
- Packing media and supporting plates;
- Liquid spray nozzles to distribute the scrubbing liquid;
- Demister pads to remove liquid droplets from the clean flue gas; and
- An induced draft fan for moving the flue gas through the scrubber.

The packing media is composed of 1- to 3-inch (2.5- to 7.6-cm) diameter plastic shapes that are intended to maximize the surface area.

HOW DOES A PACKED-BED SCRUBBER WORK?

The scrubbing liquid used is important.

- With water as the scrubbing liquid there is removal of soluble gases. HCl is highly soluble in water and is efficiently captured in wet scrubbers.

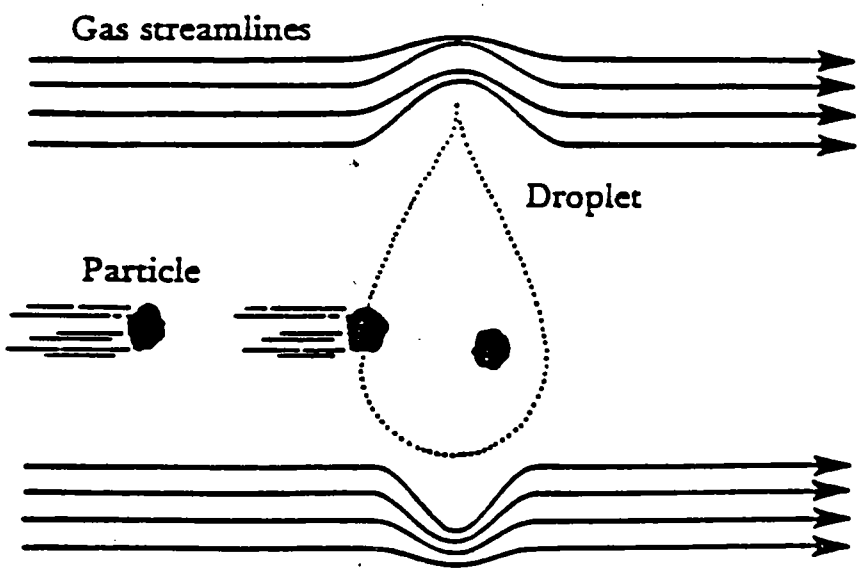

Figure 4-1. Impaction.[1]

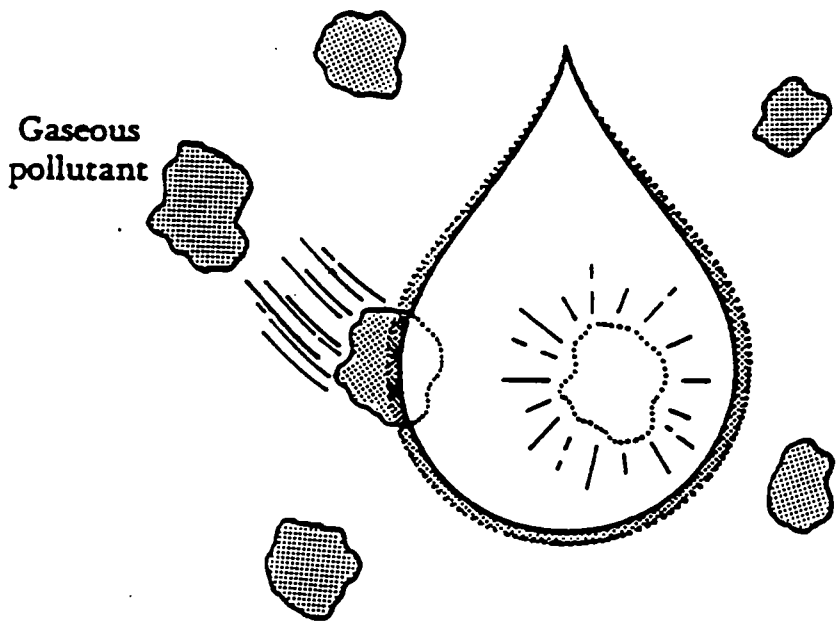

Figure 4-2. Absorption.[1]

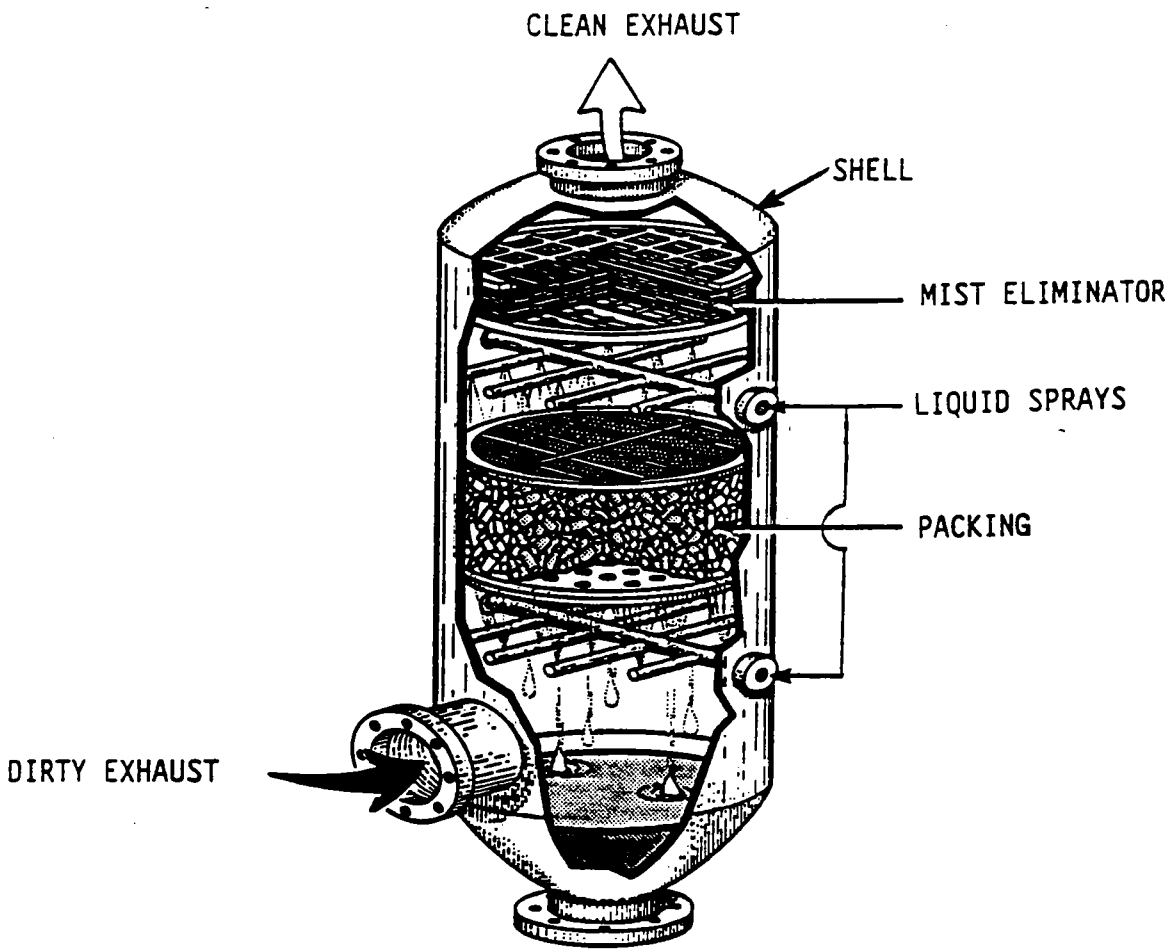

Figure 4-3. Countercurrent-flow packed-bed scrubber.[1]

- Alkaline (caustic) materials, such as lime, are added to the water to neutralize the acids collected in the scrubbing liquid. The liquid is neutralized to reduce corrosion of equipment and keep the pH (a measure of the water's acidity) of the water discharge within acceptable ranges required by wastewater treatment facilities.
- Addition of alkaline materials is needed to achieve significant reductions of acid gases, such as SO_2 which are less soluble in water than is HCl.

Packed-bed scrubbers are designed to maximize the surface area of the liquid/gas interface to increase opportunities for absorption of the acid gases at low fan energy costs. Relatively large amounts of scrubbing liquid per unit of flue gas are used.

- Packed-bed scrubbers intended for acid gas control use an alkaline scrubbing liquid; example materials are:
  - -- Lime (CaO);
  - -- Sodium hydroxide (NaOH); and
  - -- Sodium carbonate (Na_2CO_3).
- Scrubbing liquid is sprayed onto the packing media from the top and bottom.
- The liquid passes downward due to gravity, wetting the surface of the packing media.
- The dirty flue gases enter the bottom of the scrubber and travel countercurrent (opposite) to the flow of the liquid.
- The wet surface of the packing media creates a large surface area of liquid/gas interface for absorption.
- The acid gases are absorbed and captured in the liquid.
- The acid gases react with the alkaline materials in the scrubbing liquid and are neutralized.
- Particulate matter is collected in the scrubbing liquid through impaction.
- The flue gases pass out the top of the scrubber unit through the demister pads which remove any entrained droplets of liquid that may contain absorbed acid gases and particulate matter.
- The dirty scrubbing liquid containing the collected particulate, acid gas/sorbent reaction products, and the unreacted sorbent materials passes out the bottom of the scrubber and is recycled or sent to wastewater treatment.

VENTURI SCRUBBERS

Figure 4-4 shows a venturi scrubber.

POLLUTANTS CONTROLLED

Venturi scrubbers are high-energy scrubbers used for the control of fine particulate emissions. Hydrochloric acid gas, if present, also is controlled by a venturi scrubber.

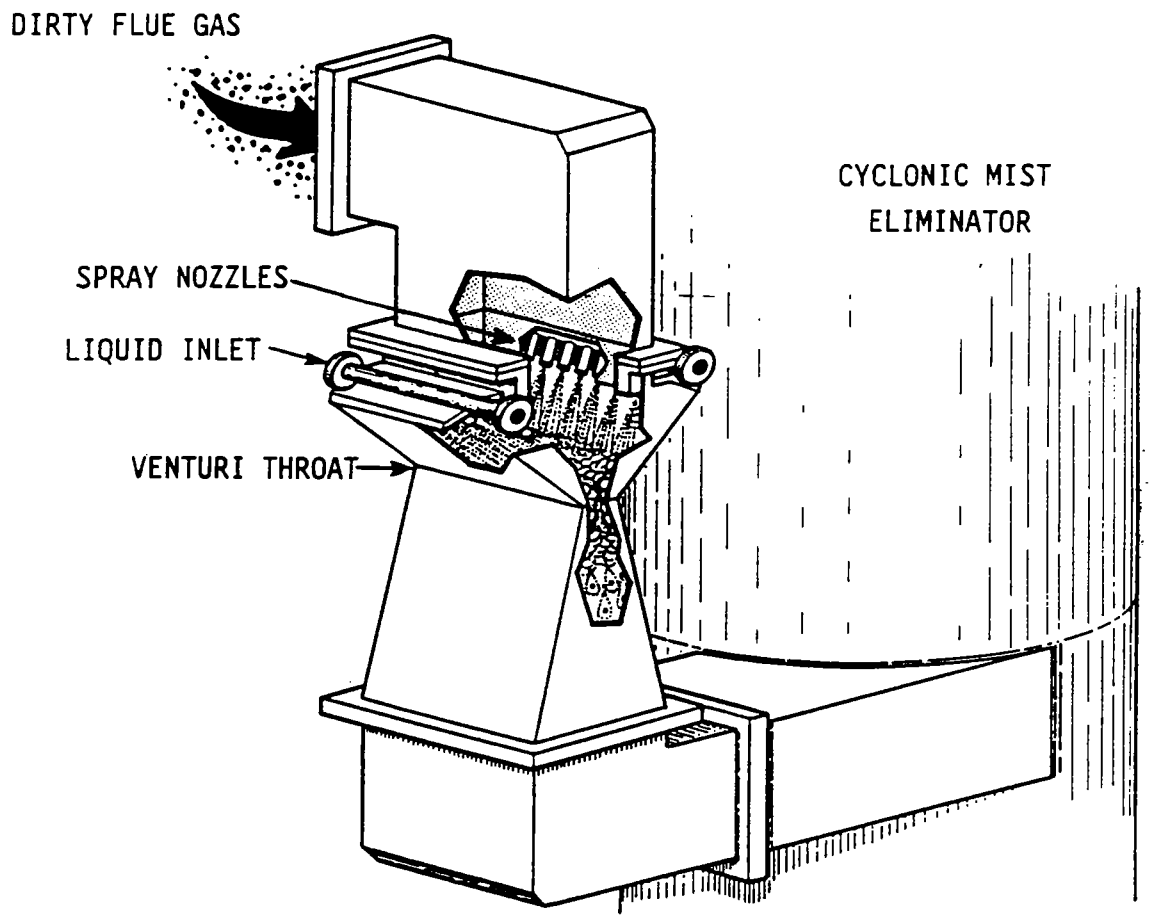

Figure 4-4. Spray venturi with rectangular throat. [1]

DESCRIPTION OF VENTURI SCRUBBER

- A venturi scrubber consists of:
  - -- A constriction in the ductwork referred to as a venturi throat;
  - -- Spray nozzles at the entrance to the venturi throat that supply the scrubbing liquid, usually water;
  - -- A cyclonic mist eliminator for removing entrained water droplets; and
  - -- An induced draft fan for moving the flue gas through the scrubber
- Some venturi scrubbers have an adjustable throat that can be used to vary the size of the opening.

HOW DOES A VENTURI SCRUBBER WORK?

Venturi scrubbers are designed to maximize turbulence and mixing of water droplets and dirty flue gas to improve pollutant capture efficiency.

- The venturi throat has the smallest cross-sectional area in the ductwork and consequently the gas has the highest speed at this location.
- As the flue gases speed up at the entrance to the venturi section, water is injected into the flue gas stream through spray nozzles or through the force of the high speed gases passing over water running down on the sides of the venturi.
- The high gas speeds through the constricting throat create turbulence which breaks the water droplets into smaller fine droplets and causes mixing.
- Collection efficiency increases with higher gas speeds and turbulence; however, higher gas speeds require more energy. The amount of energy is measured as the change in pressure across the venturi or the pressure drop in inches of water column. For scrubbers with adjustable throats, decreasing the size of the throat opening increases pressure drop and collection efficiency.
- Higher pressure drops require more fan energy and result in higher operating costs.
- The water droplets, containing the captured particulate matter, are separated from the clean gas stream in the cyclonic mist eliminator using centrifugal force. Figure 4-5 shows a cyclonic mist eliminator.
- The dirty scrubber water is sent to wastewater treatment. Some facilities may recycle the scrubber water after it goes through a settling tank. If your facility has such a recycle system, the solids content and pH of the recycle waters must be controlled.

SPRAY TOWERS

Figure 4-6 shows a spray tower scrubber.

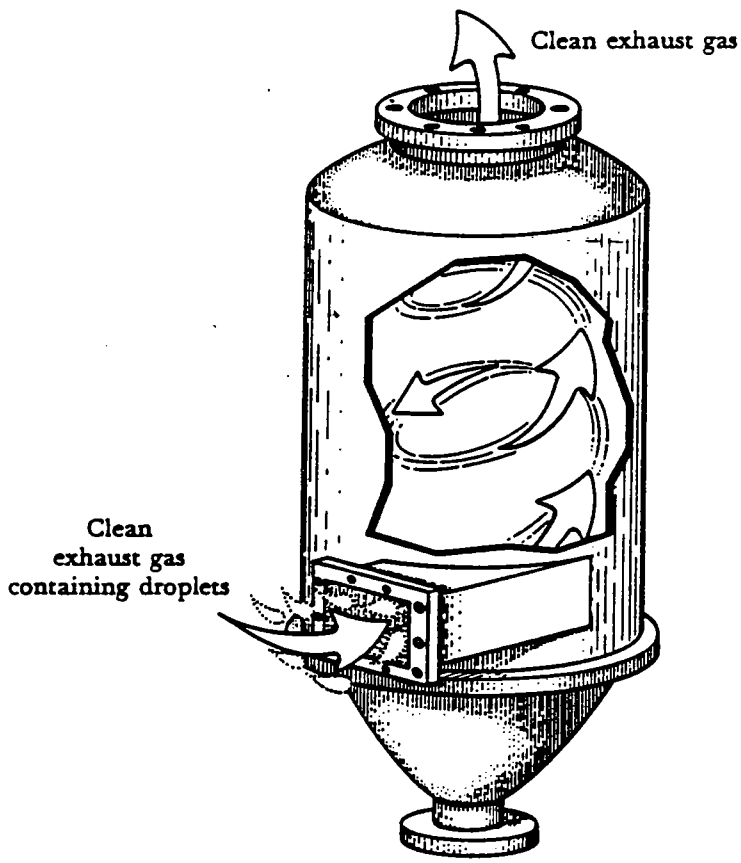

Figure 4-5. Cyclonic mist eliminator.[1]

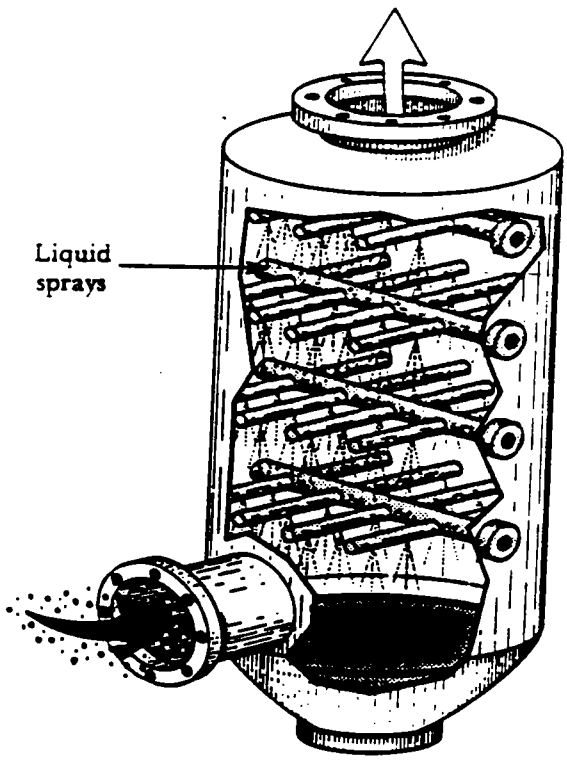

Figure 4-6. Countercurrent-flow spray tower.[1]

POLLUTANTS CONTROLLED

Spray towers are low-energy scrubbers used to control large-particle emissions.

- Spray towers are only effective for relatively large particles and are limited in applicability to multiple chamber incinerators.
- Controlled-air incinerators have inherently low particulate mass emission rates and fine particle size distributions that cannot be effectively controlled by spray towers.

DESCRIPTION OF SPRAY TOWER SCRUBBER

Spray towers are relatively simple scrubbers consisting of:

- A hollow cylindrical steel vessel; and
- Spray nozzles for injecting the scrubbing liquid.

HOW DOES A SPRAY TOWER SCRUBBER WORK?

Spray towers are designed to use many spray nozzles to create a large amount of fine liquid droplets for impacting and capturing particulate matter.

- The dirty exhaust gas enters the bottom of the scrubber and travels upward.
- Water droplets are sprayed downward by a series of spray nozzles designed to cover the entire cross-sectional area of the scrubber.
- The cleaned exhaust gas exits out the top of the scrubber.

FABRIC FILTERS

Figure 4-7 shows a pulse-jet fabric filter.

POLLUTANTS CONTROLLED

Fabric filters are designed to remove solid particulate matter from the flue gas stream by filtering the flue gas through fabric bags.

- Fabric filters are especially effective at removing fine particulate matter.
- When used with a dry scrubber (see next section), the fabric filter cake will help remove acid gases from the flue gases.

POLLUTANT COLLECTION PRINCIPLES

- Particulate - the dirty flue gases are passed through fabric bags which filter out the particulate matter creating a "cake" (i.e., a coating) of collected particulate matter on the bag that further increases filtration. The principle is very similar to that of a household vacuum cleaner.

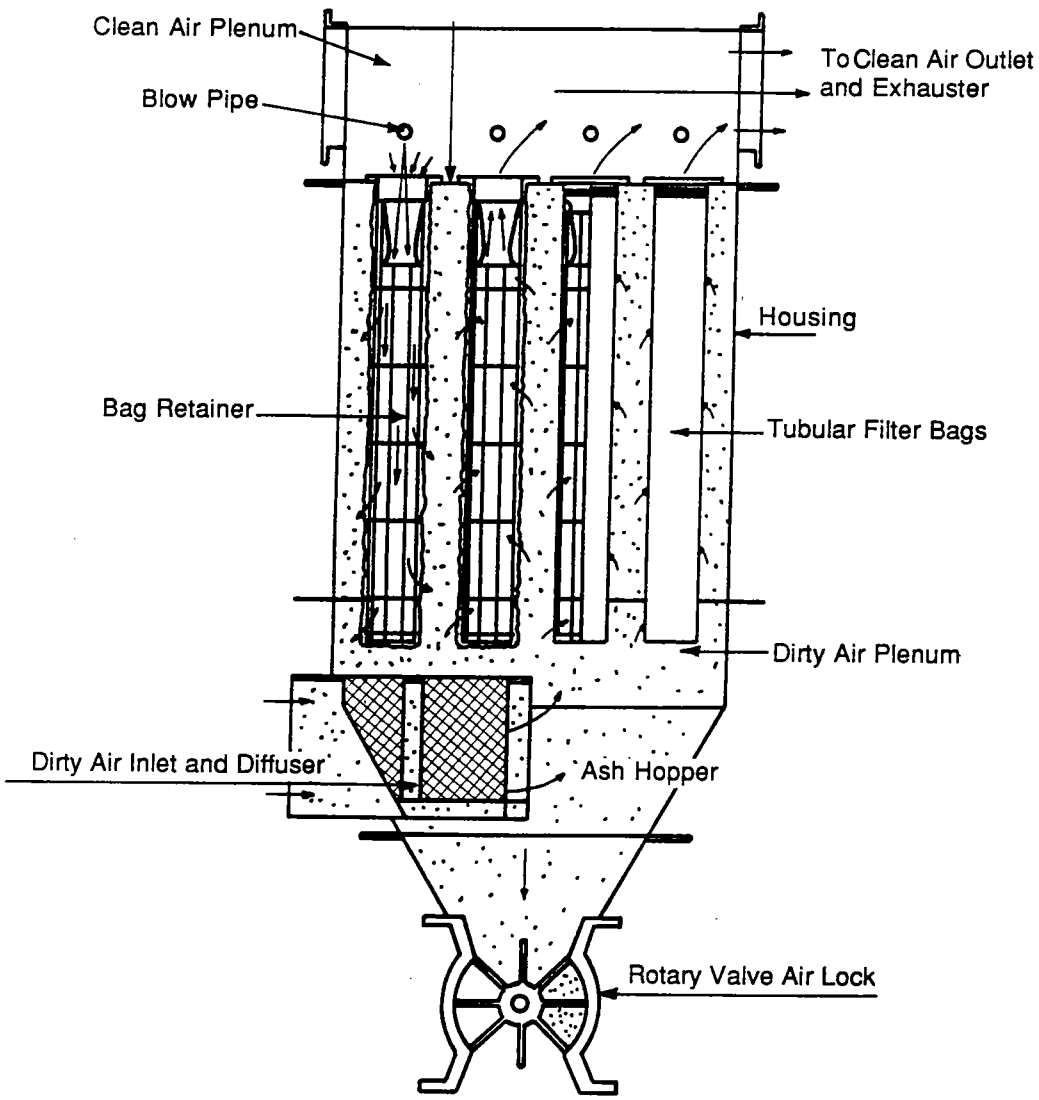

Figure 4-7. Pulse-jet baghouse.[2]

- Acid gases - when used with dry scrubbers (see next section), the alkaline material injected by the scrubber is collected in the filter bag along with the pollutants. As the acid gases pass through the cake they react with the alkaline material, form solid salts, and are captured.

DESCRIPTION OF A PULSE-JET FABRIC FILTER

- Pulse jets are one of three fabric filter types classified by bag cleaning technique. Pulse-jet fabric filters are used on hospital waste incinerators.
- A pulse-jet fabric filter consists of:
  - -- Dirty air inlet and a plate (diffuser) with holes in it that uniformly distributes the flue gas;
  - -- A dirty air chamber or plenum which contains the fabric bags;
  - -- A tube sheet, with holes for each bag, which supports the bags and separates the dirty air plenum from the clean air plenum;
  - -- The tubular filter bags with supporting wire frame bag retainers;
  - -- The bag cups and venturi's to which the individual bags are attached and which inject the pulse of cleaning air into the bags;
  - -- The air compressor which supplies the compressed air for cleaning the bags;
  - -- The ash hopper which holds the collected particulate after it is cleaned from the bag; and
  - -- A rotary valve air lock which discharges the ash from the hopper.

HOW DOES A PULSE-JET FABRIC FILTER WORK?

The openings in the mesh weave of a fabric filter bag are relatively large and can only capture large particles. Actual filtration of fine particles is performed by the cake of filtered-out material that builds up on the bag surface.

- The dirty flue gas enters through the air inlet at the bottom of the unit and is distributed through the diffuser.
- The dust-laden gas flows upward through the dirty air plenum and is filtered through the bags with the filtered-out dust cake forming on the outside of the bags.
- On a timed frequency or at a pre-determined pressure drop, the bags are cleaned.
- The bags are cleaned by a blast of compressed air injected into the top of the bag tube.
- The air blast creates a shock wave that travels down the bag, fracturing the filter cake.
- The filter cake falls into the ash hopper at the bottom of the unit and is removed through the rotary valve air lock.

DRY SCRUBBERS - GENERAL

POLLUTANTS CONTROLLED

Dry scrubbers remove acid gases, primarily HCl and SO_2.

POLLUTANT COLLECTION PRINCIPLES

Dry scrubbers inject alkaline sorbent materials into the dirty flue gas. The acid gases begin to react with the alkaline sorbents to produce solid particulate salts that are collected by a particulate control device, usually a fabric filter (see previous section), that follows the dry scrubber. The unreacted sorbent is also captured on the fabric filter cake where additional acid gas reacts with the sorbent and is captured.

TYPES OF DRY SCRUBBERS USED ON HOSPITAL INCINERATORS

- Spray dryers
- Dry injection

SPRAY DRYERS

DESCRIPTION OF SPRAY DRYERS

- Figure 4-8 shows a schematic of a spray dryer system. Figure 4-9 shows an internal view of the spray dryer absorber vessel.
- The primary components of a spray dryer system are:
  - -- Lime slaker, if pebble lime is purchased;
  - -- Sorbent mixing tank;
  - -- Sorbent feed tank;
  - -- Atomizer feed tank;
  - -- Rotary atomizers or air atomizing nozzles;
  - -- Spray dryer absorber reaction vessel;
  - -- Solids recycle tank; and
  - -- Particulate control device.

HOW DOES A SPRAY DRYER WORK?

Spray dryers are designed to spray an alkaline slurry of sorbent material into the hot flue gases where the acid gases are absorbed into the slurry droplets and reacted with the alkaline material to form solid particle reaction products.

- Spray dryer facilities usually purchase pebble lime (CaO) for use.
- The pebble lime is converted to calcium hydroxide [$Ca(OH)_2$] by the addition of water in the slaker.
- The calcium hydroxide is mixed with water in the mixing tank to produce a slurry containing 5 to 20 percent solids.
- The slurry is stored in the feed tank and is transferred to the atomizer feed tank immediately prior to use.
- The atomizers produce small droplets of slurry that are injected into the absorber reaction vessel.

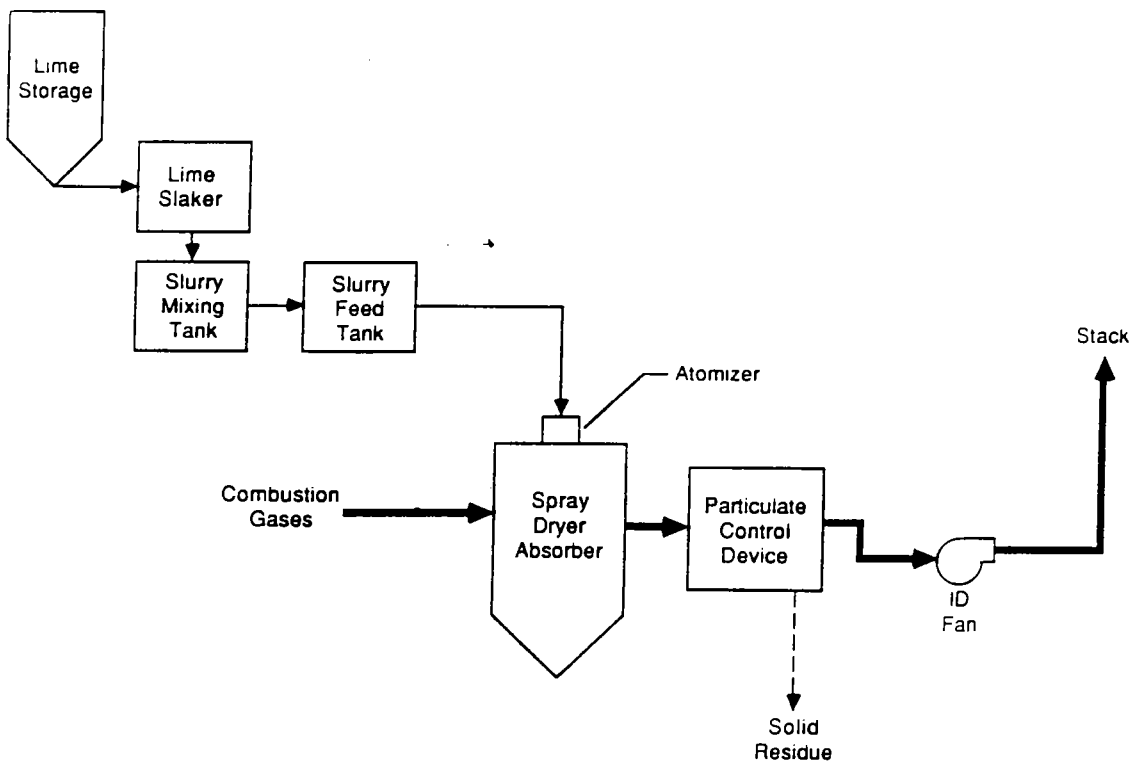

Figure 4-8. Components of a spray dryer absorber system.

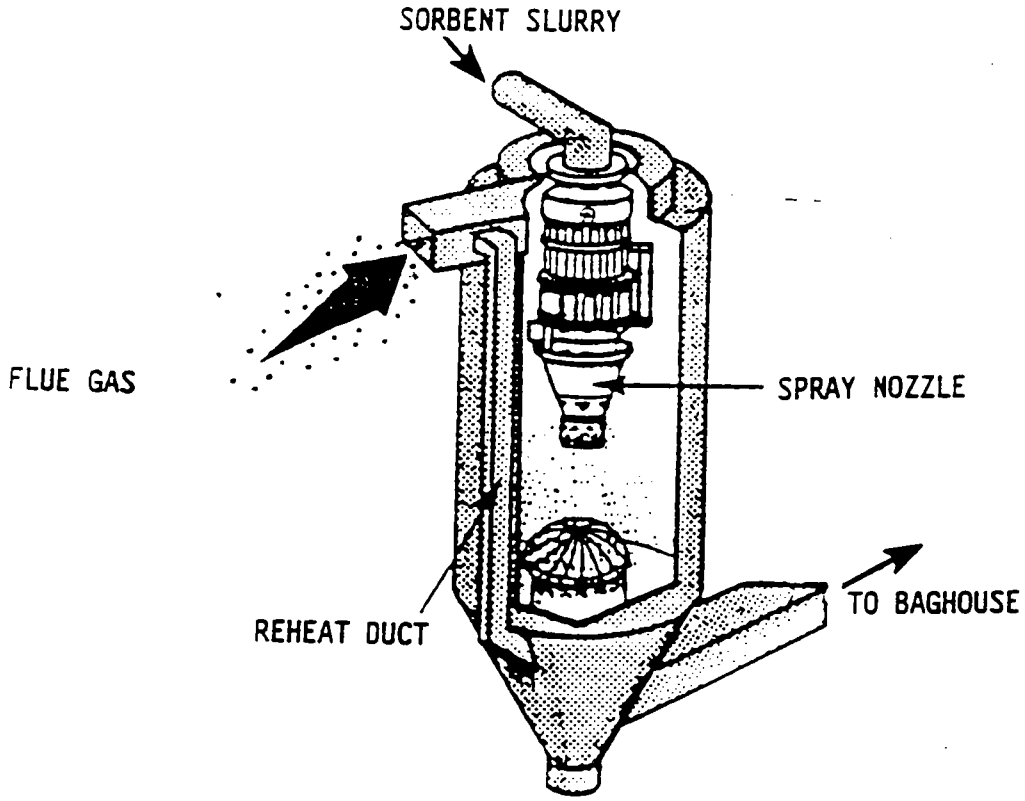

Figure 4-9. Spray dryer absorber vessel.

- The alkaline sorbents in the slurry react with the acid gases producing $CaCl_2$ and $CaSO_4$ solid salts.
- The hot flue gases dry the moisture from the slurry and the reacted and unreacted sorbent either is entrained in the flue gas stream or drops to the bottom of the reaction vessel.
- The entrained sorbent and reaction products are carried to the particulate control device where they are captured.
- The sorbent and reaction products that drop to the bottom of the reaction vessel can either be disposed of or retained in the solids recycle tank for recycle back to the mixing tank.

DRY INJECTION

Figure 4-10 shows a dry injection system schematic.

DESCRIPTION OF DRY INJECTION

Dry injection systems consist of:

- Dry sorbent storage tank;
- Blower and pneumatic line for transfer of the sorbent;
- Injector;
- Expansion/reaction chamber (optional); and
- Particulate control device (fabric filter or ESP) for collection of the dry sorbent.

In some cases, the expansion/reaction chamber shown in Figure 4-10 is not included.

HOW DOES DRY INJECTION WORK?

Dry injection systems are similar to spray dryers with the exception that the sorbent materials are injected into the flue gases as a dry powder. Since there is no moisture, the reaction rate is slower than with a spray dryer.

- The dry injection system uses finely divided alkaline sorbent material, usually calcium hydroxide or sodium bicarbonate, with the approximate consistency of talcum powder.
- The dry sorbent material is blown down the pneumatic line to the flue gas exhaust duct.
- Transfer through the pneumatic line provides fluidization and breaks up any clumps of sorbent.
- The sorbent is injected into the flue gas duct which creates turbulence that results in mixing of the sorbent with the flue gas.
- Absorption of the acid gases by the sorbent begins in the flue gas ductwork.
- An expansion/reaction chamber may be included to increase the residence time of the gases in the system, allowing more time for the reaction to occur.

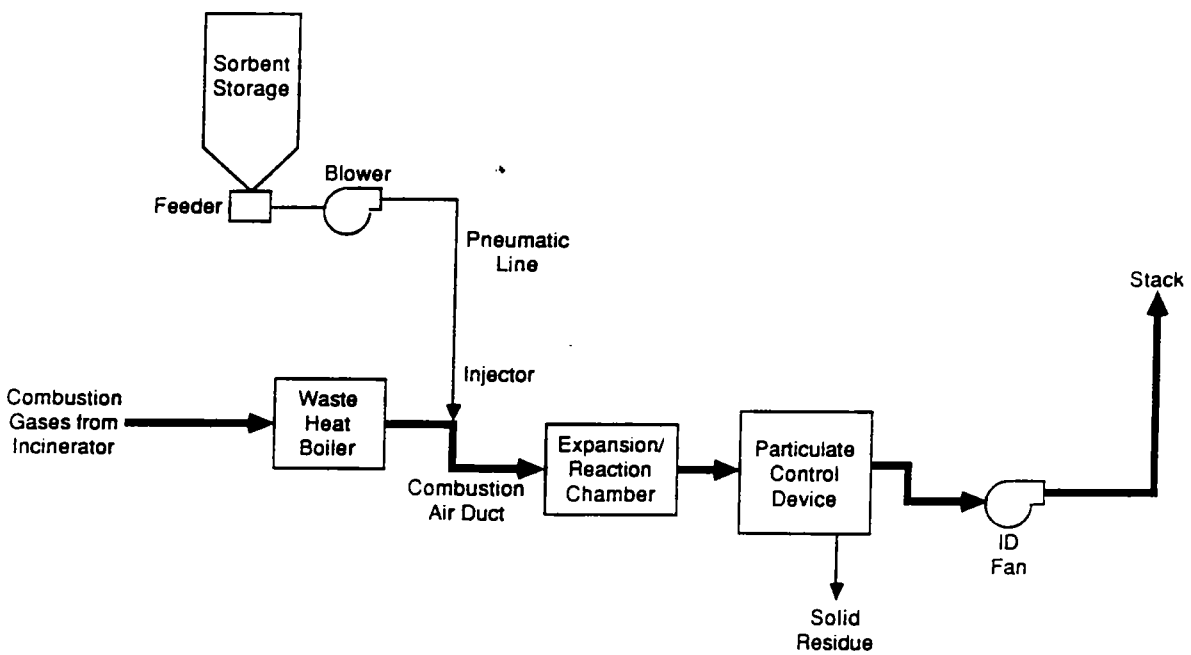

Figure 4-10. Components of a dry injection absorption system.

- The sorbent and reaction products are carried by the flue gas to the particulate control device where the solids are collected.
- If a fabric filter is used as the particulate control device, acid gas removal may be further enhanced by reaction with the sorbent collected in the filter cake.

Figure 4-11 presents a schematic of another variation on the dry injection system. In this system, the dry alkaline sorbent is injected directly into a contactor/reactor vessel rather than into the duct.

ELECTROSTATIC PRECIPITATORS

POLLUTANTS CONTROLLED

Electrostatic precipitators (ESP's) are used to remove particulate matter from flue gas streams. They have been used for over 50 years on many industrial processes.

POLLUTANT COLLECTION PRINCIPLES

Particulate matter must first be charged with electricity before it can be collected in an ESP. Once the particles or liquid aerosols that makeup the particulate matter are charged, they move towards an oppositely charged surface because of electrostatic attraction (opposite charges attract each other, the same charges repel each other). The collected particles are removed by rapping or washing the collecting surface. This charging, collecting, and removal process is commonly referred to as precipitation.

DESCRIPTION OF A SINGLE-STAGE, HOT-SIDE, PLATE ESP

- ESP's can be classified according to a number of design features. These features include the method of charging (single-stage or two-stage), the method of particle removal from collection surfaces (wet or dry), the temperature of operation (cold-side or hot side), and the structural design and operation of the discharge electrodes (tubular or plate). The ESP's likely to be used on medical waste incinerators are single-stage, hot-side, plate ESP's and are discussed here.
- Most ESP's used to reduce particulate matter emissions from boilers and other industrial processes are single-stage ESP's. These units use very high voltage to charge particles. The particles, once charged, move in a direction perpendicular to the gas flow and are collected on the oppositely charged collection surface. Because particle charging and collection occurs in the same stage, these ESP's are called single stage ESP's.
- Collected particles are removed from the unit by rapping the collection electrodes or by spraying water on the electrodes to wash the particles away.

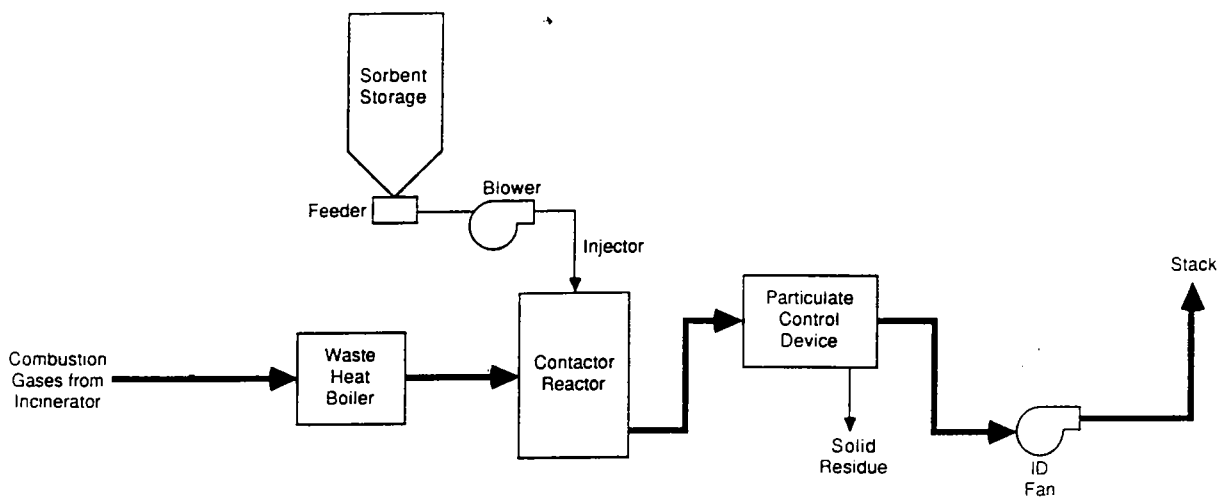

Figure 4-11. Components of a dry injection adsorption system.

- ESP's are grouped according to the temperature of the flue gas entering the unit. Therefore, the ESP's used on medical waste incinerators are likely to be hot-side units. These ESP's are larger than cold-side ESP's because the higher gas temperature makes the volume of gas treated larger.
- ESP's use either flat plates or cylindrical tubes to collect particulate matter. Most ESP's use plates as collection electrodes. In this arrangement, dirty gas flows into a chamber consisting of a series of small diameter discharge electrodes (wires) especially spaced between rows of plates. Figure 4-12 shows the gas flow through a plate ESP and the discharge and collection plate electrodes. Discharge electrodes are approximately 0.05 to 0.15 inches (0.02 to 0.06 centimeters) in diameter. Collection plates are usually between 20 and 40 feet (6 and 12 meters) high and spaced from 4 to 12 inches (1.6 to 4.7 centimeters) apart.
- Figure 4-13 is a schematic of a single-stage, hot-side plate ESP. The major components are:
  - -- Discharge electrodes (wires) that hang between the collection plate electrodes and that provide the electrical energy required to charge the particles and liquid aerosols in the dirty gas
  - -- Collection electrodes that are placed parallel to each other and collect the charged particulate matter
  - -- High-voltage equipment including a step-up transformer, a high-voltage rectifier, and automatic circuitry that controls the electric field between the discharge and collection electrodes.
  - -- Rappers that remove collected particulate matter that has accumulated on the collection electrodes
  - -- A hopper that is used to store the collected particulate matter temporarily prior to disposal
  - -- A hopper discharge device that removes the collected material from the hopper
  - -- A shell structure that encloses the electrodes and supports the precipitator components in a rigid frame to promote electrode alignment and configuration

HOW DOES AN ESP WORK?

The following steps in sequence describe how an ESP works:

- A high-voltage, pulsating, direct current is applied to the discharge electrodes and the collection electrodes with the discharge electrode being negatively charged and the collection electrode being grounded. The applied voltage creates an electric field and is increased until it produces a Corona discharge, which can be seen as a luminous blue glow around the discharge electrode.
- The dirty exhaust gas enters the ESP such that the gas flows between the collection plate electrodes

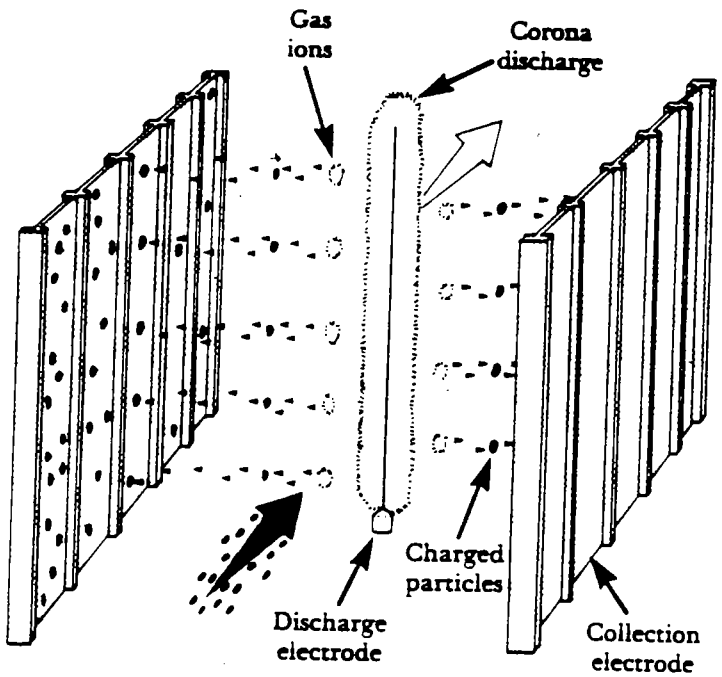

Figure 4-12. Plate ESP. [7]

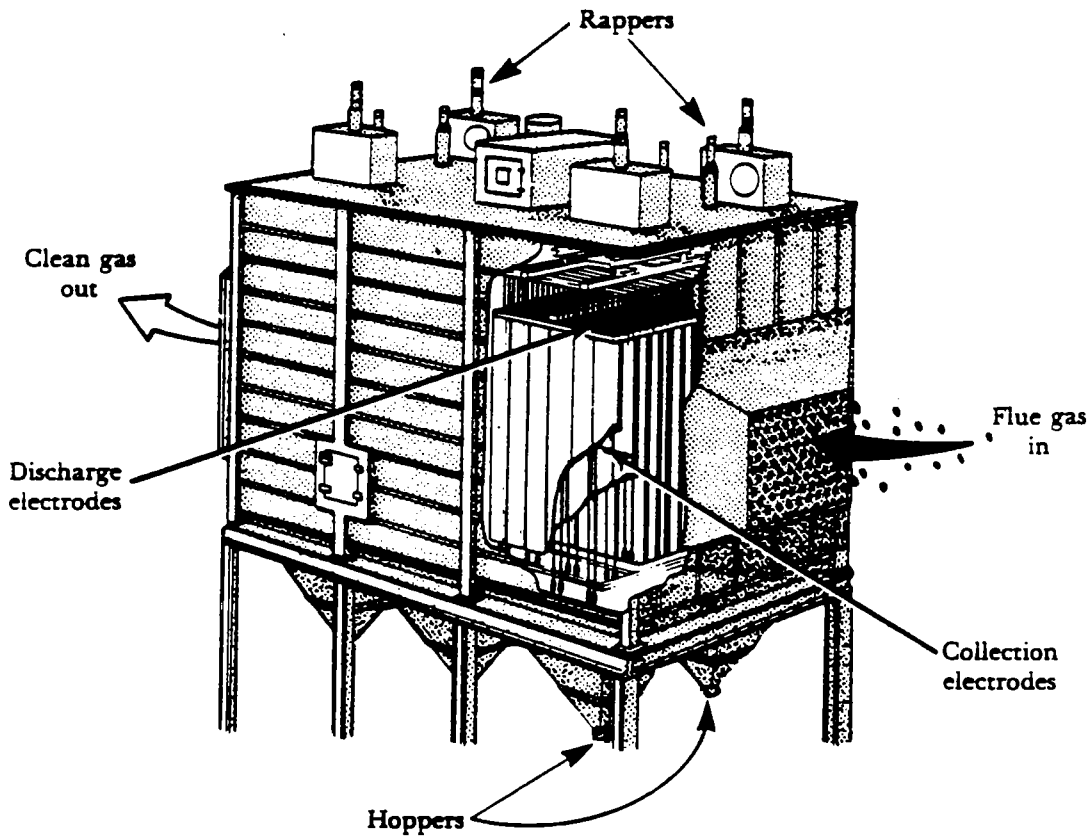

Figure 4-13. Electrostatic Precipitator.[7]

- As the dirty gas comes into contact with the corona, the gas particles become negatively charged.
- The negatively charged particles migrate to the collection electrode because they are repelled from the negatively charged discharge electrodes (like charges) and attracted to the collection electrodes (opposite charges).
- When the charged particles reach the collection plate, the charge on the particle is only partially discharged. The charge is slowly leaked to the grounded collections electrode. A portion of the charge is retained and allows the particle to adhere to the plate and promotes cohesion of other particles to the collected particles on the plate.
- The collection plates are rapped periodically to remove the collected particles. Plates are rapped when the accumulated dust layer is relatively thick (0.03 to 0.5 inches [0.01 to 0.2 centimeters]). This procedure allows large sheets of dust to fall off the plates and helps eliminate dust reentrainment.
- The dislodged dust falls into the hopper where it is removed with a hopper discharge device such as a slide gate or drawer (manual dust removal) or a trickle valve, rotary airlock valve, screw conveyor, or pneumatic conveyor (automatic dust removal).

REVIEW EXERCISE

1. Which of the following types of air pollution control devices are used on hospital incinerators?

   a. Wet scrubbers
   b. Fabric filters
   c. Dry scrubbers
   d. All of the above

2. Fine particulate emissions are controlled very effectively by which types of devices?

   a. Packed-bed scrubbers
   b. Venturi scrubbers
   c. Fabric filters
   d. Dry scrubber systems
   e. Electrostatic precipitators

3. Pulse-jet fabric filters use a blast of _____ _____ for cleaning the bags

4. A dry scrubber is always followed by a high efficiency particulate matter control device. True or False?

5. Where does acid gas removal from the flue gas occur in a dry injection system?

   a. Venturi contactor
   b. Flue gas ductwork
   c. Fabric filter
   d. All of the above

6. Both the spray dryer and dry injection types of dry scrubbers inject dry alkaline sorbent into the flue gas stream. True or False?

1. d. All of the above

2. b, c, d, and e

3. compressed air

4. True

5. d. All of the above

(continued)

REVIEW EXERCISE (CONTINUED)

7. A venturi scrubber's control efficiency and operating costs increase with increased gas velocity and pressure drop in the venturi throat. True or False?

8. The majority of the fine particulate collected by a fabric filter is filtered out by the _____ _____.

6. False. The spray dryer injects liquid slurry.

7. True

8. filter cake

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SESSION 5.
MONITORING AND AUTOMATIC CONTROL SYSTEMS

SESSION 5. MONITORING AND AUTOMATIC CONTROL SYSTEMS

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SESSION 5.
MONITORING AND AUTOMATIC CONTROL SYSTEMS

SESSION GOAL AND OBJECTIVES

GOAL

To familiarize you with:

- The difference between a parameter that is monitored and automatically controlled and a parameter that is simply monitored;
- The types of operating parameters that may be controlled or monitored;
- The basic types of automatic control systems used on incinerators; and
- The types of monitors that may be included on your incinerator/air pollution control system.

OBJECTIVES

Upon completing this session, you should be able to:

1. List the operating parameters that may be controlled and/or monitored;
2. Distinguish between a monitored and controlled parameter and a parameter which is only monitored;
3. Identify the instruments used to monitor operating parameters;
4. Explain the basic types of control systems typically used on incinerators; and
5. Identify the monitoring and control systems included on your incinerator/air pollution control system.

INTRODUCTION

The type of control system and the operating parameters that are monitored will be different for each incinerator. In this session, the parameters most likely to be monitored and/or controlled are discussed.

It is important to make a distinction between a parameter that is monitored and a parameter that is monitored and automatically controlled. When a parameter is monitored, it means that information is obtained by a sensing device in the incinerator and the information is transmitted to a receiver such as a display meter or recorder for you to view. However, the information from the sensor does not automatically control any operations. Figure 5-1 is a simplified schematic of a temperature monitoring system.

When a monitored parameter is used for control, the information transmitted from the sensor is used to adjust some function(s) within the incineration system that in turn controls the monitored parameter. The control system includes a controller to send a signal to the operating system which is adjusted. Figure 5-2 is a simplified schematic of a temperature control loop which adjusts the primary chamber combustion air blower and burner operations to control the temperature. Control systems use setpoints for the monitored/controlled parameter (in this case the primary chamber temperature) to determine when action will be initiated for the adjusted parameter (in this case, increasing/decreasing the combustion air and turning on or off the primary burner).

A simple control system which you are all familiar with that uses a setpoint is the household thermostat, as shown in Figure 5-3. The desired temperature of the room is set, and the furnace automatically turns on and off in order to maintain this temperature. A temperature dial is provided so you can monitor the room temperature. An example of a temperature monitor/control display which is used on an incinerator is presented in Figure 5-4. This controller has low and high setpoints. Two pointers are used for setting the high and low setpoints, and the third pointer indicates the actual temperature.

So that you can fully appreciate how your incinerator operates, you should know

- Which parameters are monitored and how the monitored value is displayed; and
- Which of the monitored parameters are automatically controlled, and what incinerator operating functions they adjust.

The next section lists the most frequently monitored/controlled parameters and the operating functions that they may be used to adjust. Each incinerator will use different monitoring and control systems.

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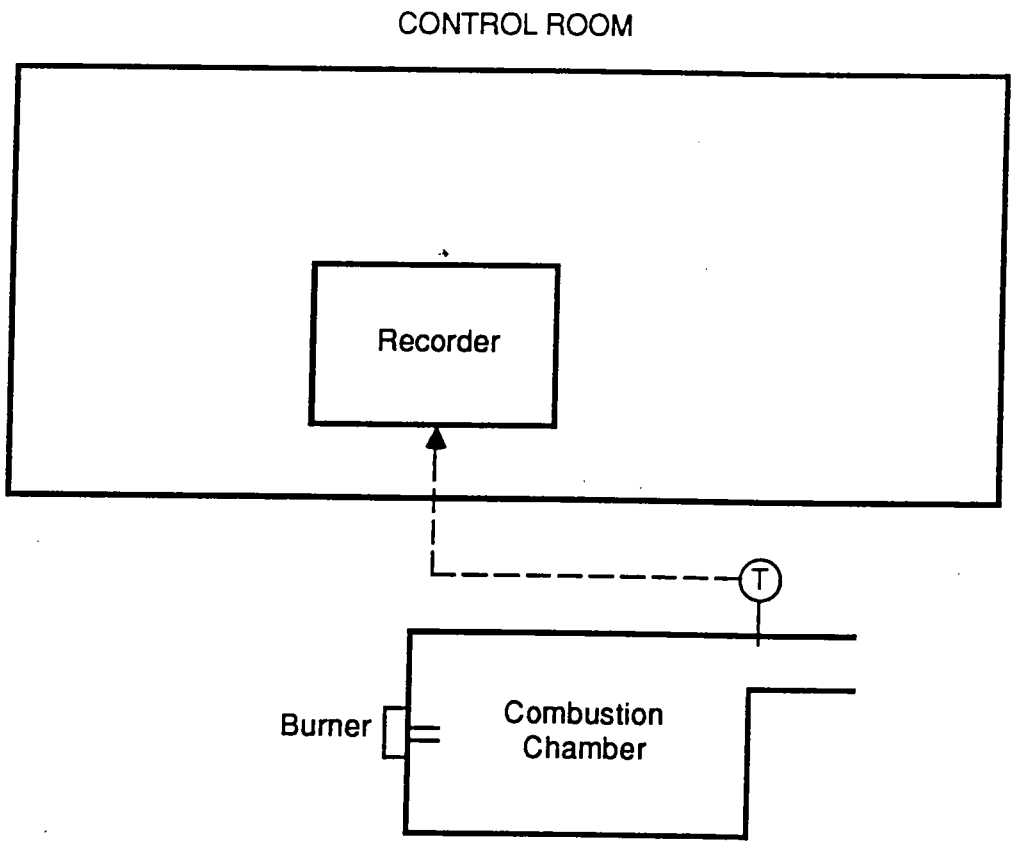

Figure 5-1. Schematic of a temperature monitoring system.

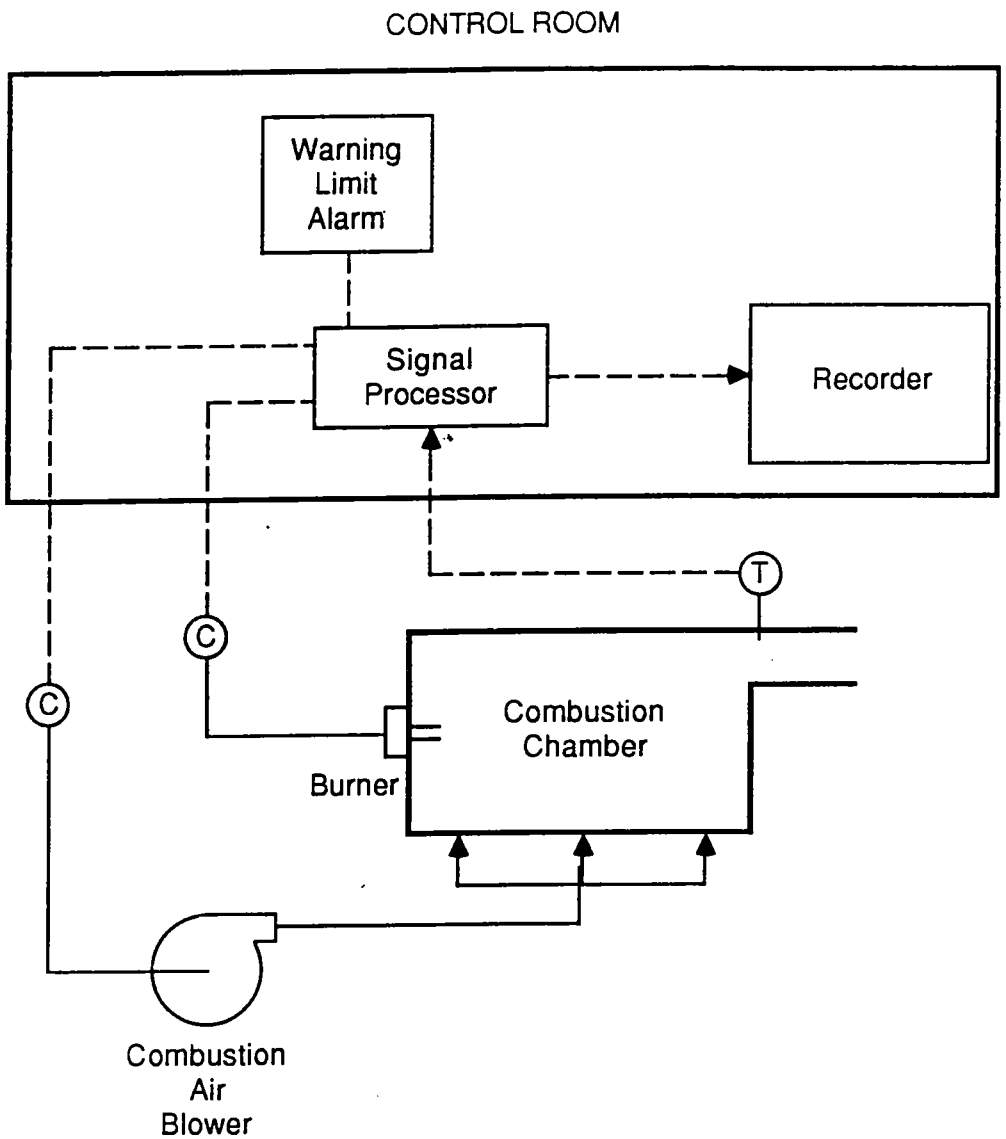

Figure 5-2. Schematic of a temperature control loop.

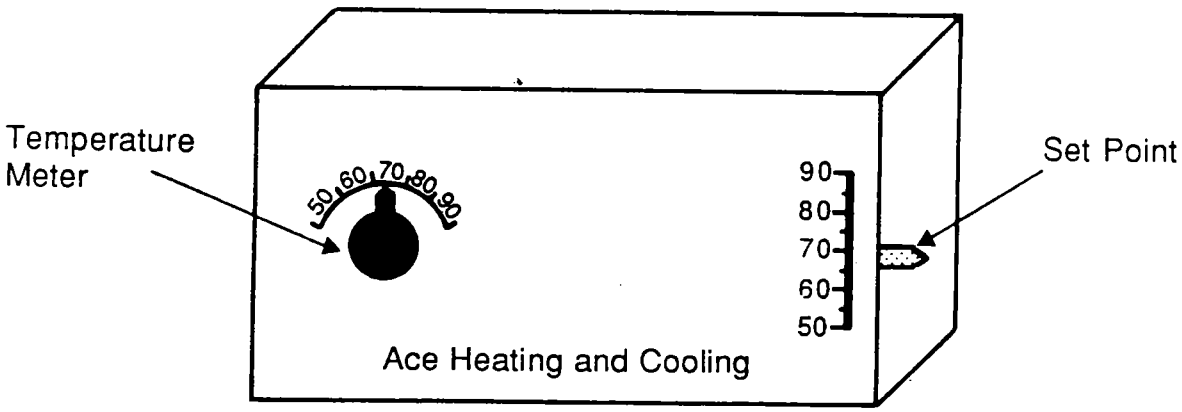

Figure 5-3. Thermostat with temperature "setpoint."

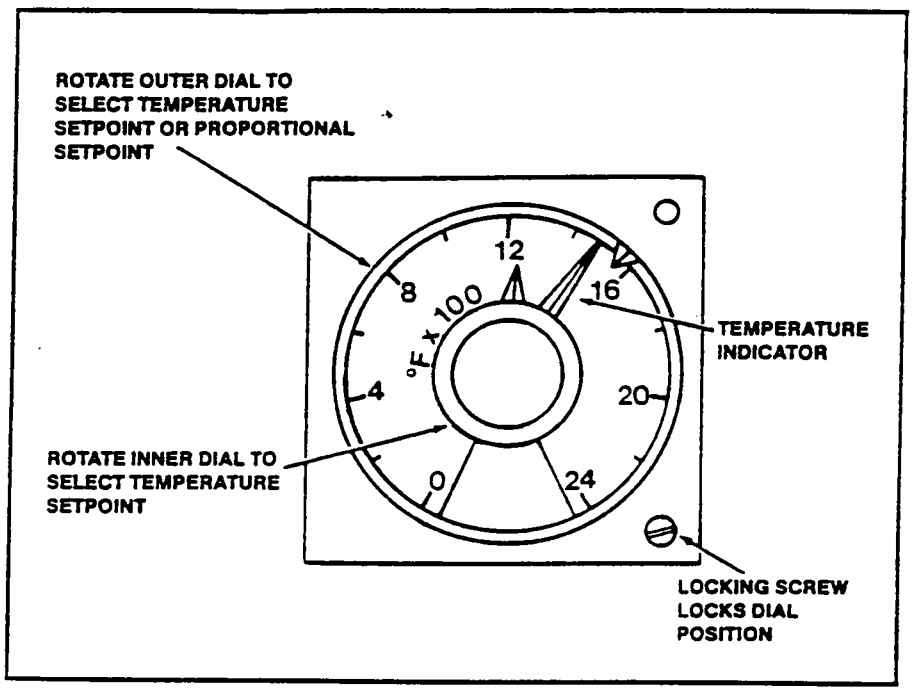

Figure 5-4. Temperature controller/meter. [1]

OPERATING PARAMETERS

INCINERATOR OPERATING PARAMETERS

The incinerator operating parameters that may be either monitored and/or used as control parameters are listed in Table 5-1. The functions which are typically adjusted when the parameters are used as a control function also are listed in Table 5-1. Temperature is almost always monitored. Typically, the other parameters are monitored only on larger incinerators or if regulatory agencies require that specific parameters be measured, e.g., opacity.

WET SCRUBBER OPERATING PARAMETERS

The wet scrubber operating parameters that may be either monitored and/or used as control parameters are listed in Table 5-2.

FABRIC FILTER OPERATING PARAMETERS

The fabric filter operating parameters that may be monitored and/or used as control parameters are listed in Table 5-3, along with the operating functions which might be adjusted.

TYPES OF INCINERATOR AUTOMATIC CONTROL SYSTEMS

The control systems used for incinerators vary from manually controlled units to highly sophisticated electronically controlled units. Three basic levels of control systems are briefly described below, as an introduction to the typical control systems used on hospital waste incinerators.

MANUAL CONTROL

With a totally manual control system, you make all adjustments including turning burners on or off, adjusting combustion air dampers, and adjusting stack dampers. The on/off cycling of auxiliary burners to control combustion chamber temperatures between low and high setpoints is a simple automatic control which is a step up from full manual control. Also, the use of a barometric damper will automatically control incinerator draft.

AUTOMATIC TIMER SEQUENCE

A preset timer sequence may be used for controlling an incinerator. With this type control system, a time sequence is activated when the incinerator is turned on. The time sequence controls combustion air and burner operations in conjunction with temperature setpoints. In a typical timer control sequence, forced draft combustion blower settings (either on/off or low/high) are activated based on the preset time sequence. For example, the primary combustion air blower may start off in the "low" air setting and continue to supply air at a low rate until 1 hour into the cycle; at this time, the control time causes the blower to shift to the "high" combustion air rate.

TABLE 5-1. TYPICAL MONITOR AND CONTROL PARAMETERS FOR INCINERATORS.

Monitored/controlled parameter	Purpose	Incinerator functions controlled (when applicable)
Temperature (primary and secondary chambers)	Indicates temperature operating range; Control parameter	Combustion air Auxiliary burners
Draft	Indicates pressure in chamber; Control parameter	Barometric damper ID fan damper
Oxygen	Indicates excess air level	Combustion air
Carbon monoxide	Indicator of combustion efficiency	--
Opacity	Indicator of emissions	--
Charge rate	Records charge rate	Automatic feed system interlock

TABLE 5-2. TYPICAL MONITOR AND CONTROL PARAMETERS FOR SCRUBBERS.

Monitored parameter	Scrubber functions controlled (when applicable)
Pressure and pressure drop	Venturi throat ID fan
Scrubber liquid flow rate or pressure	Liquid flow control valve
Scrubber liquid pH	Caustic flow control valve
Inlet temperature	Emergency quench/dilution air Bypass stack Prequench

TABLE 5-3. TYPICAL MONITOR AND CONTROL PARAMETERS FOR FABRIC FILTERS

Monitored parameter	Fabric filter operating functions controlled
Pressure drop	Cleaning cycle
Inlet gas temperature	Emergency bypass stack

The auxiliary burners also are turned on/off or shifted from low to high fire rates based on the timer sequence. Low and high temperature setpoints are provided to override the time control sequence if the low/high temperature setpoints are exceeded; that is, if the high temperature setpoint is exceeded, the burner will cycle back to low fire even though the burner would normally be operating at a high fire based on the time sequence.

AUTOMATIC CONTROL

With a typical fully automatic control system, the combustion air level is automatically adjusted over a full operating range (rather than just high/low settings). The system adjusts the combustion air based on input from temperature and/or oxygen monitors. The burners are cycled on or off if preset low and high temperature setpoints are reached. The incinerator draft is automatically controlled by a barometric damper or control dampers on the induced draft fan.

MONITORING AND CONTROL EQUIPMENT

The following sections describe the types of instrumentation used to monitor or control the operating parameters described previously.

TEMPERATURE

Thermocouples are used to monitor temperatures in the incinerator's combustion chambers and inlet gas to the air pollution control system. The thermocouples usually are located near the exit of each combustion chamber and upstream of the air pollution control device. The temperature readout may be a strip or circular recorder, a digital display, or a temperature gauge. The chart recorder provides a permanent record of the temperatures experienced by the thermocouples. Thermocouples usually are very reliable instruments. However, to avoid operational problems, regular replacement of thermocouples is recommended. Some incinerators may employ dual thermocouples in order to detect thermocouple malfunctions. These malfunctions should be reported to the maintenance department.

Most incinerators are equipped so that the minimum temperatures required by regulations or recommended by manufacturers are maintained. These minimum temperatures are maintained through the use of temperature setpoints. Once the temperature measured by the thermocouple drops below the temperature setpoint, then the temperature is increased by either burning auxiliary fuel or by adjusting the combustion air supply or both.

INCINERATOR DRAFT AND APC PRESSURE DROP

Pressure drop is measured with a differential pressure gauge. To monitor incinerator draft, one side (high-pressure side) of this instrument is always open to the ambient air while the other side (low-pressure side) is connected by tubing or piping to the incinerator chamber. Incinerator draft can be automatically controlled using a

barometric damper for natural draft systems. Figure 5-5 is a schematic of a barometric damper. The damper automatically opens and closes (via a mechanical system) to maintain a constant pressure differential between the incinerator chamber and the atmosphere, as measured by the draft monitor. For induced draft systems, the draft typically is controlled by opening and closing a damper located before or after the induced draft fan. Figure 5-6 shows a damper control system for an induced draft fan. Airflow is decreased as the damper is closed, as depicted in the figure. The damper can be adjusted manually or can be automatically adjusted by a mechanical system based upon the output from the draft monitor.

To monitor the pressure drop across an APC device, a differential pressure gauge also is used. The high-pressure side of the gauge is connected upstream of the control device and the low-pressure side is connected downstream of the control device to measure the pressure drop across the APC.

OXYGEN CONCENTRATION

Some incinerators may be equipped with oxygen monitors. The oxygen sensor typically is located in the duct to the stack or in a duct at the exit of the secondary combustion chamber. These monitors analyze the oxygen concentration in the combustion gases from the secondary combustion chamber so that the operator can ensure that enough oxygen is available for proper combustion. For some incinerators with oxygen analyzers, the oxygen levels measured are used to automatically control the combustion air feed rates to the incinerator.

The two main designs used for oxygen analyzers are in situ and extractive analyzers. Figure 5-7 depicts the in situ and extractive designs. In situ oxygen analyzers provide rapid response to changes in the oxygen content of the gas because the sensor is actually mounted in direct contact with the gas stream. The extractive technique involves the continuous withdrawal of a sample of gas that is transported via a sample line to the analyzer which is located some distance from the sampling point. Figure 5-8 is a schematic of an example extractive analyzer system showing the gas conditioning and calibration components of the system.

CARBON MONOXIDE CONCENTRATION

Some incinerators may be equipped with carbon monoxide (CO) monitors. These monitors analyze the CO concentration in the combustion gases from the secondary combustion chamber to ensure that proper combustion conditions are maintained and CO emissions are minimized. In general, high CO levels indicate that incomplete combustion is occurring. Typically, CO monitors are not part of the automatic process control system.

As with oxygen analyzers, CO analyzers usually are located at the secondary combustion chamber exit or in the stack breaching and may be either in situ or extractive. However, CO analyzers are usually

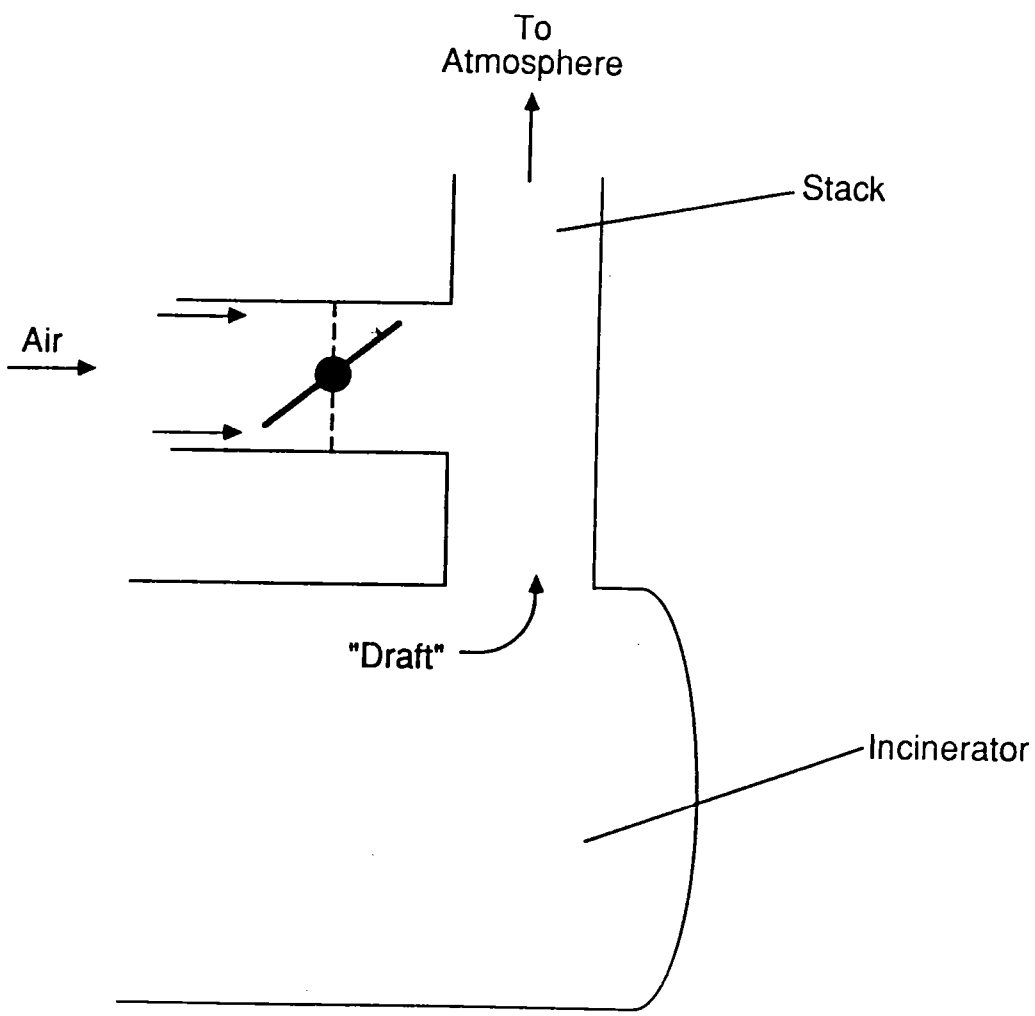

Figure 5-5. Barometric damper.

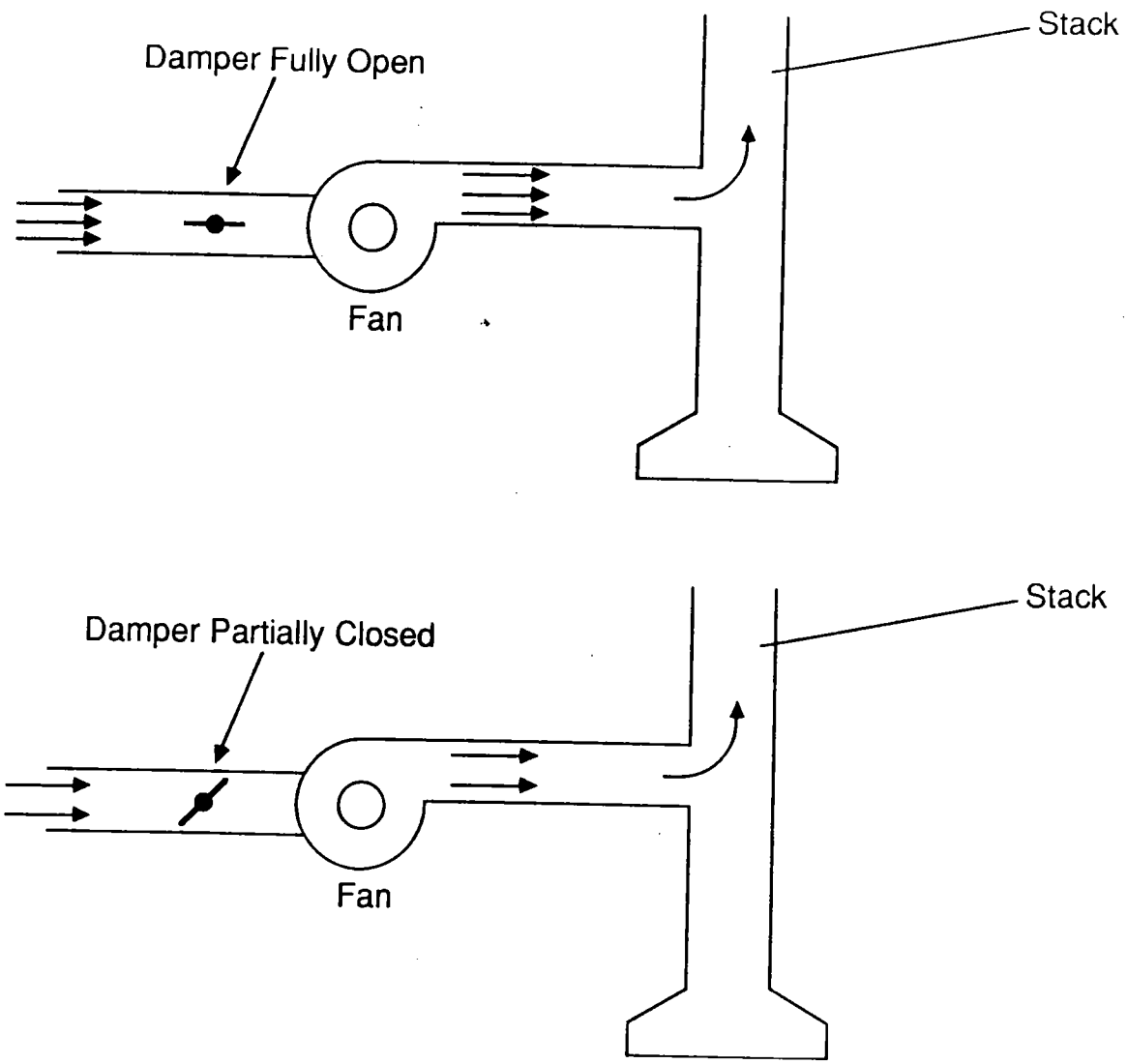

Figure 5-6. Constant speed fan with damper control.

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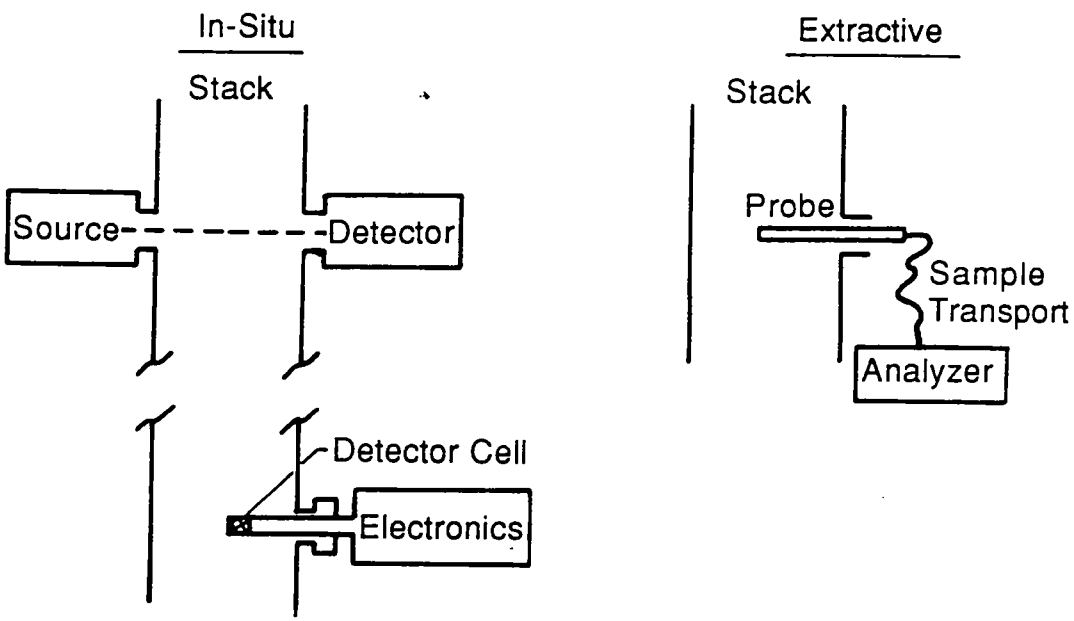

Figure 5-7. Schematic of in situ and extractive monitors.

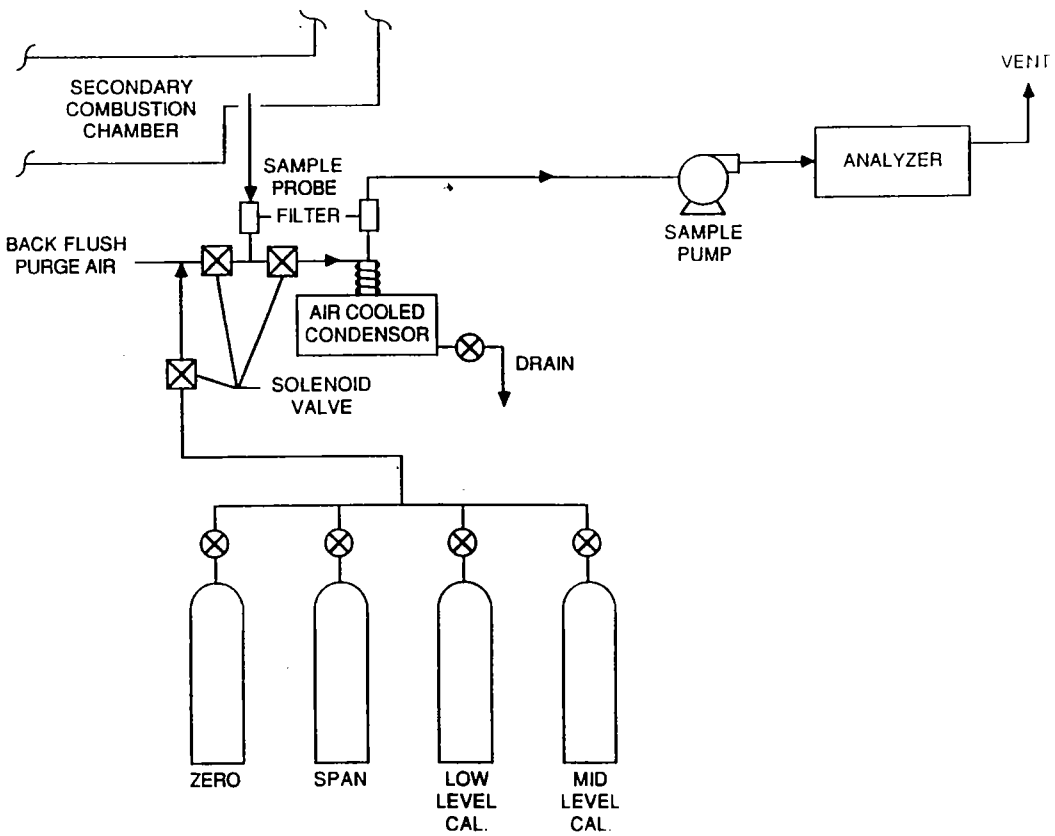

Figure 5-8. Schematic of extractive monitoring system.

extractive because water vapor in the exhaust gas interferes with the CO analysis and, therefore, must be removed through gas conditioning steps associated with the extractive analyzer. Problems with CO analyzers are usually associated with pluggage in the system or small air in-leaks that distort the readings.

OPACITY

Opacity monitors (transmissometers) are used as indicators of proper operation rather than as part of the automatic control system. Opacity monitors are almost always located in the stack or stack breeching and measure the amount of light absorbed by the stack plume from a light source directed across the stack. Figure 5-9 is a schematic of transmissometer installation. A transmissometer cannot be used after a wet scrubber because the gas stream contains so much moisture that a visible plume caused by the moisture interferes with the opacity measurement.

CHARGING RATE

Waste charging rate can be monitored manually or automatically. Manual monitoring involves weighing each load of waste and recording the weight of the charge. Automatic monitoring involves use of a weigh scale or weigh hopper that automatically records the weight of each charge placed on the scale or in the hopper.

SCRUBBER LIQUID pH

As the acid gases are scrubbed from the exhaust gas, the scrubber liquor pH will become acidic. Caustic solution can be added to the scrubber liquor to neutralize the solution. The pH is monitored using a pH electrode. The electrode is placed into a sump or a pipe through which the scrubber liquor flows. The output from the pH meter can be used to control the pH of the scrubber liquor automatically by operating a valve which controls the flow of caustic solution to the scrubber liquor.

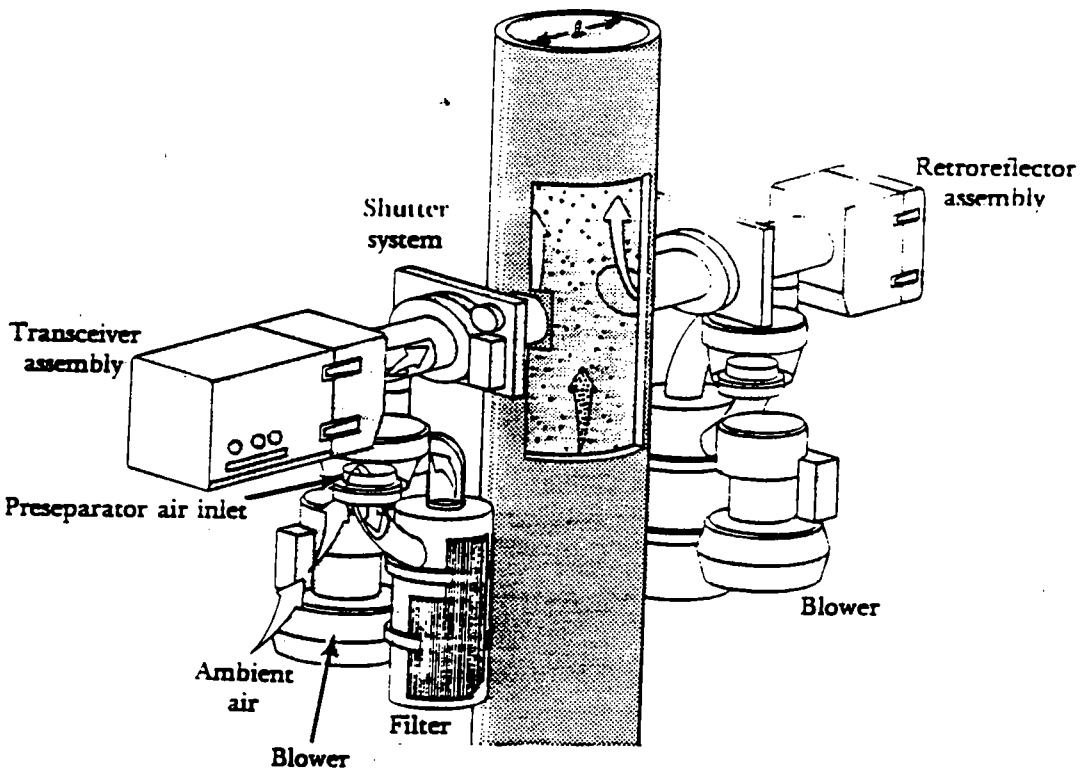

Figure 5-9. Typical transmissometer installation for measuring opacity. [2]

REVIEW EXERCISE

1. List five incinerator operating parameters that may be either controlled or monitored.

2. List three wet scrubber operating parameters that may be either controlled or monitored.

3. When a control parameter such as temperature is used to adjust an operating function (such as an auxiliary burner), _____ often are used to determine when the function is activated.

4. Thermocouples are used to monitor _____.

5. Thermocouples usually are located at the _____ of each combustion chamber and upstream of the air pollution control device.

6. Pressure drop is usually measured with a _____ _____ gauge.

7. Oxygen monitors usually are located at the exit to the _____ combustion chamber or in the ductwork of the _____.

8. The two basic types of oxygen and CO monitors used are called in situ and _____.

9. Typically, CO monitors are part of the automatic process control system. True or False?

10. Opacity monitors are used as indicators of proper operation and are not part of the automatic control system. True or False?

1. Temperature, draft, oxygen concentration, carbon monoxide concentration, opacity, charge rate

2. Pressure and pressure drop, scrubber liquid flow rate, scrubber liquid pH, temperature of inlet gas

5. setpoints

4. temperature

5. exit

6. differential pressure

7. secondary, stack

8. extractive

9. False

10. True

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SESSION 6.
INCINERATOR OPERATION

SESSION 6. INCINERATOR OPERATION

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SESSION 6.
INCINERATOR OPERATION

SESSION GOAL AND OBJECTIVES

GOAL

To familiarize you with:

- Proper waste handling procedures;
- Proper waste charging procedures;
- Key operating parameters for the incinerator and how they can be monitored and controlled;
- Proper ash removal and handling procedures; and
- Special actions required and possible problems with startup and shutdown of the incinerator.

OBJECTIVES

Upon completing this session, you should be able to:

1. Recognize the do's and don'ts of waste handling and charging;
2. Identify the key operating parameters for multiple-chamber and controlled-air incinerators;
3. State the operating range that is considered acceptable for each key operating parameter;
4. Describe how to monitor each key operating parameter;
5. List the special actions required for startup and shutdown of the incinerator; and
6. Recognize the do's and don'ts of ash removal and handling.

INTRODUCTION

Many types of incinerators are used for the incineration of medical wastes. The capacity of the incinerators varies tremendously because each incinerator model is designed differently; design criteria, operating parameters, and operating procedures will vary. The type of control system and the degree of automatic control and monitoring used with a specific incinerator also will vary.

As a result, this course cannot instruct you on how to operate your specific incinerator and is not intended to do so. Specific onsite training from the manufacturer of your incinerator, or a qualified consultant, is recommended. The objective of this session is to provide you with a basic understanding of the most important operating parameters and how you can monitor and control them. With a basic understanding of the key parameters, you should be able to better understand the operation of your system.

The operator is in control of many of the factors that have an impact on the performance of the incinerator including:

- Startup and shutdown;
- Waste charging procedures;
- Monitoring and adjusting operating parameters; and
- Ash handling.

The primary concern is to assure that the incinerator is operated in a manner so that:

- Infectious materials in the waste are rendered harmless; and
- Air pollution emissions are minimized.

In this session we will:

- Discuss proper waste handling procedures;
- Identify key operating parameters;
- Identify recommended operating ranges for the key parameters;
- Discuss operation of controlled-air incinerators; and
- Discuss operation of multiple-chamber incinerators.

WASTE HANDLING

Typically, you will be responsible for handling the waste prior to charging it to the incinerator. The primary concern with infectious waste handling is to avoid exposure of yourself and others to pathogens and avoid injury from sharp objects such as needles and broken glass. Proper procedures dictate that:

- Sturdy containers (including bags) are used;
- Waste handling is minimized;
- Mechanical waste charging devices are properly operated and maintained; and
- The waste storage area is secure and away from public traffic.

STURDY CONTAINERS

As an operator, you probably do not have control over the type of waste containers that are used. However, if breakage and spillage is a problem, you have an obligation to notify hospital management. Several things can be done if bag breakage is a problem. These include:

- Using stronger bags;
- Double bagging;
- Loading less material into each bag;
- Placing the bags in rigid containers such as cardboard boxes or barrels which can be incinerated.

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MINIMIZING WASTE HANDLING

As an operator, you have some control over the handling of the waste. The less you handle the waste the less chance there is of breaking bags or injuring yourself. You should think of ways you can minimize handling of the waste.

One example of how waste handling can be minimized is the use of rolling carts to transport and store the waste before charging. Once the red bags are placed in the carts and transported to the incinerator, the bags should not need to be handled again until the bags are loaded directly from the cart into the incinerator charging system. It does not make sense to unload the bags from the cart and pile them on the ground and then have to pick them up again to load them into the incinerator.

PROPER OPERATION OF WASTE CHARGING SYSTEM

To minimize breaking and spilling bags, the mechanical charging system should be properly operated.

Hopper/Ram Systems. Do not overfill the hopper by jamming waste into it. Do not force the hopper door closed.
Automatic Cart Dump Systems. Do not overfill the carts.

SECURE STORAGE

The waste should be stored in a safe and secure way--even if stored only for a short period of time. The following are guidelines:

- The waste storage area should be out of the way of normal hospital pedestrian traffic.
- The area should be secure from public access.
- The storage area or containers should be secure from rodents which can contract and transmit disease.

An example of poor waste storage is throwing the bags in a pile on the loading dock adjacent to the hospital parking lot. An example of better waste storage is to leave the bags in transport carts inside an area protected by a chainlink fence and with limited access. An example of even better waste storage is to leave the bags in transport carts inside a well ventilated building which houses the incinerator charging system. Some State regulations require that infectious wastes be stored under refrigeration if they are not to be incinerated within a specified time period (e.g., 24 hours).

DO'S AND DON'TS OF WASTE HANDLING

DO:

- Minimize your handling of the waste.
- Report repeated problems with bag breakage/spillage to hospital administrators.

- Assure that the waste to be charged is safely stored if it will not be immediately charged.

DON'T:

- Throw bags around and cause the bags to break and spill.
- Misuse mechanical charging systems and cause the bags to break and spill.

KEY OPERATING PARAMETERS

In this section, the key operating parameters for controlled-air and multiple-chamber incinerators are identified, and operating ranges consistent with "good operating practice" for the key parameters are presented. The rationales for the operating ranges also are presented. However, incinerator designs differ, and operation of a particular incinerator outside the recommended ranges may be appropriate. The objective is to operate the incinerator in such a manner to achieve complete combustion, sterilize the ash, and minimize air pollutants. Furthermore, in many cases, specific operating limits are established by regulatory agencies; these limits may differ from the recommended operating ranges presented here. Obviously, the incinerator should be operated within the regulatory limits.

First, the key operating parameters for controlled-air incinerators are presented and discussed. Then the operating parameters for multiple-chamber incinerators are presented and discussed.

KEY OPERATING PARAMETERS FOR CONTROLLED-AIR INCINERATORS

Table 6-1 summarizes the key operating parameters and recommended operating ranges for the typical controlled-air incinerator.

The key operating parameters are:

- Primary chamber temperature;
- Secondary chamber temperature;
- Charging rate;
- Primary chamber combustion air level;
- Total combustion air level;
- Combustion gas oxygen concentration; and
- Primary combustion chamber draft.

Each of these parameters is briefly discussed below.

Primary and Secondary Combustion Chamber Temperatures. The key parameter most likely to be monitored by the operator is the temperature of both chambers. The temperature ranges for the two chambers are different because the functions of the two chambers are different.

Both upper and lower limits on the temperature range for each chamber are necessary.

TABLE 6-1. KEY INCINERATOR OPERATING PARAMETERS AND RECOMMENDED OPERATING RANGE: CONTROLLED-AIR INCINERATOR

Parameter	Incinerator type		
	Batch feed	Intermittent feed	Continuous duty
Primary chamber temperature, °F	1000° to 1800°	1000° to 1800°	1000° to 1800°
Combustion (secondary) chamber temperature, °F	1800° to 2200°	1800° to 2200°	1800° to 2200°
Charging rate, lb/h	Fill chamber once at beginning of cycle	10 to 25 percent of rated capacity at 5 to 15 min intervals	10 to 25 percent of rated capacity at 5 to 15 min intervals
Primary chamber combustion air (percent of stoichiometric)	30 to 80	30 to 80	30 to 80
Total combustion air (percent excess air)	140 to 200	140 to 200	140 to 200
Combustion gas oxygen concentration, percent	12 to 14	12 to 14	12 to 14
Primary chamber draft, in w.c.	-0.05 to -0.1	-0.05 to -0.1	-0.05 to -0.1
Burndown period, h	2 to 5	2 to 5	Not applicable

- The temperature is maintained above the lower limit to assure complete combustion of organic compounds and destruction of pathogens.
- The temperature is maintained below the upper limit to prevent damage to the incinerator refractory and slagging of the ash.

The recommended operating ranges which are considered to be good operating practice are as follows:

- Primary chamber lower limit: Greater than 1000°F (540°C).

The chamber must be maintained at a temperature sufficient to maintain combustion, combust the fixed carbon in the waste, and sterilize the remaining ash. For continuous-duty, controlled-air incinerators, a minimum temperature of 1000°F (540°C) also is recommended. However, a higher temperature such as 1400°F (760°C) may be needed to assure combustion of the fixed carbon since the retention time of the ash in the incinerator may be less than for batch and intermittent-duty incinerators. The temperature necessary to achieve an acceptable ash burnout quality should be used.

- Primary chamber upper limit: less than 1800°F (980°C).

The primary chamber must be maintained below a temperature where slagging of the waste occurs and damage to the refractory may occur.

It should be cautioned that a higher primary chamber temperature is not necessarily always better (e.g., 1700°F is not necessarily better than 1200°F). Many factors must be considered, including waste characteristics. One manufacturer reports that based on their experience, the volatilization rate of plastics can be significantly affected by the temperature in the primary chamber (i.e., more rapid volatilization at 1800°F than 1100°F). Based on their experience, operating the primary chamber at the lower end of the recommended range helps to minimize rapid increases in flue gas volume when highly volatile wastes are charged and results in improved operation because the secondary chamber is not overloaded with volatile gases.

- Secondary chamber lower limit: greater than 1800°F (980°C).

The temperature of the secondary chamber must be maintained at a high enough level to assure complete combustion of all organic compounds. The exact temperature required for this is dependent upon many things, including the compound, the oxygen level, how well the gases are mixed with the oxygen, and how long they are in the combustion chamber. A lower limit of 1800°F is recommended.

- Secondary chamber upper limit: less than 2200°F (1200°C).

The temperature of the secondary chamber must be maintained below a level which causes damage to the refractory; this level usually is around 2200°F (1200°C) for sustained operation, but is dependent on the type refractory used.

NOTE: Many regulatory agencies have established specific lower temperature limits for each combustion chamber. These limits may differ from the recommended limits presented in Table 6-1. Therefore, if your permit establishes a lower level temperature limit, you must operate above this limit.

Typical regulatory limits are:

1. Primary chamber temperature--must operate at greater than 1400°F (760°)
2. Secondary chamber temperature--must operate at greater than 1600°F (870°C)

Charging Rate. Each incinerator is designed for a specific heat input rate. The heat input comes from the waste, and as necessary, auxiliary fuel burner(s). Under ideal conditions, an incinerator operates under "steady state", that is with a constant, steady heat input.

For controlled-air incinerators, the heat release from the waste is controlled, within a range, by controlling the combustion air to the primary chamber. In a sense, the fundamental control of the heat release in an incinerator is obtained by controlling the quantity and frequency of waste charges, especially if the waste contains a significant quantity of volatile compounds.

Steady state operating conditions are approached as:

- The waste composition (heat content, moisture, volatiles) becomes more consistent;
- The charge loads decrease in size; and
- The charges are made more frequently.

Therefore, frequent charges of smaller volume may be more desirable than one large charge.

Because waste feed charging procedures are so important and because they can be controlled by the operator, proper charging procedures are discussed separately in the next section.

Primary and Secondary Combustion Air Level and Combustion Gas Oxygen Concentration. The primary chamber air is maintained below the stoichiometric level in controlled-air incinerators. Excess air is supplied to the secondary chamber. The total combustion air level typically is 140 to 200 percent excess air. Excess air is necessary to help assure that sufficient oxygen is available for complete combustion.

The oxygen level in the stack gas is an indicator of the excess air level. An oxygen concentration of 12 to 14 percent roughly coincides with 140 to 200 percent excess air.

Combustion Chamber Draft. A negative combustion chamber pressure typically is maintained. Excessive negative pressure is not desirable because it can cause fine particulate matter to be pulled from the primary chamber through the secondary chamber and out the stack. Also, excessive

negative pressure can cause excessive air infiltration through leaks into the incinerator. A typical range for the draft in the primary chamber is -0.05 to -0.10 inch of water column (in. w.c.) (-0.012 to -0.025 kilopascals [kPa]).

KEY OPERATING PARAMETERS FOR MULTIPLE-CHAMBER INCINERATORS

Table 6-2 summarizes the key operating parameters for the typical multiple-chamber incinerator.

The key operating parameters are:

- Primary chamber temperature;
- Secondary chamber temperature;
- Charging rate;
- Ignition chamber combustion air level (percent excess air);
- Total combustion air level (percent excess air);
- Combustion gas oxygen concentration; and
- Primary and secondary combustion chamber pressure.

Each of these parameters is briefly discussed below. Many of these operating parameters have already been discussed in detail for controlled-air incinerators. Therefore, the discussion is abbreviated here.

Primary And Secondary Combustion Chamber Temperature.

The key parameter most likely to be monitored by the operator of a multiple-chamber incinerator is the temperature of each chamber. The temperature is maintained above the recommended lower limit to assure complete combustion of organic compounds and sterilization of the ash. The temperature is maintained below the upper limit to prevent waste slagging and damage to the incinerator refractory. The recommended ranges are:

- Primary chamber--1000° to 1400°F (540° to 760°C)
- Secondary chamber--1800° to 2200°F (980° to 1200°C)

As noted in Table 6-2, a higher temperature is recommended in the primary chamber when incinerating pathological wastes. The higher temperature is recommended to facilitate the burndown of the waste.

Many regulatory agencies have established lower limits for each combustion chamber. If your operating permit establishes a lower temperature limit, you must operate the incinerator above this limit.

Charging Rate. The charging rate and procedures used are very important for operation of a multiple-chamber incinerator.

Note that charging rates for general refuse/red bag and pathological wastes are presented differently in Table 6-2 because of their different waste characteristics. For general refuse/red bag waste, it is important to make frequent, small charges to avoid large surges of volatile

TABLE 6-2. KEY INCINERATOR OPERATING PARAMETERS AND RECOMMENDED OPERATING RANGE: MULTIPLE-CHAMBER INCINERATOR

Parameter	Pathological waste	General refuse
Ignition chamber temperature, °F	1600 to 1800	1000 to 1400
Combustion (secondary) chamber temperature, °F	1800 to 2200	1800 to 2200
Charging rate	Single layer on hearth	10 to 25% of rated capacity at 5- to 15-min intervals
Ignition chamber combustion air (percent excess air)	80	150
Total combustion air (percent excess air)	120 to 200	250 to 300
Combustion gas oxygen concentration, percent	10 to 14	15 to 16
Ignition chamber draft, in. w.c.	-0.05 to -0.1	-0.05 to -0.1

combustible gases that can exceed the capacity of the combustion air supplied in the primary and secondary chambers. Pathological waste must be exposed to a direct flame to achieve combustion.

Primary And Secondary Chamber Combustion Air Levels And Combustion Gas Oxygen Concentration. The primary chamber for a multiple-chamber incinerator is typically maintained at an excess air level of about 200 percent. A multiple-chamber incinerator is operated at an overall excess air level of about 250 to 300 percent. This results in combustion gas oxygen levels in the 15 to 16 percent range. Multiple-chamber incinerators burning pathological wastes typically are operated at lower excess air levels than incinerators burning general refuse. Less excess air is used because pathological waste contains less volatiles and the heat input comes primarily from auxiliary burners.

Primary Chamber Draft. A negative pressure must be maintained in the combustion chambers. Sufficient draft must be maintained to move the combustion gases through the incinerator. Too much draft will cause excessive entrainment of particulate matter from the primary chamber, which will be emitted as an air pollutant. Excessive draft also will increase the air in-leakage to the incinerator which increases the excess air level. The typical range for the primary chamber draft is -0.05 to -0.10 in. w.c. (-0.012 to -0.025 kPa).

OPERATION OF CONTROLLED-AIR INCINERATORS

This section discusses the operation of controlled-air incinerators, including:

- Proper waste charging;
- How to monitor and control the key operating parameters;
- Proper ash handling; and
- Starting up and shutting down the incinerator.

PROPER WASTE CHARGING PROCEDURES

Proper waste charging is probably the most important procedure for the operator. Remember that the heat input rate to an incinerator is very important because the incinerator is sized for a particular heat release rate:

- If the release rate is too low, the incinerator will not operate efficiently and excessive auxiliary fuel will be required.
- If the heat release rate is too high, incomplete combustion is likely to occur causing pollution.

As an operator, you should be aware that the heat content of wastes may vary and therefore you may need to vary the charging procedures--that is, you may need to charge more or less waste.

Special care should be taken to avoid overcharging the incinerator (beyond its intended use) with pathological wastes (animal carcasses and

body parts) because of the high moisture content and low heat value of this type waste. (Incineration of large quantities of these wastes is discussed later).

In Session 3, the operating mode of controlled-air incinerators was described as:

- Single batch;
- Intermittent duty; or
- Continuous duty.

The charging procedures used for these three operating modes are slightly different and are discussed separately below.

Single-Batch Incinerators. The following general principles apply for charging single batch incinerators.

- These incinerators are usually small and, therefore, are charged manually.
- The incinerator is charged cold.
- The waste is loaded into the ignition chamber, which is filled to the capacity recommended by the manufacturer.
- The incinerator chamber should not be overstuffed. Overstuffing can result in blockage of the air port to the combustion chamber. Overstuffing also can result in damage to the primary burner.
- After charging is completed, the charge door is closed and sealed.
- Once operation is initiated, no further charges are made until the next operating cycle (i.e., after the incinerator cools and ash is removed).
- Prior to ignition of the waste, the secondary combustion chamber is preheated. A minimum secondary temperature of 1800°F (980°C) is recommended prior to ignition of the waste in the primary chamber.

The manufacturer should be consulted regarding proper preheat procedures; improper preheat can result in refractory damage.

Intermittent-Duty Incinerators. Intermittent-duty, controlled-air incinerators typically are used for shift type operation. The incinerator must be shut down for ash removal. The charging/operating system is designed to accommodate multiple charges safely throughout the operating cycle rather than relying on a single-batch charge. Either manual or automated charging systems are used.

The following general principles apply for charging intermittent-duty incinerators:

- Stable combustion is best maintained with a constant heat input to the incinerator.
- Frequent, smaller charges are more desirable than one big charge.

- Overcharging (feeding too much waste in a charge) can cause excessive emissions because of rapid volatilization of organic compounds that overload the secondary chamber.
- Feeding too little waste results in inadequate heat input and excessive auxiliary fuel use.
- A recommended charging frequency is 10 to 25 percent of the rated capacity (lb/h) at 5 to 15 minute intervals.
- Another rule of thumb is to recharge the incinerator after the previous charge has been reduced by 50 to 70 percent in volume (as observed through a viewport).
- Charging volume and frequency will vary with waste composition and the incinerator design. Differences in charging procedures are appropriate for small manually fed units and large mechanically fed units. For large systems using mechanical charging, frequent charges will not interrupt incinerator operation because the mechanical system limits entry of excess air. Frequent, smaller charges are desirable. For smaller manually fed units, each time the door is opened, excess air enters and disrupts combustion. Also, opening the door creates a potential safety hazard. Less frequent charging is desirable. However, the charges should not be so large as to overload the incinerator.
- After the last charge of the day is completed, the incinerator is set to initiate burndown. The limiting factor on how long the incinerator can be operated without shutting down is how quickly ash builds up on the hearth. Typically, the operating period during which the incinerator is charged with waste is limited to 12 to 14 hours.

Continuous-duty incinerators. Continuous-duty incinerators typically are large units equipped with mechanical feed systems.

The mechanical feed system often is automatically operated so that the charge is fed on a timed sequence. Proper charging involves:

- Frequent charges of 10 to 25 percent of rated capacity (lb/h) every 5 to 15 minutes.
- Charging frequency may need to be adjusted to accommodate major changes in waste heat value.

CONTROLLING AND MONITORING KEY OPERATING PARAMETERS

The specific controls and monitors for each incinerator will be different. Some incinerators will have mostly manual controls and few monitors. Other incinerators will have highly automated control systems with many monitors to assist the operator. In this section, we will review some basic procedures the operator can follow for controlling and monitoring key operating parameters. How much control you actually have over the operation of your incinerator depends on the specific design and installation of the incinerator.

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The operating parameters which we will discuss include:

- Charging rate;
- Primary and secondary chamber temperatures;
- Combustion air levels; and
- Combustion chamber draft.

Charge Rate. The charge rate--or heat input rate--is critical to proper operation and is one parameter over which the operator has direct control. The incinerator must be operated with a charge rate consistent with its design so that the automatic or manual air and temperature controllers can do their job.

Monitoring the charge rate. The charge rate can be easily monitored. It is not necessary to monitor the rate exactly--unless required by regulation.

The operator can monitor the charge rate in several ways:

- Recording the amount and the time of each charge;
- Noting the source and type of waste;
- Observing trends in the primary and secondary temperatures;
- Observing the depth of the waste bed in the primary chamber; and
- Observing ash burnout quality.

1. Using a charging log. Recording the time and amount of each charge is called keeping a "charging log."

When you keep a charging log, you record the time each charge is made and the quantity of each charge (1 bag, 5 bags, 1 hopper, etc.). Monitoring charging in this way should provide sufficient information to determine if charging procedures are consistent and to provide information for making adjustments. For example, if overcharging is the suspected cause of black smoke, it is only necessary to reduce the number of bags charged in each batch and observe whether the reduced size of each load eliminates the emission problem.

If you want to know about how much waste you are charging with each load, you can weigh your loads for a day to get an average weight. In this case, you record the time each charge is made and the weight of the charge. This approach requires a scale. Some mechanical systems will automatically record the time and weight of a charge. Routinely recording the weight of all charges should not be necessary, unless regulations require it. However, this approach is highly recommended if you want to monitor your charging rate.

2. Observing trends in the primary and secondary combustion chamber temperatures. You should monitor primary and secondary combustion chamber temperature trends (that is, whether the temperatures are steady or are rising or falling). This information helps you evaluate whether the charging rate is correct.

It is expected that the temperatures will rise and fall in a cycle after each charge. However, major swings (for example, outside the recommended operating ranges) may be an indication of a need to adjust charging procedures.

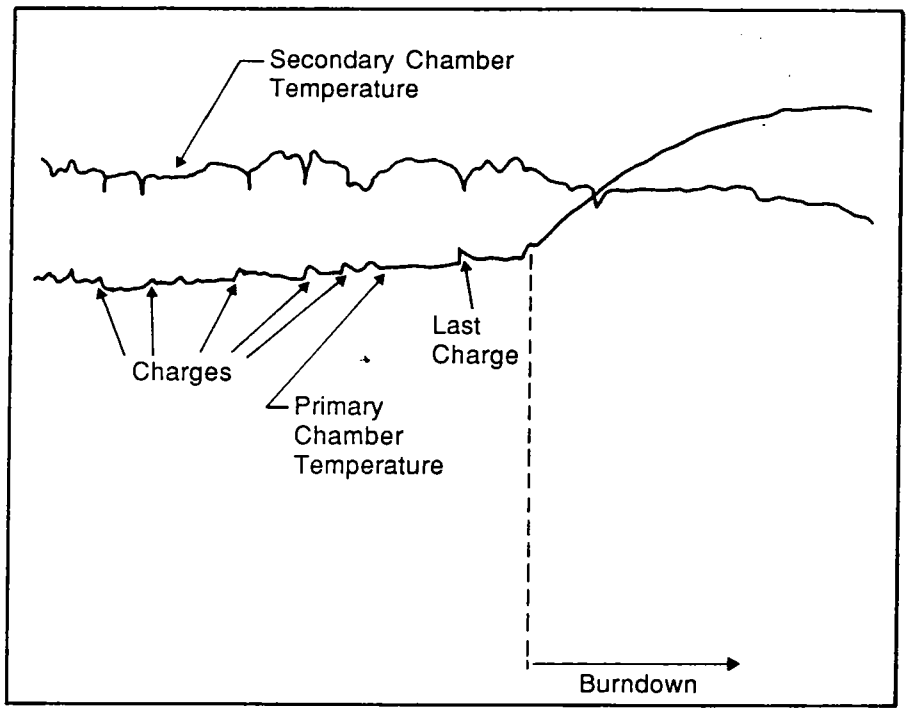
You should look for:

- Primary chamber temperature drop--if the primary chamber temperature falls below the desired low temperature setpoint and the auxiliary fuel burner is activated, the chamber is low on fuel and is overdue for a charge. (This assumes that the automatic combustion air control system is properly operating and that proper air has been provided to the primary chamber). Note: When very wet or low Btu waste is added to the primary chamber, a drop in temperature is expected. Adding more waste will further decrease the temperature.
- Secondary chamber temperature increase--if the secondary temperature begins to rise above the desired high temperature setpoint, the chamber may be receiving more fuel--in the form of combustion gases from the primary chamber--than the automatic air and burner control system can handle. Assuming the primary chamber air control system is properly operating, this situation indicates excess volatile emissions from a charge; i.e., the previous charge was too large or was too soon after the last charge.

Figure 6-1 depicts a temperature record for a controlled-air incinerator charged with a waste containing a significant volatile content. The impact of the charge on the temperatures can be seen. Primary and secondary temperatures as key parameters are further discussed in the next section.

3. Observing the waste bed. If view ports are available in the primary chamber, you can observe the waste bed. If the pile of unburned waste (other than normal ash buildup) inside the chamber is rapidly and steadily increasing in size, then the amount charged is greater than the amount which can be consumed in the same period of time. On the other hand, if all the waste is consumed well in advance of the next charge, it may be desirable to increase the charge size.

4. Observing ash quality. If all the combustible waste is not burned, it may be because the charge rate is too high and not enough time has been provided for complete combustion. Another reason for poor ash quality is insufficient underfire air. The term "burnout" is used to describe the amount of combustible material left in the ash. If all the waste is burned and no combustible material is left in the ash, the burnout is 100 percent. If only half the combustible waste is burned and one-half of the remaining ash is combustible, the burnout is 50 percent; this level of burnout is not good.



TEMPERATURE TREND

Figure 6-1. Example combustion chamber temperature trends--high volatile content waste.[1]

Control of the charge rate. The charge rate can be controlled by you. The rate can be controlled by either charging less waste with each load or by charging less frequently. For example: if an incinerator has an automatic hopper/ram charging system which is automatically controlled to charge one hopper every 10 minutes, the operator can reduce the charging rate simply by not filling the hopper to the top. The other approach would be to change the automatic timer to charge less frequently; for example, every 15 minutes instead of every 10 minutes. If the charge rate is to be increased for a system using a hopper/ram assembly, the frequency of charges would need to be increased (every 7 minutes, for example) because you should not overfill a hopper.

Primary and Secondary Chamber Temperatures.

Monitoring temperatures. You use temperature gauges to monitor the primary and secondary chamber temperatures. All incinerators should have a temperature gauge and, preferably, a temperature recorder. A recorder will assist you in seeing temperature trends.

Controlling temperatures. You can control temperature in three ways:

- Adjusting the charging rate;
- Adjusting the combustion air level; and
- Adjusting the auxiliary burner setpoints.

The importance of charging rate already has been discussed. Adding additional waste will generally increase the temperature; in a controlled-air incinerator, the automatic air control system will act to limit the temperature increase to the desired temperature setpoint. Note: if the fuel has a low heat content, such as pathological wastes or very wet waste, the temperature can actually decrease when a charge is added.

For a controlled-air unit, controlling the combustion air affects the temperature. Adjusting the combustion air is the primary control mechanism used, other than adjusting the charge rate. Increasing the air in the primary chamber increases the primary chamber temperature and increasing the air in the secondary chamber decreases the secondary chamber temperature. Usually, the automatic control system on a controlled-air unit will control the air levels. The automatic control system's operation will be based on:

- A clock timer sequence which operates in conjunction with each batch charge; or
- The temperature output from the thermocouples; or
- Some combination of the above two.

Actual adjustments to air damper settings or time/temperature setpoints normally are not made by you unless problems are persistent. Only properly trained operators should make damper adjustments on an automatic control system.

The final temperature control available to you is use of the auxiliary burners in the primary and secondary chambers. Again, these burners normally are automatically controlled; the burner is activated by a temperature setpoint. Only properly trained operators should adjust setpoints.

Primary Chamber and Secondary Chamber Combustion Air Levels And Stack Gas Oxygen Level.

Monitoring combustion air levels. Two means of monitoring air levels which are available to you are:

- An oxygen monitoring system; and
- Visual observations (indirect indicator).

The only way to actually measure the combustion excess air level is to use an oxygen monitor. Some incinerators have an oxygen monitor installed in the stack to monitor the overall excess air level. When such a monitor is available, you should assure that the combustion gas oxygen remains within the desired range.

Visual observation within the combustion chambers (through sealed glass observation ports) and of the stack gas will assist the operator in determining whether air levels may be incorrect. You should look for the following:

- Primary Chamber--The primary chamber is supposed to operate with deficient oxygen. The waste bed should be burning with a dark red color, and smoke will likely be present. If roaring bright yellow or orange flames are present, too much air is available. The problem may be air infiltration from leaks or improper combustion air settings.
- Secondary Combustion Chamber--The secondary burner flame should be burning with a bright yellow/orange flame and should not be smoking. A smoking flame indicates too little burner air.
- Stack Gas--The stack gas should be clean. Black smoke indicates incomplete combustion caused by insufficient air in the secondary chamber. (This situation is discussed in Session 8).

Control of Combustion Air. The combustion air levels are controlled by adjusting the combustion air dampers. Depending upon the control system, you may or may not have direct control of the air dampers. The air dampers are usually automatically controlled to maintain the desired combustion chamber temperatures. If you suspect persistent problems with combustion air levels, the damper settings should be checked and adjusted by a trained/qualified technician.

In some cases, a manual "emergency" override for automatically controlled systems may be present on the control panel for use when black smoke at the stack indicates incomplete combustion. Such an override will fully open the secondary air damper to allow maximum air while fully closing the damper to the primary chamber to decrease combustion; typically, the override also will shut off the secondary burner.

Incinerator Draft. The draft in the primary chamber must be maintained within the desired operating range. If the draft is too high, entrainment of particulate matter may occur, or air infiltration through leaks may be excessive. If the draft is too low, the chamber may reach a positive pressure, which is not desirable because smoke and hot gases might puff from the chamber door seals. A negative pressure in the incinerator is needed to prevent fugitive emissions.

Monitoring incinerator draft. A draft gauge is required to measure the pressure in the incinerator chamber. Your incinerator may or may not have such a gauge.

Control of incinerator draft. For natural draft systems, the draft may be controlled by a motorized barometric damper or stack damper, or it may be uncontrolled. Depending upon your system, these dampers may be manually controlled or may have an automatic control to maintain a preset draft.

For systems using an induced draft fan, a damper at the fan inlet or outlet is usually used to control the fan suction. Again, the damper may be controlled manually or automatically.

OTHER PARAMETERS TO MONITOR

Other parameters you should monitor include:

- Stack opacity;
- Stack gas carbon monoxide; and
- Burner flame pattern.

Stack Gas Opacity. Stack gas opacity provides an indirect measurement of particulate matter concentration in the stack gas. As particulate matter increases so does opacity.

You should make a habit of observing the stack emissions. If high opacity emissions occur, proper operation of the equipment should be checked and operating procedures should be changed, if necessary. Session 8 further discusses how opacity can be used to identify combustion problems and some possible operating changes to correct the problems.

If your incinerator is equipped with a transmissometer (continuous monitor for opacity) you should learn the acceptable opacity range and frequently check the instrument data to assure that the incinerator is operating within the acceptable range; pay attention to the "high opacity alarm" when it goes off.

Combustion Gas Carbon Monoxide. Carbon monoxide gas (CO) is formed during incomplete combustion. Excessive levels indicate that a poor combustion condition exists. Levels greater than 100 ppm are usually considered excessive. Your State may specifically regulate the level of CO.

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The CO level of the combustion gas can be monitored by an instrument. If your incinerator continuously monitors CO, you should routinely check the levels to assure they stay within the acceptable range. If they do not, changes in your charging procedures or adjustments to combustion air levels are probably necessary. If no CO instrument is installed, you cannot determine CO levels.

Burner Flame Pattern. If sealed observation ports are available, you should check the burner flame pattern daily. The burner flame should:

- Be bright yellow/orange;
- Not smoke;
- Not move back and forth abruptly; and
- Not hit the refractory walls.

Figures 6-2a, 6-2b, and 6-2c schematically show proper and improper flame patterns. If you suspect a burner problem, report the problem to the maintenance department.

SUMMARY OF CONTROL AND MONITORING TECHNIQUES FOR CONTROLLED-AIR INCINERATORS

The control and monitoring of a controlled-air incinerator is complex. Five of the key operating parameters that are very interrelated are:

- Charge rate;
- Primary chamber temperature;
- Secondary chamber temperature;
- Primary chamber combustion air level; and
- Secondary chamber combustion air level.

A typical controlled-air incinerator system will have some type of automatic control system which controls both the temperature and amount of combustion air to both chambers. The system monitors the chamber temperatures and controls the combustion air levels and auxiliary burners to maintain the desired setpoints. For the automatic control system to operate properly, the incinerator must be charged with an amount of waste consistent with the incinerator's design capacity.

The charge rate to the incinerator is the single most important parameter that you can control. The operator monitors combustion chamber temperatures and temperature trends to evaluate whether the charge rate is appropriate. If an oxygen monitor is available, the stack gas oxygen level is monitored to confirm that combustion air levels are consistent with good operating practice.

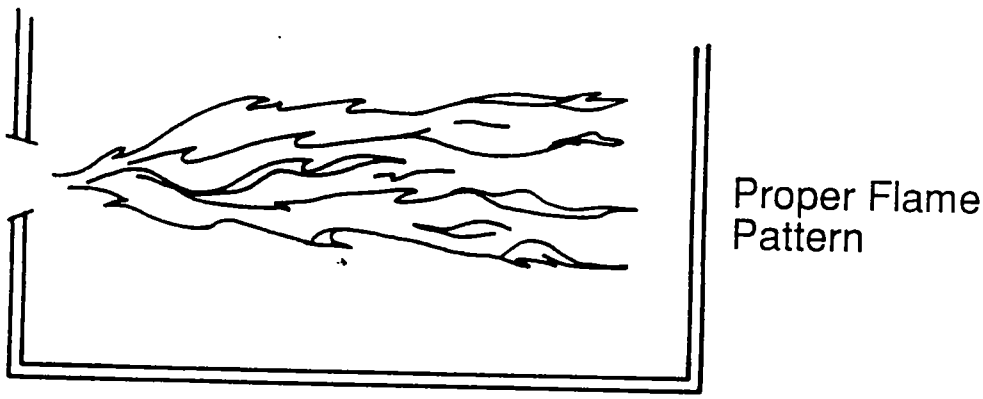
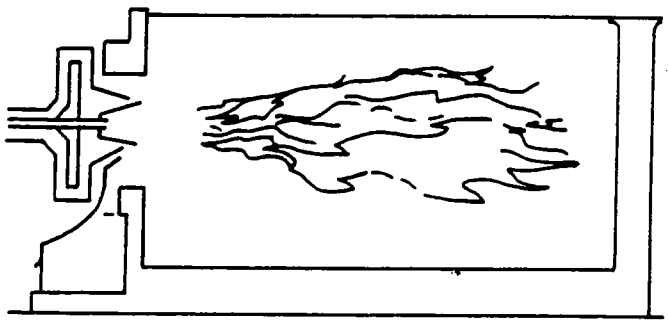
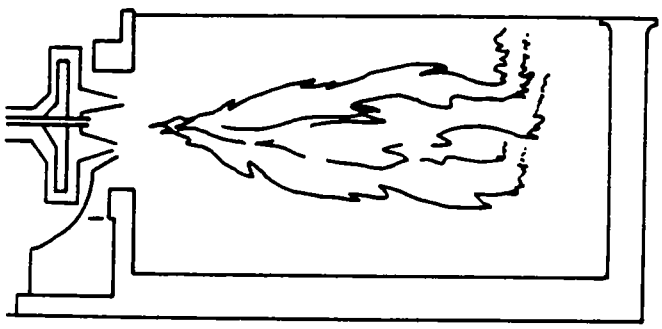


Figure 6-2a. Proper flame pattern.[22]



Detached Flame; Too Much Burner Air



Smoking Flame; Not Enough Air

Figure 6-2b. Improper burner air.[22]

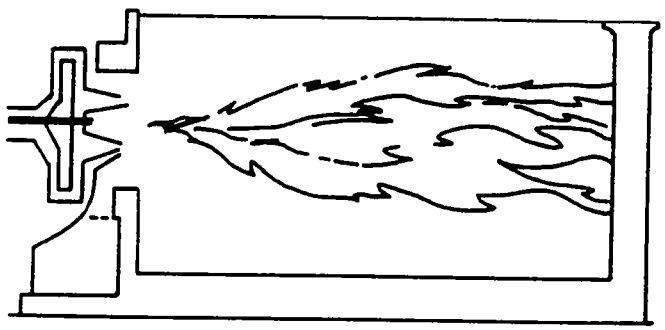


Figure 6-2c. Flame impingement.[22]

If monitored values such as temperature, ash quality, and stack opacity indicate operational problems, then adjustments to the automatic control system should be considered. These adjustments should only be made by someone who is properly trained and qualified. Ideally, you will be properly trained and qualified to make minor adjustments to the control system settings--such as damper settings and setpoints. The ability to understand and make such adjustments will allow you to control and operate the system for optimum performance.

PROPER ASH HANDLING PROCEDURES

Batch-feed and intermittent-duty incinerators require that the ash be removed from the incinerator at the end of each incineration cycle. (Sometimes, if the incineration cycle is short, it will not be necessary to clean out the ash after each cycle.) The following are guidelines for good operating procedures when ash is manually removed:

- The incinerator should be allowed to cool sufficiently so that it is safe for the operator to remove the ash. This cooling can take as long as 8 hours.
- You should exercise extreme caution since the refractory may still be hot and the ash may contain local hot spots, as well as sharp objects.
- The ash and combustion chamber should not be sprayed with water to cool the chamber because this can damage the refractory.
- A flat, blunt shovel or raking tool, not sharp objects that can damage the refractory, should be used for removing the ash.
- Avoid pushing ash into the underfire air ports.
- Avoid bumping or knocking burner nozzle assemblies or thermocouple housings.
- Place the ash into a noncombustible container such as metal, not cardboard.
- After the ash has been removed, dampen the ash with water to further cool the ash and minimize fugitive (windblown) emissions.
- Assure that the ash door is securely closed and the seal is good; visually inspect the condition of the sealing material and make sure nothing (such as a piece of ash) is caught in the door.
- Store the removed ash in a safe manner until disposal; cover the ash container to prevent windblown dust.
- Discard the ash according to approved procedures (according to your permit).

Continuous-duty incinerators have automatic ash removal systems. Generally, your job is to assure that the system is properly operating. This includes:

- Being on the lookout for jams in conveyor systems.
- Assuring that water flow is maintained to quench sprays and pits.
- Assuring that the water level in the quench pit is maintained so that the water seal with the incinerator is not broken.
- Assuring that full ash containers are removed and replaced with empty containers.

- Inspecting ash quality, noting problems, and determining whether operating changes are required.

STARTUP AND SHUTDOWN PROCEDURES

Startup and shutdown of an incinerator typically requires special steps to be taken. Specific manufacturer's instructions should be followed. Some general recommended procedures are listed below.

Single-batch feed incinerators.

Startup:

- Remove the ash from the previous cycle;
- Charge the incinerator; do not overcharge;
- Seal the charge door;
- Preheat the secondary combustion chamber to a predetermined temperature (1800°F [980°C] is recommended);
  The manufacturer should be consulted regarding proper preheat procedures; improper preheat can result in refractory damage.
  Note: If the incinerator is overloaded and the waste in the primary chamber enters the air passageway to the secondary chamber, the waste may self-ignite during the preheat period. This situation should be avoided; and
- Activate the primary chamber combustion air and burner to ignite the waste.

Shutdown:

- After the waste burns down and all volatiles have been released, the final burndown period is initiated.
  - -- Increase the primary combustion air level to improve combustion of the fixed carbon.
  - -- Maintain the temperature in the primary chamber at a minimum temperature using the auxiliary burner for a predetermined length of time to assure that the fixed carbon is combusted.
  - -- When the burndown period is complete, as indicated by maintaining the preset temperature in the primary chamber for a preset period of time, the cooldown period is initiated.
  - -- Shut down the primary and secondary burners.
  - -- Keep the combustion blowers operating to assist in cooldown.

Intermittent-Duty Incinerators. The general procedures for startup and shutdown of an intermittent-duty incinerator are as follows.

Startup:

- Ignite the primary and secondary burners and preheat the combustion chambers.

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- After the secondary temperature has reached a minimum predetermined temperature (1800°F [980°C] is recommended), activate the combustion air blowers. The manufacturer should be consulted regarding proper preheat procedures; improper preheat can result in refractory damage.
- Charge the incinerator.

Shutdown. After the last charge of the day, the incinerator is set to initiate a burndown/cooldown procedure. Depending upon the incinerator, this sequence will be manually or automatically activated and controlled. The burndown/cooldown procedure is essentially the same as the procedure discussed for the batch-type incinerator.

Continuous Duty Incinerators. The general startup and shutdown procedures for continuous-duty incinerators are:

Startup. The startup procedure is essentially the same as for intermittent-duty incinerators. The combustion chambers should be preheated before charging the first load of waste.

Shutdown. Shutdown of a continuous-duty incinerator involves stopping the charging process and maintaining temperatures in the combustion chamber until the remaining waste burns down to ash and is finally discharged from the system in a normal manner.

Special Considerations.

Pathological waste. If the waste being incinerated is pathological waste or contains a large amount of pathological waste, it will be necessary to leave the ignition burner on during the entire process. In fact, incinerators intended for burning primarily pathological waste will usually have additional burners in the primary chamber.

You should remember:

- To destroy pathological waste efficiently, the waste must be directly exposed to the burner flame.
- Loading pathological waste into the incinerator in large piles will result in inefficient combustion. A single layer of waste should be placed onto the hearth.
- If large volumes of pathological waste are to be incinerated, an incinerator specially designed for pathological waste should be used.

DO'S AND DON'TS FOR OPERATING A CONTROLLED-AIR INCINERATOR

DO:

- Preheat the secondary chamber before igniting the waste;
- Pay careful attention to charging procedures and charging rates;
- Look out for and pay attention to extreme differences in waste characteristics;

- Monitor combustion chamber temperatures and learn to recognize trends that are good and trends that indicate a problem;
- Routinely monitor stack gas opacity, especially after charging;
- Pay attention to the other monitors you may have at your facility, such as oxygen, CO, and opacity;
- Make good use of viewports to visually check the combustion chambers and learn to recognize problems;
- Pay attention to operation of your auxiliary burners; are they properly cycling on and off? At the right time?
- Inspect the ash quality. If visual inspection indicates poor burnout--large recognizable pieces of combustible waste such as hospital scrubs--check your equipment and/or make changes to operating procedures/conditions;
- Note problems that indicate the need for adjustment of automatic control system dampers and setpoints--if you are not trained to make adjustments, call maintenance;
- Handle and dispose of the bottom ash properly and carefully;
- Operate the primary burner(s) when burning pathological waste.

DON'T:

- Overcharge the incinerator; and
- Charge large amounts of pathological waste to the incinerator unless it is designed for pathological waste.

OPERATION OF MULTIPLE-CHAMBER INCINERATORS

INTRODUCTION

Multiple-chamber incinerators may have a grate or a fixed (solid) hearth in the primary chamber. Incinerators with grates are designed for use with general refuse, and combustion of medical infectious wastes containing significant quantities of fluids is not recommended in this type incinerator.

Multiple-chamber incinerators designed specifically for burning pathological wastes always have a solid hearth. Caution should be exercised when burning general refuse/red bag wastes in an incinerator designed specifically for pathological waste. Red bag wastes likely will contain much more volatile combustible material than pathological wastes and will have a higher heat value (Btu/lb). Overcharging the incinerator with red bag waste will result in excess emissions. The proper charging rate for the waste being burned should be carefully determined by trained personnel. Charging procedures consistent with the type of waste being charged should be established.

PROPER WASTE CHARGING PROCEDURES

Most multiple-chamber incinerators used for hospital wastes are designed for intermittent duty operation. Typically, the waste is charged by hand to the incinerator through the open charging door or by a mechanical charging system such a hopper/ram.

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Remember that the heat input rate to an incinerator is a very important parameter because the incinerator is designed for a specific heat input rate. The heat input from the waste is determined by the amount of waste and the heat content of that waste. Because the heat content of red bag waste and pathological waste is so different, operation of an incinerator when burning these two types of wastes is different. Proper charging procedures for both types of waste are discussed below.

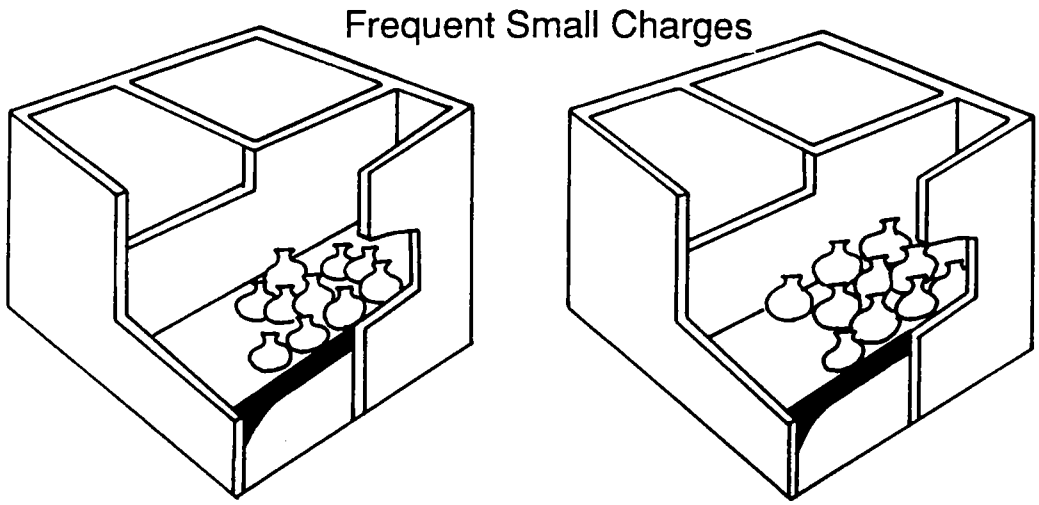
Red Bag Waste. The heat content of red bag waste is variable, depending upon the contents of the bag. Proper operation dictates that:

- Sufficient waste should be charged to the incinerator to sustain the desired temperature without excessive use of the primary burner; and
- To maintain the incinerator chamber below the upper temperature limit and to prevent emissions, the charge rate should not exceed the capacity of the incinerator at any time.

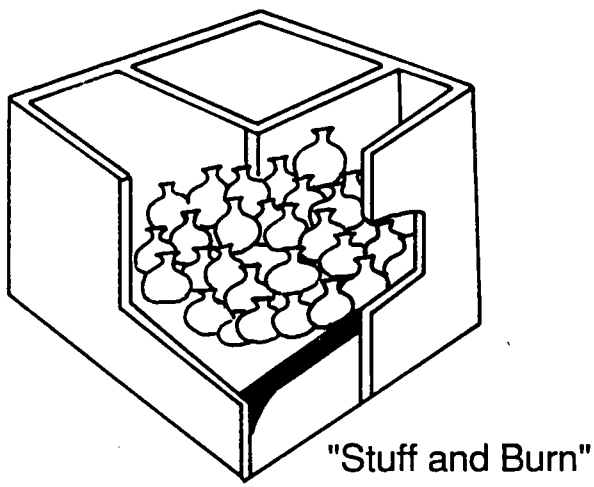
Therefore, recommended charging procedures include:

- Use of frequent, small batches rather than one large batch. The objective is to avoid causing a rapid release of volatile compounds that exceeds the combustion capacity of the incinerator. The frequency and size of each charge will be determined by the incinerator you have and the type of waste. A recommended procedure is to charge about 10 percent of the rated capacity (lb/h) every 15 minutes.
- Keeping a fairly consistent waste bed in the incinerator. The incinerator should not be jammed full, nor should it be empty.
- Avoiding "stuffing and burning" in the incinerator; that is, do not fill the incinerator chamber to full capacity, floor to ceiling, ignite the waste, and allow the incinerator to operate unattended. The proper charging of frequent, small batches versus the improper "stuff and burn" charging approach is illustrated in Figure 6-3.
- When recharging the incinerator:
  - -- Make sure the primary burner is turned off.
  - -- The waste bed should be stoked, if necessary, and partially burned waste from the previous charges should be pushed towards the back of the hearth. The new waste charge should be fed to the front end of the hearth (near the charge door). This procedure allows good exposure of the partially combusted waste to the overfire air and allows a good flame from the waste bed to be maintained. On the other hand, if cold, new waste is thrown on top of the existing waste bed, it partially smothers the burning bed which can result in increased emissions. These proper and improper recharging procedures are shown in Figure 6-4.

Pathological Waste. Pathological waste has a low heat content, high moisture content, and contains a low percentage of volatiles. The waste must be exposed to the auxiliary burners to be combusted. The following charging procedures are recommended.

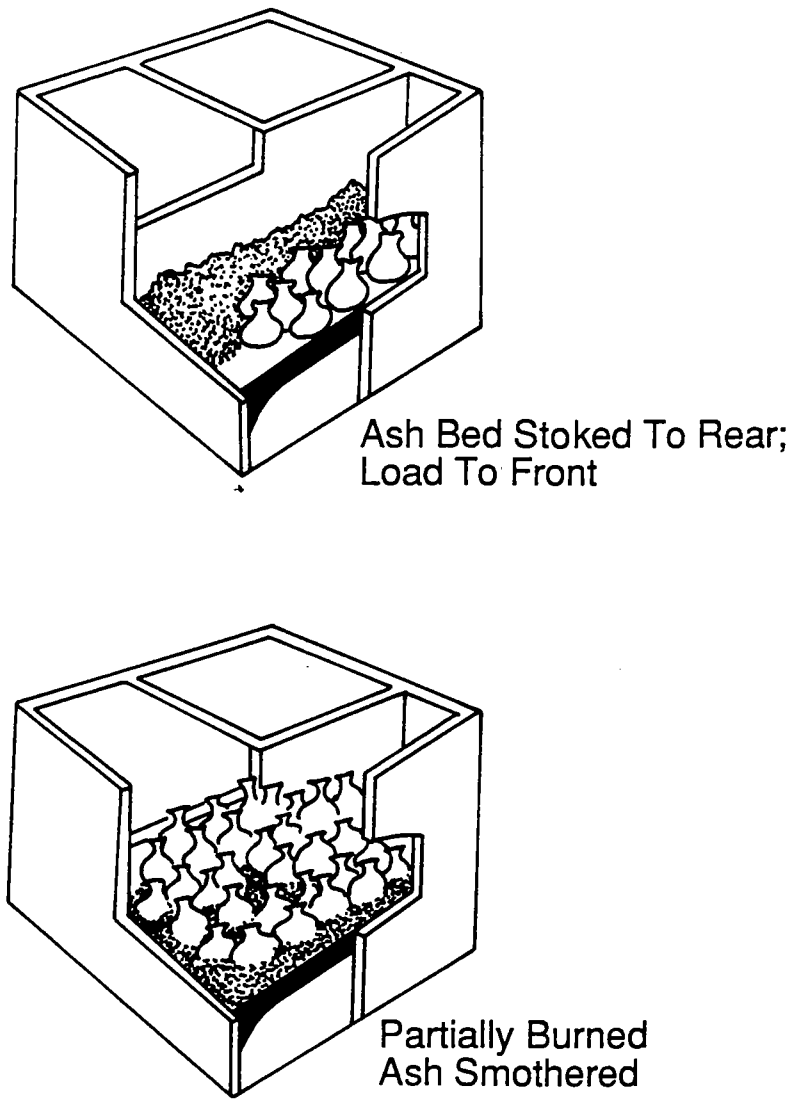


PROPER CHARGE PROCEDURES



IMPROPER CHARGE PROCEDURES

Figure 6-3. Proper and improper charge procedures.



RECHARGING PROCEDURES

Figure 6-4. Proper and improper charging: waste bed distribution.

- The waste should be placed on the hearth in an even layer that provides maximum exposure to the burner(s) flame(s). The waste should not be deeply piled.
- Recharging the incinerator should not be done until considerable reduction in volume (greater than 75 percent) of the previous charge has occurred.
- When recharging the incinerator:
  - -- Turn off the primary burner(s);
  - -- Place the fresh charge in a layer on top of the ash bed to provide maximum exposure to the burner flame(s); and
  - -- Close the charge door before restarting the primary burner(s).

CONTROLLING AND MONITORING KEY OPERATING PARAMETERS

The specific controls and monitors for each multiple-chamber incinerator will be different. Some incinerators have mostly manual controls with few monitors. Some incinerators have more automated controls and monitors to assist the operator.

In this section, we will review some basic steps you can take for controlling and monitoring the key operating parameters. Specific details of control and how much control you actually have over the operation of your incinerator depends on the specific incinerator.

The operating parameters discussed below include:

- Charging rate;
- Primary and secondary combustion chamber temperatures;
- Combustion air levels; and
- Combustion chamber draft.

Charging Rate. The single most important operating parameter that you can easily control is charging of the incinerator. The incinerator must be operated with a charge rate consistent with its design capacity.

Monitoring the charging rate. The charge rate can be easily monitored. It is not necessary to monitor the rate exactly--unless required by regulation.

The operator can monitor the charging rate in several ways:

- Recording the amount and the time of each charge;
- Noting the type and source of wastes;
- Monitoring combustion chamber temperature trends;
- Observing the depth of the waste bed in the primary chamber; and
- Observing ash burnout quality.

1. Charging log. Recording the time and amount of each charge is called keeping a "charging log."

Record the time when each charge is made and the quantity of each charge (1 bag, 5 bags, etc.). Monitoring charging in this way should

provide sufficient information to determine if charging procedures are consistent and to make adjustments. For example, if overcharging is suspected, it is only necessary to reduce the number of bags charged in each batch. If you want to know the amount of waste you are charging with each load, you can weigh your loads for a day to get an average weight. Record the time each charge is made and its weight. This approach requires a scale. Routinely recording the weight of all charges should not be necessary, unless regulations require it.

2. Observing trends in the primary and secondary combustion chamber temperatures. You should monitor primary and secondary combustion chamber temperature trends (that is, whether the temperatures are steady, rising, or falling). This information helps you evaluate whether the charging rate is correct. It is expected that the temperatures will rise and fall in a cycle after each charge. However, major swings in temperature may be an indication of a need to change charging procedures.

You should look for:

- Primary or secondary chamber temperature drop--if the primary chamber temperature is falling towards the lower temperature limit, this indicates that the incinerator is low on waste and it is time to recharge; the primary chamber burner should cycle on when the lower temperature limit is reached.
- Primary or secondary chamber temperature increase--if the primary chamber temperature is rising towards or exceeds the upper temperature limit, additional charges should be delayed.

3. Observing the waste bed. If view ports in the primary chamber are available, you can observe the waste bed. If the pile of unburned waste (in excess of the ash) inside the chamber is steadily increasing in size, then the amount charged is greater than the amount which can be consumed in the same period of time. The charge rate should be reduced. On the other hand, if all the waste is consumed well in advance of the next charge, it may be desirable to increase the charge rate. If view ports are not available, the bed depth can be observed when the charging door is opened. If most of the previous charge is still unburned, do not recharge.

4. Observing ash quality. If all the combustible waste is not burned and recognizable pieces of waste are found in the ash, it may be because the charge rate is too high and not enough time has been provided for complete combustion. You can evaluate ash quality by simply looking at the ash and determining whether complete or near complete combustion has occurred. If recognizable pieces of combustible waste--such as magazines, plastic tubing, pieces of scrub gowns--are seen in the ash, the ash quality is poor. You should expect to see recognizable noncombustible objects such as bottles and cans.

Another way to visually evaluate ash quality is by the color of the ash. If the ash is black, it probably contains a lot of unburned carbon. Ash that is light gray or white, indicates better burnout.

5. Observing the stack emissions. When black smoke is emitted from the stack after charging, the amount charged probably was too much. The incinerator does not have the capacity to combust all the volatiles released. This situation may be correctable by increasing the secondary combustion air. If increasing the secondary combustion air does not alleviate the problem, the size of the charge should be decreased.

Control of the charging rate. The charging rate is probably the easiest parameter for you to control. The rate can be controlled by changing either the amount of waste charged with each load or by changing the charging frequency.

Primary and Secondary Chamber Temperature.

Monitoring temperatures. You use temperature gauges to monitor the primary and secondary chamber temperatures. All incinerators should have a temperature gauge and preferably a temperature recorder. A temperature recorder allows you to monitor trends in temperature.

Control of temperatures. You can control temperature by controlling three parameters:

- Charging rate;
- Combustion air level; and
- Auxiliary burner operation.

The importance of charging rate has already been discussed. For a multiple-chamber incinerator, you essentially control temperature by controlling the charging rate. Increasing the waste feed rate increases temperature; decreasing the waste feed rate decreases temperature. You must balance the charging rate and air supply to sustain the desired temperature without causing emissions. If sufficient temperature cannot be maintained in the primary and secondary chambers, either the charging rate is too low, insufficient heat is being added by the auxiliary burner, or the excess air levels are too high. Remember, as additional excess air is added, it cools the combustion gases; this is one of the reasons that incinerator draft should be closely monitored.

The combustion air levels are adjusted by opening or closing the dampers controlling the overfire air. Generally, opening the dampers allows more air to enter the incinerator. Actual control of the air depends on the type of combustion air system used, natural draft or forced draft. The primary auxiliary burner can be used to increase temperatures, if necessary.

For pathological incinerators, the primary and secondary burners must be used to control incinerator temperature since little or no heat input is derived from the waste. The combustion chamber temperatures are increased or decreased by increasing or decreasing the auxiliary firing rate in the primary chamber. If excess fuel usage is noted or proper temperatures cannot be sustained, the combustion air settings should be checked. Too much excess air will result in greater fuel usage. Since

waste properties (heat content and moisture) will not normally change for pathological wastes, the incinerator should operate steadily once it is properly adjusted. Once the air settings are properly adjusted, they should not have to be frequently changed.

Primary and Secondary Combustion Air Levels and Combustion Gas Oxygen Level.

Monitoring of combustion air. Three ways that you can monitor combustion air levels include:

- Using an oxygen monitoring system;
- Observing damper settings; and
- Observing stack gas opacity.

Oxygen monitors. An oxygen monitor provides the most accurate means for determining the excess air level. Some incinerators have an oxygen monitor installed in the stack to monitor the overall multiple-chamber level. When such a monitor is installed, the operator should assure that the oxygen remains in the desired range (11 to 16 percent).

Damper settings. Some older multiple-chamber incinerators use natural draft openings for the combustion air. The operator can monitor the combustion air rate by the relative damper setting; a damper that is fully open allows more combustion air to enter the incinerator than a damper that is half open. Although a damper setting does not indicate the actual combustion air rate or the excess air level, it does provide a relative indicator. Other multiple-chamber incinerators use a forced air blower to supply overfire combustion air. The damper setting on the blower provides a relative indicator of the combustion air being supplied; more air will be supplied when the damper is open relative to when the damper is closed.

Visual observation of stack gas opacity. The stack gas should be clean. Black smoke indicates incomplete combustion caused by insufficient air.

Control of combustion air. The combustion air levels are controlled by adjusting the combustion air dampers. The operator controls the amount of air entering the incinerator by opening or closing the dampers. Note that if the operator does not have a direct way to measure the combustion air levels, such as an oxygen monitor, it is difficult to determine the most desirable damper setting. Consequently, if your dampers have been preset by a technician using monitoring equipment to determine the excess air levels, it may not be appropriate for you to adjust the damper setting. You should not adjust damper settings unless you have been properly trained to do so.

Incinerator Draft. It is important to keep a negative pressure (draft) in the incinerator to maintain combustion airflow through the incinerator and to prevent fugitive emissions. However, excessive draft can result in entrainment of particulate matter which will exit the incinerator combustion stack.

Monitoring draft. A draft gauge is required to measure the negative pressure in the incinerator chamber.

Controlling draft. The draft within the chamber is controlled by adjusting control dampers on the incinerator. For incinerators operating under natural draft conditions, a damper in the stack gas flue may be used to control draft; or a mechanized barometric damper often is used to control the incinerator draft automatically to a preset level. If the incinerator has an induced draft fan, dampers at the inlet or outlet of the fan typically are used to control draft. These dampers may be manually controlled, or may be mechanized to automatically adjust and control incinerator draft to a preset level.

Other Parameters to Monitor. Other parameters you should monitor include:

- Stack gas opacity;
- Stack gas carbon monoxide; and
- Burner flame pattern.

These items were discussed in the previous section on controlled-air incineration, and the discussion is not repeated here.

SUMMARY OF CONTROL AND MONITORING TECHNIQUES FOR MULTIPLE-CHAMBER INCINERATORS

The primary control parameter for a multiple-chamber incinerator is the charging rate. Since both the primary and secondary chambers operate with excess air, the combustion rate in the primary chamber cannot be strictly controlled. Consequently, proper charging of the incinerator is essential. The operator uses combustion chamber temperatures to monitor incinerator operation. The charging rate (heat input) must be consistent with incinerator capacity. The primary chamber auxiliary burner typically will be set to cycle on when insufficient heat input is provided by the waste. Adjustments to the air dampers also may be required to maintain the proper draft and combustion air levels; damper control is often automatically controlled by a mechanized system.

For pathological waste incinerators, the primary control variable is the heat input rate from the primary chamber burner(s). Since the heat content of the waste is insufficient to sustain combustion, the auxiliary burners operate continuously, and the combustion air levels required remain essentially constant.

PROPER ASH HANDLING PROCEDURES

Ash is manually removed by the operator at the end of each incineration cycle. Proper ash handling procedures for multiple-chamber incinerators are essentially the same as for batch and intermittent-duty, controlled-air incinerators. The following are guidelines for good operating procedures for manually removing ash from the incinerator:

- Allow the incinerator to cool sufficiently so that it is safe for the operator to remove the ash. This cooling can take as long as 8 hours or more.
- Do not spray the ash and combustion chamber with water to cool the chamber because this can damage the refractory.
- Use a flat blunt shovel or raking tool, not sharp objects that can damage the refractory, for removing the ash. You should exercise extreme caution since the refractory may still be hot and the ash may contain local hot spots, as well as sharp objects.
- Avoid bumping or knocking of burner nozzle assemblies or thermocouple housings.
- Place the ash into a noncombustible container such as a metal container, not cardboard.
- Dampen the ash with water to cool the ash and minimize fugitive (windblown) emissions.
- Store the ash in a safe manner until final disposal. Cover the ash container to prevent windblown dust.
- Discard the ash according to approved procedures (according to your permit).

STARTUP AND SHUTDOWN PROCEDURES

Startup and shutdown of the incinerator requires some special steps to be taken to minimize emissions. Specific manufacturer's instructions should be consulted. The following are recommended procedures for good operating practice.

Startup

- Inspect the ash from the previous cycle. Is ash quality acceptable? If not, adjustments to operating procedures will be required. Remove the ash from the previous incineration cycle.
- Preheat the secondary combustion chamber to the minimum recommended temperature (e.g., 1800°F [980°C]).
- Charge the incinerator with the first charge.
- Close the door.
- Ignite the waste using the primary burner.

Shutdown

- After the waste in the last charge has burned down, the primary chamber temperature will be maintained by the auxiliary burner at the preset minimum combustion chamber temperature. This period is called the burndown period.
- The burndown period is continued for a predetermined length of time or until visual inspection indicates that burnout of the waste bed is sufficient. When the burndown period is completed, the primary and secondary burners are shut down.

For pathological incinerators, shutdown of the incinerator is determined by inspecting the ash bed. If all the material has been combusted, shut down the primary and secondary burners. If waste still

remains on the hearth, continue to incinerate until acceptable burndown has occurred.

DO'S AND DON'TS FOR OPERATING A MULTIPLE-CHAMBER INCINERATOR

DO:

- Preheat the secondary chamber prior to startup
- Pay careful attention to charging procedures and rates
- Shut off the primary burner when charging
- Monitor combustion chamber temperatures and learn to recognize trends that indicate proper operation and trends that indicate problems
- Monitor combustion chamber draft and maintain draft within the proper operating range
- Routinely monitor stack gas opacity, especially after charging
- Pay attention to operation of your auxiliary burners; are they properly cycling on and off? At the right times?
- Properly and carefully dispose of the ash
- Inspect the ash. Does visual inspection indicate poor burnout--are pieces of uncombusted waste present? If ash quality is poor, make changes to operating procedures/conditions
- For pathological wastes, operate the primary burner at all times

DON'T:

- Overcharge the incinerator
- Deeply pile pathological waste on the hearth

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REVIEW EXERCISE

1. The real concern about infectious (red bag) waste is that:

   a. It stinks
   b. It may contain organisms that can cause disease
   c. It is messy

2. Proper waste handling includes:

   a. Handling the waste as little as possible
   b. Using strong containers
   c. Not overstuffing the charging hopper
   d. Properly storing the waste
   e. All of the above

3. It is not the operator's problem if bags spill and break. True or False?

4. Multiple-chamber incinerators may use either ____ ____ openings or ____ draft blowers to provide combustion air.

5. A major way that the operator can control the incinerator is to control the _____ _____.

6. The most important parameters that the operator should rely upon to monitor operation are the primary and secondary chamber temperatures. True or False?

7. When burning pathological waste it is not necessary to preheat the secondary combustion chamber. True or False?

1. b. It may contain organisms that cause disease

2. e. All of the above

3. False. The operator should be concerned about broken bags and report problems to the appropriate hospital personnel.

4. natural draft, forced

5. charging rate

6. True. The temperatures indicate operating trends.

REVIEW EXERCISE

8. A monitor(s) that would be helpful to an operator for controlling a multiple-chamber incinerator is:

   a. A combustion gas oxygen monitor
   b. An opacity monitor
   c. All of the above
   d. a and b

9. Key operating parameters for controlled-air incinerators include: _____, _____, and _____

10. Three key operating parameters for multiple-chamber incinerators are _____, _____, and _____.

11. The temperature within the secondary combustion chamber should be:

    a. Maintained below 2200°F
    b. Maintained above 1800°F
    c. Disregarded
    d. None of the above
    e. a and b

7. False. The secondary chamber should always be preheated.

8. a. An oxygen monitor allows the operator to monitor excess air levels.

9. Any of the following:

   Primary chamber temperature, secondary chamber temperature, charging rate, combustion air level, combustion gas oxygen concentration, or combustion chamber draft.

10. Any three of the following:

    Primary chamber temperature, secondary chamber temperature, charge rate, total combustion air level, combustion gas oxygen concentration, chamber draft.

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REVIEW EXERCISE

12. The operator should pay attention to _____ in the combustion chamber temperatures.	11. e. a and b
13. It is always better to charge the incinerator with very large charges and as few times as possible in a day. True or False?	12. trends or changes
14. During startup of the incinerator, the operator should _____ the secondary combustion chamber.	13. False
15. Because pathological waste has a _____ heat content and high _____ - content, it requires special charging and operating procedures.	14. preheat
19. The operator should routinely look at the stack outlet to monitor the stack gas _____.	18. low, moisture
	19. opacity

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SESSION 7.
AIR POLLUTION CONTROL SYSTEMS OPERATION

SESSION 7. AIR POLLUTION CONTROL SYSTEMS OPERATION

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SESSION 7.
AIR POLLUTION CONTROL SYSTEMS OPERATION

SESSION GOAL AND OBJECTIVES

GOAL

To familiarize you with:

- The key operating parameters and how to monitor those parameters for the various types of air pollution control systems (APCS) on hospital incinerators; and
- Special operating considerations for APCS startup and shutdown.

OBJECTIVES

Upon completing this session, you should be able to:

1. Identify the key operational parameters for your APCS;
2. Describe the operational ranges considered acceptable for these parameters;
3. Describe how to monitor the key parameters; and
4. Name the steps to take to ensure proper operation of your APCS during startup and shutdown.

INTRODUCTION

During this session we will discuss the key operational parameters, monitoring of those parameters, and startup and shutdown of the following APCS:

- Wet scrubbers
  - -- venturi scrubber
  - -- packed-bed scrubber
  - -- spray towers
- Fabric filters
- Dry scrubbers
  - -- spray dryer
  - -- dry injection scrubber
- Electrostatic precipitators

WET SCRUBBERS - GENERAL

SCRUBBER OPERATION

Many of the key operating parameters, monitoring methods, and operation techniques are the same for both venturi and packed-bed scrubbers. Because of their greater complexity, venturi scrubbers will be addressed first in the following discussion. The discussion of packed-bed

scrubbers will focus only on those items that differ from venturi scrubbers. Spray towers are relatively simple to operate, requiring only that a proper liquid flow rate be maintained. Spray towers will not be discussed separately.

VENTURI SCRUBBERS

KEY OPERATING PARAMETERS

The key operating parameters that are necessary for effective operation of a venturi scrubber are liquid supply, energy as measured by pressure drop (ΔP), and suspended solids in the scrubbing water.

RECOMMENDED OPERATING RANGES FOR KEY PARAMETERS

Proper operation of a venturi scrubber requires that scrubber ΔP, water supply, and solids content be maintained within acceptable ranges as specified by the manufacturer or by the air agency permit specifications. Recommended ranges of the parameters are:

- Pressure drop--20 to 30 in. w.c. (5.0 to 7.5 kPa)
- Liquid supply--7 to 10 gallons per thousand actual cubic feet (gal/1,000 acf) (0.9 to 1.3 liters per actual cubic meter [ℓ/m^3])
- Solids content--0 to 3 percent

MONITORING OF KEY PARAMETERS

To ensure proper operation of a venturi scrubber, the operator must monitor the key operating parameters and determine the pressure drop and liquid supply.

- Scrubber parameters which can be monitored by the operator include:
  - -- venturi pressure drop;
  - -- liquid flow rate; and
  - -- fan static pressure, rpm, or amperage.
- Pressure drop can usually be monitored directly from installed gauges or manometers.
- The liquid supply can be obtained by comparing the liquid flow rate, which is usually indicated by installed gauges, with the gas flow rate. The gas flow rate can be obtained from fan specifications, which relate gas flow rate to either fan static pressure, rpm, or amperage. At least one of these fan parameters is usually readily available from manufacturer installed gauges.
- Suspended solids content is not easily measured. Acceptable levels are usually obtained by maintaining adequate scrubbing liquid recirculation rates.

VENTURI SCRUBBER OPERATION

Proper operation of the scrubber also requires that the operator be able to correct problems when the key operating parameters fall outside acceptable ranges.

- Pressure drop across the venturi throat can be increased by adjusting the fan damper, increasing fan energy, or by adjusting the throat constriction on a variable-throat venturi scrubber.
- Liquid supply can be increased by increasing the liquid flow rate.
- If suspended solids cause solids buildup problems, the makeup water and blowdown rates should be increased.

VENTURI SCRUBBER STARTUP

Startup of a venturi scrubber requires adherence to the following in-sequence steps:

- Turn on the liquid recirculation system and liquid flow to the venturi throat and the mist eliminator;
- Adjust the liquid flow rates to those specified by the manufacturer;
- If the fan is equipped with a damper, close the damper;
- Start the fan;
- Gradually open the damper until the proper gas flow rate is established;
- Recheck the liquid flow rate, compare with the gas flow rate, and adjust as necessary to obtain the proper liquid supply;
- Check the scrubber pressure drop and adjust the fan energy or fan damper as necessary to obtain the desired pressure drop; and
- Initiate the liquid blowdown to treatment or disposal, as specified by the manufacturer.

VENTURI SCRUBBER SHUTDOWN

To shut a venturi scrubber system down, the following procedures should be adhered to in sequence:

- Shut off the scrubber fan;
- Wait until the fan impeller has stopped turning and shut off the scrubber water recirculation pump; and
- Shut off the makeup water supply system.

PACKED-BED SCRUBBER

KEY OPERATING PARAMETERS

The key operating parameters for a packed-bed scrubber are liquid supply, pH, suspended solids content, and inlet gas temperature.

RECOMMENDED OPERATING RANGES FOR KEY PARAMETERS

Because packed-bed scrubbers are usually used on hospital incinerators primarily for acid gas control, pH maintenance is important. High suspended solids levels can cause the same pluggage problems as for venturi scrubbers. Packed-bed units do not have high pressure drop requirements to enhance scrubbing; instead, they rely on high liquid supply rates and increased surface area for absorption. High inlet gas temperature can damage plastic packing media.

- The recommended range for liquid supply is 10 to 15 gal/1,000 acf (1.3 to 2.0 ℓ/m^3).
- The recommended range of pH is 5.5 to 7.0.
- The recommended range for suspended solids is 1 to 3 percent.
- Acceptable inlet gas temperatures are dependent on the packing media and scrubber material of construction and should be specified by the manufacturer.

MONITORING OF KEY PARAMETERS

Monitoring of liquid supply and suspended solids for packed-bed scrubbers are the same as discussed above for venturi scrubbers.

- Liquid feed pH usually can be monitored directly from a manufacturer-installed pH meter.
- A thermocouple usually is provided to monitor the gas inlet temperature.

PACKED-BED SCRUBBER OPERATION

Operation of packed-bed scrubbers with respect to liquid supply and suspended solids is the same as that for venturi scrubbers.

- The liquid feed pH can be increased by increasing the alkaline sorbent material feed rate to the scrubber water.
- Gas inlet temperatures can be controlled by controlling the flue gas exhaust temperatures from the incinerator or by adjusting an ambient air damper upstream of the scrubber.

PACKED-BED SCRUBBER STARTUP AND SHUTDOWN

Startup and shutdown procedures for packed-bed scrubbers are the same as those indicated above for venturi scrubbers.

FABRIC FILTERS

KEY OPERATING PARAMETERS

The key operating parameters for pulse-jet fabric filters are the maximum and minimum flue gas temperatures, the pressure drop through the unit, and the cleaning air pressure.

RECOMMENDED OPERATING RANGES FOR KEY PARAMETERS

Proper operation of a pulse-jet fabric filter requires that flue gas temperatures do not get high enough to damage the bags or low enough to allow condensation of moisture or acid gases to blind or corrode the bags. The bags should be cleaned on a frequency that will prevent excessive pressure drops that could result in ruptured bags and excessive fan energy costs. The cleaning air pressure should be high enough to ensure a shock wave in the bag sufficient to dislodge the filter cake.

- The maximum flue gas temperature is dependent on the bag material and should be specified by the manufacturer.
- The minimum gas temperature is dependent on the moisture content and acid gas content of the gas stream and should be maintained above the dewpoints of both. In practice, the fabric filter vendor or hospital engineer should specify a minimum flue gas temperature.
- The recommended pressure drop range for a pulse-jet fabric filter is 5 to 9 in. w.c. (1.2 to 2.2 kPa).
- The recommended range for the cleaning air pressure is 60 to 100 psig (410 to 690 kPa).

MONITORING OF KEY PARAMETERS

To ensure proper operation of a fabric filter, the operator should ensure that all bags are intact, without holes or tears, and that the bags are cleaned on an appropriate frequency with adequate cleaning air pressure. The integrity of the bags should be checked by a visual inspection when the system is off-line for routine maintenance.

- Parameters that can be monitored to maintain optimum fabric filter performance are:
  - -- opacity;
  - -- pressure drop; and
  - -- temperature.
- Opacity readings are taken at the stack by a trained observer or from an opacity monitor. Visible emissions of greater than 5 percent opacity may indicate holes in the bags or too frequent cleaning. If high opacities are observed, the bags should be inspected visually by maintenance personnel.
- A manometer or pressure gauge is usually provided by the manufacturer for measuring pressure drop. Excessively high pressure drop can indicate:
  - -- inadequate cleaning;
  - -- bag blinding; or
  - -- excessive gas volume.
- Fabric filters on hospital incinerators should be equipped with continuous stripchart temperature recorders and high temperature alarms. The stripchart recorder will indicate whether potential bag damage may have occurred due to high temperature. The alarm should be set lower than the critical bag damage temperature to

allow for preventive actions. The alarm temperature setting depends on the type of bag fabric used. These same devices can be used to monitor against excessively low temperature.

FABRIC FILTER OPERATION

Under normal conditions, the operator only has to monitor the key parameters and ensure that the airflow rate through the fabric filter is sufficient to maintain negative draft in the combustion chamber of the incinerator.

- If the flue gas temperature approaches the damage point, emergency procedures should be taken to reduce the temperature by:
  - -- bypassing the fabric filter;
  - -- dropping the incinerator temperature by increasing combustion airflow in the secondary chamber or reducing auxiliary fuel rates; or
  - -- introducing cooling ambient air.
- If the dewpoint temperature is approached, the incinerator secondary chamber burner firing rates should be increased to raise the inlet temperature.
- If the pressure drop is too high, the bag cleaning frequency should be increased.
- If the cleaning air pressure is too low, adjust the pressure gauge on the compressed air system.

FABRIC FILTER STARTUP

Precautions should be taken during initial startup of a new fabric filter or after bag replacement to prevent abrasion damage to the new bags before a protective coating of dust has formed. Condensation of moisture and acid gases should be prevented at all startups to prevent acid attack and bag "blinding."

- New bag abrasion can be prevented by:
  - -- operation of the incinerator at reduced throughput of waste charge material to allow the gradual buildup of the dust cake; and
  - -- precoating the bags
- Condensation of acid gases and moisture in a cold fabric filter can be prevented by operating the incinerator on auxiliary fuel prior to charging with waste until the fabric filter is heated.

FABRIC FILTER SHUTDOWN

The top priority during shutdown of a fabric filter is to avoid dewpoint conditions with resulting condensation.

- The incinerator secondary chamber burner should be left on for a few minutes after waste combustion is completed to remove moisture from the fabric filter.

- After the secondary chamber burner is shut down, ambient air should be drawn through the system to purge remaining combustion products.
- After combustion products are purged, the fabric filter should be allowed to go through 5 to 20 minutes of bag cleaning to remove the filter cake that could cause blinding if condensation occurs later in the unit after shutdown.

DRY SCRUBBERS - GENERAL

DRY SCRUBBER OPERATION

The basic operating principle for both spray dryers and dry injection is to mix an adequate supply of alkaline sorbent with the flue gas and allow sufficient contact time for the reaction to occur. On most units, outlet gas stream acid gas monitors will provide a direct indication of system performance.

SPRAY DRYERS

KEY OPERATING PARAMETERS

The key operating parameters that are necessary for effective operation of a spray dryer are sorbent feed, the slurry sorbent content, and the outlet gas wet and dry bulb temperatures. The wet bulb/dry bulb temperature readings give an indication of the saturation of the gas stream and the potential for evaporation of moisture.

RECOMMENDED OPERATING RANGES FOR KEY PARAMETERS

Effective operation of a spray dryer requires adequate sorbent for reacting with the acid gases and prevention of solids buildup. Solids buildup can occur if slurry moisture is not evaporated within the design time period. The liquid slurry feed rate and sorbent content should be balanced with the hot flue gas volume and acid gas content to ensure the desired removal of acid gases and evaporation of all moisture.

- The recommended range of slurry sorbent content is 5 to 20 percent solids by weight.
- A wet bulb/dry bulb outlet gas temperature difference of 90° to 180°F (30° to 80°C) will ensure evaporation of all moisture.

MONITORING OF KEY PARAMETERS

The sorbent content of the slurry does not require continuous monitoring. The sorbent content is set at the slurry mix tank. The outlet wet bulb and dry bulb temperatures are indicated by manufacturer-installed gauges.

SPRAY DRYER OPERATION

The feed rate of dry sorbent to the makeup water in the sorbent mix tank is adjusted to obtain the desired sorbent content of the slurry. The flow rate of slurry to the atomizer in the reaction vessel is adjusted to change the wet bulb/dry bulb temperature difference.

- The slurry flow rate is usually monitored by a magnetic flow meter.
- An increase in slurry flow will reduce the wet bulb/dry bulb temperature difference.

SPRAY DRYER STARTUP

Startup of a spray dryer should follow procedures that prevent condensation in the system and ensure evaporation of all slurry moisture in the scrubber reactor vessel.

- One method of ensuring evaporation is to use auxiliary fuel firing to bring the exhaust gas temperature up to the normal operating range before injecting the slurry.
- Another method would be to gradually increase slurry feed at startup to maintain a 90° to 180°F (30° to 80°C) wet bulb/dry bulb temperature differential.

SPRAY DRYER SHUTDOWN

Proper shutdown should ensure that no liquid moisture remains or condenses in the spray dryer or fabric filter after shutdown.

- Auxiliary fuel firing should be used to maintain temperatures above saturation until all sorbent is purged from the system.
- To prevent bag blinding and reaction product salt corrosion, the fabric filter should go through a complete cleaning cycle before shutdown.

DRY INJECTION

KEY OPERATION PARAMETERS

The key operating parameters for a dry injection system are the sorbent injection rate and the particle size of the sorbent.

- The sorbent injection rate should provide adequate sorbent for neutralization of the acid gases and is dependent on the acid gas content of the flue gas.
- As particle size decreases, the surface area to volume ratio increases which improves the efficiency of acid gas collection.

RECOMMENDED OPERATING RANGES FOR KEY PARAMETERS

The particle size and injection rate of the sorbent should be specified by the manufacturer.

- Generally the sorbent feed will have a particle size where 90 percent by weight will pass through a 325 mesh screen. This dust is approximately the consistency of talcum powder.

MONITORING OF KEY PARAMETERS

Continuous monitors for outlet acid gas concentrations are usually provided with dry scrubbing systems.

- The sorbent feed rate can be determined directly from manufacturer installed gauges.
- Proper particle sizes for the sorbent are specified at purchase and are maintained by transporting and fluidizing the sorbent through a positive pressure pneumatic conveyor. The air flow rate in the pneumatic line is set at a constant level and is not varied with the load.

DRY INJECTION OPERATION

Operation of a dry injection system is relatively simple.

- Maintain the pneumatic transfer line at a constant airflow rate.
- Monitor outlet acid gas concentration and increase sorbent injection rate to achieve desired acid gas levels.

DRY INJECTION STARTUP

There are no special startup considerations for dry injection. At startup of the incinerator, the dry sorbent can be injected without any special preparations.

DRY INJECTION SHUTDOWN

The only special concern for shutdown of a dry injection system is to put the fabric filter through a cleaning cycle after sorbent injection is stopped. This prevents possible blinding from condensation and reaction product salt damage to the fabric filter components.

ELECTROSTATIC PRECIPITATORS

KEY OPERATING PARAMETERS

The key operating parameters that are necessary for effective operation of an ESP are gas temperature, particulate resistivity, and power input.

RECOMMENDED OPERATING RANGES FOR KEY PARAMETERS

Proper operation of an ESP requires that the gas temperature, particulate resistivity, and power input be maintained within acceptable ranges as specified by the manufacturer or by the air agency permit specifications. Recommended ranges for these parameters are:

- Gas temperature range:
  - -- Hot-side ESP, 572° to 800°F (300° to 430°C)
  - -- Cold-side ESP, less than 400°F (200°C)
- Particulate resistivity range is 10^7 to 10^{10} ohm-cm
- Power ratio of secondary power to the primary power input should range from 0.5 to 0.9
  - -- secondary power = secondary voltage x secondary amperage
  - -- primary power = primary voltage x primary amperage

MONITORING OF KEY PARAMETERS

To ensure proper operation of an ESP, the operator must monitor the key parameters and make adjustments as necessary to maintain the parameters in the appropriate range.

- ESP parameters that can be monitored by the operator include:
  - -- gas inlet temperature
  - -- particulate resistivity
  - -- primary voltage
  - -- primary current
  - -- secondary voltage
  - -- secondary current
- The gas inlet temperature can be measured using a thermocouple mounted at the inlet to the ESP. A temperature readout such as a stripchart recorder or LED display should be available. Temperatures should be maintained above the dewpoints of both hydrochloric acid and moisture. Temperatures that are too low allow moisture and acid to condense causing sticky particulate that is difficult to collect and causing corrosion. Temperatures that are too high may cause damage to the ESP and in hot-side ESP's may cause the gas density to be so low that effective collection is difficult.
- Particulate resistivity is a measure of the resistance of the collected dust layer to the flow of electrical current. A high resistivity indicates that little electricity will flow. The condition of high resistivity is indicated by increased sparkover or by excessive current at greatly lowered voltages. Low resistivity (i.e., high electricity flow) means that particles lose their charge too quickly. Particles take longer to move to the collection plate, the particles are not held strongly to the collection plate, and particle reentrainment is a problem. Resistivity is measured using high voltage conductivity cells - the accepted method is the point-plane method.
- The transformer-rectifier (TR) power equipment of most modern ESP's are equipped with primary voltage and current meters on the

low-voltage (ac) side of the transformer and secondary voltage and current meters on the high-voltage rectified (dc) side of the transformer. Therefore, the input side is the primary side of the transformer. The primary meters measure voltage and current in volts and amps, respectively. The secondary meters measure voltage in kilovolts (volts multiplied by 1,000) and current in milliamps (amps divided by 1,000). To get the power ratio: (1) multiply the primary voltage reading by the primary current reading to get primary power, (2) multiply the secondary voltage reading by the secondary current reading to get the secondary power, and (3) divide the secondary power by the primary power level to get the power ratio.

ESP OPERATION

Under normal conditions, the operator need only monitor the key operating parameters and ensure that the airflow rate through the ESP is sufficient to maintain negative draft in the combustion chamber of the incinerator.

- If the dewpoint temperature is approached, the incinerator secondary chamber burner firing rates should be increased to raise the inlet temperature.
- If the flue gas temperature is too high, the temperature should be reduced by:
  - -- dropping the incinerator temperature
  - -- introducing cooling ambient air.
- If the resistivity is too high (i.e., increased sparking and/or excessive currents at greatly lowered voltages), it can be reduced by:
  - -- introducing cooling ambient air to reduce the gas temperature
  - -- adding moisture to the gas stream to both cool the gas and to enhance the conductivity of the particulate in the gas stream.
- If the resistivity is too low (i.e., increased particle reentrainment, poor collection efficiency), it can be increased by:
  - -- increasing the temperature of the gas by increasing the incinerator secondary chamber burner firing rates
  - -- checking operation of rappers
  - -- investigating incinerator feed characteristics for high-sulfur content or for excessive conditioning agents such as alkalis
  - -- improving incinerator combustion efficiency to reduce amount of carbon in collected dust.
- If the primary voltage is too low, it can be corrected by:
  - -- removing excessive ash from electrodes
  - -- checking power supply
  - -- checking for improper rectifier and control operation
  - -- checking for misaligned electrodes
  - -- checking for high resistivity.

ESP STARTUP

Startup of an ESP is generally a routine operation involving heating a number of components such as support insulators and hoppers prior to incinerator operation. The following steps should be taken to startup the incinerator.

Prior to operation of the incinerator:

- Check hoppers
  - -- level-indicating system should be operational
  - -- ash-handling system operating and sequence check - leave in operational mode
  - -- hopper heaters should be on
- Check rappers
  - -- energize control, run rapid sequence, ensure that all rappers are operational
  - -- set cycle time and intensity adjustments, using installed instrumentation - leave rappers operating
- Check TR sets
  - -- test-energize all TR sets and check local control alarm functions
  - -- set power levels and deenergize all TR controls
  - -- lamp and function-test all local and remote alarms

After the incinerator has gone through its preheat mode:

- Energize TR sets, starting with inlet field, setting Powertrac voltage to a point just below sparking.
- Successively energize successive field as load picks up to maintain opacity, keeping voltage below normal sparking (less than 10 flashes/min on spark indicator).
- Within 2 hours, check proper operation of collected dust removal system.
- After flue gas at 200°F (93°C) has entered ESP for 2 hours, perform the following steps:
  - -- check all alarm functions in local and remote
  - -- deenergize bushing heaters after 2 hours.
- Set normal rapping.

ESP SHUTDOWN

When charging has stopped and the incinerator goes into burndown mode, shut the ESP down by doing the following:

- Deenergize ESP by field, starting with inlet field to maintain opacity limit
- Deenergize outlet field when all fuel flow ceases and combustion airflow falls below 30 percent of rated flow.
- Leave rappers, ash removal system, seal-air system, and hopper heaters operational.

- Four hours after incinerator shutdown, deenergize seal-air system and hopper heaters. Secure ash removal system.
- Eight hours after incinerator shutdown, deenergize rappers.
  Note: Normal shutdown is a convenient time to check operation of alarms.

REVIEW EXERCISE

1. What is the recommended range for liquid supply to a venturi scrubber?

   a. 1-3 gal/1,000 acf
   b. 4-6 gal/1,000 acf
   c. 7-10 gal/1,000 acf
   d. 12-15 gal/1,000 acf

2. What is the recommended range for suspended solids in a venturi scrubber?

   a. 0-3 percent
   b. 4-6 percent
   c. 7-10 percent
   d. 10-15 percent

3. How can the pressure drop of a venturi scrubber be increased?

   a. Adjusting the fan damper
   b. Increasing fan energy
   c. Adjusting throat constriction
   d. All of the above

4. What is the recommended range for liquid supply to a packed-bed scrubber?

   a. 3-5 gal/1,000 acf
   b. 5-10 gal/1,000 acf
   c. 10-15 gal/1,000 acf
   d. 15-25 gal/1,000 acf

5. What is the recommended pH for a packed-bed scrubber?

   a. 2-3
   b. 3-5.5
   c. 5.5-7.0
   d. 7.0-9.0

6. What is the recommended pressure drop range for a pulse-jet fabric filter?

   a. 1-5 in. w.c.
   b. 5-9 in. w.c.
   c. 10-15 in. w.c.
   d. 15-20 in. w.c.

1. c. 7-10 gal/1,000 acf

2. a. 0 to 3 percent

3. d. All of the above.

4. c. 10 to 15 gal/1,000 acf

5. c. 5.5 to 7.0

REVIEW EXERCISE (CONTINUED)

7. Excessively high pressure drop in a fabric filter may indicate what?

   a. Inadequate cleaning
   b. Bag blinding
   c. Excessive gas volume
   d. All of the above

8. What is the recommended wet bulb/dry bulb temperature difference for a spray dryer?

   a. 10° to 25°F
   b. 25° to 50°F
   c. 50° to 75° F
   d. 90° to 180°F

6. b. 5 to 9 in. w.c.

7. d. All of the above.

8. d. 90° to 180°F

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SESSION 8.
MAINTENANCE INSPECTION--A NECESSARY PART OF YOUR JOB

SESSION 8. MAINTENANCE INSPECTION--A NECESSARY PART OF YOUR JOB

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SESSION 8.
MAINTENANCE INSPECTION--A NECESSARY PART OF YOUR JOB

SESSION GOAL AND OBJECTIVES

GOAL

To familiarize you with:

- The hourly, daily, and weekly maintenance inspections that you should make on your hospital incinerator and air pollution control device;
- Maintenance problems that should be reported to the maintenance department; and
- Recordkeeping systems.

OBJECTIVES

Upon completing this session, you should be able to:

1. List the maintenance inspections that should be made on an hourly basis;
2. List the maintenance inspections that should be made on a daily basis;
3. List the maintenance inspections that should be made on a weekly basis;
4. Identify and alert maintenance personnel of potential problems; and
5. Implement a recordkeeping system.

INTRODUCTION

Typically, you will not perform preventive maintenance activities such as lubricating of moving parts, replacing parts, and repairing equipment. This preventive maintenance work is usually done by the maintenance department. Your responsibility concerning maintenance is to inspect the different parts of the incinerator and air pollution control device on a regular basis. In this way, you will be able to detect minor problems and report them to the maintenance department before they develop into large, expensive repairs and result in improper operation and increased air emissions. Therefore, this session describes the types of inspections that should be made by the operator and the potential problems that should be reported to the hospital's maintenance department. The following sections describe the maintenance inspections that should be observed on incinerators, wet scrubbers, and fabric filters. Recordkeeping or maintaining an activities logbook also is discussed.

INCINERATOR MAINTENANCE INSPECTIONS

The incinerator maintenance inspections that you should perform are listed in Table 8-1. The following sections describe these inspections in detail.

HOURLY INSPECTIONS

The hourly incinerator inspections apply only to large incinerators with automatic ash removal conveyors. On these systems, the following inspections should be made every hour:

- The ash removal conveyor should be inspected to clear away any debris that might cause it to jam; and
- The quench pit water level should be checked and water added if necessary--water must be available to quench the ash and to maintain the air seal that the water provides on the ash removal conveyor.

DAILY INSPECTIONS

On a daily basis, stack gas monitors (if your incinerator is equipped with one) should be checked for proper operation and various pieces of equipment should be inspected and cleaned as required. The following inspections should be made daily:

- If your incinerator is equipped with stack gas monitors, make daily calibration checks on opacity monitor and check readings on oxygen, carbon monoxide or hydrogen chloride monitors--anything out of the ordinary such as unusually low or high readings should be reported to the maintenance department;
- Observe the exhaust stack for visible emissions and compare to the opacity monitor reading--you should make these exhaust stack observations several times a day especially after waste charging and during the burndown mode;
- Check thermocouple temperature readings--anything out of the ordinary such as slow response time or unusually low or high temperature readings should be reported to the maintenance department;
- On batch incinerators and prior to operation, inspect the charge door seals for closeness of fit and wear by closing the charge door and looking for any gaps in the door seal material--any gaps should be reported to the maintenance department;
- Inspect limit switches for freedom of operation and remove any obstructing debris; and
- On controlled-air incinerators, inspect and clean underfire air ports--on batch units, cleaning is best accomplished by rodding the air ports after the previous shift's ash has been removed--large, continuous feed units usually have cleaning mechanisms that may be used to rod out the air ports while the unit is in operation. [Note that multiple-chamber incinerators (i.e. excess-air units) are supplied with air through overfire air ports that are unlikely to become plugged.]

TABLE 8-1. TYPICAL MAINTENANCE INSPECTION SCHEDULE FOR A HOSPITAL WASTE INCINERATOR

Activity frequency	Incinerator component	Procedure
Hourly	Ash removal conveyor	Inspect and clean as required
	Water quench pit	Inspect water level and fill as required
Daily	Opacity monitor	Check readings; check daily calibration values
	Stack	Check exhaust for visible emissions
	Oxygen monitor	Check oxygen level of exhaust
	Thermocouples	Check temperature readings
	Limit switches	Inspect for freedom of operation and potential obstructing debris
	Underfire air ports	Inspect and rod out
Weekly	Blower intakes	Inspect for accumulations of lint, debris and clean as required
	Induced-draft fans	Inspect and clean fan housing as required. Check for corrosion and V-belt drives and chains for tension and wear
Biweekly	Control panels	Inspect and clean as required. Keep panel securely closed and free of dirt to prevent electrical malfunction
Monthly	External surface of incinerator and stack	Inspect external "hot" surfaces. White spots or discoloration may indicate loss of refractory

WEEKLY/BIWEEKLY/MONTHLY INSPECTIONS

Every week, all blower intakes and induced-draft (ID) fans used for heat recovery should be inspected for dirt accumulation and cleaned as required. Also, the ID fans used for heat recovery should be inspected for corrosion, and V-belt drives and chains should be checked to make sure they are not frayed or loose. Any corrosion or wear and any loose or frayed V-belts or chains should be reported to the maintenance department.

Every 2 weeks, the incinerator's control panel should be inspected for dirt accumulation and cleaned as required. The panel door should be kept closed to prevent dirt accumulation and electrical malfunction.

Every month, you should inspect the outer surface of the incinerator and the refractory lining inside. Any discoloration or white "hot" spots on the outer surface may indicate a loss of refractory inside the unit and should be reported to the maintenance department. These white spots are usually the first indication of internal refractory damage. When the refractory lining is cold, random cracks may be seen that vary in width from 1/32 to 3/16 inch (0.01 to 0.07 centimeter). These cracks are normal and close up when the refractory expands at operating temperatures. The purpose of inspecting the cold refractory each month is to observe any changes in existing cracks and to discover any holes larger than the cracks. These inspections are very important because replacing badly damaged refractory is very expensive. However, minor damage caught early enough may be repaired by the maintenance department using plastic refractory material.

WET SCRUBBER MAINTENANCE INSPECTIONS

The wet scrubber maintenance inspections that you should perform are listed in Table 8-2. The following section describes these inspections in detail.

DAILY INSPECTIONS

The following inspections should be made on a daily basis:

- Inspect the following equipment for leakage by looking for scrubber liquid escaping from the components and for any liquid on surfaces directly under the equipment. All leaking components should be reported to the maintenance department for repair.
  - -- scrubber liquid pump
  - -- variable throat activator
  - -- scrubber liquid lines
  - -- mist eliminator pressure lines
  - -- reagent feed system
- Inspect the scrubber liquid pump for proper operation by noting the flowmeter reading--lower flow rates than normal may indicate pump problems.
- On variable throat venturi scrubbers, inspect the variable throat activator for proper operation by moving the activator and checking the resulting pressure drop--the activator should move

TABLE 8-2. TYPICAL MAINTENANCE INSPECTION SCHEDULE FOR A VENTURI SCRUBBER

Inspection frequency	Component	Procedure
Daily	Scrubber liquid pump	Check for proper operation and leakage
	Variable throat activator	Check for proper operation and leakage
	Scrubber liquid lines	Check for leakage
	Mist eliminator pressure lines	Check for leakage
	Reagent feed system	Check for leakage
	Fan	Check for vibration and proper operation
	Fan belt[a]	Check for abnormal noise or vibration
Monthly	Duct work	Inspect for leakage

[a]Check fan belt tension whenever fan is out of service.

freely and the pressure drop should increase as the activator is moved upwards to constrict the venturi throat.

- Inspect the scrubber fan and fan belt for any abnormal vibration or noise--any abnormal vibration or noise indicates that the fan should be serviced by the maintenance department.

OTHER INSPECTIONS

Every month, the off-gas ductwork should be checked for leakage, i.e., look for holes and listen for air being sucked in. Any problems should be reported to the maintenance department for repair.

All other maintenance activities will likely be performed by the maintenance department during regular shutdowns. Such activities include inspecting the internal scrubber components for corrosion, abrasion, and material buildup (monthly); lubricating scrubber components including fan and pump (weekly); inspecting fan, pump, motor, and drag chain bearings, and damper seals, bearings, blades and blowers for wear and loose fittings (semiannually); and checking the accuracy of flowrates (semiannually).

FABRIC FILTER MAINTENANCE INSPECTIONS

The fabric filter maintenance inspections that you should perform are listed in Table 8-3. The following section describes these inspections in detail.

DAILY INSPECTIONS

The following inspections should be made on a daily basis:

- Inspect the exhaust stack for visible emissions--a sudden change in opacity may indicate the failure of one or more system components including broken/leaking bags or a malfunctioning cleaning system--the appearance of puffing smoke indicates pinhole leaks in a filter bag(s);
- Check and record fabric pressure loss and fan static pressure--sudden changes in the pressure drop may indicate problems; i.e. high pressure drop may indicate mudded bags or cleaning system failure (listen to the system-does it sound different?) while low pressure drop may indicate fabric failure (holes);
- Check the compressed air system for air leakage by observing the system's pressure gauge--air leakage may be indicated by a lower pressure than normal;
- Check all indicators on the fabric filter control panel and listen to the system in operation--you should become familiar with the sounds that your system makes when operating normally ; and
- Inspect the dust removal system to see that dust is being removed from the system by checking the conveyor for jamming, pluggage, wear, broken parts, etc.--problems with the conveyor system are indicated when the conveyor appears to be moving but no dust is dropping into the dust storage container, when the conveyor does not move, or when the conveyor makes unusual sounds.

TABLE 8-3. TYPICAL MAINTENANCE INSPECTION SCHEDULE FOR A FABRIC FILTER SYSTEM

Inspection frequency	Component	Procedure
Daily	Stack	Check exhaust for visible dust.
	Manometer	Check and record fabric pressure loss and fan static pressure. Watch for trends.
	Compressed air system	Check for air leakage (low pressure). Check valves.
	Collector	Observe all indicators on control panel and listen to system for properly operating subsystems.
	Rotating equipment and drives	Check for signs of jamming, leakage, broken parts, wear, etc.
	Dust removal system	Check to ensure that dust is being removed from the system.
	Hoppers	Check for bridging or plugging by looking into the hopper with the system shut down.

If you encounter any of the indicators of deteriorating performance listed above, you should report the problem(s) to the maintenance department for repair.

RECORDKEEPING

Recordkeeping of maintenance inspections is an important part of an equipment operation and maintenance program. The objectives of recordkeeping are to prevent premature failure of equipment, increase equipment life, and minimize air pollution. These objectives can be achieved by observing trends in the frequency and types of maintenance required and by detecting problems early through regular maintenance inspections. Table 8-4 shows an example of a daily maintenance inspection log that you could use to record the dates and times when specific inspections are performed. A similar log can be set up for inspections that occur weekly or less frequently. You could set a log up for the incinerator and another for the air pollution control device.

TABLE 8-4. DAILY MAINTENANCE INSPECTION LOG

Facility name: _____

Operator's name: _____

Date: _____

Time	Equipment inspected	Notes
	Ash removal conveyor	
	Water quench pit	
	Opacity monitor	
	Oxygen monitor	
	Underfire air ports	
	Ash pit/dropout sump	
	Stack	
	Scrubber liquid pump	
	Variable throat activator	
	Scrubber liquid lines	
	Mist eliminator pressure lines	
	Reagent feed system	
	Fan	
	Fan belt	

REVIEW EXERCISE

1. It is the operator's responsibility to _____ the different parts of the incinerator and air pollution control device on a regular basis.

2. Maintenance inspections allow you to identify minor problems before they develop into large, _____ repairs.

3. The ash removal conveyor should be inspected every hour to clean away any debris that might cause it to ____.

4. Daily calibration checks should be made on the _____ monitor.

5. The exhaust stack should be checked for _____ emissions and compared to the opacity monitor reading.

6. Limit switches should be checked for freedom of operation and any obstructing _____ removed.

7. The underfire air ports should be inspected daily and cleaned (rodded) as necessary. True or False?

8. All blower intakes and induced draft (ID) fans should be inspected weekly for ____ accumulation and cleaned as required.

9. Any frayed or loose V-belt drives and chains or any corrosion found during inspection of ID fans should be reported to the _____ department.

10. White spots or discoloration of the outer surface of the incinerator found during the monthly inspection may indicate a _____ of refractory inside the unit and should be reported to the maintenance department.

1. inspect
2. expensive
3. jam
4. opacity
5. visible
6. debris
7. True
8. dirt
9. maintenance

(continued)

REVIEW EXERCISE (CONTINUED)

11. List three of the five scrubber components that should be inspected daily for fluid leakage.	10. loss
12. The fan, including bearings and belt, should be checked daily for any abnormal _____ or vibration.	11. Scrubber liquid pump Variable throat activator Scrubber liquid lines Mist eliminator pressure lines Reagent feed system
13. Every month, the scrubber off-gas ductwork should be checked for _____ and air being sucked in.	12. noise
14. When a baghouse is used, a sudden change in the _____ of the exhaust gas may indicate the failure of one or more system components including broken/ leaking bags or a malfunctioning cleaning system.	13. holes
15. Changes in the pressure drop across the fabric filter indicate the failure of one or more system components. True or False?	14. opacity
16. You should inspect the fabric filter dust removal system to see that dust is being removed from the system by checking the conveyor for jamming, wear, broken parts. True or False?	15. True
	16. True

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SESSION 9.
TYPICAL PROBLEMS

SESSION 9.
TYPICAL PROBLEMS

SESSION GOAL AND OBJECTIVES

GOAL

To familiarize you with the most frequent operational problems and how to prevent or correct them.

OBJECTIVES

Upon completing this session, you should be able to:

1. Identify the most frequent operational problems with incinerators and air pollution control systems;
2. Recognize the causes of operational problems; and
3. Describe the actions to take to correct and prevent operational problems.

INTRODUCTION

As an incinerator operator, you will experience problems periodically with the incinerator and air pollution control system. Many times, problems can be prevented if you are aware of how to keep them from happening. Sometimes, though, there are problems that you could not have prevented, and you need to know how to correct them as quickly as possible. Knowing how to prevent and correct operational problems will help you to do your job better and will also help to reduce air pollution from the incinerator. In this session, the most frequent operational problems are identified. These problems are numbered and listed below. The possible causes for each problem are discussed along with actions you can take to correct the problem.

You will also be given information on how to prevent the problem from happening in the future. An effective preventive maintenance program can reduce the number of problems by correcting malfunctions, making changes to prolong equipment life, and correcting minor problems before they require costly, time-consuming repairs.

INCINERATOR PROBLEMS

PROBLEM NO.	PROBLEM DESCRIPTION
1	Black smoke leaving stack
2	White smoke leaving stack

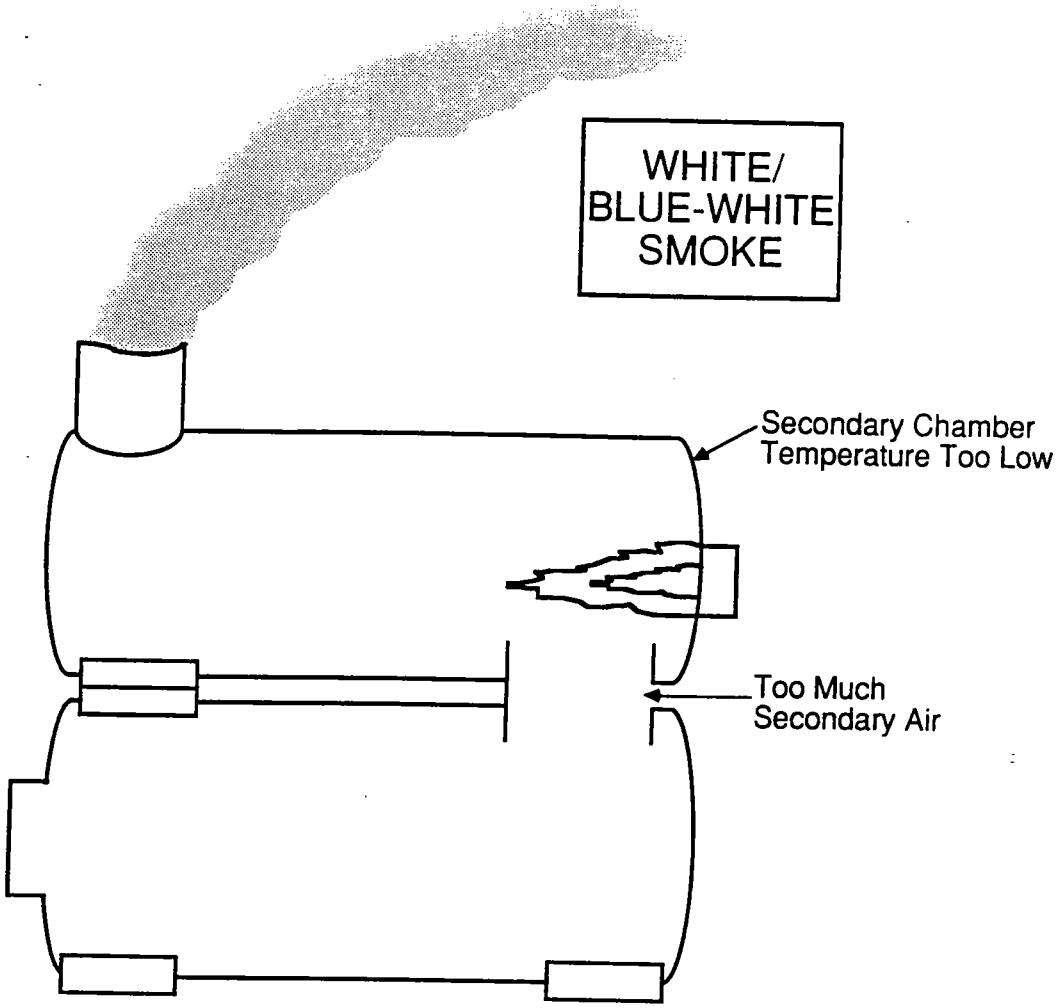


Figure 9-2. Causes of white smoke.

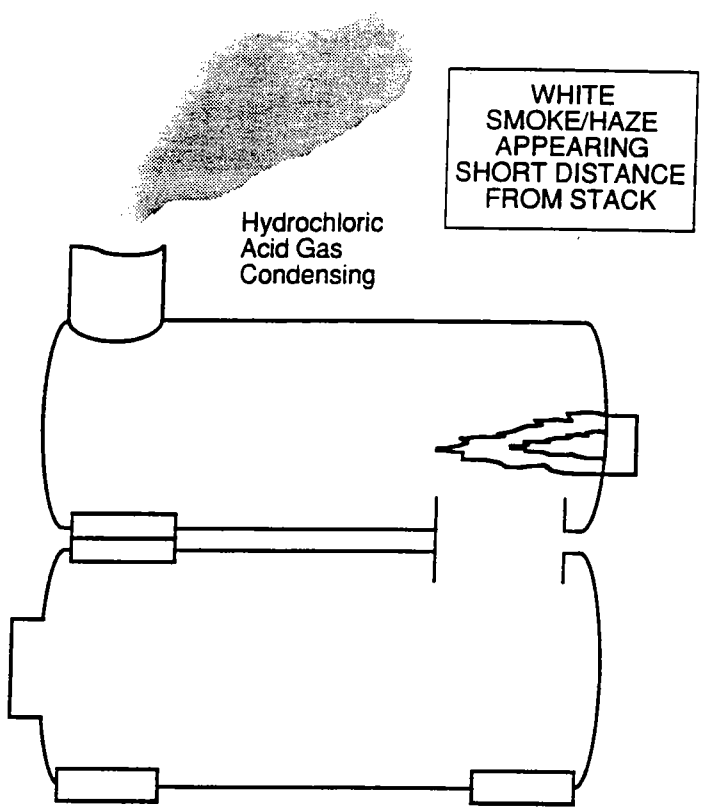


Figure 9-3. Cause of white plume a short distance above the stack.

PROBABLE CAUSE: Hydrochloric acid gas condensing

SOLUTION/PREVENTION: Not much you can do unless you can:

- Reduce amount of chlorinated waste incinerated in each load, or
- Eliminate chlorinated plastics from use in hospital, or
- Install acid gas scrubbing system

PROBLEM NO. 4 Smoke leaking from primary chamber (see Figure 9-4)

CAUSE: Positive pressure in primary chamber

- Too much underfire air
- Too much highly volatile material charged
- Problem with draft damper or induced draft fan (poor draft)
- Primary chamber temperature too high

SOLUTION/PREVENTION: Do the following, in order, to correct the problem:

- Check stack damper or fan operation
- Check/decrease underfire air
- Decrease feed rate
- Check charging door seals for leakage

PROBLEM NO. 5 Too much auxiliary fuel usage (see Figure 9-5)

CAUSE: Not enough heat input from waste to keep temperature high enough

- Inconsistent charging of incinerator
- Insufficient underfire air (starved-air units) or poor underfire air distribution
- Too much secondary combustion air
- Too much air infiltration
- Fuel leakage
- Wet waste
- Excessive draft
- Burner setting too high

SOLUTION/PREVENTION: Do the following to correct the problem:

- Charge waste at regularly timed intervals at a rate near 100 percent of incinerator capacity (Example: For 500 lb/h (230 kg/h) unit, charge 50 lb (23 kg) every 6 minutes)
- Spread wet waste with other waste through several charges--do not charge all of the wet waste at one time
- Check/increase underfire air (controlled-air unit); check air ports and distribution
- Check/reduce secondary combustion air
- Check/reduce draft
- Check charging door seals and other seals for air leakage

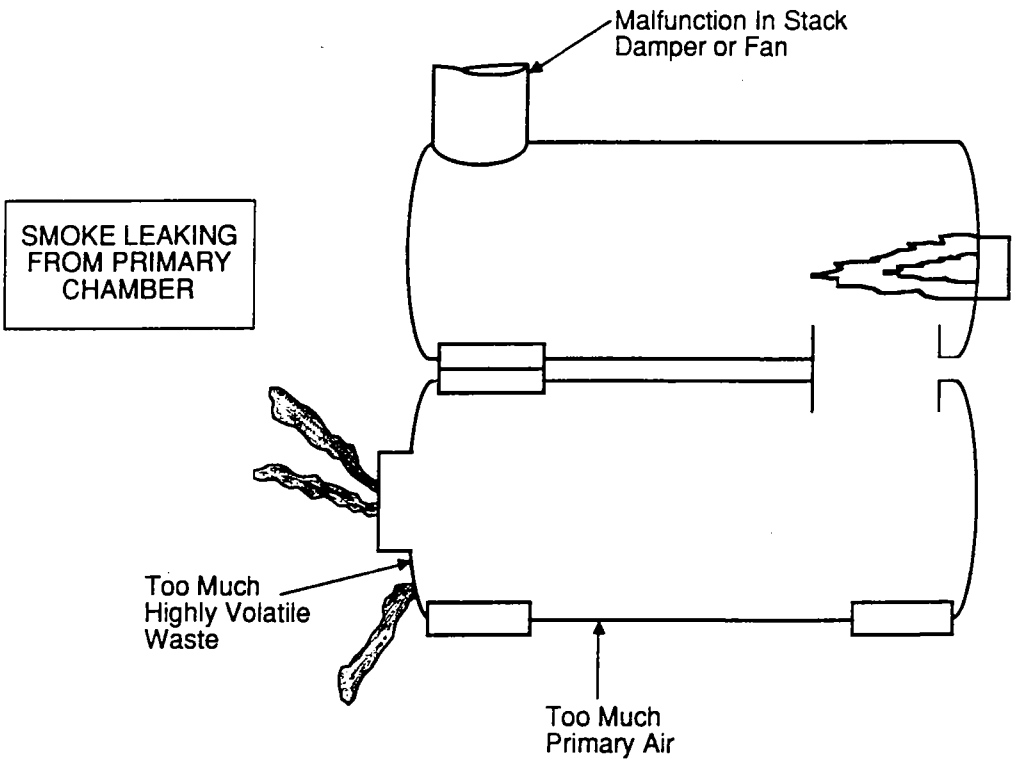


Figure 9-4. Causes of leaking smoke.

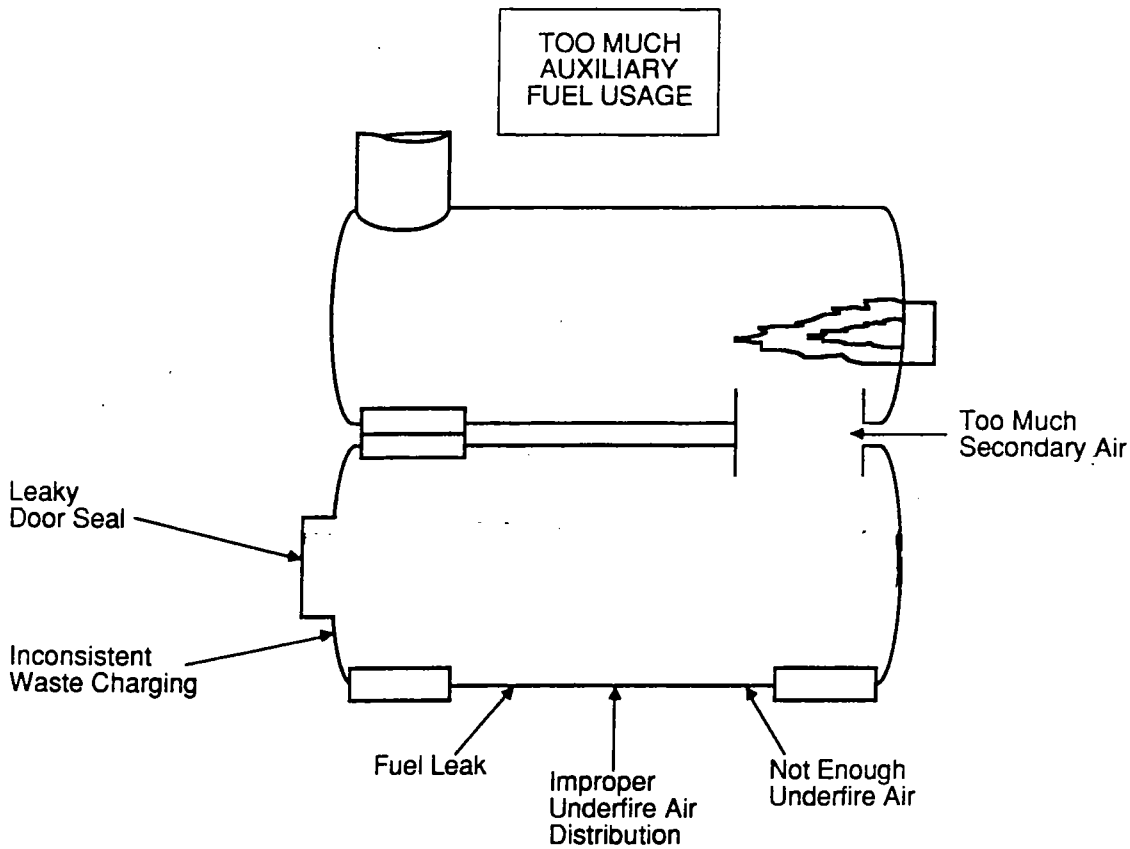


Figure 9-5. Causes of excessive auxiliary fuel use.

- Check/decrease burner setting
- Check fuel trains and burners for fuel leakage

PROBLEM NO. 6 Incomplete burnout/poor ash quality (see Figure 9-6) (Three causes of this problem are detailed below.)

CAUSE NO. 1: Not enough underfire air or poor distribution
- Improper underfire air setting
- Clinker buildup around underfire air ports
- Air ports clogged with ash from previous charges
- Poor draft

SOLUTION/PREVENTION: Do the following to correct the problem:
- Check underfire air setting and adjust if needed
- Check around underfire air ports for clinker buildup and clean as needed
- Rod underfire air ports daily to remove clinker buildup and ash

CAUSE NO. 2: Improper waste charging
- Overstuffing incinerator
- Too much wet waste

SOLUTION/PREVENTION: Do the following to correct the problem:
- Charge waste at regularly timed intervals at a rate near 100 percent of incineration capacity (Example: For 500 lb/h [230 kg/h] unit, charge 50 lb [23 kg] every 6 minutes). Do not overstuff
- Spread wet waste through several charges--do not charge all of the wet waste at one time

CAUSE NO. 3: Insufficient burndown time

SOLUTION/PREVENTION: Do the following to correct the problem:
- Allow longer burndown period
- Use primary burner to maintain temperature during burndown period

PREVENTING PROBLEMS

It is better to prevent a problem than to have to correct a problem after it has occurred. A couple of actions you can take to prevent problems with your incinerator are noted below.

1. Properly charge the incinerator.

2. Note small maintenance problems and have them fixed before they become big problems, for example, sticking or squeaking dampers, loose control arms on dampers.

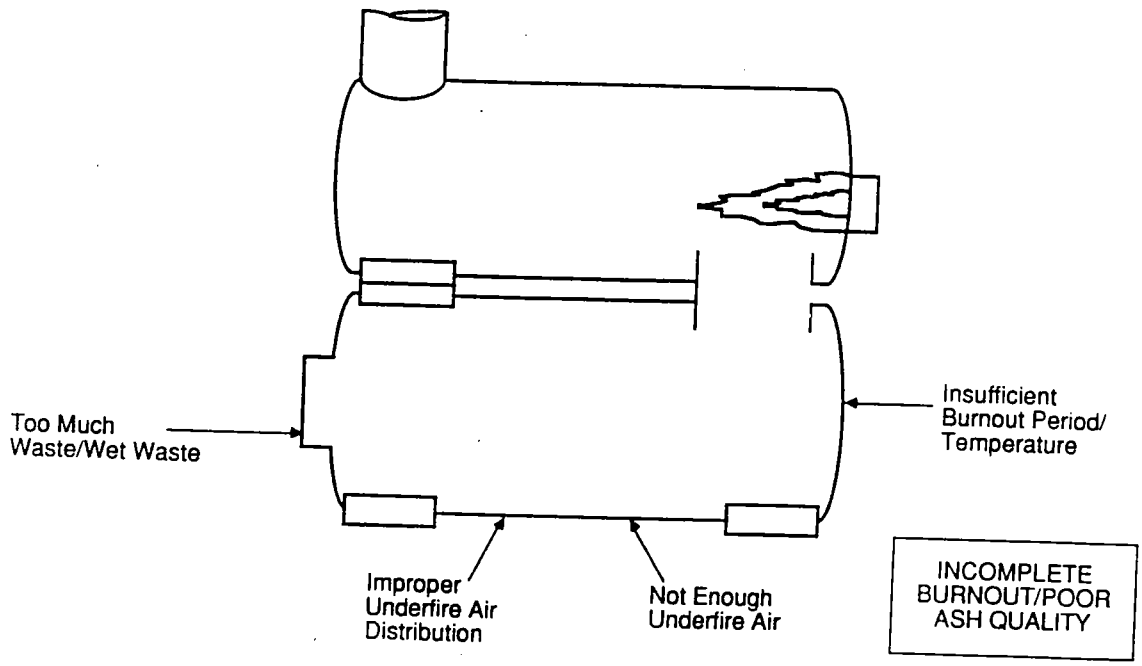


Figure 9-6. Causes of incomplete burnout/poor ash quality.

WET SCRUBBER PROBLEMS

Wet scrubber problems are usually the result of corrosion, erosion, scaling, or plugging. Corrosion is a process where the scrubber internal components are worn away by the chemical action of the acid exhaust gas from a medical waste incinerator or by the alkaline scrubber liquor. Erosion is a process where the scrubber internal components are worn away by the abrasive action of the airborne particles in the incinerator exhaust gas. Scaling occurs when the particles in the incinerator exhaust gas begin to build up on the scrubber internal components such as fan blades. Plugging occurs mainly in scrubber spray nozzles when scrubber water containing captured particulate is recycled and the particulate builds up in and around the nozzle tip.

Typically, these problems will be invisible to the operator because they occur inside the scrubber. Most operational problems encountered by wet scrubbers can be prevented with a good preventive maintenance program. Steps that you can take to detect or prevent some of these problems are outlined below. However, call maintenance whenever a problem comes up. Here is a list of wet scrubber problems.

PROBLEM NO.	PROBLEM DESCRIPTION
7	Corrosion of scrubber parts
8	Fan vibration, dampers stuck, poor nozzle spray pattern
9	Erosion of dry service components
10	Erosion in wet service components

PROBLEM NO. 7 Corrosion of scrubber parts (scrubbers, absorbers, fans, dampers, ductwork, exhaust stack, pumps, valves, pipes, tanks, feed preparation equipment)

CAUSE: Acid buildup in scrubbing liquid from absorption of sulfur dioxide, sulfur trioxide, and hydrogen chloride

SOLUTION/PREVENTION: Maintain the pH of the scrubbing liquid by doing the following:

- Check alkaline addition system for leaks daily and have the maintenance department repair if needed
- Check pH monitor that controls alkaline additions daily
- Have the maintenance department perform regular preventive maintenance on pumps, pipes, valves, tanks and feed preparation equipment in slurry service

PROBLEM NO. 8 Fan vibration, dampers stuck, poor nozzle spray pattern

CAUSE:	Scaling/plugging
SOLUTION/PREVENTION:	Preventive maintenance • Periodic cleaning of equipment
PROBLEM NO. 9:	Erosion in dry service components (fans, dampers, ductwork) • Erosion of fan blades • Holes in ductwork
CAUSE:	• Droplet carryover due to poor mist eliminator performance • Normal operation
SOLUTION/PREVENTION:	Preventive maintenance Repair/replacement of equipment
PROBLEM NO. 10:	Erosion in wet service components (scrubber and scrubber spray nozzles) (if recirculation is not practiced, then erosion in wet service will not be a problem)
CAUSE:	Suspended solids in scrubbing liquid • High recirculation flow rate compared to makeup and purge flow rates • Infrequent purging of system
SOLUTION/PREVENTION:	Preventive maintenance • Purge system frequently to prevent solids buildup • Adjust recirculation rate as needed

PREVENTING PROBLEMS

It is better to prevent a problem than to have to correct a problem after it has occurred. A few actions you can take to prevent problems with a wet scrubber are noted below.

1. Maintain proper pH for scrubber liquid.

2. If recirculation is used, maintain low level of solids in scrubbing liquid.

3. Establish preventive maintenance program to inspect and clean scrubber parts, including nozzles, fan, and dampers. (The Maintenance Department would be responsible for this action.)

FABRIC FILTER PROBLEMS

Problems with fabric filters are usually indicated by either unusually high or low pressure drop readings or by high opacity (greater than 5 percent) from the fabric filter stack. High pressure drop

indicates a higher resistance to airflow meaning that the filter bags are not being cleaned properly or that they are mudded or blinded because of condensation of moisture. Low pressure drop and high opacity indicate a lower resistance to airflow due to holes in the filter bags (caused by abrasion, too frequent cleaning, or acid gas condensation) or improper bag installation (fallen bags, improperly sealed or tensioned bags). The causes of high opacity emissions and high pressure drop are shown in Figures 9-7 and 9-8, respectively. All high opacity and high or low pressure drop readings should be reported to the maintenance department. Readings of these parameters recorded in a log book will allow you to see trends in readings that indicate a problem.

Acid gas and water condensation can be prevented by maintaining the temperature of both, the inlet gas to the fabric filter and the fabric filter itself above the dewpoints of water and the acid gas. Additionally, the inlet gas temperature must not be excessive such that damage to the filter bags or fire occurs. Some fabric filters are equipped with alarms and a bypass stack that diverts the gas if the temperature exceeds or falls below a certain limit. Filter bag abrasion may be eliminated by proper installation of the filter bags (done by the Maintenance Department, not you) assuming that the fabric filter has been properly designed. Finally, cleaning system failure (you'll know by no sound or different sounds) is best prevented by preventive maintenance on the part of the Maintenance Department.

PREVENTING PROBLEMS

It is better to prevent a problem than to have to correct a problem after it has occurred. A couple of actions you can take to prevent problems with a fabric filter are noted below.

1. Observe pressure drop readings. Any low or high readings indicates a problem and should be reported to the maintenance department.

2. Observe opacity. High opacity indicates fabric failure and should be reported to the maintenance department.

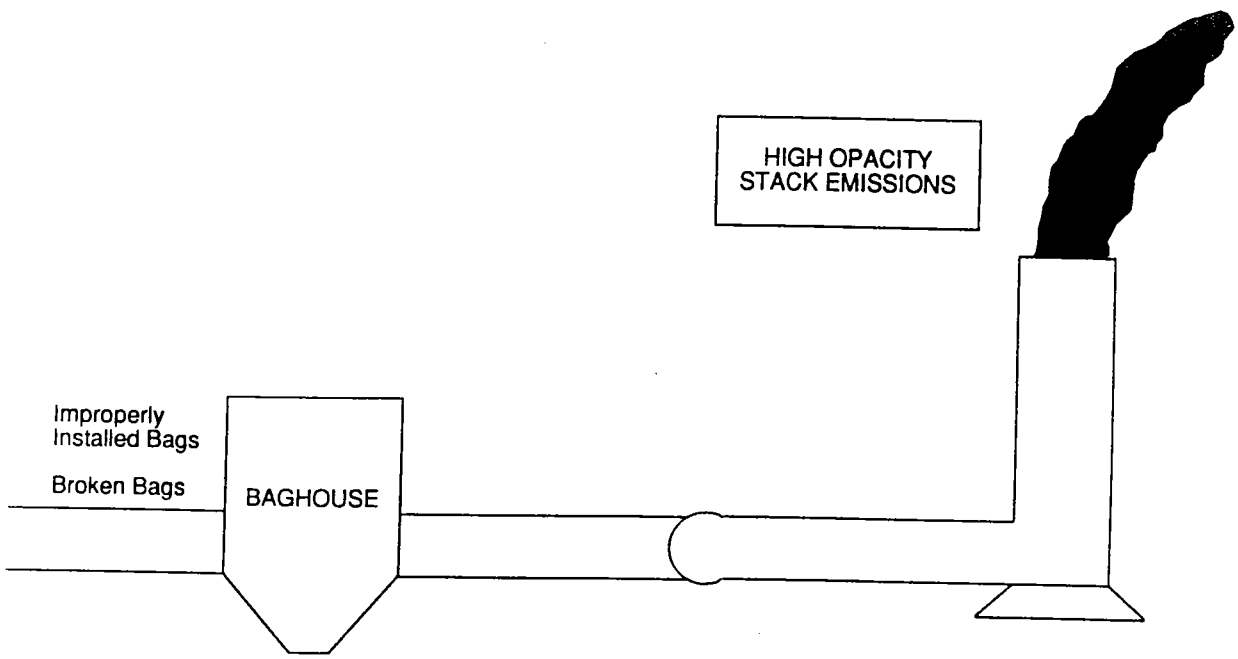
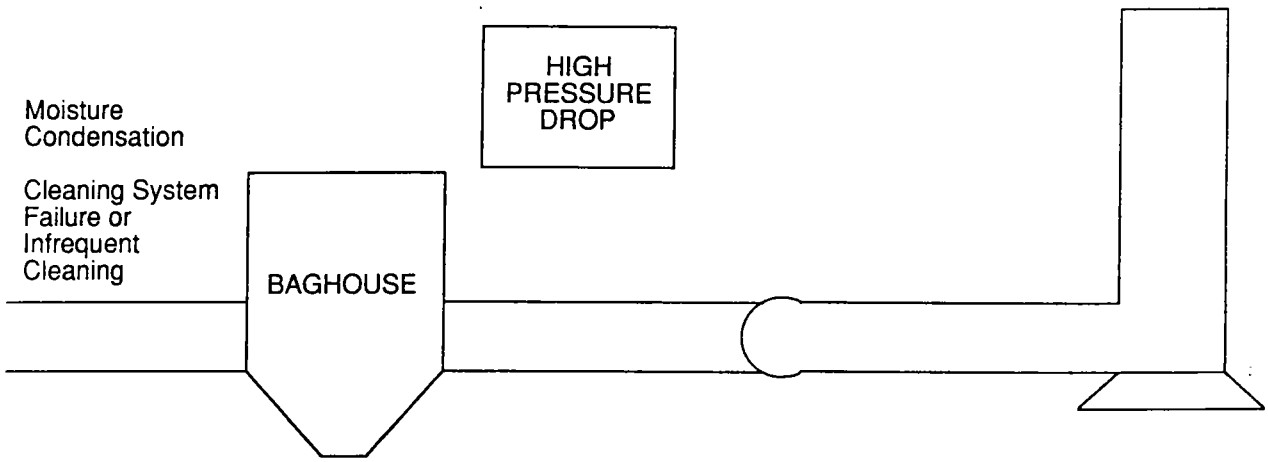


Figure 9-7. Causes of high opacity emissions.



HIGH PRESSURE DROP IN FABRIC FILTER

Figure 9-8. Causes of high pressure drop across fabric filter.

REVIEW EXERCISE

1. Which of the following problems is probably caused by too much air entering the incinerator and insufficient temperature?

   a. Black smoke leaving stack
   b. White smoke leaving stack
   c. Poor ash quality
   d. Incomplete burnout

2. Increasing the charging rate is a possible solution to the problem of black smoke leaving the stack. True or False?

3. If smoke is leaking from the primary chamber, there may be either too much underfire air, poor draft, or too much highly volatile material in the charge. True or False.

4. Which of the following are possible causes for incomplete burnout and poor ash quality.

   a. Not enough underfire air
   b. Improper waste charging
   c. Insufficient burndown time or temperature
   d. All of the above
   e. None of the above

5. Corrosion of parts of a wet scrubber is caused by:

   a. Too much iron in the water
   b. Acid buildup in the scrubbing liquid
   c. Both of the above
   d. Neither of the above

1. b. White smoke leaving the stack

2. False?

3. True

4. d. All of the above

(continued)

REVIEW EXERCISE (CONTINUED)

6. Problems such as plugging, stuck dampers, and fan vibration resulting from deposits on fan blades are caused by:

   a. Scaling
   b. Erosion
   c. Corrosion

7. Erosion in the scrubber and scrubber spray nozzles can be reduced by which of the following?

   a. Rod out spray nozzles regularly
   b. Purge system frequently
   c. Adjust recirculation rate if needed
   d. All of the above
   e. b and c only

8. When a fabric filter is operating normally, the opacity of stack emissions should be very low (less than 5 percent). True or False?

9. Which of the following are possible causes of fabric failure resulting in high opacity?

   a. Improper installation of filter bags
   b. High temperature in the fabric filter baghouse
   c. Acid gas condensation on the filter bags
   d. Abrasion of the filter bags
   e. All of the above
   f. b, c, and d

10. High pressure drop indicates a high resistance to flow. True or False?

5. b. Acid buildup in the scrubbing liquid

6. a. Scaling

7. e. b and c only

8. True

9. e. All of the above

10. True

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SESSION 10.
STATE REGULATIONS

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SESSION 10. STATE REGULATIONS

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SESSION 10.
STATE REGULATIONS

SESSION GOAL AND OBJECTIVES

GOAL

To familiarize you with major aspects of air pollution regulations that apply to your incinerator.

OBJECTIVES

Upon completing this session, you should be able to:

1. List the air pollutants from hospital waste incinerators that are likely to be regulated by your State;
2. Recognize the types of requirements that may be included in regulations; and
3. Describe how regulatory agencies determine whether your facility is complying with applicable regulations.

INTRODUCTION

Many State regulations include requirements to reduce air pollutant emissions from incineration of general hospital wastes and infectious wastes. Some or all of the requirements may be specified according to the size of the incinerator. For example, large incinerators may be required to meet stricter requirements for more pollutants than small incinerators, and very small incinerators may have few restrictions.

State regulations typically include the following types of requirements which are discussed in this session:

- Emission limits for air pollutants that leave the incinerator stack;
- Operating practices/limits;
- Continuous monitoring of emissions or other indicators of performance;
- Recordkeeping and reporting; and
- Operator training.

The requirements for your particular State will be summarized later. In addition to these requirements, your facility will have received a "permit" from the State and/or local Agency which may include specific requirements for your incinerator and air pollution control system that may be more strict than the general State regulations.

THE AIR POLLUTANTS

Listed below are the air pollutants from hospital waste incinerators that may be covered by emission limits in State regulations

Particulate matter;
Carbon monoxide;
Sulfur dioxide;
Nitrogen oxides;
Hydrochloric acid gas;
Toxic metals (arsenic, beryllium, cadmium, chromium, nickel, lead, mercury); and
Organics (dioxins/furans, ethylene, propylene).

REGULATORY REQUIREMENTS

EMISSION LIMITS

State regulations are designed to limit air pollutant emissions to certain acceptable levels. The emission limits may be expressed in several different ways depending on the type of pollutant.

The most common type of emission limit is the concentration standard, which limits either the mass (weight) or volume of the pollutant in the gas exiting the stack. This type of emission limit is expressed as follows and is described pictorially in Figure 10-1:

Example	Type of pollutant	Explanation
1 grain per dry standard cubic foot (1 gr/dscf) at 7 percent oxygen	Particulate matter	No more than 1 grain (there are 7,000 grains in 1 pound) of particulate matter may be contained in each cubic foot of gas leaving the stack corrected to 7 percent oxygen and standard conditions (20°C, and 1 atm) (Oxygen correction and standard conditions are explained below)
• 100 parts per million (100 ppm)	Carbon monoxide Sulfur dioxide Nitrogen oxides Hydrogen chloride	No more than 100 cubic feet (cubic meters) of pollutant may be contained in 1 million cubic feet (cubic meters) of gas leaving the stack

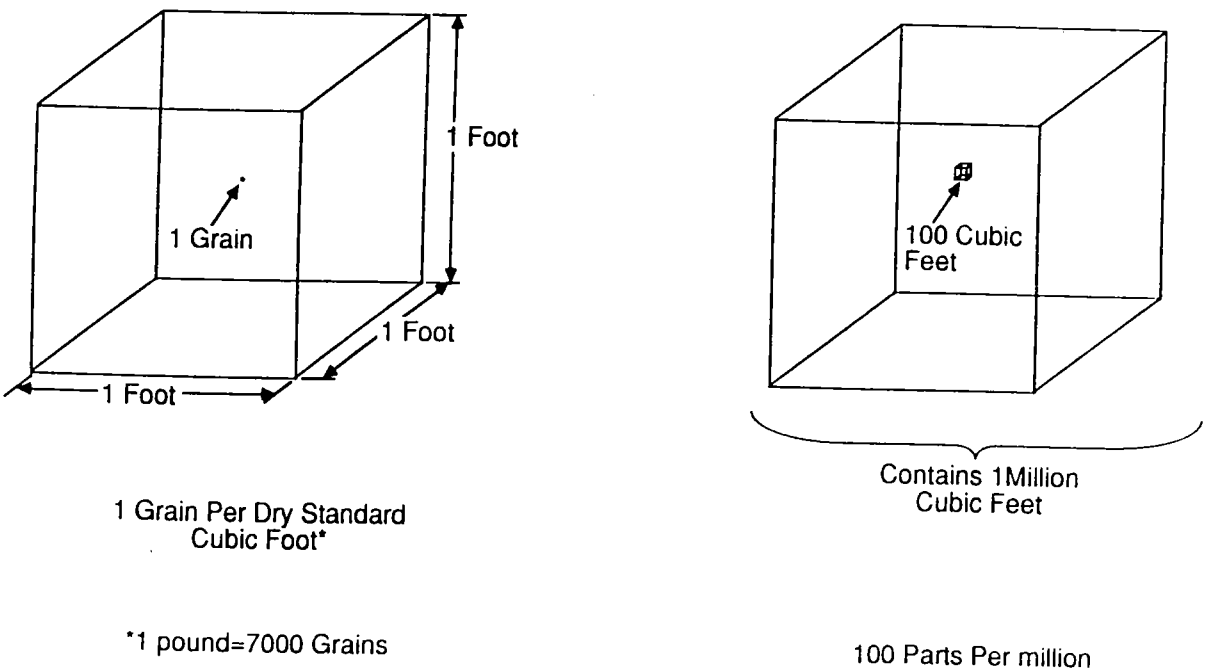


Figure 10-1. Concentration standards.

For metric units, mass/volume concentrations are expressed as milligrams per dry standard cubic meter (mg/dscm). The conversion is:

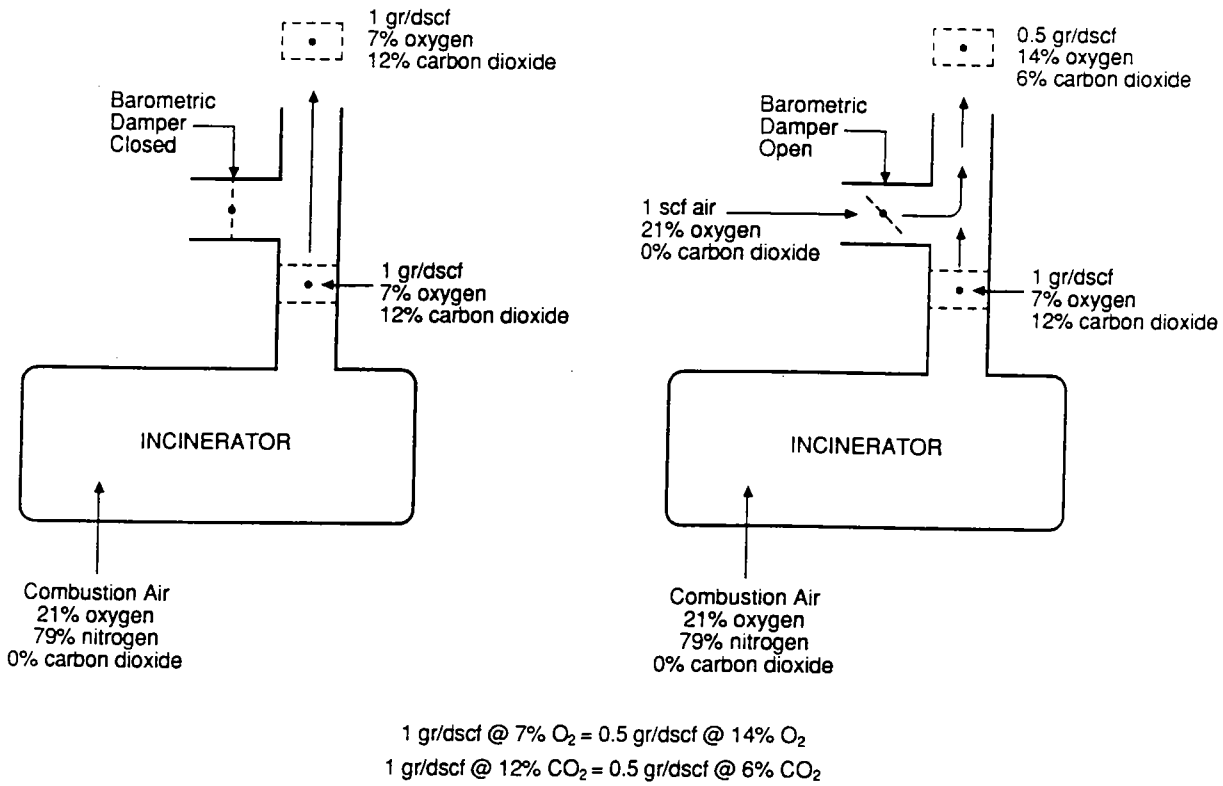
$$1 \text{ gr/dscf} = 2{,}300 \text{ mg/dscm}$$

For metric units, volume/volume concentrations are expressed as ppm. Because a concentration standard limits the amount of pollutant in a certain amount of stack gas, someone having a problem meeting the standard might be tempted to increase the amount of air to dilute the concentration of the pollutant. As air is added, the oxygen concentration in the gas increases because the air contains 21 percent oxygen. To keep this from happening, regulations usually either forbid the addition of dilution air or require that the concentration be "corrected" to a standard level of oxygen, usually 7 percent, or a standard level of carbon dioxide, usually 12 percent. Figure 10-2 illustrates this concept.

Emission limits are often given for standard conditions, e.g. 0.1 grain/dry standard cubic foot. Standard temperature is 68°F (20°C) and standard pressure is 29.92 in. w.c. (760 millimeters of mercury). A cubic foot measured at this temperature and pressure is known as a standard cubic foot. When a stack test is performed to check the level of emissions from an incinerator, both temperature and pressure are measured during the test in addition to the pollutant of interest. The test results are then converted to standard conditions (grain/dry standard cubic foot) using the temperature and pressure measured. In this way, all test results of all sources including incinerators can be compared on the same basis, i.e., all results are reduced to standard conditions.

Another type of standard is the <u>percent reduction</u> standard. Sometimes the emission limit is expressed as a percent reduction of the pollutant. In other words, the pollution control device must operate at or above a specified efficiency level (such as 90 percent removal) to reduce the pollutant emissions. This type standard frequently is used for acid gases such as HCl. For example, if the emission standard requires at least <u>90 percent reduction</u> of HCl, and the HCl in the combustion gas is entering the scrubber inlet at a rate of 20 lb/h (9.1 kg/h), then the allowed emission rate is 2 lb/h (0.9 kg/h), which is 10 percent of the amount entering the scrubber.

Another type of standard (shown below) sometimes found in State regulations is called an <u>ambient concentration standard</u>. It limits the amount of pollutant that collects at ground level in areas surrounding the emission source. Usually, the regulation requires that the pollutant be measured as it leaves the stack. This measurement information is then used by a computer to calculate the amount of the pollutant at various locations near the source.



1 gr/dscf @ 7% O_2 = 0.5 gr/dscf @ 14% O_2

1 gr/dscf @ 12% CO_2 = 0.5 gr/dscf @ 6% CO_2

Figure 10-2. Correction for dilution.

Example	Type of pollutant	Explanation
1 microgram per cubic meter (1 $\mu g/m^3$)	Toxic metals Organics Hydrogen chloride	No more than 1 microgram of pollutant may be contained in each cubic meter of air. (There are 1 million micrograms in 1 gram).

A third type of standard that is almost always included in regulations is an opacity standard. It is expressed as a limit on the degree to which the stack emissions are visible and block the visibility of objects in the background. Stack emissions of 100 percent opacity would totally block the view of background objects and indicate high pollutant levels. Zero percent opacity would provide a clear view of the background and indicate no detectable particulate matter emissions. Opacity may be estimated by taking "readings" every 15 seconds and averaging the readings over a specified time period. The "reader" must be a certified opacity reader. The U. S. EPA Reference Method 9 "Visual Determination of the Opacity of Emissions" establishes the procedures and criteria for taking opacity readings and for certification. Additionally, opacity may be estimated by comparing the opacity of the smoke to the six sections of a Ringelmann Smoke Chart. The six sections are numbered from 0 to 5 with No. 0 being completely white and No. 5 completely black. Sections 1 through 4 correspond to opacities of 20 percent (No. 1), 40 percent (No. 2), 60 percent (No. 3), and 80 percent (No. 4). Opacity is estimated by choosing the section which most closely resembles the opacity of the exhaust gas. Opacity may also be measured by an instrument called a transmissometer that is installed in the stack. The following further illustrates an opacity standard.

Example	Type of pollutant	Explanation
10 percent opacity (6-minute average)	Particulate matter	The opacity of the emissions cannot average more than 10 percent for any 6-minute period.

MONITORING AND RECORDKEEPING

- Certain types of records are commonly required by State regulations or operating permits. Most of them are listed below and involve recording the levels indicated on automatic monitoring devices periodically or require recording the parameters continuously.
  - -- Temperature of incinerator chamber(s)
  - -- Oxygen concentration of exhaust gas
  - -- Temperature at inlet and/or outlet of control device
  - -- Continuous emission monitoring records (carbon monoxide or opacity)
  - -- Weight of waste charged to incinerator
  - -- Air pollution control device operating parameters:

a. Scrubber
    - Pressure drop
    - Liquid flow rate

b. Fabric filter
    - Pressure drop

- Keeping good records of instrument readings and operating practices is important because it:
  - -- Helps you to know if a problem develops that would cause air pollution standards to be violated so that you can take corrective action
  - -- Provides proof that you are properly operating and maintaining equipment
  - -- Allows you to prepare accurate annual (or more frequent) reports that may be required by State regulations

ENFORCEMENT OF STATE REGULATIONS

State enforcement officials may inspect your incinerator if complaints are received from neighbors. Frequent complaints may cause officials to make random inspections. A State enforcement official may take the following steps to determine if you are complying with regulations:

- Examine your daily, weekly, and monthly records
- Inspect equipment and monitoring devices
- Observe your work procedures
- "Read" the opacity of stack emissions
- Measure stack emissions ("stack test")

OPERATOR TRAINING

Some State regulations now require that infectious waste incinerator operators be properly trained. The training requirements vary from State to State, but usually include some classroom and hands-on instruction.

YOUR STATE REGULATION

The table on the following pages describes the most common requirements in State regulations for air pollutant emissions from hospital incinerators. There is space in the table for you to list the specific requirements of your State's regulation and how they apply to your incinerator. Your instructor will help you complete this table. Note that the specific limitations in your operating permit are the requirements you must follow.

SUMMARY OF REGULATIONS FOR THE STATE OF _____

Type of requirement	State regulation	Your incinerator Regulated (Yes/No)	Level
Applicability			
Type of waste charged			
Size of incinerator			
Age of incinerator			
Emission limits			
Particulate matter			
Opacity			
Carbon monoxide			
Sulfur dioxide			
Hydrogen chloride			
Nitrogen oxides			
Toxic metals			
Organics			
Other			
Operating practices			
Limits on chracteristics of waste charged (moisture, volatility, etc.)			
Waste packaging			
Waste charging practices			
Primary chamber temperature			
Secondary chamber temperature			
Residence time			
Feed rate			
Ash burnout levels			
Ash handling and disposal practices			
Shutdown requirements			
Control device temperature			
Other			

(continued)

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SUMMARY OF REGULATIONS FOR THE STATE OF _____
(continued)

Type of requirement	State regulation	Your incinerator Regulated (Yes/No)	Level
Equipment requirements			
Incinerator design			
Interlock systems			
Automatic charging			
Automatic ash removal			
Other			
Recordkeeping			
Incinerator temperature			
Primary chamber			
Secondary chamber			
Control device			
Temperature			
Pressure drop			
Liquid flow rate			
Continuous monitoring records			
Weight of waste charged			
Other			
Continuous emission monitoring			
Opacity			
Sulfur dioxide			
Nitrogen oxides			
Hydrogen chloride			
Carbon monoxide			
Other			
Operator training			

REVIEW EXERCISE

1. State regulations may include which of the following?

   a. Air pollution emission limits
   b. Operating limits
   c. Monitoring and recordkeeping requirements
   d. Requirement for operator training

   1. a
   2. b and c
   3. d
   4. a, b, c, and d

2. State regulations may be different for different size incinerators. True or False?

3. The State or local agency can include special rules and limitations in your permit to operate that are more strict than typical State regulations. True or False?

4. Which of the following operating practices are sometimes regulated by States?

   a. Waste packaging and waste charging practices
   b. Ash handling and disposal practices
   c. Temperatures and residence times for incinerator chambers
   d. All of the above
   e. a and b above

5. Some State regulations require that incinerator operators be trained. True or False?

1. 4. a, b, c, and d

2. True

3. True

4. d. All of the above

(continued)

REVIEW EXERCISE (CONTINUED)

6. Name at least two types of records that you may be required to keep by State regulations.	5. True
7. Which of the following might an enforcement official do to determine if you are complying with regulations? a. Examine your records b. Inspect equipment c. Observe your work procedures d. Sample stack emissions e. All of the above	6. Any of the following: temperature of incinerator chamber(s), control device temperature, emission levels, opacity, weight of waste charged, scrubber pressure drop or liquid flow rate
8. When the stack gases are perfectly clear, that is the same as _____ percent opacity	7. e. All of the above
9. The greater the opacity reading, the better. That is, 30 percent opacity is better than 10 percent opacity. True or False?	8. zero
	9. False

SESSION 11.
SAFETY: AN IMPORTANT PART OF YOUR JOB

SESSION 11. SAFETY: AN IMPORTANT PART OF YOUR JOB

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SESSION 11.
SAFETY: AN IMPORTANT PART OF YOUR JOB

SESSION GOAL AND OBJECTIVES

GOAL

To familiarize you with steps you can take to prevent job-related injury and disease.

Objectives

Upon completing this session, you should be able to:

1. Name the activities in your job that could expose you to possible injury or disease if you do not take proper precautions;

2. Name the types of containers used for infectious waste;
3. Describe proper waste-handling procedures;

4. List the protective clothing and safety equipment you should wear on the job;

5. Recognize the types of waste that must be discarded in red bags;

6. Name types of materials that should never be fed into an incinerator;
7. Describe the safety precautions to take when charging the incinerator;
8. Describe the safety precautions to take when removing the ash from the incinerator ash compartment;
9. Describe the safety precautions to take when working around the chamber of a mechanical ram feeder, ash conveyor, or incinerator;
10. Recognize the parts of the incinerator around which special precautions are necessary;
11. Name the hazards associated with wet scrubber and fabric filter operation and how to avoid them.

WASTE HANDLING

"RED BAG" WASTE

Hospital infectious wastes usually are discarded in red plastic bags or containers marked with the universal biological hazard symbol. (See Figure 11-1.)

Figure 11-1. The biological hazard symbol.[1]

Listed below are the types of hospital waste that are considered infectious:

- Waste that has been in contact with isolation patients with communicable diseases;
- Microbiological laboratory wastes, including cultures and stocks of infectious agents;
- Blood, blood products, and body fluids;
- Pathological wastes;
- Sharps (needles, laboratory glass wastes, etc.); and
- Human and animal tissue, body parts, and bedding.

POSSIBLE HEALTH AND SAFETY PROBLEMS WITH RED BAG WASTE

- Sharp objects (e.g., needles) might pierce through a bag and pierce your skin.
- Infectious waste might spill onto your skin or clothing if a bag is opened or torn. (See Figure 11-2)
- Airborne micro-organisms might be inhaled.
- Micro-organisms might be swallowed.

HOW TO AVOID THESE PROBLEMS

DO

- Keep bags from tearing or breaking open by:
  -- Handling bags as little as possible.
  -- If necessary, asking hospital management to use:
     Stronger or double bags, and/or
     Cardboard containers or rigid carts to hold bags until they are burned.
- Wear proper protective clothing and safety equipment (See Figure 11-3)
  -- Thick rubber gloves
  -- Hard-soled rubber shoes
  -- Safety glasses
  -- Dust mask
  -- Disposable coveralls or hospital scrubs
- Change clothing and launder daily
- Wash hands with soap after handling waste and before eating or drinking.

DO NOT

- Open bags.
- Crush/compact bags.
- Eat or drink around incinerator.

Figure 11-2. Torn waste bag.

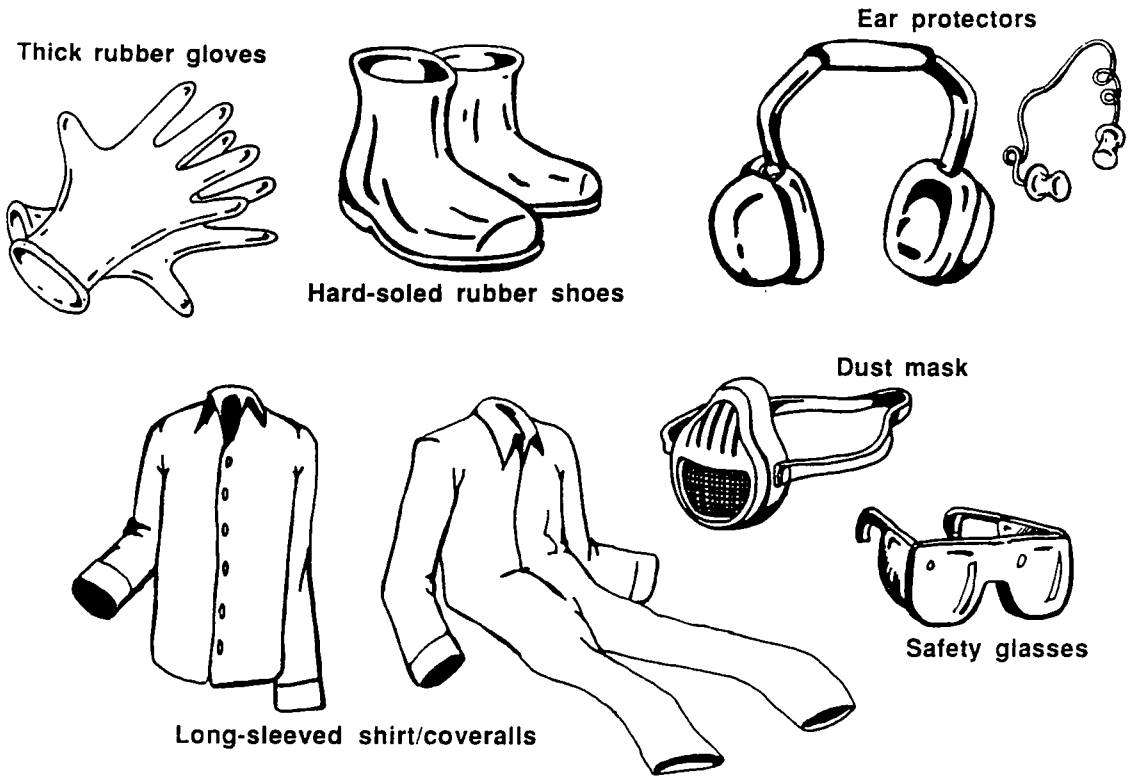

Figure 11-3. Proper safety gear.

INCINERATOR OPERATION

You may face a number of potential hazards in operating a hospital incinerator that can be avoided if you take the proper precautions.

POSSIBLE INJURIES AND SAFETY HAZARDS

- Burns caused by:
  - -- Contact with hot surfaces of incinerator or other equipment
  - -- Careless charging procedures
  - -- Careless ash removal procedures
  - -- Opening inspection ports when incinerator is operating
- Injury caused by:
  - -- Getting too close to moving belts or hydraulic cylinders
  - -- Lack of caution on elevated walkways
- Exposure to air contaminants or lack of oxygen caused by:
  - -- Leak in equipment or ductwork
  - -- Poor ventilation of area

GENERAL SAFETY PRECAUTIONS

DO

- Wear proper protective clothing with no loose flaps, belts, etc., that might get caught on moving mechanical parts
  - Thick rubber gloves
  - Hard-soled rubber shoes
  - Safety glasses
  - Dust mask
  - Disposable coveralls
- Be careful around all moving belts, hydraulic cylinders, and doors
- Avoid contact with hot surfaces of:
  - Incinerator chamber
  - Heat recovery equipment (boiler)
  - Ductwork
  - Stack
- Be on the lookout for fuel (gas/oil) leaks.
- Use caution on elevated walkways and keep your hands on the siderails. Be alert to gaps in the walkway or obstacles you could trip over.
- If you notice unusual odors around an indoor incinerator, open doors or windows to ventilate the room.
- If you develop any of the following symptoms that may indicate contaminated air or lack of oxygen, leave the area immediately:
  - Headache
  - Drowsiness
  - Shortness of breath
  - Nausea
  - Loss of coordination
  - Eye irritation

DO NOT

- Open inspection ports to look into the incinerator during operation.

- Place hands or feet into mechanical chambers of feed ram assembly or ash removal system. These units are often automatically operated. (Allow the Maintenance Department to properly deactivate, lockout, and fix if jams occur.)
- Lean on guardrails for elevated walkways or place your hands on equipment surfaces next to the walkway.

BURNER SAFETY PRECAUTIONS

Auxiliary fuel burners are equipped with flame safeguard systems which control the burner ignition process. The safeguard system is a safety feature designed to:

- Prevent the burner from igniting until it has gone through a purge cycle;
- Shut off the fuel supply if the burner fails; and
- Shut off the fuel supply if the combustion air supply fails.

If the system is not properly purged prior to ignition an explosion could occur.

You should never try and override the flame safeguard system; it is there to protect you.

CHARGING SAFETY PRECAUTIONS

DO

- Wait until previous charge has burned down.
- Be sure the primary chamber burner is off.
- Stand behind and away from the door.

DO NOT

- Look into open charge door.
- Charge bottles containing flammable liquids or explosives.

ASH REMOVAL SAFETY PRECAUTIONS

DO

- Use either
  - The mechanical ash ram or conveyor (if available), or
  - Rakes or flat shovels with handles long enough to reach the back of the compartment.
- Be careful of "hot spots" and sharp objects in the ash.
- Place ash into a noncombustible heat-resistant container (metal) and dampen with water to cool it and to reduce fugitive emissions (dust).

DO NOT

- Enter the incinerator chamber.
- Damage the incinerator refractory with the shovel or rake.
- Spray water into chamber.
- Handle ash directly; if you must pick something up by hand, wear protective gloves.

AIR POLLUTION CONTROL DEVICE OPERATION

The two types of air pollution control devices that you are most likely to find at a hospital incinerator are wet scrubbers and fabric filters. This section contains information about hazards associated with control devices and safety precautions that you should know.

WET SCRUBBERS--POSSIBLE INJURIES AND HAZARDS

- Chemical burns can be caused by the scrubber liquor if it gets on your skin or in your eyes.
- Falls could occur on wet areas around the scrubber caused by leaks in the scrubber vessel, ductwork, or piping.
- Injury could result from getting too close to a fan or fan belt drive assembly, in which clothing could get caught. A vibrating fan could cause the fan assembly to disintegrate, causing serious injury.
- Hearing loss could be caused by the noise of operation of the scrubber.

WET SCRUBBERS--SAFETY PRECAUTIONS

DO

- Avoid contact with scrubber liquor. If it does get on your skin or in your eyes, flush with water for at least 15 minutes, and seek medical attention for eye injuries.
- Know the location of the nearest eyewash and how to use it.
- Be alert for scrubber leaks and potential slippery walkways. Ask maintenance to repair major leaks.
- Stay clear of rotating fan drive shafts where clothing could get caught.
- Stay clear of fan belt drive assembly where clothing could get caught or belts could break.
- Protect your hearing by wearing earplugs or earmuffs.

DO NOT

- Place hand in fan belt/pulley assembly.
- Continue to operate scrubber if fan is severely vibrating; shut down incinerator and call maintenance.

FABRIC FILTERS--POSSIBLE HAZARDS

- Exposure to toxic chemicals could occur when handling dust collected from the fabric filter.
- Exposure to excessive heat will occur if you get too close to or touch the surfaces of the fabric filter. Fabric filters generally operate at about 350°F (180°C).
- Injury could result from getting too close to a fan or fan belt drive assembly in which clothing could get caught. A vibrating fan could cause the fan assembly to disintegrate, causing serious injury.
- Hearing loss could be caused by the noise of the operation of the fabric filter.
- Special hazards are inside the fabric filter, where you may be required to go. However, you should enter a fabric filter ONLY IF YOU HAVE BEEN SPECIFICALLY TRAINED AND EQUIPPED to survive the potential hazards inside. These hazards include the following:
  - -- Toxic gases and dust
  - -- Hot, free flowing solids
  - -- Oxygen deficiency
  - -- High voltage
  - -- Moving mechanical parts

FABRIC FILTERS--SAFETY PRECAUTIONS

DO

- Wear a dust mask to keep from inhaling dust.
- Protect your hearing by wearing earplugs or earmuffs.
- Stay clear of rotating fan drive shafts where clothing could get caught.
- Stay clear of fan belt drive assembly where clothing could get caught or belts could break.
- If you must enter the fabric filter:
  - -- Thoroughly clean bags and hopper with mechanical vibration before entering.
  - -- Purge the incinerator and fabric filter with air to drive out exhaust gases before entering.
  - -- Be sure fan is "locked out".
  - -- Be sure a second person is watching you in case you need help. This person should be trained to go for help if needed and should never enter the fabric filter, too.
  - -- Stay in the fabric filter for as short a time as possible.

DO NOT

- Place hand in fan belt/pulley assembly.
- Continue to operate fabric filter if fan is severely vibrating; shut down incinerator and call Maintenance Department.
- NEVER ENTER FABRIC FILTER UNLESS YOU HAVE BEEN PROPERLY TRAINED AND EQUIPPED.

PROPER PROTECTIVE CLOTHING AND SAFETY EQUIPMENT

To protect yourself from possible injury or exposure to harmful substances, wear the following items when working on a control device:

- Eye protection (safety glasses)
- Hearing protection
- Long-sleeved shirt
- Rubber gloves
- Hard-soled rubber shoes
- Dust mask

REVIEW EXERCISE

1. The reason you need to be especially careful when handling red bag waste is because it might contain one or more of the following things that could be harmful to you.
   a. Human blood and blood products
   b. Pathological wastes
   c. Needles
   d. Explosive chemicals
   e. All of the above
   f. a, b, and c above

2. Hospital infectious waste usually is discarded in red plastic bags or containers marked with which of the following symbols?

   a. The universal biological hazard symbol
   b. A label that says "DANGER-HAZARD"
   c. A picture of a skull and crossbones

3. To help keep waste bags from tearing or breaking open, you should _____ them as little as possible.

4. If a red bag appears to contain a suspicious substance, you should open it to be sure it is okay to put in the incinerator. True or False?

5. Name the proper clothing and equipment you should wear when handling waste.

1. f. a, b, and c above

2. a.

3. handle

4. False. Never open a red bag.

5. Thick rubber gloves
   Hard-soled rubber shoes
   Safety glasses
   Dust mask
   Disposable coveralls

REVIEW EXERCISE

6. To remove the ash from the back of the ash compartment, you should

   a. Go into the chamber and shovel it out.
   b. Use a rake or flat shovel with a handle long enough to reach the back without you having to enter the chamber.
   c. Flush it out with water.

6. b. Use a rake or shovel with a long handle.

7. If you want to look into the incinerator during operation, it is okay to open an inspection cleanout port. True or False?

7. False

8. When operating the incinerator, you should wear thick rubber shoes, safety glasses, and a dust mask. True or False?

8. True

9. Which of the following symptoms may indicate exposure to air contaminants or lack of oxygen?

   a. Headache
   b. Drowsiness
   c. Shortness of breath
   d. Nausea
   e. Loss of coordination
   f. Eye irritation
   g. All of the above
   h. All except b.

9. g. All of the above

REVIEW EXERCISE

10. You should avoid contact with the scrubber liquor because it

    a. Can cause chemical burns to your skin or eyes
    b. Will make you pass out if you smell it
    c. Will give you a fatal skin disease

10. a. Can cause chemical burns to your skin or eyes

Choose from the following words to fill in the blanks below describing the control device safety hazards you should be aware of: noise, toxic chemicals, fans, leaks, fan belt.

11. Vibrating _____

12. _____ in scrubber vessel, ductwork, or piping

13. High _____ levels

14. _____ _____ in the dust from the fabric filters

15. _____ _____ and pully assemblies

16. No special training is required before entering a fabric filter. True or False?

11. fans

12. leaks

13. noise

14. Toxic chemicals

15. Fan belt

(continued)

REVIEW EXERCISE (CONTINUED)

17. Which of the following hazards are associated with the inside of a fabric filter.

    a. Toxic gases and dust
    b. Hot, free flowing solids
    c. Oxygen deficiency
    d. High voltage
    e. Rotating equipment
    f. All of the above
    g. All except d

16. False

17. f. All of the above

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IV

GLOSSARY

14

GLOSSARY

ABSORPTION.[3] The process by which gas molecules are transferred to (dissolved in) a liquid phase.

ACID GASES.[4] Corrosive gases formed during combustion of chlorinated or halogenated compounds, e.g., hydrogen chloride (HCl).

ACTUAL CUBIC FEET PER MINUTE (acfm).[3] A gas flow rate expressed with respect to temperature and pressure conditions.

AIR, DRY.[4] Air containing no water vapor.

ASH.[5] The noncombustible inorganic residue remaining after the ignition of combustible substances.

ASH COMBUSTIBLES. The fraction of combustible organic material remaining in the bottom ash as measured by the loss on combustion technique.

ATOMIZATION.[4] The reduction of liquid to a fine spray.

AUXILIARY FUEL BURNER. Burner in either the primary or secondary chamber fueled by natural gas or fuel oil. Used to maintain temperature if waste has too little heating value.

BAG BLINDING. The loading, or accumulation, of filter cake to the point where capacity rate is diminished.

BAROMETRIC SEAL.[1] A column of liquid used to hydraulically seal a scrubber, or any component thereof, from the atmosphere or any other part of the system.

BOTTOM ASH.[5] The solid material that remains on a hearth or falls through the grate after incineration is completed.

BURN RATE. The total quantity of waste that is burned per unit of time that is usually expressed in pounds of waste per hour.

BURNDOWN PERIOD. The period of time in an incinerator's operating cycle during which no additional waste is charged to the incinerator and the primary combustion chamber temperature is maintained above a minimum temperature (using auxiliary burners as necessary) to facilitate the solid phase combustion of the waste bed.

BURNOUT. A measure of ash quality; it is the percentage of the ash that is inorganic material.

CHARGE RATE. Quantity of waste material loaded into an incinerator over a unit of time but which is not necessarily burned. Usually expressed in pounds of waste per hour.

CHARGING DOOR. The opening through which waste is charged to the incinerator.

CLEANOUT DOOR. Openings in the primary and secondary chamber that are used to remove ash.

CLINKERS.[5] Hard, sintered, or fused pieces of residue formed in an incinerator by the agglomeration of ash, metals, glass, and ceramics.

COCURRENT OR CONCURRENT.[4] Flow of scrubbing liquid in the same direction as the gas stream.

COLLECTION EFFICIENCY.[1] The ratio of the weight of pollutant collected to the total weight of pollutant entering the collector.

COMBUSTION. A thermal process in which organic compounds are broken down into carbon dioxide (CO_2) and water (H_2O).

COMBUSTION AIR.[5] The air used to burn a fuel or waste.

COMBUSTION GAS.[5] The mixture of gases and vapors produced by burning.

CONDENSATION.[1] The physical process of converting a substance from the gaseous phase to the liquid phase via the removal of heat and/or the application of pressure.

CONTROLLED AIR INCINERATION.[5] Incineration utilizing two or more combustion chambers in which the amounts and distribution of air to each chamber are controlled. Partial combustion takes place in the first zone (chamber) and subsequent zones are used to complete combustion of the volatilization gases.

COOLDOWN PERIOD. The period of time at the end of an incinerator's operating cycle during which the incinerator is allowed to cool down. The cooldown period follows the burndown period.

CROSSFLOW.[4] Flow of scrubbing liquid normal (perpendicular) to the gas stream.

CYCLONE.[4] A device in which the velocity of an inlet gas stream is transformed into a confined vortex from which inertial forces tend to drive particles to the wall.

DAMPER.[2] An adjustable plate installed in a duct to regulate gas flow.

DEMISTER.[4] A mechanical device used to remove entrained water droplets from a scrubbed gas stream.

DENSITY.[2] The ratio of the mass of an object to the volume of the object.

DRAFT.[1] A gas flow resulting from pressure difference; for example, the pressure difference between an incinerator and the atmosphere, which moves the products of combustion from the incinerator to the atmosphere. (1) Natural draft: the negative pressure created by the difference in density between the hot flue gases and the atmosphere. (2) Induced draft: the negative pressure created by the vacuum action of a fan or blower between the incinerator and the stack. (3) Forced draft: the positive pressure created by the fan or blower, which supplies the primary or secondary air.

EXCESS AIR. Burning with combustion air supply greater than stoichiometric air requirements.

FIXED CARBON. The nonvolatile organic portion of waste.

FLAME PORT. Opening between the primary chamber and mixing chamber of a multiple chamber incinerator through which combustion gases pass.

FORCED DRAFT. (See Draft).

FUGITIVE EMISSIONS. Emissions not released through a duct or stack such as furnace leaks and wind blown ash.

GRID.[1] A stationary support or retainer for a bed of packing in a packed bed scrubber.

HEADER.[1] A pipe used to supply and distribute liquid to downstream outlets.

HEATING VALUE. The amount of heat that is released when a material is combusted usually expressed as Btu/lb.

HEARTH.[5] The bottom of a furnace on which waste materials are exposed to the flame.

HEAT INPUT. Total energy released from burning; (heating value [Btu/lb]xfeed rate [lb/h]).

HUMIDITY, ABSOLUTE.[2] The weight of water vapor carried by a unit weight of dry air or gas.

HUMIDITY, RELATIVE.[2] The ratio of the absolute humidity in a gas to the absolute humidity of a saturated gas at the same temperature.

INCINERATOR. A thermal device which combusts organic compounds using heat and oxygen.

INDUCED DRAFT FAN.[3] A fan used to move a gas stream by creating a negative pressure. (See Draft).

INFECTIOUS WASTE. Waste capable of producing an infectious disease in humans.

INORGANIC MATERIAL.[5] Chemical substances of mineral origin, not containing carbon to carbon bond.

INTERLOCK. Part of an automatic control system which tie together operation of different incinerator components.

LIQUID-TO-GAS RATIO.[3] The ratio of the liquid (in gallons per minute) to the inlet gas flow rate (in acfm).

LIQUOR.[1] A solution of dissolved substance in a liquid (as opposed to a slurry, in which the materials are insoluble).

MAKEUP WATER.[3] Water added to compensate for water losses resulting from evaporation and water disposal.

MIST ELIMINATOR.[3] Equipment that removes entrained water droplets downstream from a scrubber.

MIXING CHAMBER. Zone in an excess air incinerator between the primary and secondary chamber where combustion gases and secondary combustion air are mixed.

NATURAL DRAFT. (See Draft).

OPACITY.[4] Measure of the fraction of light attenuated by suspended particulate.

OVERFIRE AIR PORT.[5] Point of entry of combustion air introduced above and beyond the fuel or waste bed.

PACKED-BED SCRUBBER.[3] Equipment using small plastic or ceramic pieces, with high surface area to volume ratios for intimate gas/liquid contact for mass transfer.

PARTICLE.[4] Small discrete mass of solid or liquid matter.

PARTICLE SIZE.[4] An expression for the size of liquid or solid particle usually expressed in microns.

PARTICULATE EMISSION.[4] Fine solid matter suspended in combustion gases carried to the atmosphere. The emission rate is usually expressed as a concentration such as grains per dry standard cubic feet (gr/dscf) corrected to a common base, usually 12 percent CO_2.

PARTICULATE MATTER.[4] As related to control technology, any material except uncombined water that exists as a solid or liquid in the atmosphere or in a gas stream as measured by a standard (reference) method at specified conditions. The standard method of measurement and the specified conditions should be implied in or included with the particulate matter definition.

PATHOGENIC. Waste material capable of causing disease.

PATHOLOGICAL WASTE. Waste material consisting of anatomical parts.

PATHOGEN. Organism capable of causing disease, generally a bacteria or virus.

PENETRATION.[4] Fraction of suspended particulate that passes through a collection device.

pH.[1] A measure of acidity-alkalinity of a solution.

PILOT. A burner that is used to ignite waste and auxiliary fuel during startup.

PLUME. Combustion gases exhausted from the stack.

PRESSURE DROP.[3] The difference in static pressure between two points due to energy losses in a gas stream.

PRESSURE, STATIC.[4] The pressure exerted in all directions by a fluid; measured in a direction normal (perpendicular) to the direction of flow.

PRIMARY CHAMBER. Chamber with hearth or grate that receives waste material and in which the waste is ignited.

PRODUCTS OF INCOMPLETE COMBUSTION. Materials other than carbon dioxide, water, and acid gases that are produced when organic materials are burned.

PYROLYSIS. The chemical destruction of organic materials in the presence of heat and the absence of oxygen.

QUENCH.[1] Cooling of hot gases by rapid evaporation of water.

REAGENT. Reactive material used to remove acid gases from the combustion gases.

RED BAG WASTE. As used in this document, red bag waste refers to infectious waste; the name comes from the use of red plastic bags to contain the waste and to clearly identify that the waste should be handled as infectious.

REFRACTORY.[6] Nonmetallic substances used to line furnaces because they can endure high temperatures and resist abrasion, spalling, and slagging.

RESIDENCE TIME. Amount of time the combustion gases are exposed to mixing, temperature, and excess air for final combustion.

RETENTION TIME. Length of time that solid materials remain in the primary chamber.

SATURATED GAS.[1] A mixture of gas and vapor to which no additional vapor can be added, at specified conditions.

SECONDARY COMBUSTION CHAMBER. Component of the incinerator that receives combustion gases from the primary chamber and completes the combustion process.

SIZE DISTRIBUTION.[4] Distribution of particles of different sizes within a matrix of aerosols; numbers of particles of specified sizes or size ranges, usually in micrometers.

SLURRY.[1] A mixture of liquid and finely divided insoluble solid materials.

SMOKE.[4] Small gasborne particles resulting from incomplete combustion; particles consist predominantly of carbon and other combustible material; present in sufficient quantity to be observable independently of other solids.

SPECIFIC GRAVITY.[1] The ratio between the density of a substance at a given temperature and the density of water at 4°C.

SPRAY NOZZLE.[1] A device used for the controlled introduction of scrubbing liquid at predetermined rates, distribution patterns, pressures, and droplet sizes.

STACK.[5] Any chimney, flue, vent, or duct arranged to discharge combustion gases to the air.

STANDARD CUBIC FEET PER MINUTE (scfm).[3] A gas flow rate expressed with respect to standard temperature and pressure conditions.

STARVED-AIR INCINERATION. Controlled air incineration in which the primary chamber is maintained at less than stoichiometric air conditions.

STOICHIOMETRIC AIR. The theoretical amount of air required for complete combustion of waste to CO_2 and H_2O vapor.

STUFF AND BURN. A situation in which the charging rate is greater than burning rate of the incinerator.

THERMOCOUPLE. A thermoelectric device used to measure temperatures.

TRANSMISSOMETER. A monitoring device used to measure combustion gas opacity.

UNDER-FIRE AIR. Combustion air which enters the fuel bed from orifices in the hearth.

VAPOR.[4] The gaseous form of substances that are normally in the solid or liquid state and whose states can be changed either by increasing the pressure or by decreasing the temperature.

VIEW PORT. Sealed glass ports for observing the combustion chamber during operation.

VOLATILE MATTER. That portion of waste material which can be liberated with the application of heat only.

WET BULB/DRY BULB. Wet bulb temperature is indicated by a wet bulb psychrometer and dry bulb temperature is measured by an accurate thermometer. Together, they provide a measure of relative humidity.

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16. ABSTRACT

This document is Volume I of a three-volume training course for operators of hospital waste incinerators. Volume II is the Presentation Slides (EPA 450/3-89-004). Volume III is the Instructor Handbook (EPA 450/3-89-010). This training course was originally prepared by the Control Technology Center for the State of Maryland. The purpose of this course is to provide hospital waste incinerator operators with a basic understanding of the principles of incineration and air pollution control and to identify, generally, good operation and maintenance (O&M) practices. Proper O&M, in addition to reducing air emissions, improves equipment reliability and performance, prolongs equipment life, and helps to ensure proper ash burnout. The course is not intended to replace site-specific, hands-on training of operators with the specific equipment to be operated.

Volume I is narrative in style and can be used as a reference at the completion of the class. Review questions and answers for students are provided at the end of each classroom session. The course includes 11 separate classroom sessions covering topics such as basic combustion principles and incinerator design; air pollution control equipment design, function, operation, and monitoring; incinerator operation; maintenance inspections; typical problems; and State regulations. Volume II contains classroom materials including a copy of the presentation slides so that students can follow along during the class and worksheets that can be completed during the classroom sessions.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
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OPERATION AND MAINTENANCE OF HOSPITAL MEDICAL WASTE INCINERATORS

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OPERATION AND MAINTENANCE OF HOSPITAL MEDICAL WASTE INCINERATORS

EPA Contracts No. 68-02-4395
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DISCLAIMER

This document generally describes the proper operation of a hospital waste incinerator. It is based on EPA's review and assessment of various scientific and technical sources. The EPA does not represent that this document comprehensively sets forth procedures for incinerator operation, or that it describes applicable legal requirements, which vary according to an incinerator's location. Proper operation of an incinerator is the responsibility of the owner and operator.

Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

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This document was prepared by Midwest Research Institute located in Cary, North Carolina. Principal authors were Roy Neulicht, Mark Turner, Dennis Wallace, and Stacy Smith. Participating on the project team for EPA were Ken Durkee and James Eddinger of the Office of Air Quality Planning and Standards, Charles Masser of the Air and Energy Engineering Research Laboratory, James Topsale of Region III, Charles Pratt of the Air Pollution Training Institute, and Justice Manning of the Center for Environmental Research Information. Also participating on the project team were Carl York and William Paul of the Maryland Air Management Administration.

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PREFACE

The hospital medical waste incinerator program was funded as a project of EPA's Control Technology Center (CTC).

The CTC was established by EPA's Office of Research and Development (ORD) and Office of Air Quality Planning and Standards (OAQPS) to provide technical assistance to State and local air pollution control agencies. Three levels of assistance can be accessed through the CTC. First, a CTC HOTLINE has been established to provide telephone assistance on matters related to air pollution control technology. Second, more in-depth engineering assistance can be provided when appropriate. Third, the CTC can provide technical guidance through publication of technical guidance documents, development of personal computer software, and presentation of workshops on control technology matters.

The technical guidance projects, such as this one, focus on topics of national or regional interest that are identified through contact wth State and local agencies. In this case, the CTC became interested in developing a training course for operators of hospital waste incinerators through a request by the State of Maryland. This document was prepared to be used as the basis for development of the training materials. The document also is intended as a technical guide for use by Federal, State, and local agency personnel, hospital waste management personnel, and hospital incinerator operators.

This document provides information on the operation and maintenance (O&M) procedures that should be practiced on hospital waste incinerators and associated air pollution control equipment to minimize air emissions. This document provides only a general overview of proper O&M procedures with the intention of identifying good operating practices. Operators of hospital waste incinerators should have O&M manuals for the manufacturer which provide specific O&M instruction for their equipment. This document should be viewed as a supplement to the manufacturer's O&M recommendations.

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1.0 INTRODUCTION

The main objective of this document is to identify the operation and maintenance (O&M) procedures that should be practiced on hospital waste incinerators and associated air pollution control equipment to minimize air emissions. Proper O&M, in addition to reducing air emissions, improves equipment reliability and performance, prolongs equipment life, and helps to ensure proper ash burnout. This document provides only general guidance on proper O&M procedures with the intention of identifying good operating practices. The operator of a hospital waste incinerator should have O&M manuals from the manufacturer which provide specific O&M instructions for their equipment. This document does not provide such specific instructions, and is not intended to do so. The document is intended as a technical guide for use by Federal, State, and local agency personnel, hospital waste management personnel, and hospital incinerator operators.

The concern about disposal of infectious wastes generated by hospitals is increasing rapidly due to the fear of the spread of viruses such as acquired immune deficiency syndrome (AIDS) and hepatitis B, as well as the concern about exposure to toxic metals and organics. Incineration continues to be an attractive infectious waste disposal option for hospitals encountering high disposal costs, refusal of their waste at treatment and disposal facilities, and tighter regulation. Proper incineration sterilizes pathogenic waste, reduces waste volumes by over 90 percent, and, in some cases, may provide economic benefits through waste heat recovery. Onsite incineration is an attractive option because it reduces handling and transportation of the wastes and because waste heat recovery can have economic advantages for the facility. The need for disposal of infectious wastes and problems associated with such disposal also has spurred the interest in special commercial incineration facilities. In either case, the operating facility must address the problems of air emissions and ash disposal from the incinerator.

Hospital waste incinerators may emit a number of pollutants depending on the waste being incinerated. These pollutants include: particulate matter, acid gases, toxic metals, toxic organic compounds, carbon

monoxide, sulfur oxides, nitrogen oxides, and pathogens and viruses. Proper operation of the incinerator will reduce the emissions of most of these pollutants. Air pollution control devices are available to further control these pollutants.

In response to public concern about hospital incineration, several States recently have enacted or are in the process of enacting regulations which govern the incineration of general hospital wastes and infectious wastes, specifically. These regulations specify emission limits for hospital incinerators, and frequently they also address operating practices related to waste handling and charging, combustor operations, ash characteristics, and ash handling practices. Some of the operating practices that have been specified in these regulations include:

1. Limits on characteristics of wastes charged to the incinerator;
2. Specific requirements for waste packaging and waste charging practices;
3. Combustor temperature limits;
4. Ash burnout levels; and
5. Ash handling and disposal practices.

The combustion efficiency of a hospital waste incinerator and the pollutant removal efficiency of its associated air pollution control equipment ultimately is affected by equipment O&M. Regardless of how well the equipment is designed, poor O&M practices will lead to the deterioration of components and a resultant decrease in both combustion quality and pollutant removal efficiency. In addition, O&M practices impact equipment reliability, on-line availability, continuous compliance with emission limits and operating practice standards, and regulatory agency/source relations. Lack of timely and proper O&M leads to a gradual deterioration in the equipment, which in turn increases the probability of equipment failure and decreases both the reliability and on-line availability of the equipment. Frequent violations of emission limits or operating the facility outside the limits of operating practices established by regulations can result in public complaints, increased frequency of inspection, potential fines for noncompliance, and in some cases, mandatory shutdown until emission problems are solved. Good O&M practices are essential to safe, reliable operation of the facility.

This document summarizes technical information related to the proper operation and maintenance of hospital waste incinerators and associated air pollution control systems. Chapter 2 presents background information on hospital waste incineration systems including a summary of combustion principles and descriptions of the types of incinerators typically used for hospital waste. Chapter 3 presents background information on add-on air pollution control systems for hospital waste incinerators. Chapter 4 identifies key operating parameters and good operating practices for hospital waste incineration and air pollution control systems. Operating parameters which can be monitored and/or automatically controlled also are discussed in Chapter 4. Chapter 5 provides general guidance on the maintenance of incinerators and air pollution control systems. Chapter 6 describes instrumentation which can be used for the control and monitoring of the key operating parameters. Chapter 7 identifies some common operational problems associated with hospital waste incinerators and air pollution control systems; the possible causes and solutions to the problems are discussed. Chapter 8 discusses recordkeeping procedures which can assist in operating and maintaining an incineration system. Chapter 9 provides general safety guidelines, and Chapter 10 presents a glossary of terms.

2.0 HOSPITAL INCINERATION SYSTEMS

2.1 INTRODUCTION

Incineration is the process by which combustible materials are burned, producing combustion gases and noncombustible residue and ash. The product combustion gases are vented directly to the atmosphere or to the atmosphere after treatment in an air pollution control device. The noncombustible ash residue is removed from the incinerator system and is disposed of in a landfill. Incineration provides the advantage of greatly reducing the mass and volume of the waste. This reduction substantially reduces transportation and disposal costs. For infectious hospital wastes, another major objective of the incineration process is the destruction of infectious organisms (pathogens) that may exist in the waste. The destruction of the pathogens is caused by their exposure to the high temperatures which exist within the incinerator. Incineration of hospital wastes also is attractive aesthetically because it destroys organic components of the waste that the community often finds objectionable when wastes are disposed of in landfills.

Two additional objectives achievable through proper operation of hospital waste incinerators are minimizing organic content in the solid residue and controlling atmospheric emissions to acceptable levels. Generally, tight control on organics in the ash, i.e., good burnout, promotes waste reduction and pathogen destruction. Reduction of atmospheric emissions of constituents that are potentially harmful to human health and the environment is a prerequisite to acceptance of hospital incineration as a feasible disposal alternative by the community.

The overall purpose of this technical document is to present information on the operation of hospital waste incineration systems that can contribute to achieving these objectives. This chapter provides background information on the incineration process that will enhance the usefulness of the remainder of the document. It presents information on basic incineration principles and processes and integrates this information to promote an understanding of hospital waste incineration as an overall system.

The hospital waste incineration process can be separated into the following steps:

1. Waste preparation;
2. Waste charging;
3. Waste combustion;
4. Treatment of the combustion gases, (i.e., add-on air pollution control); and
5. Residue ash handling.

Waste heat recovery also may be included as a part of the incinerator system. The incineration process and the major subsystems of an incineration system are depicted in Figure 2-1. An incinerator operates as a system in which all of the process steps mentioned above are interrelated. For example, the charging procedures implemented by the operator will affect how well the wastes burn in the combustion chamber and, consequently, the ash quality. Proper operation of a system requires an understanding of the principles of operation of each of the components and of the interrelationship of those components for a particular system configuration.

The remainder of this chapter presents background information on hospital incineration processes in three parts. Section 2.2 presents fundamental concepts on pathogen destruction and combustion principles. Section 2.3 describes hospital waste characteristics and briefly addresses how these characteristics affect incineration. Section 2.4 describes incineration system components and the different incinerator systems that are used to treat hospital wastes.

2.2 FUNDAMENTAL CONCEPTS RELATED TO HOSPITAL WASTE INCINERATION

An understanding of how an incinerator operates as a system requires familiarity with some basic scientific and engineering principles. This section provides a brief discussion of the key principles related to two basic areas--pathogen destruction and combustion chemistry/physics. The discussions are quite abbreviated and are designed to provide the reader with the basic information needed to understand the remainder of this document; they do not provide complete coverage of the subject areas.

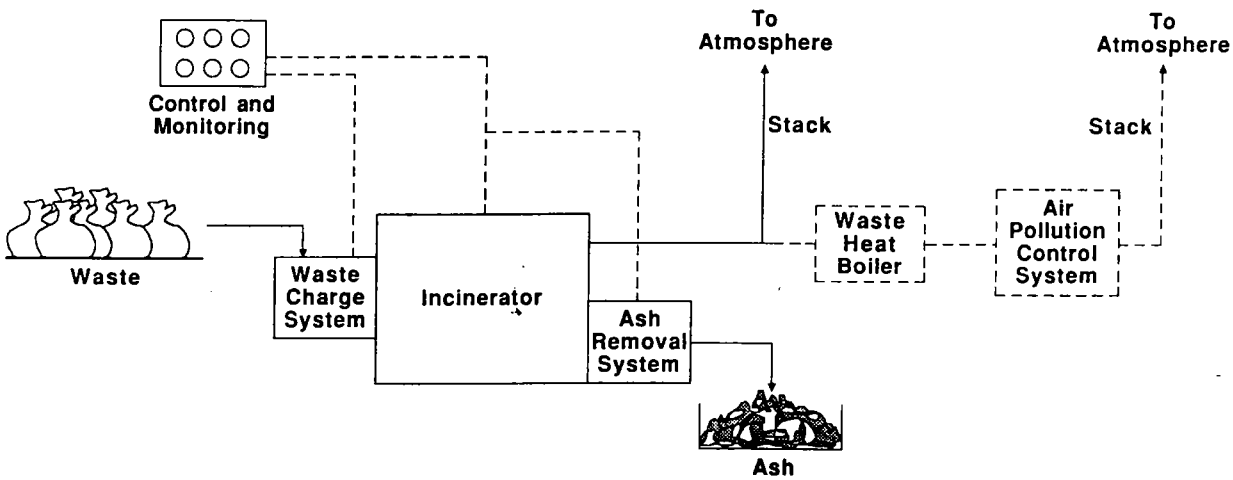

Figure 2-1. Major components of an incineration system.

Those readers desiring more information on these subjects should consult References 1 through 3 on pathogen destruction and References 4 through 8 on combustion.

2.2.1 Pathogen Destruction

The primary objective of hospital waste incineration is the destruction of pathogens in infectious wastes. The U. S. Environmental Protection Agency (EPA) has defined infectious waste as "waste capable of producing an infectious disease . . . . For a waste to be infectious, it must contain pathogens with sufficient virulence and quantity so that exposure to the waste by a susceptible host could result in an infectious disease."[1] Some examples of hospital wastes which may be considered to be infectious are:[1]

1. Microbiological laboratory wastes including cultures and equipment which has come in contact with cultures of infectious agents;
2. Blood and blood products (such as serum, plasma);
3. Sharps, including needles, laboratory glass wastes, and glass pipets;
4. Surgical, autopsy, and obstetrical wastes which have had contact with patient blood or body fluids;
5. Wastes which have had contact with communicable disease isolation wastes;
6. Human and animal tissue containing pathogens with sufficient virulence and quantity so that exposure to the waste by a susceptible human host could result in an infectious disease; and
7. Dialysis unit wastes; i.e., wastes that were in contact with the blood of patients undergoing hemodialysis.

The pathogens in infectious waste can be destroyed by the high temperatures achieved in hospital incinerators. Data on the incinerator conditions required to destroy the universe of pathogens that are present in infectious waste are quite limited, but they do indicate that temperature and time of exposure are important. Emissions of micro-organisms from the incinerator could be attributed to insufficient retention time and temperature as a result of the following conditions:

1. Initial charging of the incinerator before operating temperatures are achieved;

2. Failure to preheat the refractory lining;

3. Temperature fluctuations caused by intermittent use;

4. Exceeding design airflow rates, thereby reducing the retention time;

5. Charging beyond incinerator capacity; and

6. Excessive moisture content of the waste.

Other factors such as the type of refractory lining, the positioning and number of burners, and the precision of temperature controlling devices also can have a significant bearing on the effectiveness of sterilization.[2,3] The destruction of micro-organisms in the incinerator ash also depends on temperature and time exposure.

2.2.2 Principles of Combustion[4-9]

In principle, combustion of hospital waste is a chemical process that is equivalent to combustion of fossil fuels for energy recovery. It is a chemical reaction that involves rapid oxidation of the organic substances in the waste and auxiliary fuels. This violent reaction releases energy in the form of heat and light and converts the organic materials to an oxidized form. Some of the basic principles related to the combustion process are discussed in the following subsections. Specifically, the basic chemical reactions, stoichiometric air requirements, thermochemical relations, and volumetric flows are discussed in the first four subsections. In the last subsection, the combustion process is discussed in general terms, and the role of waste characteristics in that process is outlined.

2.2.2.1 Chemical Reactions. The organic portion of hospital waste consists primarily of carbon (C), hydrogen (H), and oxygen (O). These elements are involved in the reactions that generate most of the energy and the bulk of the combustion gas products that are released during incineration. Other elements found to a lesser degree are metals, sulfur (S), nitrogen (N), and chlorine (Cl). Although these elements are of lesser importance to the main "combustion reaction," they play an important role in potential air pollution problems.

The reaction chemistry in the combustion zone is quite complex and involves a wide variety of organic compounds and free radical species. However, a general understanding of combustion can be achieved by treating these reactions simply as a combination of carbon and hydrogen in the organic material with the oxygen in the combustion air and organic material. These simplified reactions can be represented by the chemical equations:

$$C + O_2 \rightarrow CO_2 + \text{Heat} \qquad (2\text{-}1)$$

$$2H_2 + O_2 \rightarrow 2H_2O + \text{Heat} \qquad (2\text{-}2)$$

When complete combustion occurs, carbon and hydrogen combine with the oxygen of the combustion air to form carbon dioxide (CO_2) and water vapor (H_2O), respectively, as shown above. If incomplete combustion occurs, carbon monoxide (CO) also will be formed.

Available thermodynamic equilibrium data and bench-scale test data indicate that organic chlorine which enters the combustion chamber reacts almost completely to form hydrogen chloride (HCl) and elemental chlorine (Cl_2). Unless the system has very low H:Cl ratios in the feed, almost no Cl_2 is formed.[8] The HCl and any Cl_2 that is formed leave the combustion chamber in vapor phase.

Sulfur that is chemically bound in organic materials making up the hospital waste is oxidized during the combustion process to form sulfur dioxide (SO_2) at a rate directly proportional to the sulfur content of the waste. Some SO_2 may react with alkaline reagents also present in the waste or ash. However, the amount of SO_2 involved in such reactions is expected to be negligible due to the high HCl content of the flue gas. Because it is a stronger acid than SO_2, HCl will react more quickly with available alkaline compounds than SO_2 and will tie up the alkaline compounds before they have a chance to react with SO_2. Consequently, essentially all organic sulfur present in the waste will leave the combustion chamber as vapor phase SO_2.

Nitrogen enters the combustion chamber as a component of the waste and in the combustion air. It can react in the combustion chamber to produce nitrogen oxides (NO_x). The NO_x is formed by one of two general

mechanisms. "Thermal NO_x" is the result of the reaction between molecular nitrogen and molecular oxygen, both of which enter the combustion zone in the combustion air. "Fuel NO_x" results from the oxidation of nitrogen which enters the combustion zone chemically bound within the fuel structure. The rate of thermal NO_x formation is sensitive to the flame temperature. The detailed mechanisms of fuel NOx formation are not well understood, but the formation is not extremely sensitive to temperature.[9]

2.2.2.2 Stoichiometric Combustion Air. The theoretical amount of oxygen required for complete combustion is known as the stoichiometric or theoretical oxygen and is determined by the nature and the quantity of the combustible material to be burned. Combustion oxygen is usually obtained from atmospheric air. The additional oxygen (or air) over and above the stoichiometric amount is called "excess air."

The overall chemical composition (ultimate analysis) of the waste/fuel mixture can be used to calculate the mass-based stoichiometric oxygen requirements with the factors in Table 2-1. Volumetric oxygen requirements can be estimated with the following equation:

$$\dot{Q}_o = \dot{M}_o \cdot K \qquad (2\text{-}3)$$

$\dot{Q}_o$ = volumetric flow of O_2 (scm/h)
$\dot{M}_o$ = Mass flow of O_2 (kg/h)
K = 0.2404 scm O_2/kg O_2 at 20°C and 1 atm.

Total volumetric air requirements can be estimated by multiplying volumetric oxygen requirements by 5.

2.2.2.3 Thermochemical Relations. Thermochemical calculations are used to estimate heat release and heat transfer associated with combustion. These calculations permit determination of the energy released by the combustion process and assessment of the transfer of the energy to the environment. Thermochemical calculations involve determination of fuel (or waste) heating values, heat contents of entering and leaving streams, and any other heat losses. A definition of terms that will be helpful for understanding these calculations is presented below.

Heat of combustion. Heat energy evolved from the union of a combustible substance with oxygen to form CO_2 and H_2O (and SO_2) as the end

TABLE 2-1. STOICHIOMETRIC OXYGEN REQUIREMENTS AND COMBUSTION PRODUCTS YIELDS[10]

Elemental waste component	Stoichiometric oxygen requirement	Combustion product yield
C	2.67 lb/lb C	3.67 lb CO_2/lb C
H_2	8.0 lb/lb H_2	9.0 lb H_2O/lb H_2
O_2	-1.0 lb/lb O_2	
N_2	--	1.0 lb N_2/lb N_2
H_2O	--	1.0 lb H_2O/lb H_2O
Cl_2	-0.23 lb/lb Cl_2	1.03 lb HCl/lb Cl_2
		-0.25 lb H_2O/lb Cl_2
F_2	-0.42 lb/lb F_2	1.05 lb HF/lb F_2
		-0.47 lb H_2O/lb F_2
Br_2	--	1.0 lb Br_2/lb Br_2
I_2	--	1.0 lb I_2/lb I_2
S	1.0 lb/ lb S	2.0 lb SO_2/lb S
P	1.29 lb/lb P	2.29 lb P_2O_5/lb P
Air N_2	--	3.31 lb N_2/lb $(O_2)_{stoich}$

Stoichiometric air requirement = $4.31x(O_2)_{stoich}$.

products, with both the reactants starting and the products ending at the same conditions, usually 20°C (68°F) and 1 atm (29.92 in Hg).

Gross or higher heating value--HV_G or HHV. The quantity of heat evolved as determined by a calorimeter where the combustion products are cooled to 16°C (60°F) and all water vapor is condensed to liquid. Usually expressed in terms of kcal/g or kcal/m^3 (Btu/lb or Btu/scf).

Net or lower heating value--HV_N or LHV. Similar to the higher heating value except that the water produced by the combustion is not condensed but is retained as vapor at 18°C (60°F). Expressed in the same units as the gross heating value.

Enthalpy or heat content. Total heat content, expressed in kcal/g (Btu/lb), above a standard reference condition.

Sensible heat. Heat, the addition or removal of which results in a change of temperature.

Latent heat. Heat associated with a change of phase, e.g., from liquid to vapor (vaporization) or from liquid to solid (fusion), without a change in temperature. Usually expressed as kcal/g (Btu/lb).

Available heat. The quantity of heat available for intended (useful) purposes. The difference between the gross heat input to a combustion chamber and all the losses.

For steady-state operations:

$$\text{Heat in (sensible + HHV)} = \text{Heat out (sensible + latent + available)} \quad (2\text{-}4)$$

Heat is liberated in the combustion process at the rate of 7.8 kcal/g of carbon burned and 34 kcal/g of hydrogen burned (14,100 Btu per pound of carbon burned and 61,000 Btu per pound of hydrogen burned). Alternatively, heat is liberated from the combustion process at a rate that is equal to the product of the mass flow rate of the waste (and auxiliary fuel) and the higher heating value of waste (and fuel). A major latent "heat loss" is the energy required to evaporate moisture in the waste and vaporize organic constituents. The energy required to raise the temperature of the evaporated moisture and any excess air to combustion chamber temperatures is a part of the sensible "heat loss."

Maximum combustion temperatures are attained at stoichiometric conditions. As the amount of excess air is increased above the stoichiometric point, the combustion temperature is lowered because energy is used to heat the combustion air from ambient temperature to the combustion chamber temperature. The greater the volume of the excess air, the greater the "heat loss" due to raising the air temperature. As the amount of excess air is decreased, the combustion temperature increases until it becomes maximum at the stoichiometric point. Below the stoichiometric point, the temperature decreases because complete combustion has not occurred. Since the complete combustion reaction (which is exothermic) has not occurred, the maximum heat is not generated. A graphical representation of the relationship between combustion temperature and excess air level is shown in Figure 2-2.

As the excess-air level increases, the volume of oxygen supplied to the incinerator that is not reacted increases, resulting in a higher oxygen concentration in the effluent gas stream. Since the total amount by weight (kg) of carbon dioxide generated during combustion is based on stoichiometric ratios, it remains constant for a specific quantity of carbon in the waste. However, as the excess-air level increases, the concentration of carbon dioxide in the total combustion gas stream decreases due to dilution from the excess air (oxygen and nitrogen). The oxygen concentration and carbon dioxide concentration of the effluent gas stream are useful indicators of the combustion excess air levels and are useful for monitoring the combustion process.

2.2.2.4 Volumetric Gas Flows. Gas flows through a combustion system and air pollution control system are a major consideration in the design and operation of those systems. Three key principles that are important to understanding the operation of those systems are the relationship of volumetric flow to gas residence time, the volume occupied by compounds (either organic constituents or water) vaporized in the combustion chamber, and the relationship of gas volume to temperature and pressure.

Complete destruction of pathogens and complete combustion of organic constituents require exposure of the materials to high temperatures for minimum residence times. Some State regulations now require a minimum residence time in the secondary combustion chambers, and operators must

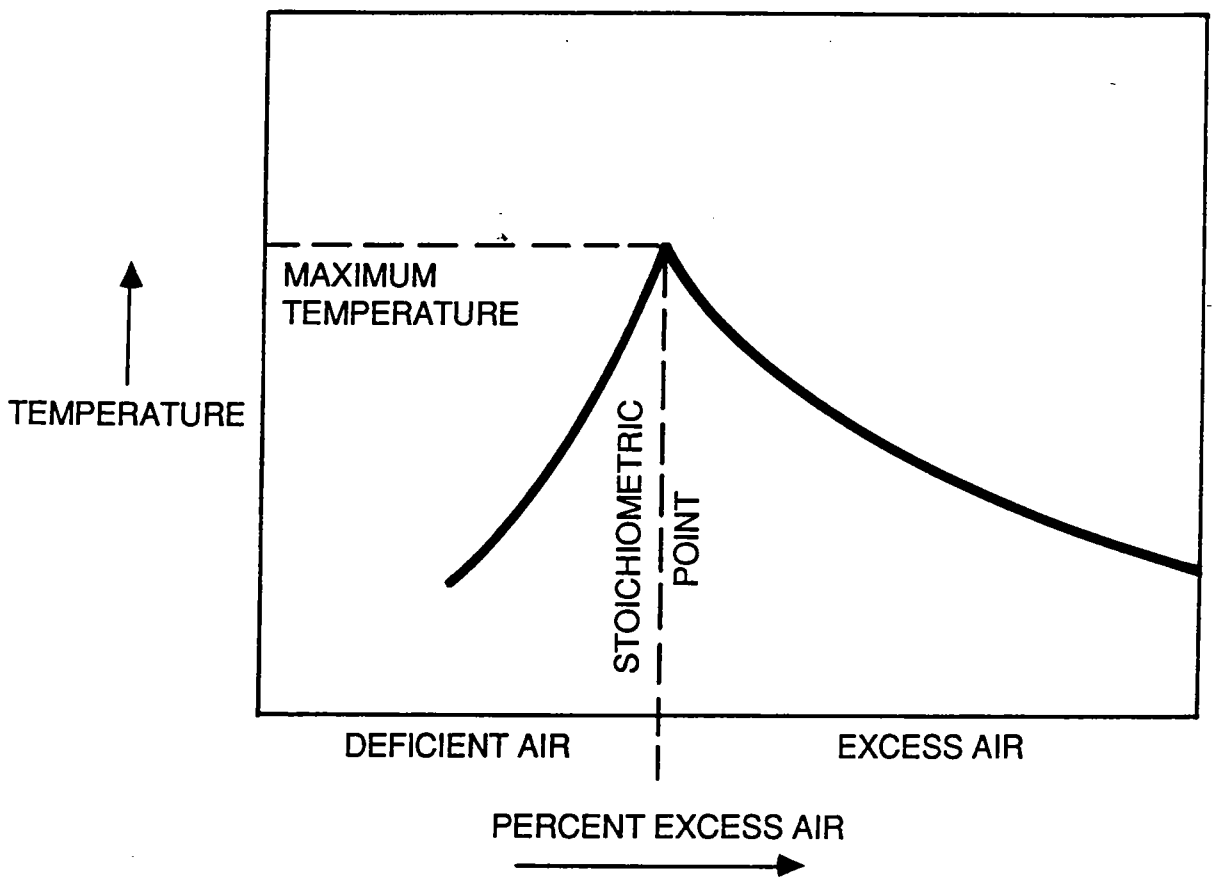

Figure 2-2. Relationship of temperature to excess air.[7]

comply with these requirements. The residence time is a function of chamber volume and volumetric flow rate and can be estimated (plug flow assumed) with the following equations:

$$t = \frac{60\ V}{Q_{gas}} \tag{2-5}$$

$$Q_{gas} \doteq Q_{air} + Q_{H_2O} \tag{2-6}$$

where:

t = residence time, s

V = combustion chamber volume, m^3

Q_{gas} = combustion gas flow rate at combustion chamber conditions, m^3/min

Q_{air} = combustion airflow rate at combustion chamber conditions, m^3/min

Q_{H_2O} = release rate of free moisture from the waste at combustion chamber conditions, m^3/min

These equations assume complete turbulent flow in the combustion chamber and that the volume of combustion gas is approximately equal to the volume of combustion air.

As waste is exposed to high temperatures in the combustion chamber, some materials in that waste are volatilized into the vapor or gas phase. Two issues of particular concern are the volume of water vapor produced by the moisture in the waste and the volume of gas produced by highly volatile organic materials such as solvents that evaporate almost instantly as they are exposed to high temperatures. The volume of gas produced from a given mass of material can be calculated from the equation:

$$V_i = 24.04\ \frac{M_i}{MW_i} \tag{2-7}$$

where:

V_i = volume of compound i at standard conditions, scm

M_i = mass of compound i, kg

MW_i = molecular weight of compound i, g/g mole

This equation estimates volumes at standard conditions, which are defined to be 20°C (68°F) and 1 atm (29.92 in. Hg). The paragraphs below describe how volumes can be estimated for different temperatures and pressures.

The volume that a gas occupies, or the volumetric flow rate of a gas, is dependent on the temperature and pressure of the gas. Estimates of gas volume or gas volumetric flow can be modified to reflect different temperatures or pressures with the equations:

$$V_2 = V_1 \frac{T_2 P_1}{T_1 P_2} \tag{2-8}$$

$$Q_2 = Q_1 \frac{T_2 P_1}{T_1 P_2} \tag{2-9}$$

where:

V_i = volume at condition i, m^3

T_i = temperature at condition i, K (where K = 273+°C)

P_i = absolute pressure at condition i, atm

Q_i = volumetric flow at condition i, m^3/min

2.2.2.5 <u>The Combustion Process</u>. The goal of the combustion process is complete combustion of the organic constituents in the waste feed. Complete combustion requires sufficient air in the combustion chamber, sufficient temperatures in the combustion bed and combustion gas, sufficient time over which materials are exposed to a temperature profile, and mixing that assures good contact of the waste/fuel with the combustion air.

Each organic substance in hospital waste has a characteristic minimum ignition temperature that must be attained or exceeded, in the presence of oxygen, for combustion to occur. Above the ignition temperature, heat is generated at a higher rate than it is lost to the surroundings, and the elevated temperatures necessary for sustained combustion are maintained.

The residence time of a constituent in the high-temperature region should exceed the time required for the combustion of that constituent to

take place. Residence time requirements establish constraints on the size and shape of the furnace for a desired firing rate. Because the reaction rate increases with increasing temperature, a shorter residence time will be required for combustion at higher temperatures if good combustion conditions are present.

Adequate oxygen supplies and turbulence and the resultant mixing of organic materials and oxygen are also essential for efficient combustion. Inadequate mixing of combustible gases and air in the furnace can lead to emissions of incomplete combustion products, even from an otherwise properly sized unit with sufficient oxygen. Turbulence will speed up the evaporation of liquid fuels for combustion in the vapor phase. In the combustion of waste solids, turbulence will help to break up the layer of combustion products formed around a burning particle of waste. Under nonturbulent conditions, the combustion rate is slowed because this layer of combustion products decreases the amount of oxygen that contacts the surface of the particle.

For hospital waste incinerators, the distribution of combustion air between the primary and secondary chambers and the methods used to inject that air to the chamber are key operating considerations. The distribution of air between the two chambers affects the amount of oxygen that is available for reaction in each chamber. (See the discussion of stoichiometry above.) The method of injection of the air to the two chambers is one of the factors that controls turbulence and mixing.

The chemical and physical characteristics of the waste stream also have significant effects on the combustion process and on the composition of the effluents from the process. Generally, wastes can be characterized by a "proximate analysis," which is a laboratory determination of four waste characteristics--volatile matter, fixed carbon, moisture, and ash or noncombustibles. The paragraphs below define these four parameters and describe their effects on the combustion process.

Volatile matter is that portion of the waste which can be liberated (i.e., vaporized) with the application of heat only (i.e., no chemical reaction occurs). Actual combustion of volatile matter is a gas-phase reaction (i.e., the combustion occurs after the material has been vaporized). Key factors that must be considered when volatile matter is

introduced to the combustor are the rate at which the material is vaporized and the ability of the combustor to provide adequate volume and airflow for that release.

Fixed carbon is the nonvolatile carbon portion of the waste and must be burned at higher temperatures and at increased duration of exposure to the combustion air. The combustion of fixed carbon is a solid-phase reaction. An incinerator should be operated with a solids residence time that is sufficient for fixed carbon combustion.

Moisture, which is evaporated from the waste as temperatures of the waste are raised in the combustion chamber, passes through the incinerator, unchanged, as water vapor. Two major impacts that this moisture has on the combustion system are increasing volumetric flow and reducing residence time of the combustion gases. It also absorbs energy and reduces the temperature in the combustor.

Unlike organic constituents, inorganic constituents, specifically metals, are not "destroyed" during the combustion process. Rather, they are distributed or partitioned among the incinerator effluent streams. Metals constituents can leave the combustion chamber as bottom ash or in the combustion gas. The relative distribution of the metals between these streams is based on such factors as the chemical form of the metals charged to the combustor, the localized reaction atmosphere in the combustion chamber, localized chamber temperatures, and localized chamber airflows. Metals that leave the chamber as bottom ash ultimately can reach a land disposal site or can be lost to the atmosphere as fugitive emissions. Metals can leave the combustion chamber in the gas stream either as entrained particulate matter or as a metal vapor. If the metals emissions from an incinerator are of concern, they can be reduced by using an add-on air pollution control system. The efficiency of such a control system will depend on the control system design and operating characteristics and the physical characteristics of the metals, particularly the solid/vapor distribution and the size distribution of the metals that are entrained as particles.

2.3 HOSPITAL WASTE CHARACTERISTICS

Hospital wastes are heterogeneous mixtures of general refuse, laboratory and pharmaceutical chemicals and containers, and pathological wastes. All of these wastes may contain potentially infectious wastes. In some cases, the wastes fired to hospital incinerators also may contain wastes classified as hazardous under the Resource Conservation and Recovery Act (RCRA) or low-level radioactive waste.

General refuse from hospitals is similar to generic wastes from residences and institutions and includes artificial linens, paper, flowers, food, cans, diapers, and plastic cups. Laboratory and pharmaceutical chemicals can include alcohols; disinfectants; antineoplastic agents; and heavy metals, such as mercury. Infectious wastes include isolation wastes (refuse associated with isolation patients); cultures and stocks of infectious agents and associated biologicals; human blood and blood products; pathological wastes; contaminated sharps; and contaminated animal carcasses, body parts, and bedding.[1] Examples of wastes defined as infectious are presented in Table 2-2.[1] In the U.S., infectious wastes are required to be discarded in orange or red plastic bags or containers. Often these "red bag" wastes may contain noncontaminated general refuse discarded along with the infectious waste.

Incinerators are thermal systems; they are designed to operate at a certain heat input (kcal/h or Btu/h). Under the most efficient operating conditions, the heat input rate would be constant at or near the maximum design rate. Furthermore, all of the heat input would come from the waste, with little or no need for auxiliary fuel. The waste characteristics, i.e., heat content and moisture content of the waste being charged to the incinerator, will affect the operator's ability to maintain good combustion conditions in the incinerator without the use of auxiliary fuel.

The chemical and physical characteristics of the different waste materials that are fired to hospital waste incinerators vary widely. A study of hospitals in Ontario provided information on the heating value, bulk density, and moisture content of different waste materials. The results from this study are presented in Table 2-3 (SI units) and Table 2-4 (English units).[2]

TABLE 2-2. EXAMPLES OF INFECTIOUS WASTE[1]

Waste category	Examples[a]
Isolation wastes	• Wastes from patients with diseases considered communicable and requiring isolation • Refer to Centers for Disease Control, Guidelines for Isolation Precautions in Hospitals, July 1983
Cultures and stocks of infectious agents and associated biologicals	• Specimens from medical and pathology laboratories • Cultures and stocks of infectious agents from clinical, research, and industrial laboratories; disposable culture dishes, and devices used to transfer, inoculate and mix cultures • Wastes from production of biologicals • Discarded live and attenuated vaccines
Human blood and blood products	• Waste blood, serum, plasma, and blood products
Pathological waste	• Tissues, organs, body parts, blood, and body fluids removed during surgery, autopsy, and biopsy
Contaminated sharps	• Contaminated hypodermic needles, syringes, scalpel blades, pasteur pipettes, and broken glass
Contaminated animal carcasses, body parts, and bedding	• Contaminated animal carcasses, body parts, and bedding of animals that were intentionally exposed to pathogens

[a]These materials are examples of wastes covered by each category. The categories are not limited to these materials.

TABLE 2-3. CHARACTERIZATION OF HOSPITAL WASTE[2]

Component description	HHV dry basis, kJ/kg	Bulk density as fired, kg/m^3	Moisture content of component, weight %	Heat value as fired, kJ/g
Human anatomical	18,600-27,900	800-1,200	70-90	1,860-8,370
Plastics	32,500-46,500	80-2,300	0-1	32,300-46,500
Swabs, absorbants	18,600-27,900	80-1,000	0-30	13,000-27,900
Alcohol, disinfectants	25,500-32,500	800-1,000	0-0.2	25,500-32,500
Animal infected anatomical	20,900-37,100	500-1,300	60-90	2,090-14,900
Glass	0	2,800-3,600	0	0
Beddings, shavings, paper, fecal matter	18,600-20,900	320-730	10-50	9,300-18,800
Gauze, pads, swabs, garments, paper, cellulose	18,600-27,900	80-1,000	0-30	13,000-27,900
Plastics, PVC, syringes	22,500-46,500	80-2,300	0-1	22,300-46,500
Sharps, needles	140	7,200-8,000	0-1	140
Fluids, residuals	0-23,200	990-1,010	80-100	0-4,640

TABLE 2-4. CHARACTERIZATION OF HOSPITAL WASTE[2]

Component description	HHV dry basis, Btu/lb	Bulk density as fired, lb/ft^3	Moisture content of component, weight %	Heat value as fired, Btu/lb
Human anatomical	8,000-12,000	50-75	70-90	800-3,600
Plastics	14,000-20,000	5-144	0-1	13,900-20,000
Swabs, absorbants	8,000-12,000	5-62	0-30	5,600-12,000
Alcohol, disinfectants	11,000-14,000	48-62	0-0.2	11,000-14,000
Animal infected anatomical	9,000-16,000	30-80	60-90	900-6,400
Glass	0	175-225	0	0
Beddings, shavings, paper, fecal matter	8,000-9,000	20-45	10-50	4,000-8,100
Gauze, pads, swabs, garments, paper, cellulose	8,000-12,000	5-62	0-30	5,600-12,000
Plastics, PVC, syringes	9,700-20,000	5-144	0-1	9,600-20,000
Sharps, needles	60	450-500	0-1	60
Fluids, residuals	0-10,000	62-63	80-100	0-2,000

Hospital waste can vary considerably in composition and consequently in heat content, moisture content, and bulk density. Hospital waste can vary in Btu content from a low value of about 3,400 kJ/kg (1,500 Btu/lb) (primarily low-Btu, high-moisture anatomical waste) to 45,000 kJ/kg (20,000 Btu/lb) (low-moisture, high-heat content plastics such as polyethylene). Because of the potential for a wide range in waste characteristics and the impact of varying waste characteristics on incinerator performance, large volumes of wastes with unusually high or low Btu or moisture contents should be identified so that charging procedures and rates to the incinerator can be adjusted accordingly as described in Chapter 4.0.

The chemical composition of the waste materials also may affect pollutant emissions. Wastes containing metals and plastics are of particular concern. Metals which vaporize at the primary combustion chamber temperature (e.g., mercury) may become metal oxides with particle size distributions primarily in the size range of 1 μm or less. These small particles may become easily entrained and exhausted with the combustion gases with limited capture by conventional air pollution control equipment. Halogenated plastics, such as polyvinyl chloride, will produce acid gases such as HCl. The presence of the chlorinated waste also may contribute to the formation of toxic polycyclic organic material such as dioxins and furans under poor operating conditions.

Some plastics such as polyethylene and polystyrene do not contain significant amounts of halogens and can be incinerated efficiently without major concern for acid gas or toxic pollutant formation. However, the high heating value of these and other plastic materials can cause excessively high temperatures in the primary combustion chamber. The potential for refractory damage, slagging, and clinker formation increases unless charging rates are adjusted or the plastics are mixed with other wastes of lower heat content.

2.4 TYPES OF HOSPITAL WASTE INCINERATOR SYSTEMS

2.4.1 Introduction[7,11,12]

The terminology used to describe hospital waste incinerators that has evolved over the years is quite varied. Multiple names have been used for the same basic types of incinerators, and much of the terminology does not enhance precise definitions that can be used to define good O&M practices. However, most incinerators have been grouped historically into one of three types--"multiple-chamber," "controlled-air," and "rotary kiln."

Most incineration systems installed before the early 1960's were "multiple-chamber" systems designed and constructed according to Incinerator Institute of America (IIA) standards. The multiple-chamber incinerator has two or more combustion chambers. These "multiple-chamber" systems are designed to operate at high excess-air levels and, hence, are often referred to as "excess-air" incinerators. Multiple-chamber, excess-air incinerators are still found at many hospitals. Many of the multiple-chamber incinerators were designed specifically for pathological wastes and are still being used for that purpose. Note that although the term "multiple-chamber" incinerator typically is used to describe this type of excess-air incinerator, the typical controlled-air and rotary kiln units also contain multiple chambers.

The incineration technology that has been installed most extensively for hospital wastes over the last 15 years generally has been "controlled-air" incineration. This technology is also called "starved-air" combustion, "modular" combustion, and "pyrolytic" combustion. The systems are called "controlled air" or "starved air" because they operate with two chambers in series and the first chamber operates at substoichiometric conditions. Similar modular "controlled-air" units which operate with excess-air levels in the primary chamber are also manufactured and sold for combustion of municipal solid waste (MSW); however, these units apparently are not widely used for hospital waste incineration.

Rotary kiln-type incineration systems have been widely used for hazardous waste incineration in the U.S. The rotary kiln has two combustion chambers. The primary chamber is a horizontal rotating kiln

that typically operates with excess air. However, some manufacturers now have rotary kilns designed to operate with a substoichiometric atmosphere in the kiln; these kilns use special seals and air injection schemes.[13] The exhaust gases exit the kiln to a fixed secondary chamber. Rotary kiln incineration technology is being applied to hospital waste incineration at a few locations in the U.S. and Canada.[11]

This historical grouping of incineration types is of some assistance in characterizing how hospital waste incinerators operate, but it is limited because it does not address the complete combustion "system" and how the incinerator is operated. Three important factors which help to characterize the hospital waste incinerator system and its operation are (1) the air distribution to the combustion chambers, (2) the mode of operation and method of moving waste through the system, and (3) the method of ash removal. For hospital waste incinerators, air distribution can be classified based on whether the primary chamber operates under substoichiometric (starved) or excess-air conditions. The mode of operation can be single batch, intermittent duty, or continuous duty. Ash is removed on a batch or a semicontinuous basis. Table 2-5 characterizes the major types of incinerators that are likely to be found at U.S. hospitals with respect to these three factors described above. The remainder of this section describes the types of incinerators as classified in Table 2-5.

2.4.2 Multiple-Chamber Incinerators[14]

Two traditional designs that are used for multiple chamber incinerators are the "in-line hearth" and "retort" hearth. Figure 2-3 depicts the in-line hearth design. For in-line hearth incinerators, combustion gases flow straight through the incinerator, with turns in the vertical direction only (as depicted by the arrows in Figure 2-3). Figure 2-4 depicts the retort hearth multiple-chamber incinerator. In the retort hearth design, the combustion gases turn in the vertical direction (upward and downward) as in the in-line incinerator, but also turn sideways as they flow through the incinerator. Because the secondary chamber is adjacent to the primary chamber (they share a wall) and the

TABLE 2-5. CLASSIFICATION OF HOSPITAL INCINERATORS

Type of incinerator	Air supply[a]	Waste feed	Ash removal
Multiple chamber	Excess	Manual or mechanical batch feed; single or multiple batches per burn	Batch at end of burn
Batch/controlled air	Starved	Batch (manual or mechanical); 1 batch per burn	Batch at end of burn
Intermittent duty controlled air	Starved	Manual or mechanical batch feed; multiple batches per burn	Batch at end of burn
Continuous duty controlled air	Starved	Mechanical continuous or multiple batch feed	Intermittently or continuously during burn
Rotary kiln	Excess	Mechanical semicontinuous or continuous feed	Continuous

[a]Indicates whether primary chamber operates at below (starved) or above (excess) stoichiometric air levels.

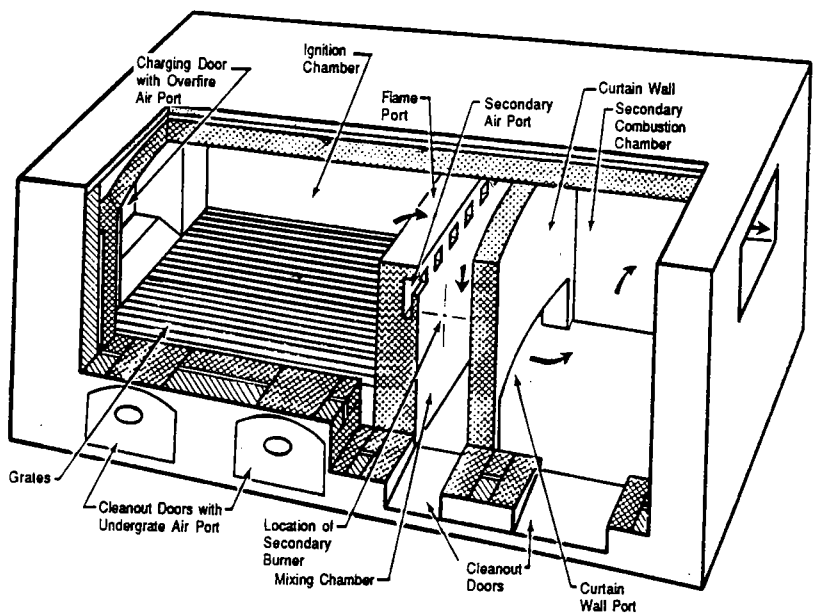

Figure 2-3. In-line multiple-chamber incinerator with grate.[15]

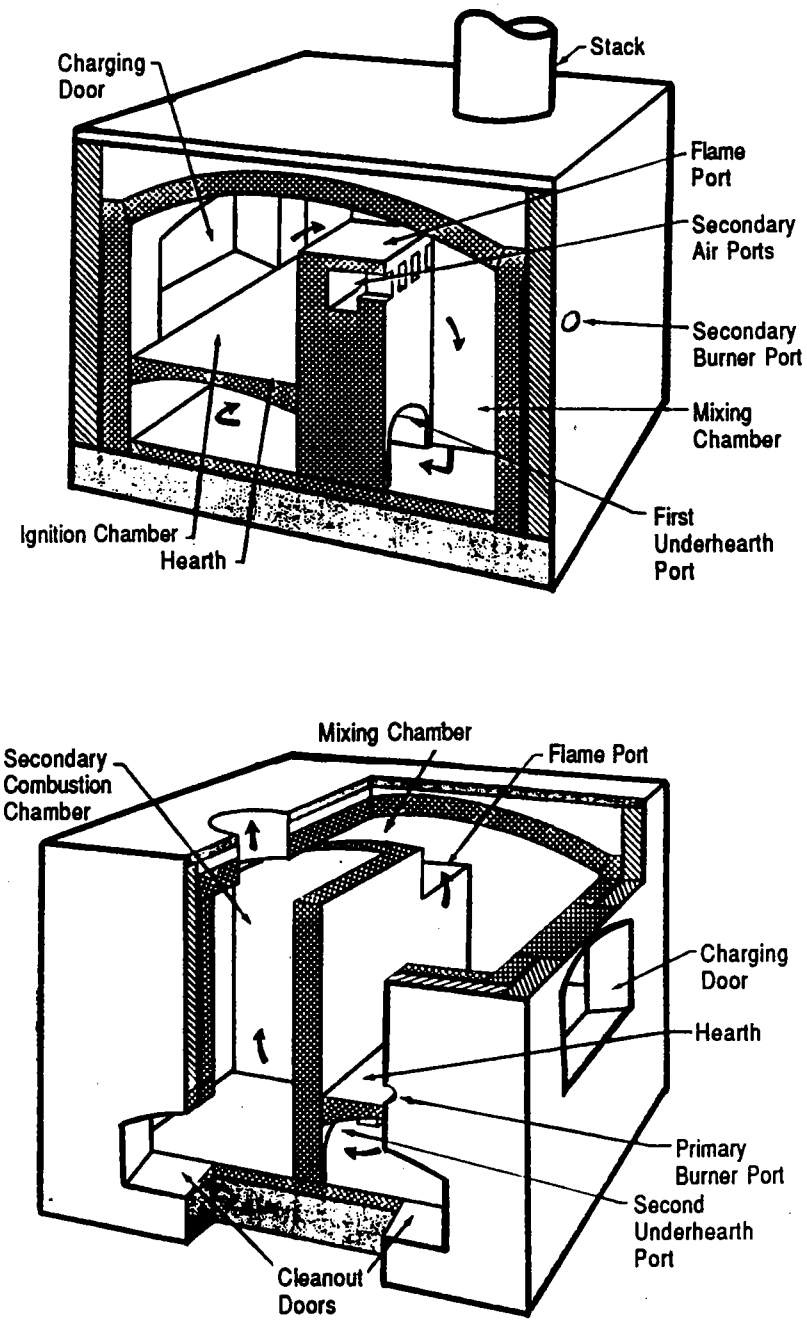

Figure 2-4. Retort multiple-chamber incinerator for pathological wastes.[14]

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gases turn in the shape of a U, the design of the incinerator is more compact. In-line incinerators perform better at capacities greater than 750 lb/h. The retort design performs more efficiently than the in-line design at capacities less than 750 lb/h. The retort design is the most common design used in hospital waste applications.

Multiple-chamber incinerators may have fixed hearths or grates or a combination of the two in the primary chamber. The use of grates for a system incinerating infectious waste is not recommended because liquids, sharps, and small, partially combusted items can fall through the grates prior to complete combustion or sterilization.

Multiple-chamber incinerators frequently are designed and used specifically for incinerating pathological ("Type 4" anatomical) wastes. Pathological waste has a high moisture content and may contain liquids; consequently, a pathological incinerator always will be designed with a fixed hearth. A raised "lip" at the door often is designed into the hearth to prevent liquids from spilling out the door during charging. Because the heating value of pathological waste is low and is not sufficient to sustain combustion, the auxiliary burner(s) provided in the primary chamber of pathological incinerators are designed for continuous operation and with sufficient capacity to provide the total heat input required.

2.4.2.1 Principle of Combustion and Air Distribution. Combustion in the multiple-chamber incinerator occurs in two (or more) combustion chambers. Both chambers are operated with excess air (thus these units often are referred to as "excess-air" incinerators). Ignition of the waste, volatilization of moisture, vaporization of volatile matter, and combustion of the fixed carbon (solid-phase combustion) occur in the primary chamber. The combustion gases containing the volatiles exit the primary chamber through a flame port into a mixing chamber and then pass into the secondary combustion chamber. Secondary air is added into the flame port and is mixed with the combustion gas in the mixing chamber. A secondary burner is provided in the mixing chamber to maintain adequate temperatures for complete combustion as the gases pass into and through the secondary combustion chamber.

The incinerator is designed for surface combustion of the waste which is achieved by predominant use of overfire combustion air and limiting the amount of underfire air in the primary chamber. Multiple-chamber, excess-air incinerators operate with an overall excess-air range of 300 to 600 percent.[14] In older units, combustion air typically was provided by natural draft via manually adjusted dampers and air in-leakage through doors. Newer multiple-chamber incinerators often use forced-draft combustion air blowers to provide the combustion air to the combustion chambers.[15]

2.4.2.2 Mode of Operation. Multiple-chamber incinerators typically are designed for single batch or intermittent-duty operation. That is, this type of incinerator typically does not have an automatic, continuous ash removal system which would make continuous operation possible. Consequently, the incinerator must be shut down at routine intervals (for example, daily) for ash removal, and the incinerator is operated "intermittently."

2.4.2.3 Waste Feed Charging Systems. Waste feed charging to multiple-chamber units is typically done manually. The waste is loaded into the primary chamber through the open charging door. Mechanical charging systems, such as hopper/ram-feed systems also may be used.[15] (Hopper/ram-feed systems are discussed in the next section.)

2.4.2.4 Ash Removal Systems. For the typical multiple-chamber incinerator, ash is removed manually after the incinerator is shut down. The charging and/or ash cleanout doors are opened, and either a rake or shovel is used to remove the ash.

2.4.2.5 Use of Multiple-Chamber Incinerators for Incinerating Hospital Wastes. The use of multiple-chamber, excess-air incinerators for incineration of red-bag wastes has several drawbacks. First, operating in the surface-combustion excess-air mode in the primary chamber results in entrainment of fly-ash which can cause excessive particulate matter emissions. Second, since the incinerator is designed to operate with the primary chamber in an excess-air mode, the combustion air levels and the combustion rate within the primary chamber are not easily controlled. Consequently, the incinerator control system may not provide a sufficient level of control to assure complete combustion when waste composition and

volatile content of the waste fluctuates over a wide range. Red bag wastes are not homogeneous and may vary widely in volatile content and moisture content. Third, operating with high levels of excess air is less energy efficient because it requires auxiliary fuel usage to maintain secondary combustion chamber temperatures.

Multiple-chamber, excess-air incinerators are better suited to incineration of pathological wastes than red bag wastes because the consequences of the above-mentioned drawbacks are not as severe for pathological wastes.[2] The volatile content of pathological waste is low, and in general, the waste composition is not highly variable. The primary burner provides most of the heat input and the incinerator operates in a steady, constant mode with a steady, consistent combustion air input and excess-air level.

In some cases, older multiple-chamber incinerators may be upgraded to include more modern technology. Recently, some older multiple-chamber units have been retrofitted so that the incinerator operates with substoichiometric air levels in the primary chamber; in essence, these units have been converted into the controlled-air units discussed in the next section.[15]

2.4.3 Controlled-Air Incinerators

2.4.3.1 Principle of Controlled-Air Incineration.[16] The principle of controlled-air incineration involves sequential combustion operations carried out in two separate chambers. Figure 2-5 is a simplified schematic of an incinerator that operates on the controlled-air principle. The primary chamber (sometimes referred to as the ignition chamber) accepts the waste, and the combustion process is begun in a below stoichiometric oxygen atmosphere. The amount of combustion air to the primary chamber is strictly regulated ("controlled"). The combustion air usually is fed to the system as underfire air. Three processes occur in the primary chamber. First, the moisture in the waste is volatilized. Second, the volatile fraction of the waste is vaporized, and the volatile gases are directed to the secondary chamber. Third, the fixed carbon remaining in the waste is combusted. The combustion gases containing the

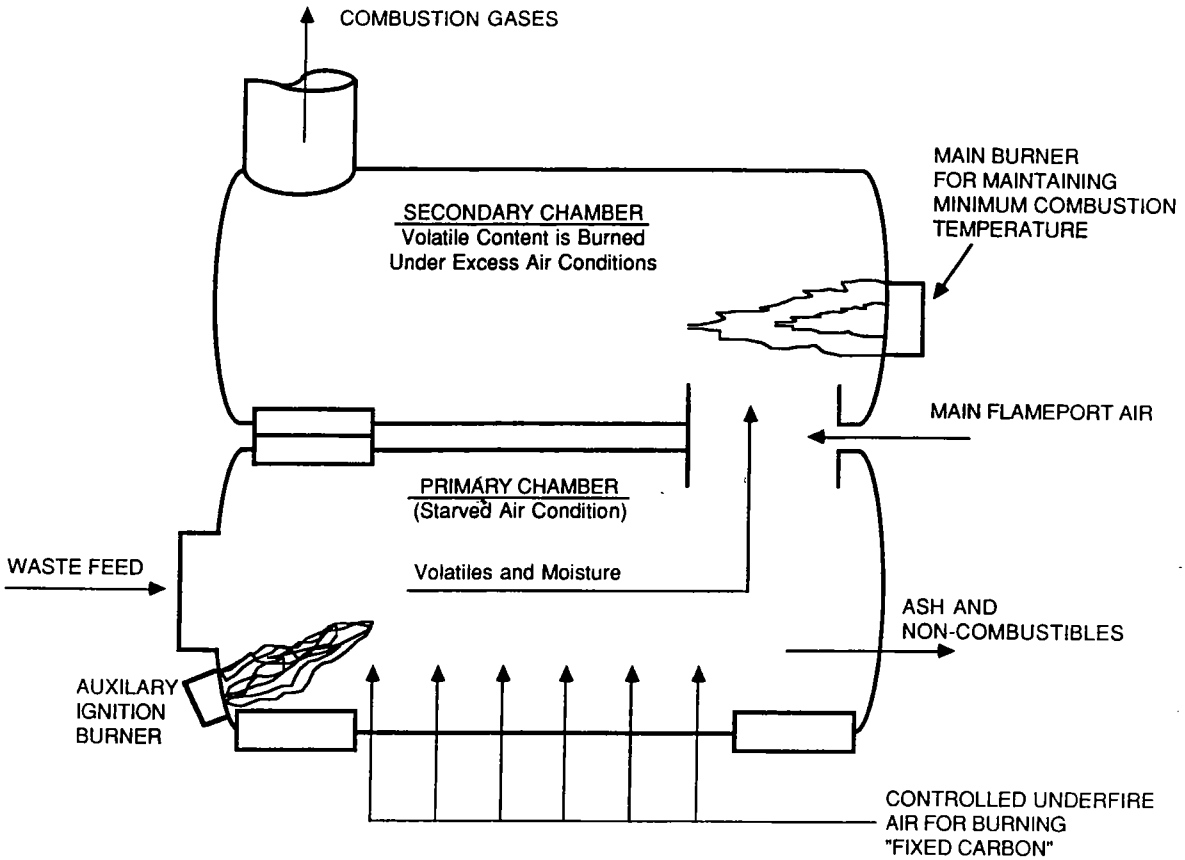

Figure 2-5. Schematic of a controlled-air incinerator.[16]

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volatile combustible materials from the primary chamber are directed to the secondary chamber (sometimes referred to as the "combustion chamber"). There, the combustion air is regulated to provide an excess-air combustion condition and is introduced to the chamber in such a manner as to produce turbulence and promote good mixing of the combustion gases and combustion air. This gas/air mixture is burned, usually at high temperatures. The burning of the combustion gases under conditions of high temperature, excess oxygen, and turbulence promotes complete combustion.

Combustion control for a controlled-air incinerator is usually based on the temperature of the primary (ignition) and secondary (combustion) chambers. Thermocouples within each chamber are used to monitor temperatures continuously; the combustion air rate to each chamber is adjusted to maintain the desired temperatures. Systems operating under controlled-air principles have varied degrees of combustion air control. In many systems, the primary and secondary combustion air systems are automatically and continuously regulated or "modulated" to maintain the desired combustion chamber temperatures despite varying waste composition and characteristics (e.g., moisture content, volatile content, Btu value).[11] In other systems (particularly batch or intermittent-duty systems), the combustion air level control is simplified and consists of switching the combustion air rate from a "high" to a "low" level setting when temperature setpoints are reached or at preset time intervals.

The controlled-air technique has several advantages. Limiting air in the primary chamber to below stoichiometric conditions prevents rapid combustion and allows a quiescent condition to exist within the chamber. This quiescent condition minimizes the entrainment of particulate matter in the combustion gases, which ultimately are emitted to the atmosphere. High temperatures can be maintained in a turbulent condition with excess oxygen in the secondary chamber to assure complete combustion of the volatilized gases emitted from the primary chamber. The temperature of the secondary chamber can be maintained in the desired range (hot enough for complete combustion but not hot enough to cause refractory damage) by separately controlling the excess-air level in the secondary chamber; as the excess-air level is increased, the temperature decreases. Second,

control of the primary chamber combustion air to below stoichiometric levels maintains primary chamber temperatures below the melting and fusion temperatures of most metals, glass, and other noncombustibles, thereby minimizing slagging and clinker formation.

For the controlled-air incinerator, the capacity of the secondary combustion chamber dictates (i.e., limits) the burning rate; the combustion chamber must have adequate volume to accept and completely oxidize all the volatile gases generated in the primary chamber and to maintain sufficient combustion air so that excess oxygen is available.

2.4.3.2 Batch/Controlled-Air Incinerators.[11] In this type of unit, the incinerator is charged with a single "batch" of waste, the waste is incinerated, the incinerator is cooled, and the ash residue is removed; the cycle is then repeated. Incinerators designed for this type of operation range in capacity from about 50 to 500 lb/h. In the smaller sizes, the combustion chambers are often vertically oriented with the primary and secondary chambers combined within a single casing. Figure 2-6 is a schematic of a controlled-air incinerator intended for batch operation.[17] This unit's combustion chambers are rectangular in design and are contained within the same casing.

Batch/controlled-air units can be loaded manually or mechanically. For the smaller units up to about 300 lb/h, manual waste feed charging typically is used. Manual loading involves having the operator load the waste directly to the primary chamber without any mechanical assistance. For a batch-type unit, one loading cycle per day is used. The incinerator is manually loaded; the incinerator is sealed; and the incineration cycle is then continued through burndown, cooldown, and ash removal without any additional charging. Ash is removed manually at the end of the cycle by raking or shoveling the ash from the primary chamber.

2.4.3.3 Intermittent-Duty, Controlled-Air Incinerators. The charging procedures of an incinerator that could operate in single batch mode often are varied to include multiple charges (batches) during the 12- to 14-hour operating period before final burndown is initiated. These intermittent-duty units typically operate in the 50 to 1,000 lb/h range. The intermittent charging procedure allows the daily charge to the incinerator to be divided into a number of smaller charges that can be

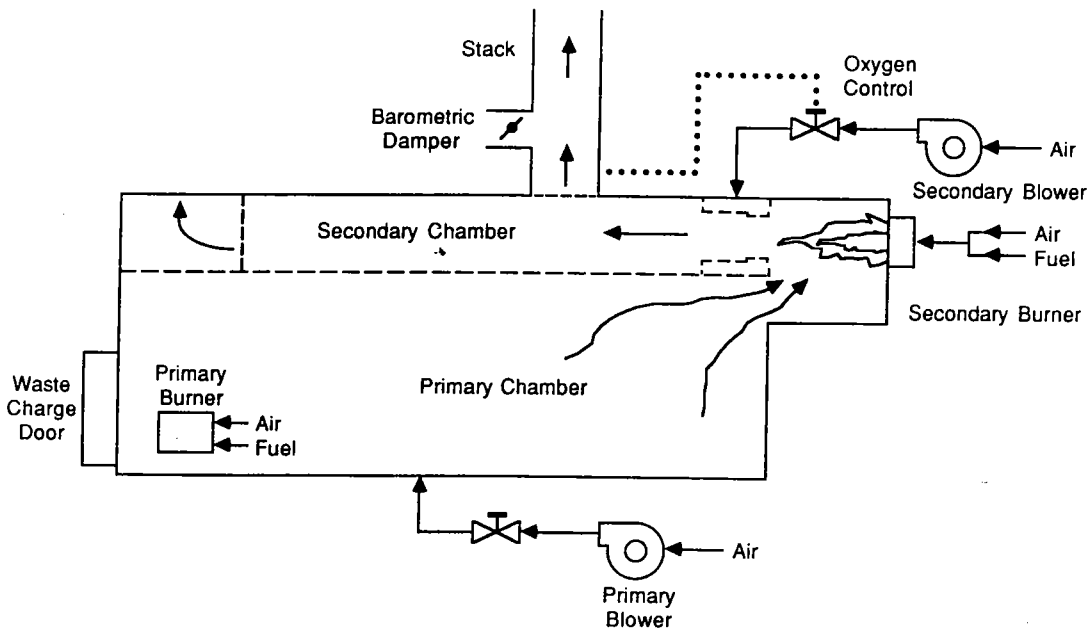

Figure 2-6. Schematic of a single batch controlled-air incinerator.[17]

introduced over the combustion cycle. Consequently, a more uniform gas stream is fed to the secondary chamber. Figure 2-7 is a schematic of a controlled-air incinerator which is intended for intermittent-duty operation. This unit has a vertically oriented primary chamber followed by a horizontal combustion chamber. This unit, although not shown with a mechanical feeder, can be fitted with a hopper/ram assembly.

A typical daily operating cycle for a controlled-air, intermittent-duty-type incinerator is as follows:

Operating step	Typical duration
1. Cleanout of ash from previous day	15 to 30 minutes
2. Preheat of incinerator	15 to 60 minutes
3. Burndown	2 to 4 hours
4. Cooldown	5 to 8 hours

For intermittent-duty operation, the daily waste loading cycle of the incinerator is limited to about an 8- to 14-hour period. The waste loading period is limited by the amount of ash the primary chamber can physically hold prior to shutting down the unit for ash removal. The remainder of the 24-hour period is required for burndown of the ash, cooldown, ash cleanout, and preheat.

For smaller units, the waste often is fed manually. For units in the 300 to 500 lb/h range, mechanical waste feed systems often are employed, and for units above 500 lb/h, mechanical waste feed systems typically are employed. The typical mechanical waste feed system is a hopper ram assembly. Figure 2-8 is a schematic of a typical hopper ram assembly.[20] In a mechanical hopper/ram feed system, waste is manually placed into a charging hopper, and the hopper cover is closed. A fire door isolating the hopper from the incinerator opens, and the ram moves forward to push the waste into the incinerator. The ram reverses to a location behind the fire door. After the fire door closes, the ram retracts to the starting position and is ready to accept another charge. A water spray to quench the ram face as it retracts typically is provided. The entire charging sequence normally is timed and controlled by an automatic sequence. The cycle can be started manually by the operator or, in some systems, the cycle is automatically started on a predetermined basis.

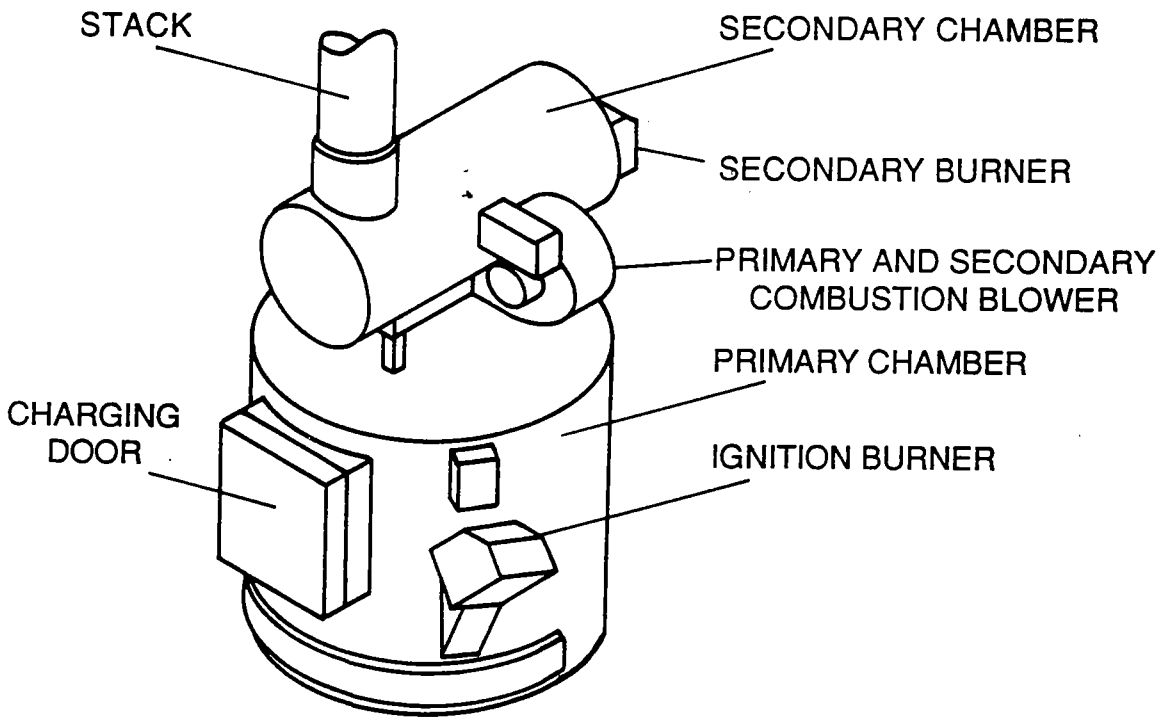

Figure 2-7. Example intermittent-duty, controlled-air incinerator .[19]

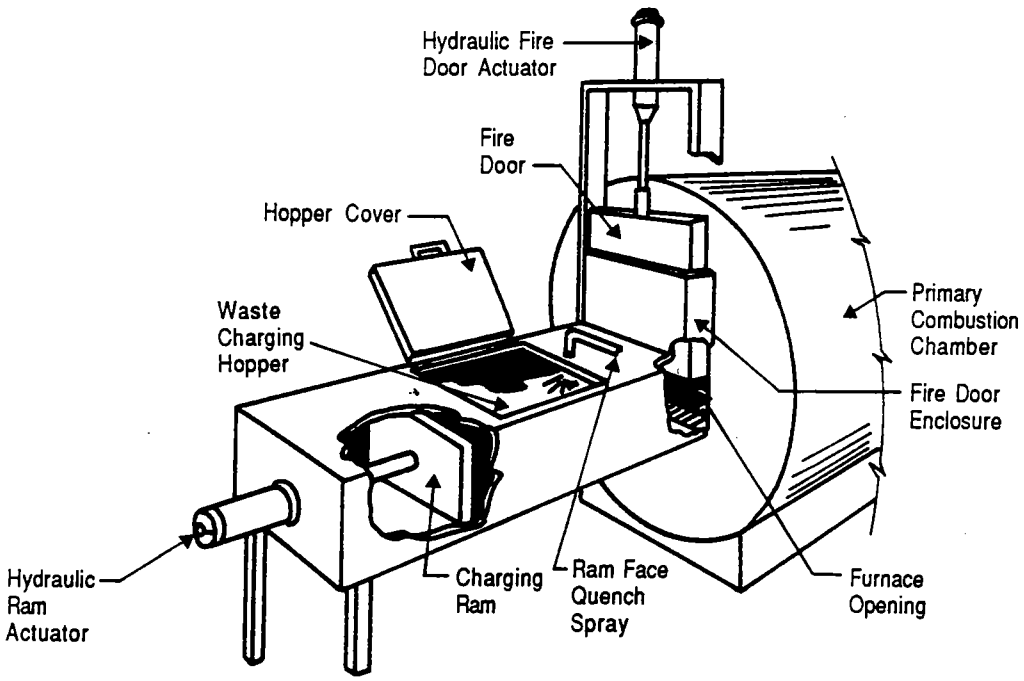

Figure 2-8. Hopper/ram mechanical waste feed system.[20]

Mechanical loading systems have several advantages. First, they provide added safety to the operating personnel by preventing heat, flames, and combustion products from escaping the incinerator during charging. Second, they limit ambient air infiltration into the incinerator. This assists in controlling the combustion rate by strictly controlling the quantity of available combustion air. Third, they facilitate charging the incinerator with smaller batches of waste at regulated time intervals.[11]

With intermittent-duty incinerators, ash removal is a limiting factor for the incinerator operations. As with the single batch-operated units, the ash is removed at regular intervals (typically daily) after the incinerator has gone through a cooldown cycle. The ash usually is manually removed by raking and/or shoveling from the primary chamber.

2.4.3.4 Continuous-Duty, Controlled-Air Incinerators. Controlled-air units intended for continuous operation are available in the 500 to 3,000 lb/h operating range. Continuous-duty, controlled-air units operate according to the controlled-air principles of the systems described earlier. However, continuous operation requires a mechanism for automatically removing ash from the incinerator hearth. The ash must be moved across the hearth, collected, and removed from the combustion chamber.

Continuous-duty units typically have mechanical waste feeding systems. For large continuous-duty units, the charging sequence may be fully automatic. The incinerator can be automatically charged with relatively small batches (in relation to the primary chamber capacity) at frequent, regulated time intervals. The use of frequent, small charges promotes relatively stable combustion conditions and approximates steady-state operation. For large systems, the mechanical charging system may include waste loading devices such as cart dumpers, which automatically lift and dump the contents of carts that are used to collect and contain the waste, into the charge hoppers. Use of these loading devices reduces the operator's need to handle infectious waste and, consequently, further improves worker safety.

For smaller units, the mechanical waste feed charging ram is sometimes used to move the ash across the hearth. As a new load is pushed

into the incinerator, the previous load is pushed forward. Each subsequent load has the same effect of moving the waste across the hearth. The waste should be fully reduced to ash by the time it reaches the end of the hearth. For larger systems, one or more special transfer rams are provided to move the waste across the hearth. Figure 2-9 depicts a continuous-duty, controlled-air incinerator with a stepped hearth and multiple ash transfer rams.[21] The use of the stepped hearth promotes "mixing" the ash bed as the ash is moved from hearth to hearth and, consequently, promotes improved solid-phase combustion.

Typically, when the ash reaches the end of the hearth, it drops off the end of the hearth into a discharge chute. One of two methods for collecting ash is usually used. The ash can discharge directly into an ash container positioned within an air-sealed chamber or sealed directly to the discharge chute. When the container is full, it is removed from the chamber and replaced with an empty ash container. The second method is for the ash to discharge into a water pit. The water bath quenches the ash, and it also forms an air seal with the incinerator. A mechanical device, either a rake or a conveyor, is used to remove the ash from the quench pit intermittently or continuously. The excess water is allowed to drain from the ash as it is removed from the pit, and the wetted ash is discharged into a collection container.[11]

2.4.4 Rotary Kilns

A rotary kiln also utilizes two-stage combustion and has two combustion chambers. Figure 2-10 is a simplified schematic of a rotary kiln. The primary combustion chamber is a rotating cylindrical chamber which is slightly inclined from the horizontal plane; hence, the name "rotary kiln." The secondary chamber often is cylindrical in shape and oriented horizontally much like the secondary chambers described for controlled-air incinerators, or it may be box-like as depicted in Figure 2-11.

2.4.4.1 Principle of Operation. The rotating kiln is inclined at an angle determined during design of the system. Waste is fed to the higher end of the kiln by a mechanical feed system. Typically, combustion

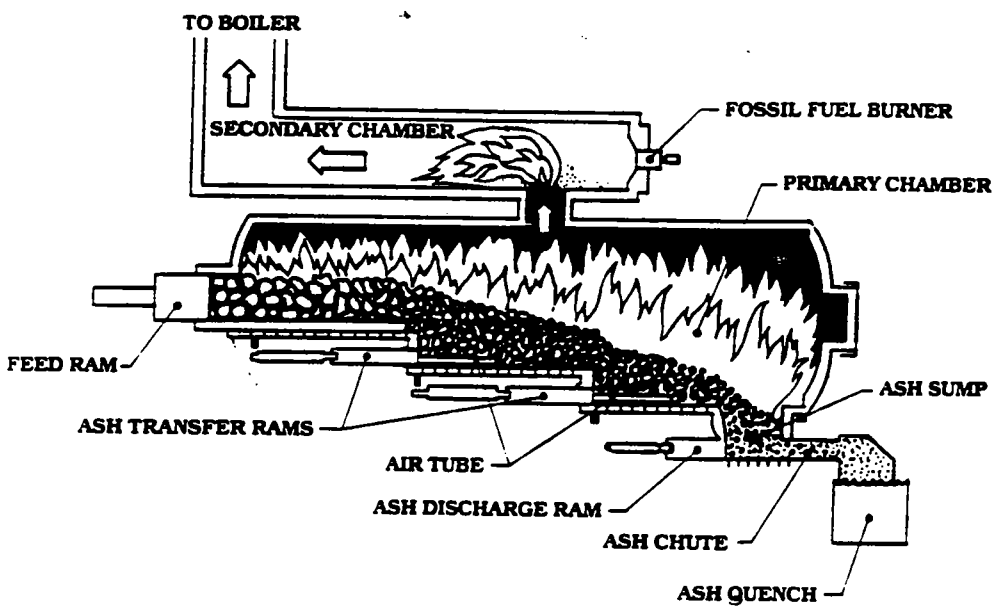

Figure 2-9. Incinerator with step hearths and automatic ash removal.[21]

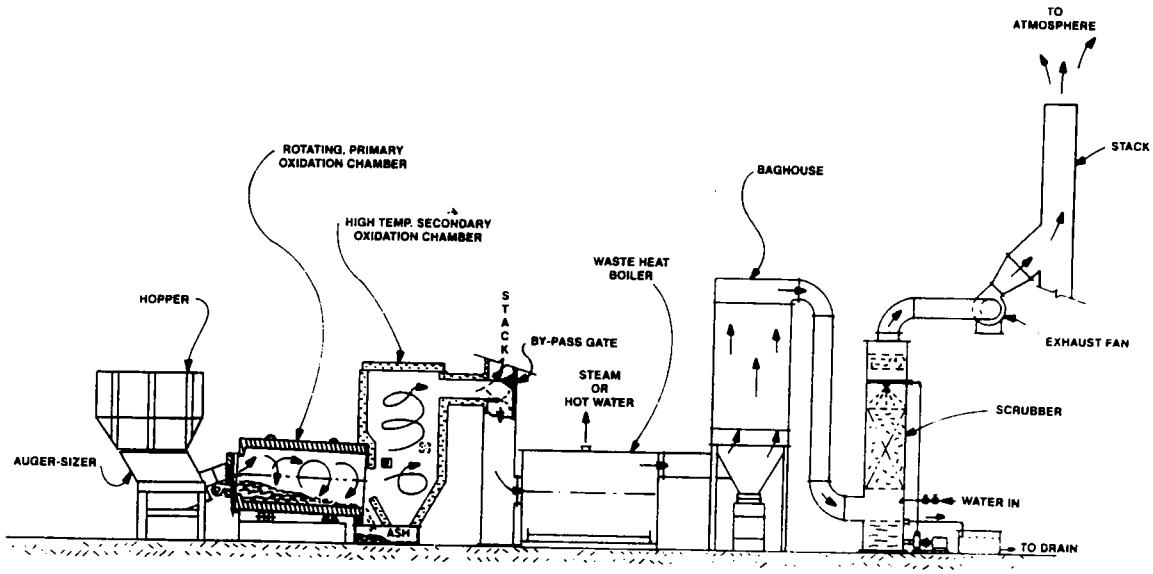

Figure 2-10. Rotary kiln with auger feed.[22]

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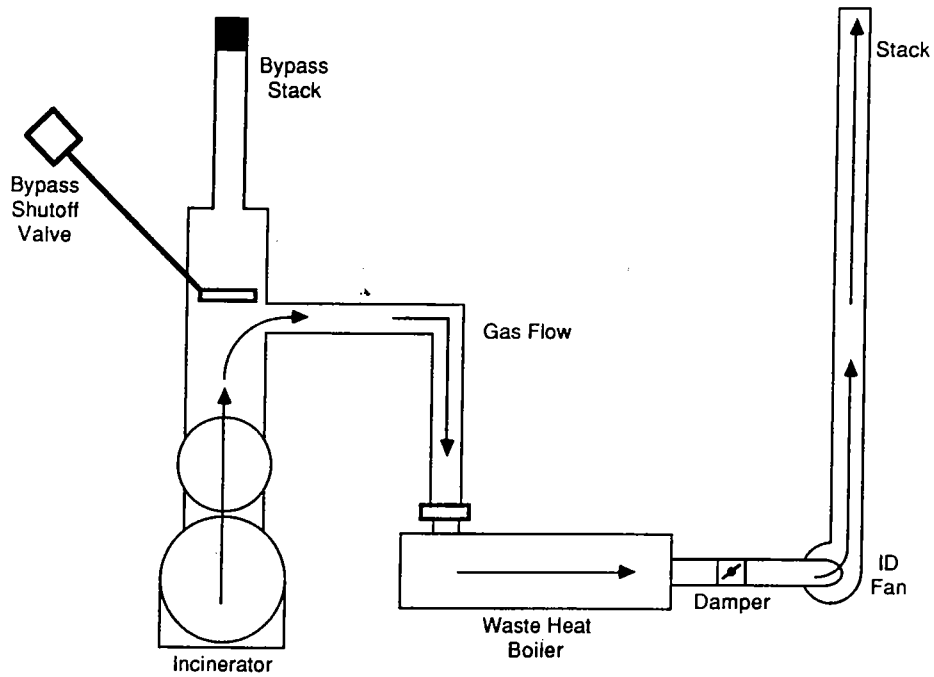

Figure 2-11. Incinerator with waste heat boiler and bypass stack.

air is provided to the kiln such that an excess-air atmosphere exists. However, some manufacturers now have rotary kilns designed to operate with a substoichiometric atmosphere in the kiln; these kilns use special seals and air injection schemes. Running the kiln substoichiometric decreases kiln sizes required and reduces auxiliary fuel usage in the secondary chamber. Inside the kiln, moisture and volatiles are vaporized from the waste, and the waste is ignited. An auxiliary burner provided in the kiln maintains the desired combustion temperature if sufficient heat input is not available from the waste. As the kiln rotates, the solids are tumbled within the kiln and slowly move down the incline toward the discharge end. The turbulence of the waste within the kiln provides exposure of the solid waste to the combustion air. Combustion of the solids occurs within the kiln, and the residue ash is discharged from the end of the kiln into an ash removal system.

The volatile gases pass into the secondary chamber where combustion of the gases is completed. A secondary burner is used to maintain the secondary chamber temperature, and secondary combustion air is added to the chamber as necessary to maintain the desired excess-air level.

2.4.4.2 Mode of Operation. Since the solid waste continuously moves down the length of the rotating kiln, the incineration system is designed to operate in a continuous mode with a semicontinuous or continuous waste feed input. Consequently, a rotary kiln typically has a mechanical waste feed system and a system for continuous ash removal.

2.4.4.3 Charging System. The waste feed system must provide waste to the kiln in a continuous or semicontinuous manner. One manufacturer that provides rotary kiln incinerators for hospital waste applications uses an auger-feeder system to feed the waste continuously to the kiln.[22] Waste is fed to the feed hopper, and the auger-feeder continuously discharges the waste from the bottom of the hopper to the kiln.

The hopper/ram feed system of the type previously described also has been used for feeding rotary kilns (particularly in hazardous waste incineration applications).

2.4.4.4 Ash Removal. As the kiln rotates, the ash is continuously discharged from the end of the kiln. A system for collecting the ash and continuously or semicontinuously removing the ash is required. Automated

ash removal systems such as those previously described for the continuous-duty, controlled-air incinerators are used.

2.4.5 Auxiliary Equipment

2.4.5.1 Waste Heat Boilers. Incinerator manufacturers often provide waste heat boilers as an option to their incineration units. Waste heat boilers are used in conjunction with a hospital waste incinerator to generate steam or hot water for use in the hospital. The combustion gases from the incinerator pass through the waste heat boiler prior to being emitted to the atmosphere via the stack. Use of a waste heat boiler requires that an induced draft fan be added to the system. Furthermore, incinerators equipped with waste heat boilers have a system for diverting the combustion gases directly to the atmosphere and bypassing the boiler. This bypass system is required for safety (for example, to avoid excessive pressures in the incinerator should the fan cease operation) and for normal operation if demand for waste heat is low (so the boiler can be taken off line). Typical systems include either a second "bypass" stack before the waste heat boiler or a breeching directly connecting the incinerator to the stack and bypassing the boiler. Figure 2-11 is a schematic of a controlled-air unit with waste heat recovery.[16]

2.4.5.2 Auxiliary Waste Liquid Injection. Incinerators also may include the capability to inject liquid wastes into the primary chamber. Generally liquid waste incineration is accomplished through either an atomizing nozzle or burner assembly in the primary chamber. Wastes such as used solvents can be readily incinerated via liquid injection.

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3.0 AIR POLLUTION CONTROL

3.1 INTRODUCTION

Hospital incinerators are potentially significant sources of air pollutants. Pollutants of concern from hospital incinerators include particulate matter; toxic metals; toxic organics; carbon monoxide (CO); and the acid gases, hydrogen chloride (HCl), sulfur dioxide (SO_2), and nitrous oxides (NO_x). Emission rates of these pollutants can be limited by removing pollutant generating materials from the waste feed material, proper operation of the incinerator, and add-on pollution control equipment. The objectives of this Chapter are to describe the factors affecting formation and generation of the pollutants and to identify and discuss control strategies that can be used to control the pollutant. Section 3.2 will describe the factors affecting pollutant formation and generation including the effects of waste feed composition. Section 3.3 will discuss air pollution control strategies.

3.2 POLLUTANT FORMATION AND GENERATION

The pollutants of concern from hospital incinerators either exist in the waste feed material or are formed in the combustion process.

Particulate matter. Particulate matter emissions from the combustion of hospital wastes are determined by three factors: (1) suspension of noncombustible materials, (2) incomplete combustion of combustible materials, and (3) condensation of vaporous materials. The ash content of the waste feed material is a measure of the noncombustible portion of the waste feed and represents those materials which will not burn under any conditions in the incinerator. Emissions of noncombustible materials result from the suspension or entrainment of ash by the combustion air added to the primary chamber of the incinerator. The more air added, the more likely that noncombustibles will become entrained. Particulate emissions from incomplete combustion of combustible materials result from improper combustion control of the incinerator. Condensation of vaporous materials results from noncombustible substances that volatilize at

primary combustion chamber temperatures with subsequent cooling in the flue gas. These materials usually condense on the surface of other fine particles.

Toxic metals. Particulate metal emissions are dependent on the metals content of the feed material. Metals may exist in the waste as parts of discarded instruments or utensils, in plastics, paper, pigments, and inks, or as discarded heavy metals used in laboratories. Many metals are converted to oxides during combustion and are emitted primarily as submicron to micron size particles. Metals that volatilize at primary combustion chamber temperatures may selectively condense on small, difficult to control particles in the incinerator flue gas. Metals generally thought to exhibit fine-particle enrichment are arsenic (As), cadmium (Cd), chromium (Cr), manganese (Mn), nickel (Ni), molybdenum (Mo), lead (Pb), antimony (Sb), selenium (Se), vanadium (V), and zinc (Zn).[1]

Toxic organics. Organic material found in the waste feed material theoretically can be completely combusted to form water (H_2O) and carbon dioxide (CO_2). However, incomplete combustion will result in emissions of organics found in the waste feed and in the generation of new organic species from complex chemical reactions occurring in the combustion process. When chlorine is available in the form of PVC plastic materials, these organics can include highly toxic chlorinated organics, such as dioxins and furans. Combustion conditions that favor increased particulate matter emissions due to incomplete combustion also favor increased organic emissions.

Carbon monoxide (CO). As noted above, complete combustion of organic material will result in the formation of H_2O and CO_2. The concentration of CO in the incinerator exhaust gas stream is an indicator of the combustion efficiency of the unit. The formation of CO is dictated by the oxygen concentration in the incinerator, the degree of mixing of the fuel and air, and the temperature of the gases. Carbon monoxide is an intermediate product of the reaction between carbonaceous fuels and oxygen. Combustion conditions that result in incomplete combustion will produce CO as well as particulate matter and organics.

Acid gases. The principal acid gas of concern from hospital incinerators is HCl. The determining factor in HCl formation and emission

is the availability of chlorine in the feed material. In the presence of available hydrogen, as would exist in highly organic hospital wastes, most of the available chlorine will be converted to HCl. Sulfur dioxide generation is similar to HCl; most of the sulfur in the wastes will be converted to SO_2 during combustion irregardless of incinerator design or operation.

Nitrogen enters the combustion chamber as a component of the waste and in the combustion air. It can react in the combustion chamber to produce NO_x.

3.3 CONTROL STRATEGIES

Formation and generation of all of the pollutants discussed above are dependent on either the availability of certain materials in the waste feed or on the efficiency of the combustion process. Removing problem materials from the waste feed and improving combustion efficiency are, therefore, two control strategies for reducing pollutant emissions. If pollutants are formed and generated, add-on pollution control equipment represents a third control strategy for emissions reduction. Table 3-1 presents the control strategies that can be effective for each of the pollutants of concern.

3.3.1 Controlling Feed Material

Controlling feed material consists of either establishing procedures that eliminate the use of certain materials, specifying segregation of certain wastes at the point of origin, or removing problem materials from the waste material prior to incineration. Obviously, eliminating the use of certain materials or establishing segregation procedures are more feasible. The substitution of nonchlorinated plastics (e.g., polyethylene) for PVC, where possible, would reduce the chlorine input to the incinerator. Materials that could be segregated from waste to be incinerated include noncombustible fine dust and powders that could contribute to particulate matter emissions, heavy metals from dental clinics or laboratories, PVC plastics that contribute to HCl formation, and other chlorine- or sulfur-containing materials.

TABLE 3-1. CONTROL STRATEGIES FOR AIR POLLUTANTS FROM HOSPITAL WASTE INCINERATORS

Pollutants	Control strategy		Add-on pollution control equipment			
	Controlling feed material	Combustion control	Venturi scrubber[a]	Packed-bed scrubber[b]	Fabric filter	Dry scrubber
Particulate matter	X	X	X	c	X	
Toxic metals	X		X	c	X	
Toxic organics		X	c	c		c
Carbon monoxide		X				
Hydrogen chloride	X		c	X		X
Sulfur dioxide	X		c	X		X
Nitrous oxides	X	X				

[a]Venturi scrubber with water as the scrubbing media.
[b]Packed-bed scrubber utilizing an alkaline sorbent.
[c]Will achieve some limited control but not designed for high-efficiency collection.

3.3.2 Combustion Control

Complete combustion of combustible material requires adequate temperatures, excess air, turbulence, mixing, and retention time. Because of the variability in hospital waste with respect to heating values, moisture contents, etc., incinerator operating parameters should be varied with the variations in the waste to maximize combustion. In general, higher temperatures, excess air rates, mixing, and retention time result in improved combustion and lower emissions of particulate matter, organics, and CO. However, as these factors are increased there is an economic penalty in auxiliary fuel costs and energy loss. In addition, combustion control has little or no effect on emissions of HCl and SO_2. In both cases, most of the chlorine and sulfur will be converted to HCl and SO_2 under the entire range of combustion conditions which normally occur in a hospital incinerator. As opposed to the other pollutants, both NO_x and toxic metal emissions can actually be increased by combustion adjustments that increase temperatures and excess air rates. Therefore, the waste feed composition should be considered before making adjustments to control combustion.

3.3.3 Add-On Air Pollution Control Systems

Add-on air pollution control systems (APC's) used on hospital incinerators are usually wet scrubbers, fabric filters, or dry scrubbers. Wet scrubbers, in their various designs, are used to remove particulate matter as well as HCl and SO_2; fabric filters are used to remove particulate matter; dry scrubbers are used to remove HCl and SO_2.

3.3.3.1 Wet Scrubbers. Venturi, spray tower, and packed-bed scrubbers are the most common types of wet scrubber systems used on hospital incinerators. Venturi scrubbers are used primarily for particulate matter control and packed-bed scrubbers are used primarily for acid gas control. However, both types of systems achieve some degree of control for both particulate matter and acid gases. A third scrubber type is spray towers. Spray towers are used to remove particulate matter; however, they are relatively inefficient for the removal of fine

particulate matter. These units are not effective for controlling particulate emissions from controlled-air incinerators and are used exclusively on multiple-chamber units which can emit significant quantities of large particles. There are other scrubber types with potential application to hospital waste incinerators including (but not limited to) the wet ionizing scrubber, the collision scrubber, and the Hydro-sonic® steam ejector scrubber.[3,4] Hydro-sonic® scrubber uses supersonic steam ejector drives to accelerate the injected water droplets and provide mixing. The Hydro-sonic® scrubbers are reported to offer high efficiency on fine particulate emissions at relatively low energy costs where there is a source of waste heat for steam production. Use of these scrubbers is not widespread on hospital waste incinerators. Detailed operation and maintenance information for these units controlling hospital waste incinerators is not readily available, and they will not be discussed in this document.

Wet scrubbing principles.[2] Wet scrubbers capture relatively small dust particles with large liquid droplets. Droplets are produced by injecting liquid at high pressure through specially designed nozzles, by aspirating the particle-laden gas stream through a liquid pool, or by submerging a whirling rotor in a liquid pool. These droplets collect particles by using two primary collection mechanisms--impaction and diffusion.

In a wet scrubbing system, dust particles will tend to follow the streamlines of the exhaust stream. However, when liquid droplets are introduced into the exhaust stream, particles cannot always follow these streamlines as they diverge around the droplet (Figure 3-1). The particle's mass causes it to break away from the streamlines and impact on the droplet. Impaction is the predominant collection mechanism for scrubbers having gas stream velocities greater than 0.3 m/s (1 ft/s). Most scrubbers operate with gas stream velocities well above 0.3 m/s. Therefore, at these velocities, particles having diameters greater than 1.0 micrometer (μm) are collected by this mechanism.

Very small particles (less than 0.1 μm in diameter) experience random movement in an exhaust stream. These particles are so tiny that they are bumped by gas molecules as they move in the exhaust stream. This bumping,

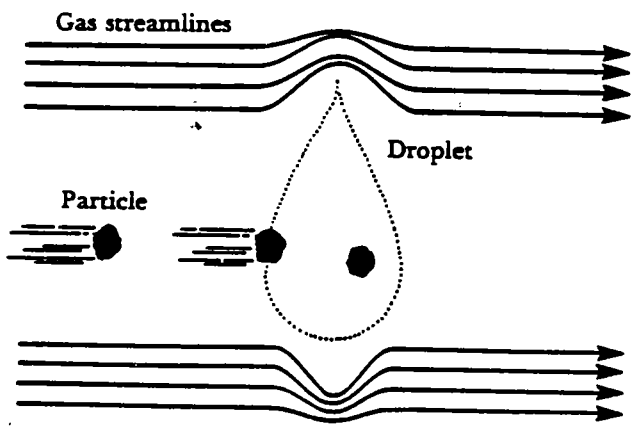

Figure 3-1. Impaction.[5]

or bombardment, causes them to move first one way and then another in a random manner, i.e., diffuse, through the gas. This irregular motion can cause the particles to collide with a droplet and be collected.

The rate of diffusion depends on relative velocity, particle diameter, and liquid-droplet diameter. As with impaction, collection due to diffusion increases with an increase in relative velocity (liquid- or gas-phase input) and a decrease in liquid-droplet size. However, collection by diffusion increases as particle size decreases. This mechanism enables certain scrubbers to remove the very tiny particles effectively.

The process of dissolving gaseous pollutants in a liquid is referred to as absorption. Absorption is a mass-transfer operation in which mass is transferred as a result of a concentration difference. Absorption continues as long as a concentration differential exists between the liquid and the gas from which the contaminant is being removed. In absorption, equilibrium depends on the solubility of the pollutant in the liquid.

To remove a gaseous pollutant by absorption, the exhaust stream must be passed through (brought in contact with) a liquid. Three steps are involved in absorption. In the first step, the gaseous pollutant diffuses from the bulk area of the gas phase to the gas-liquid interface. In the second step, the gas moves (transfers) across the interface to the liquid phase. This step occurs extremely rapidly once the gas molecules (pollutant) arrive at the interface area. In the third step, the gas molecule(s) diffuses into the bulk area of the liquid, thus making room for additional gas molecules to be absorbed. The rate of absorption (mass transfer of the pollutant from the gas phase to the liquid phase) depends on the diffusion rates of the pollutant in the gas phase (first step) and in the liquid phase (third step).

To enhance gas diffusion, and, therefore, absorption:

1. Provide a large interfacial contact area between the gas and liquid phases;

2. Provide good mixing of the gas and liquid phases (turbulence); and

3. Allow sufficient residence, or contact, time between the phases for absorption to occur.

Venturi scrubbers. A venturi scrubber consists of a liquid sprayed upstream from a vessel containing a converging and diverging cross-sectional area as illustrated in Figure 3-2. The portion of the venturi which has the minimal cross-sectional area and consequently the maximum gas velocity is commonly referred to as the throat. The throat can be circular as shown in Figure 3-2 or rectangular as shown in Figure 3-3. As the gas stream approaches the venturi throat, the gas velocity and turbulence increases. Liquid droplets serve as the collection media and can be created by two different methods. The most common method is to allow the shearing action of the high gas velocity in the throat to atomize the liquid into droplets. The other method is to use spray nozzles to atomize the liquid by supplying high pressure liquid through small orifices.

To attain a high collection efficiency, venturi scrubbers need to achieve gas velocities in the throat in the range of 10,000 to 40,000 feet per minute. These high gas velocities atomize the water droplets and create the relative velocity differential between the gas and the droplets to effect particle-droplet collision. The effectiveness of a venturi scrubber is related to the square of the particle diameter and the difference in velocities of the liquor droplets and the particles.

The performance of a venturi scrubber is strongly affected by the size distribution of the particulate matter. For particles greater than 1 to 2 μm in diameter, impaction is so effective that penetration is quite low. However, penetration of smaller particles, such as the particles in the 0.1 to 0.5 μm range is very high. Unfortunately, small particle size distribution is typical for fuel combustion sources including hospital waste incinerators and results from the condensation of partially combusted organic compounds and metallic vapors.

The particulate matter collection efficiency in a venturi scrubber system increases as the static pressure drop increases. The static pressure drop is a measure of the total amount of energy used in the scrubber to accelerate the gas stream and to atomize the liquor droplets. The pressure drop across the venturi is a function of the gas

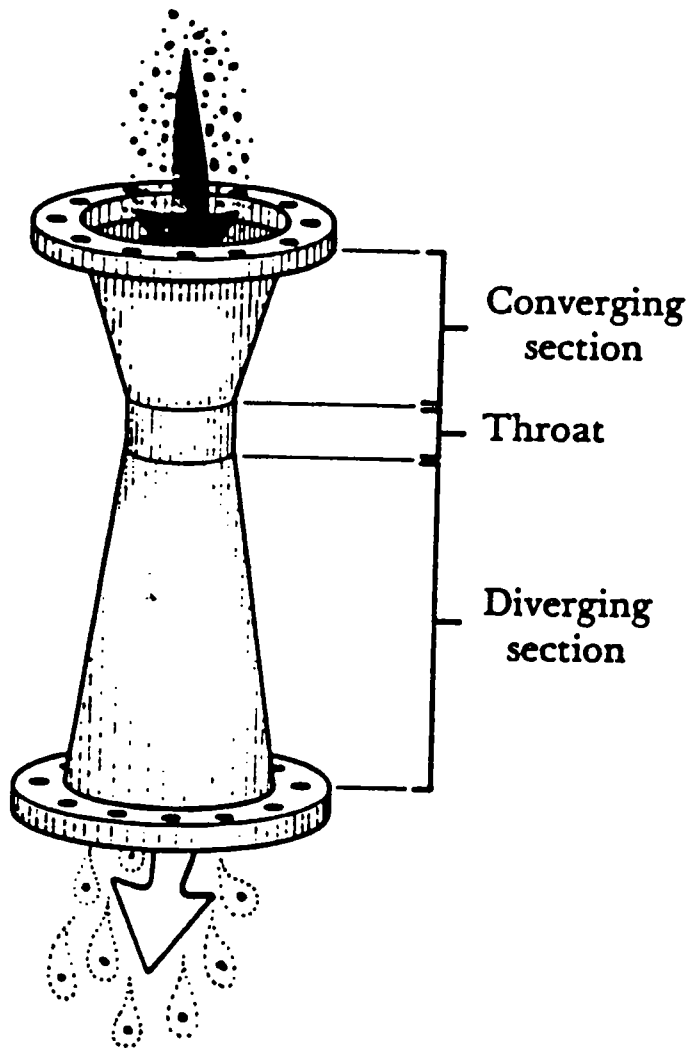

Figure 3-2. Spray venturi with circular throat.[6]

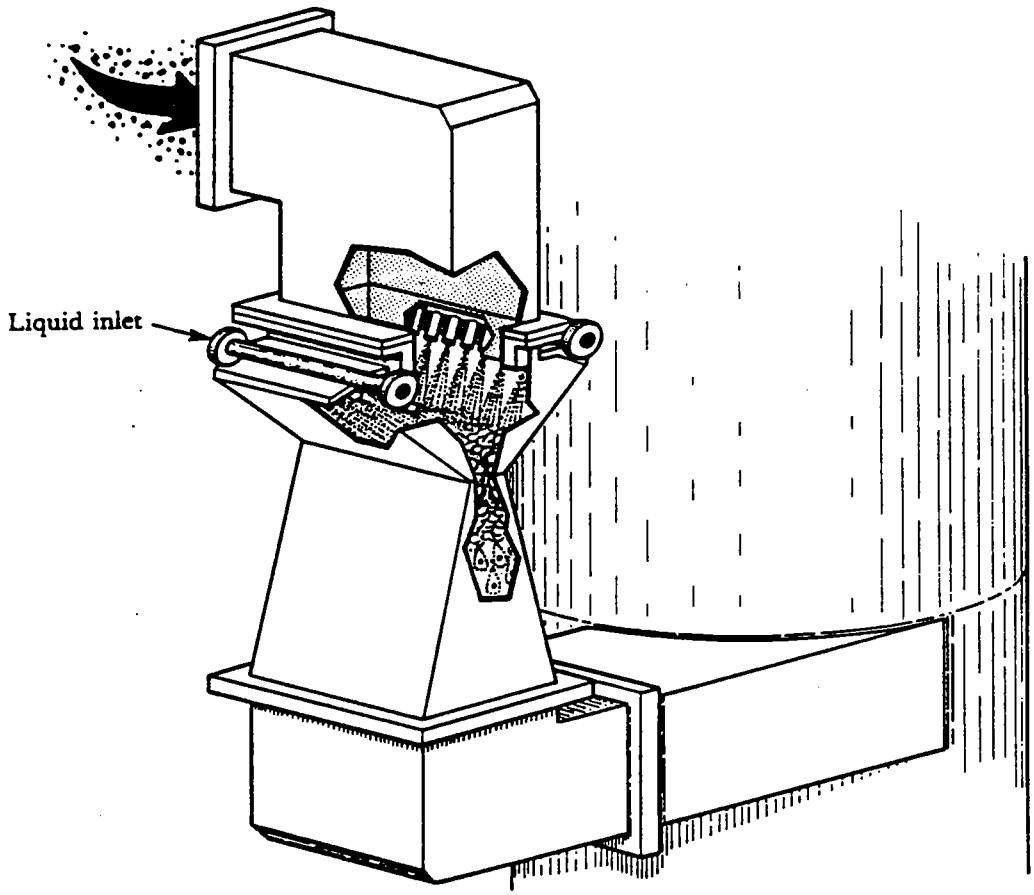

Figure 3-3. Spray venturi with rectangular throat.[7]

velocity and liquid/gas ratio and in practice acts as a surrogate measure for gas velocity. The Calvert equation can be used to predict the pressure drop for a given throat velocity. The Calvert equation is:[8]

$$\Delta P = (5 \times 10^{-5})\ v^2\ (L/G) \qquad (3\text{-}1)$$

where

ΔP = pressure drop, in. w.c.

v = the gas velocity in the venturi throat, ft/s, and

L/G = the liquid-to-gas ratio, gal/Macf.

The equation implies that pressure drop is equal to the power required to accelerate the liquid to the gas velocity. The Calvert equation predicts pressure drop reasonably well for the range of L/G ratios from 5 to 12 gal/Macf. At L/G ratios above 12, measured pressure drops are normally about 80 percent of the value predicted by the Calvert equation. In practice it has been found that at L/G ratios less than 3 gal/Macf, there is an inadequate liquid supply available to completely cover the venturi throat.

Other variables that are important to venturi scrubber performance are the liquid surface tension and liquid turbidity. If surface tension is too high, some small particles which impact on the water droplet will "bounce" off and not be captured. High surface tension also has an adverse effect on droplet formation. High liquid turbidity, or high suspended solids content, will cause erosion and abrasion of the venturi section and ultimately lead to reduced performance of the system.

A list of the major components of commercial scrubber systems is provided below.

1. Venturi section;
2. Spray nozzles;
3. Liquor treatment equipment;
4. Gas stream demister;
5. Liquor recirculation tanks, pumps, and piping;
6. Alkaline addition equipment;
7. Fans, dampers, and bypass stacks; and

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8. Controllers for venturi throat area, caustic feed, makeup water, and emergency water quench for temperature excursions.

Packed-bed scrubbers. A packed-bed scrubber generally is used for acid gas removal. The large liquor-to-gas surface area created as the liquor gradually passes over the packing material favors gas diffusion and absorption. Packed-bed scrubbers are not effective as stand-alone scrubbers for collection of fine particulate matter (less than 2.5 μm) since the gas velocity through the bed(s) is relatively low. However, packed beds are effective for the removal of particle-laden droplets or charged particles when used as a downstream collector behind a venturi or electrostatically-enhanced wet scrubber.

Packed beds can be either vertical or horizontal. Figure 3-4 illustrates a vertically oriented scrubber. Regardless of the orientation of the bed, the liquor is sprayed from the top and flows downward across the bed. Proper liquor distribution is important for efficient removal of gases.

Absorption is the primary means of collection of acid gases in packed-bed scrubbers. The effectiveness of absorption in packed beds is related to the uniformity of the gas velocity distribution, the surface area of the packing material, the amount and uniform distribution of scrubber liquid, and the pH and turbidity of the scrubbing liquid.

Gas absorption is affected by the extensive liquid surface contacted by the gas stream as the liquid flows downward over the packing material. A variety of available packing materials offer a large exposed surface area to facilitate contact with and absorption of acid gases. The packing materials range in size from 0.5 to 3 in. and are randomly oriented in the bed.

Typically, sodium hydroxide (NaOH) or occasionally sodium carbonate (Na_2CO_3) is used with water to neutralize the absorbed acid gases in a packed-bed scrubber. These two soluble alkali materials are preferred because they minimize the possibility of scale formation in the nozzles, pump, and piping. For the typical case of using NaOH as the neutralizing agent, the HCl and SO_2 collected in the scrubber react with NaOH to produce sodium chloride (NaCl) and sodium sulfite (Na_2SO_3) in an aqueous solution.

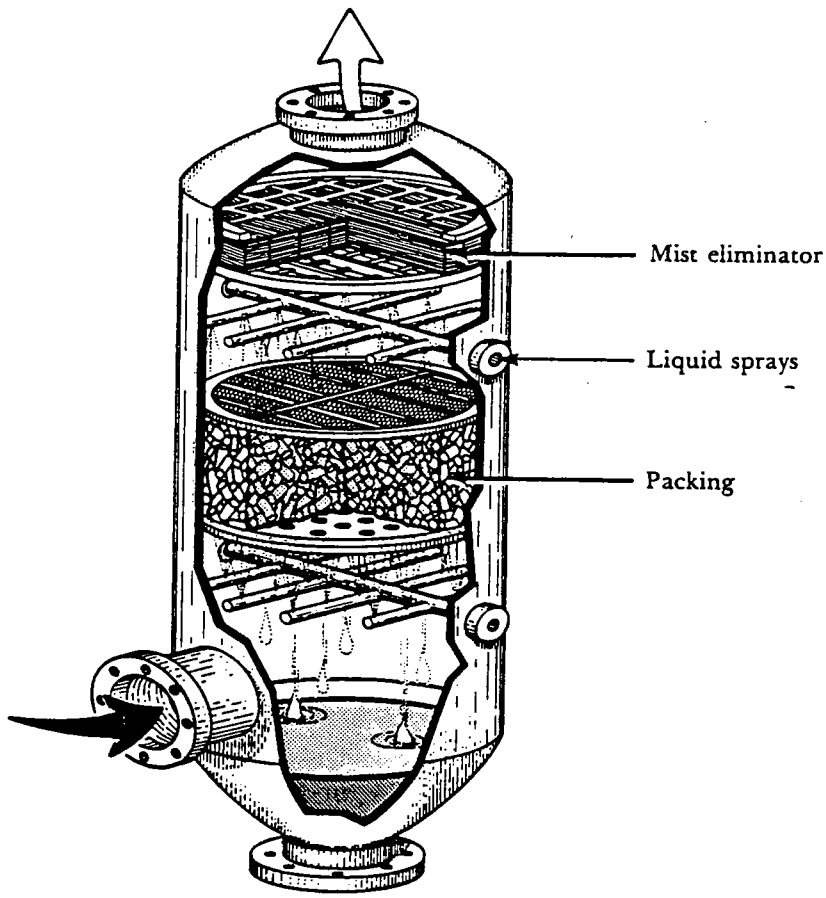

Figure 3-4. Countercurrent packed tower absorber.[9]

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One of the major problems with these scrubbers is the accumulation of solids at the entry to the bed and within the bed. The dissolved and suspended solids levels in the liquor must be monitored carefully to maintain performance.

Spray Towers.[2] Spray towers are relatively simple scrubbers. Most units consist of an empty cylindrical steel vessel containing nozzles that spray the liquid scrubbing media into the vessel. Most units use countercurrent flow with the exhaust gas stream entering the bottom of the vessel and moving upward, while the liquid is sprayed downward. Figure 3-5 shows a typical countercurrent flow spray tower. Countercurrent flow exposes the exhaust gas with the lowest pollutant concentration to the freshest scrubbing liquid.

Many nozzles are placed across the tower at different heights to spray all of the exhaust gas as it moves up through the tower. The major purpose of using many nozzles is to form a tremendous amount of fine droplets for impacting particles and to provide a large surface area for absorbing gas. Theoretically, the smaller the droplets formed, the higher the collection efficiency achieved for both gaseous and particulate pollutants. However, the liquid droplets must be large enough to not be carried out of the scrubber by the exhaust stream. Therefore, spray towers use nozzles to produce droplets that are usually 500 to 1000 μm in diameter. The exhaust gas velocity is kept low, from 0.3 to 1.2 m/s (1 to 4 ft/s) to prevent excess droplets from being carried out of the tower. Because of this low exhaust velocity, spray towers must be larger than other scrubbers that handle similar exhaust stream flow rates. Another problem occurring in spray towers is that after the droplets fall short distances, they tend to agglomerate or hit the walls of the tower. Consequently, the total liquid surface area for contact is reduced, thus reducing the collection efficiency of the scrubber.

Spray towers are low-energy scrubbers. Contacting power is much lower than in venturi scrubbers, and the pressure drops across such systems are generally less than 2.5 cm (1 in.) of water. The collection efficiency for small particles is correspondingly lower than in more energy-intensive devices. They are adequate for the collection of coarse particles larger than 10 to 25 μm in diameter, although with increased

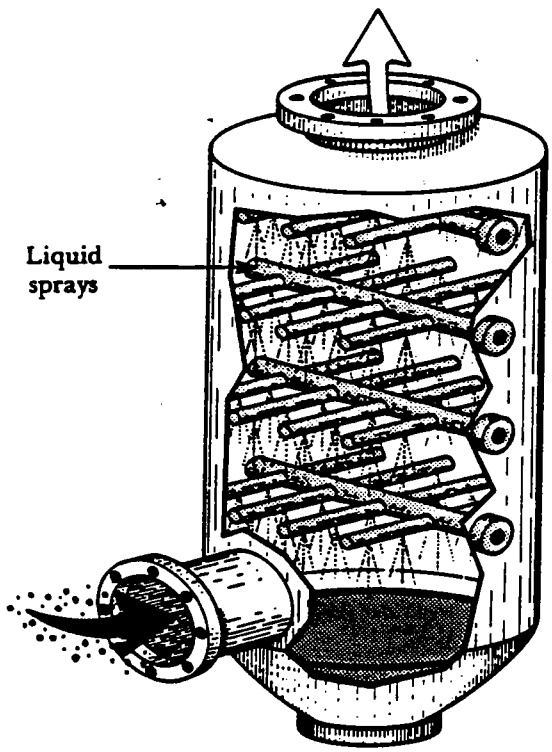

Figure 3-5. Countercurrent-flow spray tower.[10]

liquid inlet nozzle pressures, particles with diameters of 2.0 μm can be collected. Smaller droplets can be formed by higher liquid pressures at the nozzle. The highest collection efficiencies are achieved when small droplets are produced and the difference between the velocity of the droplet and the velocity of the upward-moving particles is high. Small droplets, however, have small settling velocities, so there is an optimum range of droplet sizes for scrubbers that work by this mechanism.

Because of their inherent design, particulate matter emissions from controlled-air incinerators are usually composed of relatively fine particulate matter. Therefore, spray towers are not commonly applied to controlled-air units. Multiple-chamber incinerators, however, can emit large quantities of relatively large particle particulate matter and are often controlled by spray towers.

3.3.3.2 Fabric Filters. Fabric filters (i.e., baghouses) are used on a limited number of hospital incinerators for control of particulate matter emissions. They have some advantages over wet scrubbers in that they are highly efficient at removing fine particles if they are properly operated and maintained. However, poor operation and maintenance (O&M) can result in bag blinding, bag corrosion, or bag erosion.

Filtration principles.[11] Fabric filtration is one of the most common techniques used to collect particulate matter. A fabric filter is a collection of bags constructed of a fabric material (nylon, wool, or other) hung inside a housing. The combustion gases are drawn into the housing, pass through the bags, and are exhausted from the housing through a stack to the atmosphere. When the exhaust stream from the incinerator is drawn through the fabric, the particles are retained on the fabric material, while the cleaned gas passes through the material. The collected particles are then removed from the filter by a cleaning mechanism typically by using blasts of air. The removed particles are stored in a collection hopper until they are disposed.

With a new filter, the open areas in the fabric are of sufficient size that particles easily penetrate the bag. Over time, a cake builds on the bag surface, and this cake acts as the primary collection medium. Particles are collected on a filter and cake by a combination of several mechanisms. The most important are impaction and direct interception.

In collection by impaction, the particles in the gas stream have too much inertia to follow the gas streamlines around the fiber and are impacted on the fiber surface. In the case of direct interception, the particles have less inertia and barely follow the gas streamlines around the fiber. If the distance between the center of the particle and the outside of the fiber is less than the particle radius, the particle will graze or hit the fiber and be "intercepted". Impaction and direct interception mechanisms account for 99 percent collection of particles greater than 1 μm aerodynamic diameter in fabric filter systems.

Fabric filter performance. Generally, fabric filters are classified by the type of cleaning mechanism that is used to remove the dust from the bags. The three types of units are mechanical shakers, reverse air, and pulse jet. To date, the only hospital incinerators that have been identified as having fabric filters use pulse jet units. The paragraphs below briefly describe the design and operating characteristics of pulse jet filters and identify key design parameters.

A schematic of a pulse jet baghouse is shown in Figure 3-6. Bags are supported internally by rings or cages. Bags are held firmly in place at the top by clasps and have an enclosed bottom (usually a metal cap). Dust-laden gas is filtered through the bag, depositing dust on the outside surface of the bag. Pulse jet cleaning is used for cleaning bags in an exterior filtration system.

The dust cake is removed from the bag by a blast of compressed air injected into the top of the bag tube. The blast of high pressure air stops the normal flow of air through the filter. The air blast develops into a standing or shock wave that causes the bag to flex or expand as the shock wave travels down the bag tube. As the bag flexes, the cake fractures and deposited particles are discharged from the bag. The shock wave travels down and back up the tube in approximately 0.5 seconds.[11]

The blast of compressed air must be strong enough for the shock wave to travel the length of the bag and shatter or crack the dust cake. Pulse jet units use air supplies from a common header which feeds into a nozzle located above each bag. In most baghouse designs, a venturi sealed at the top of each bag is used to create a large enough pulse to travel down and up the bag. The pressures involved are commonly between 414 and 689 kPa

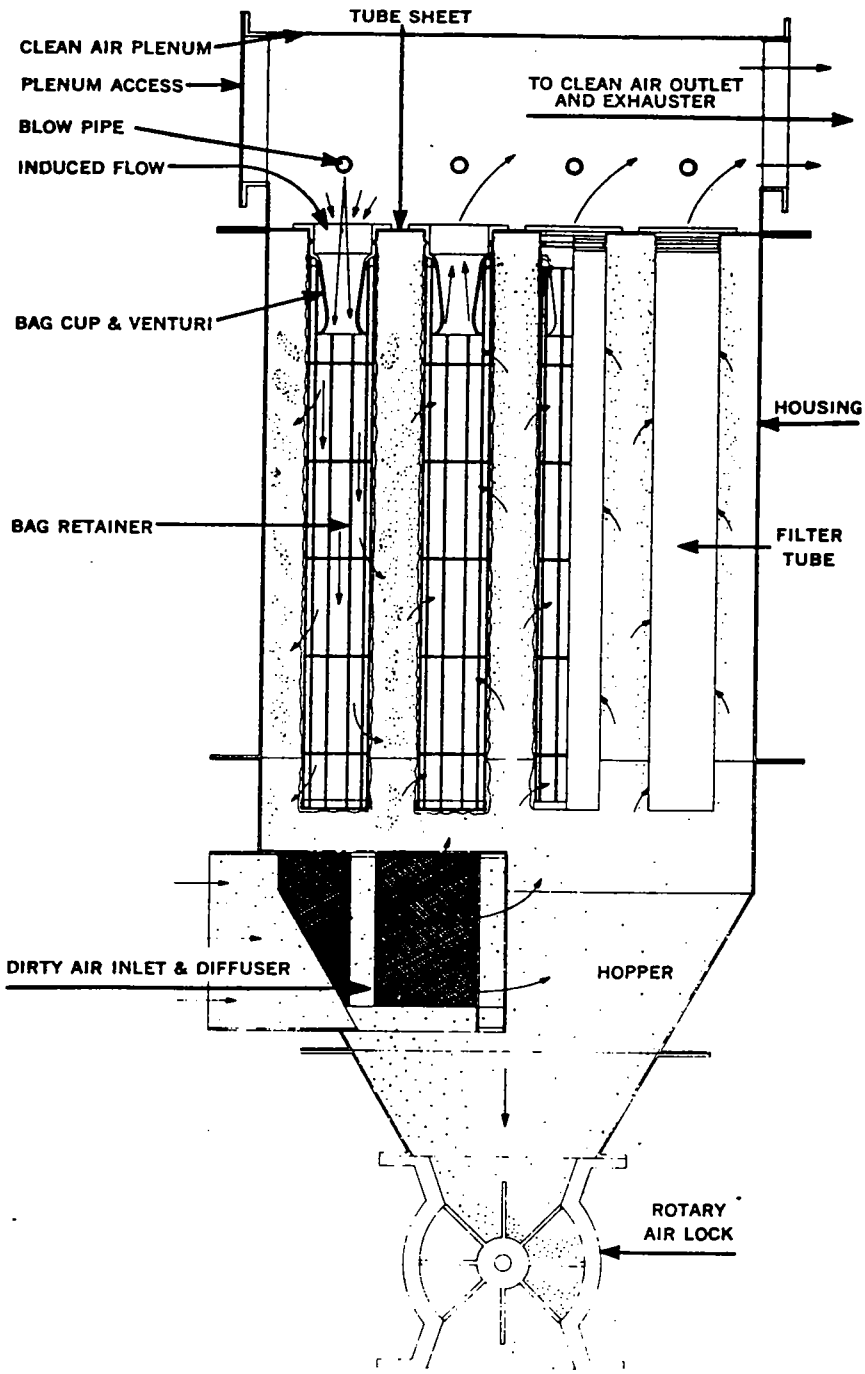

Figure 3-6. Pulse jet baghouse.[12]

(60 and 100 psig). The importance of the venturi is being questioned by some pulse jet baghouse vendors. Some baghouses operate with only the compressed air manifold above each bag.[11]

Most pulse jet filters use bag tubes that are 10 to 15 cm (4 to 6 in.) in diameter. Typically the bags are 3.0 to 3.7 m (10 to 12 ft) long, but they can be as long as 7.6 m (25 ft).[11] Generally, these bags are arranged in rows, and the bags are cleaned one row at a time in sequence. Cleaning can be initiated by a pressure drop switch, or it may occur on a timed sequence.

The key design and operating parameters for a pulse jet filter are the air-to-cloth ratio (or the filtration velocity), the bag material, operating temperature, and operating pressure drop.

The air-to-cloth ratio is actually a measure of the superficial gas velocity through the filter medium. It is a ratio of the flow rate of gas through the fabric filter (at actual conditions) to the area of the bags and is usually measured in units of acfm/ft^2. No operating data were obtained for hospital incinerators, but generally, the air-to-cloth ratio on waste combustion units is in the range of 0.025 to 0.05 m^3/s/m^2 (5 to 10 acfm/ft^2) of bag area.[13]

Generally, bag material is specified based on prior experience of the vendor. Key factors that generally are considered are: cleaning method, abrasiveness of the particulate matter and abrasion resistance of the material, expected operating temperature, potential chemical degradation problems, and cost. To date, no information has been obtained on types of material typically used for hospital incinerator applications.

The operating temperature of the fabric filter is of critical importance. Since the exhaust gas from a hospital incinerator can contain HCl, the unit should be operated at sufficiently high temperatures to assure that no surfaces drop below the acid dewpoint. Otherwise, condensation of HCl will result in corrosion of the housing or bags. The boiling point of HCl (aqueous hydrochloric acid) is 110°C (230°F); gas temperatures should be maintained at 150°C (300°F) to ensure that no surfaces are cooled below the dewpoint. Above a maximum temperature that is dependent on filter type, bags will degrade or in some cases fail completely. Gas temperatures should be kept safely below the allowed maximum.

Pressure drop in fabric filters generally is maintained within a narrow range. Pressure drops below the minimum indicate that either (1) leaks have developed, or (2) excessive cleaning is removing the base cake from the bags. Either condition results in reduced performance. Pressure drops greater than the maximum indicate that either (1) bags are "blinding", or (b) excessive cake is building on the bags because of insufficient cleaning. The primary problem that results from excessive pressure drop is reduced flow through the system and positive pressure at the combustor. Over time, high pressure drops also lead to bag erosion and degradation.

3.3.3.3 Dry Scrubbers. Dry scrubbers use absorption for the removal of sulfur dioxide, hydrogen chloride, hydrogen fluoride, and other acid gases. Some adsorption of vapor state organic compounds and metallic compounds also occurs in some dry scrubber applications. Basically, dry scrubbers use an alkaline sorbent to react with and neutralize the acid gas. The reaction product is a dry solid which can be collected by a particulate control device. Dry scrubbers usually are followed by either fabric filters or electrostatic precipitators (ESP's) for collection of the reaction products and the unreacted sorbent. Currently, there are not any hospital incinerators known to be using spray dryer absorption systems. There are at least three hospital waste incinerators which are known to be using dry injection control systems.[a]

Components and operating principles of dry scrubber systems.[13,14] There is considerable diversity in the variety of processes which are collectively termed dry scrubbing. Dry scrubbing techniques that could be applied to hospital incinerators can be grouped into two major categories: (1) spray dryer absorbers, and (2) dry injection absorption systems. Specific types of dry scrubbing processes within each group are listed below. Alternative terms for these categories used in some publications are shown in parentheses.

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[a]Southland Exchange Joint Ventures, Hampton, South Carolina (dry injection/ESP); Fairfax County Hospital, Falls Church, Virginia (dry injection/baghouse); Borgess Medical Center, Kalamazoo, Michigan (dry injection/baghouse).

1. Spray dryer absorption (semiwet)
   - Rotary atomizer spray dryer systems
   - Air atomizing nozzle spray dryer systems
2. Dry injection absorption (dry)
   - Dry injection without recycle
   - Dry injection with recycle (sometimes termed circulating fluid bed absorption)

Simplified block diagrams of the two major types of dry scrubbing systems are presented in Figures 3-7 and 3-8. The main differences between the two systems are the physical form of the alkaline reagent and the design of the vessel used for contacting the acid gas-laden stream. The alkaline feed requirements are much higher for the dry injection system. Conversely, the spray dryer system is much more complicated.

Spray dryer absorbers. In this type of dry scrubbing system, the alkaline reagent, usually pebble lime, is prepared as a slurry containing 5 to 20 percent by weight solids. This reagent must be slaked in order to prepare the reactive slurry for absorption of acid gases. Slaking is the addition of water to convert calcium oxide to calcium hydroxide. Proper slaking conditions are important to ensure that the resulting calcium hydroxide slurry has the proper particle size distribution and that no coating of the particles has occurred due to the precipitation of contaminants in the slaking water. The prepared slurry is atomized in a large absorber vessel having a residence time of 6 to 20 seconds. Atomization of the slurry is achieved through the use of: (1) rotary atomizers or (2) air atomizing nozzles. Generally, only one rotary atomizer is included in a spray dryer absorber. However, a few applications have as many as three rotary atomizers.

In rotary atomizers, a thin film of slurry is fed to the top of the atomizer disk as it rotates at speeds of 10,000 to 17,000 revolutions per minute. These atomizers generate very small slurry droplets having diameters in the range of 100 microns. The spray pattern is inherently broad due to the geometry of the disk.

High pressure air is used to provide the physical energy required for droplet formation in nozzle type atomizers. The typical air pressures are 70 to 90 psig. Slurry droplets in the range of 70 to 200 microns are

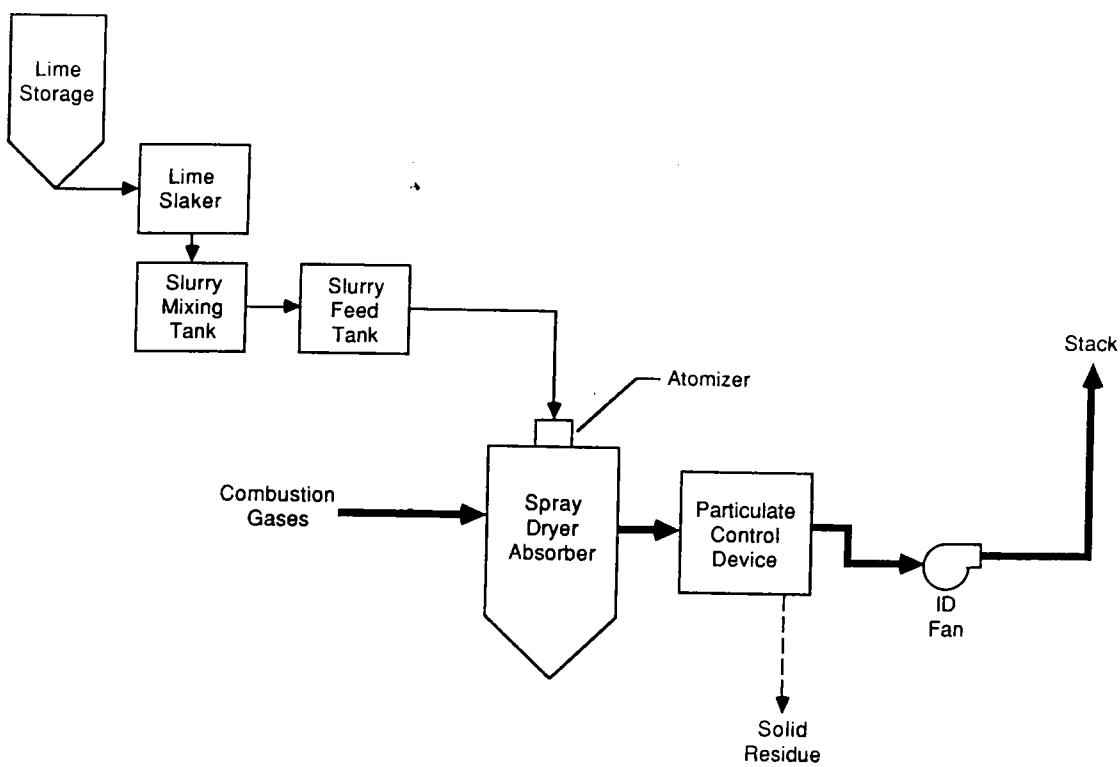

Figure 3-7. Components of a spray dryer absorber system (semiwet process).[15]

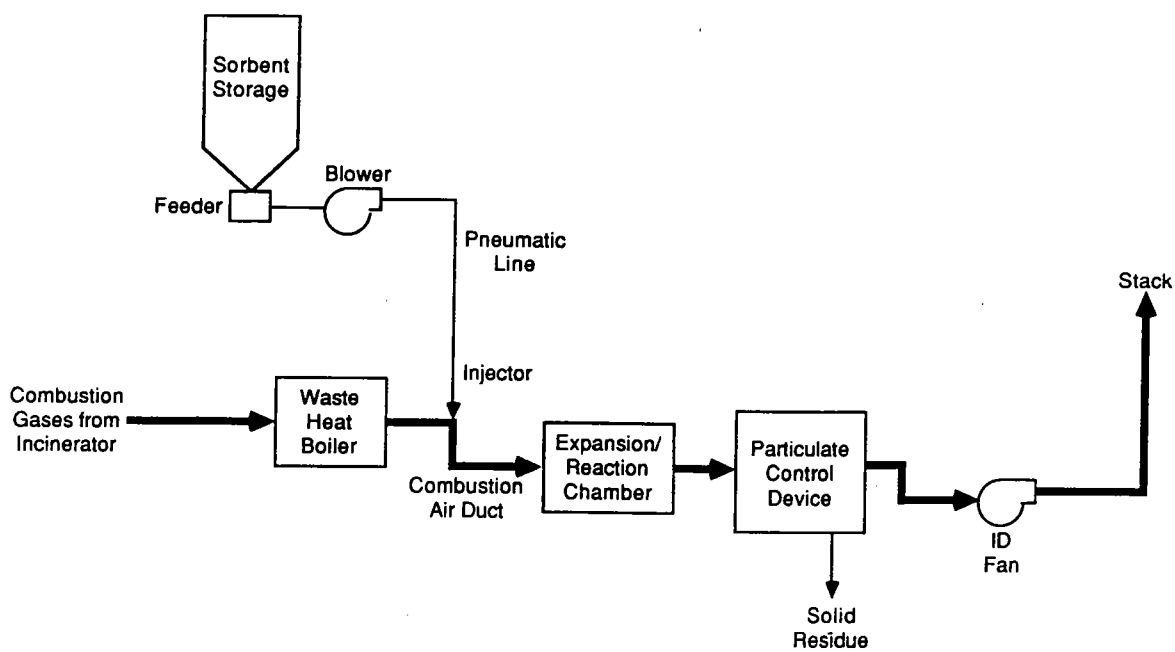

Figure 3-8. Components of a dry injection absorption system (dry process).[16]

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generated. This type of atomizer generally can operate over wider variations of the gas flow rate than can be used in a rotary atomizer. However, the nozzle atomizer does not have the slurry feed turndown capability of the rotary atomizer. For these reasons, different approaches must be taken when operating at varying system loads.

The shape of the scrubber vessel must be designed to take into account the differences in the slurry spray pattern and the time required for droplet evaporation for the two types of slurry atomizers. The length-to-diameter ratio for rotary atomizers is much smaller than that for absorber vessels using air atomizing nozzles.

It is important that all of the slurry droplets evaporate to dryness prior to approaching the absorber vessel side walls and prior to exiting the absorber with the gas stream. Accumulations of material on the side walls or at the bottom of the absorber would necessitate an outage since these deposits would further impede drying. Proper drying of the slurry requires generation of small slurry droplets and adequate mixing with the hot flue gases.

Drying that is too rapid can reduce pollutant collection efficiency since the primary removal mechanism is absorption into the droplets. There must be sufficient contact time for the absorption. For this reason, spray dryer absorbers are operated with exit gas temperatures 90° to 180°F above the saturation temperature.

Dry injection absorption systems. This type of dry scrubber uses injection of a finely divided alkaline sorbent such as calcium hydroxide (hydrated lime) or sodium bicarbonate for the absorption of acid gases. The reagent feed has particle sizes which are 90 percent by weight through 325 mesh screens. This is approximately the consistency of talcum powder. This size is important to ensure that there is adequate alkaline sorbent surface area for high efficiency pollutant removal.

Proper particle sizes are maintained by transporting the sorbent to the dry scrubber system by means of a positive pressure pneumatic conveyor. This provides the initial fluidization necessary to break up any clumps of reagent which have formed during storage. The air flow rate in the pneumatic conveyor is kept at a constant level regardless of system load to ensure proper particle sizes.

Fluidization is completed when the alkaline sorbent is injected countercurrently into the gas stream. The alkaline sorbent may be injected directly into a reaction vessel or may be injected directly into the ducting with a reaction vessel (expansion chamber) located downstream to increase residence time. The gas stream containing the entrained sorbent particles and fly ash is then ducted to a fabric filter or ESP. When a fabric filter is used for particulate control, acid gas removal may be further enhanced by the reaction with the sorbent in the filter cake.

In one version of the dry injection system, solids are recycled from the particulate matter control device back into the flue gas contactor. The primary purpose of the recycle stream is to increase reagent utilization and thereby reduce overall calcium hydroxide costs.

3.4 REFERENCES FOR CHAPTER 3

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4.0 OPERATION

The success of incineration as a technique for treating hospital waste depends on the proper operation of the incinerator and its air pollution control devices. Proper operating techniques can affect equipment reliability, on-line availability, combustion efficiency, and compliance with air pollution regulations. The operator is in control of many of the factors that affect the performance of a hospital incinerator including: (1) waste charging procedures, (2) incinerator startup and shutdown, (3) air pollution control device startup and shutdown, (4) monitoring and adjusting operating parameters for the incinerator and air pollution control system, and (5) ash handling. This section identifies key operating parameters, identifies operating ranges for key parameters, and discusses general operating procedures that can minimize unexpected malfunctions and improve the performance of the incinerator and air pollution control devices. Appropriate monitoring procedures also are discussed in this section.

4.1 GENERAL OBJECTIVES

The primary objectives associated with the proper operation of a hospital waste incineration system are to operate the system in a manner so that infectious materials in the waste are rendered harmless, waste volume is reduced, good ash quality (from an aesthetic standpoint) is ensured, and air pollution emissions of particulate matter, organic compounds, carbon monoxide, and acid gas are minimized. The operator is responsible for knowing key operating parameters and the proper operating ranges for these parameters to assure that the system is operated at its design efficiency. The operator also should know the operating procedures and monitoring techniques which will assist in maintaining those parameters within the acceptable operating range.

Because each incinerator model is designed differently, design criteria, operating parameters, and operating procedures will vary. Nonetheless, recommended operating ranges can be established for some general key parameters to assist in meeting the objectives of the

incineration process--destruction of pathogens and reduction of waste volume--while minimizing air pollution and maintaining good ash quality. To identify these key parameters and discuss proper operating procedures, incineration systems have been categorized as follows:

1. Batch/controlled-air incinerators;
2. Intermittent-duty, controlled-air incinerators;
3. Continuous-duty, controlled-air incinerators;
4. Multiple-chamber incinerators; and
5. Rotary kilns.

The operation of air pollution control systems is addressed later in this chapter.

Currently, most hospital waste incineration systems do not include an air pollution control device mainly because with proper combustion control through proper operation, the systems can meet current emission regulations. However, a growing number of States have promulgated or will soon promulgate more stringent regulations governing hospital waste incinerators that will increase the numbers of incinerators requiring add-on air pollution control devices to meet the regulations. When an air pollution control system is included as part of the incineration system, the operation of the incinerator and the control device are interrelated. Therefore, the optimum approach to describing the proper operation of incineration systems (including air pollution control devices) would be to discuss the operation of each of the possible combinations of incinerators and control devices. However, because of the large number of combinations of equipment types that may constitute an incineration system, the proper operation of incinerators and air pollution devices will be discussed separately.

This document provides a discussion of operating ranges for the key operating parameters and presents an overview of proper operating procedures and monitoring techniques. This information will provide the reader with a basic understanding of what constitutes good operating practice. However, it does not substitute for manufacturers' operating procedures. Specific steps and operating procedures for equipment will be specified by each manufacturer; furthermore, the control and monitoring systems used by each manufacturer may be different. Consequently, a

specific manufacturer's recommended and detailed operating procedures should be followed.

4.2 INCINERATOR KEY OPERATING PARAMETERS

4.2.1 Introduction

The interrelationship among an incinerator's thermal capacity, waste feed characteristics, heat input rate from the waste feed, and combustion air was discussed in Chapter 2. This section identifies the operating parameters and presents recommended operating ranges for these parameters. The majority of the key parameters and the recommended operating ranges remain the same for the different incinerator systems, but because they do differ somewhat for different types of incinerators, the parameters are presented for each type system that was described in Chapter 2. Controlled-air incinerators, multiple-chamber incinerators, and rotary kilns are discussed in order.

4.2.2 Controlled-Air Incinerators

Table 4-1 summarizes the key incinerator operating parameters and the operating range for each parameter. These parameters assume the waste is primarily a heterogeneous mixture of hospital infectious waste with a Btu content that will sustain combustion (i.e., greater than 6,000 Btu/lb). For "pathological" incinerators, burning pathological wastes, the recommended operating ranges are slightly different because waste characteristics differ significantly. An explanation of why each key operating parameter in Table 4-1 is important and a discussion of each operating range is presented below.

4.2.2.1 Primary and Secondary Combustion Chamber Temperatures. Maintaining the desired operating temperatures within each combustion chamber is critical to proper operation of a controlled-air incinerator. Both upper and lower limits on the temperature range for each chamber are of interest. The desired range of operation is different for the ignition (primary) and combustion (secondary) chambers because the functions of these chambers differ.

TABLE 4-1. KEY INCINERATOR OPERATING PARAMETERS AND RECOMMENDED OPERATING RANGE: CONTROLLED-AIR INCINERATOR

Parameter	Incinerator type		
	Batch feed	Intermittent feed	Continuous duty
Ignition chamber temperature, °F	1000° to 1800°	1000° to 1800°	1400° to 1800°
Combustion (secondary) chamber temperature, °F	1800° to 2200°	1800° to 2200°	1800° to 2200°
Charging rate, lb/h	Fill chamber once at beginning of cycle	10 to 25 percent of rated capacity at 5 to 15 min intervals	10 to 25 percent of rated capacity at 5 to 15 min intervals
Ignition chamber combustion air (percent of stoichiometric)	30 to 80	30 to 80	30 to 80
Total combustion air (percent excess air)	140 to 200	140 to 200	140 to 200
Combustion gas oxygen concentration, percent	12 to 14	12 to 14	12 to 14
Ignition chamber draft, in w.c.	-0.05 to -0.1	-0.05 to -0.1	-0.05 to -0.1
Burndown period, h	2 to 5	2 to 5	Not applicable

The literature indicates that typical operating ranges for the ignition chamber of controlled-air incinerators range from 400° to 980°C (750° to 1800°F).[1,2] The ignition chamber must be maintained at a minimum temperature sufficient to sustain combustion, combust the fixed carbon in the ash bed, and kill any micro-organisms in the waste bed so that the remaining ash is sterile. The temperature also must be maintained below a level that will damage the refractory and result in slagging of the waste.

Few studies have been conducted to determine the conditions necessary to achieve complete pathogen kill in incinerators. Barbeito et al., conducted a study on a multiple-chamber, industrial-refuse incinerator to determine the minimum operating temperatures required to prevent release of viable micro-organisms into the atmosphere. His research indicated that the destruction of the micro-organisms within the incinerator depends on the temperature and time of exposure. These parameters are affected by many factors, including charging beyond incinerator capacity and exceeding design linear velocities, which reduces retention time. Barbeito recommended a minimum primary chamber temperature of 760°C (1400°F).[1,3]

From an operational (operating efficiency) standpoint, it is desirable to operate the primary or ignition chamber at a temperature high enough to sustain combustion in the chamber and to generate sufficient volatile combustion gases and heat to maintain the desired secondary combustion temperature without the use of auxiliary fuel. Consequently, the desired primary temperature will depend somewhat on the waste composition. Furthermore, a sufficiently high temperature to effectively combust the fixed carbon in the waste bed is desired. One manufacturer's experience indicates that this temperature is in the 760° to 870°C (1400° to 1600°F) range for continuous-duty incinerators.[2] This temperature may be as low as 540°C (1000°F) for batch feed and intermittent-duty units because the burnout time can be extended in these units.[2] Operating batch feed incinerators at a low primary chamber temperature (relative to continuous-duty incinerators) helps assure that volatiles are not generated at an excessive rate which cannot be handled by the secondary chamber.

When the waste stream contains a significant amount of plastics, "cracking" of light hydrocarbons can be significant and can affect the

combustion gas volume in the secondary chamber. Operating the primary chamber at lower temperatures (540° to 650°C [1000° to 1200°F]) may help to minimize rapid increases in flue gas volume.[4] Some incinerator manufacturers use water quenching in the primary chamber to maintain gas temperatures below the 930° to 980°C (1700° to 1800°F) range and minimize cracking.[5]

At the same time, the primary chamber temperature must be maintained below the point that will result in refractory damage. It is common for modern incinerators to use nominal 1540° to 1650°C (2800° to 3000°F) quality refractory. Although this refractory is rated at 1540° to 1650°C (2800° to 3000°F), reactions can occur with contaminants in the combustion gas, making it desirable to expose this refractory to no higher than 1200°C (2200°F) on a continual basis.[2] Another, perhaps more important, limiting factor for the upper operating temperature of the primary chamber is slagging of the waste. Most ash residues begin to become soft at temperatures in the range of 1200° to 1370°C (2200° to 2500°F).[2] While thermocouples in the primary chamber indicate the temperature of the combustion gas exiting the primary chamber, the temperature in the ash bed at the hearth adjacent to the underfire air ports can be consistently higher. Consequently, although the combustion gas temperature can indicate that clinker (fused slag) formation should not be a problem, the ash bed can be hot enough to form clinkers. Experience has shown that a control temperature of 980°C (1800°F) can be used in most cases with acceptable performance with regard to clinker formation and carbon burnout, but the performance problems due to slagging may begin to occur at primary chamber temperatures as low as 760°C (1400°F).[2,6]

The secondary chamber serves to complete the combustion process initiated in the primary chamber. As with the primary chamber, it is desirable to operate within a lower and upper range. At temperatures that are too low, complete combustion may not occur. At temperatures that are too high, refractory damage may occur, residence time may be decreased, and auxiliary fuel may be unnecessarily wasted.

A minimum temperature is needed to prevent the discharge of potentially toxic products of incomplete combustion. Experimental work conducted at the University of Dayton Research Institute (UDRI) indicates

that temperature is the primary factor that affects these emissions.[7] The experimental data for thermal decomposition indicate that the destruction of a species depends predominantly on the temperature, and effectively a threshold temperature exists above which the compound will rapidly combust. The threshold temperature found for polychlorinated dibenzo-p-dioxin (PCDD) and polychlorinated dibenzofurans (PCDF) and potential precursers (e.g., hexachlorobenzene) is near 930°C (1700°F).[7]

Sufficient temperature in the secondary chamber is necessary to kill microorganisms entrained in the gas stream from the primary chamber. Again, little information on the required temperature is available, and data from studies conducted on specific incinerators are specific to those incinerators and the experimental operating conditions, e.g., residence time and turbulence. Based upon his incineration study, Barbeito recommended a minimum secondary combustion chamber temperature of 980°C (1800°F).[1] The limiting factor for the secondary combustion chamber temperature upper operating range is refractory damage. The upper limit will depend on the refractory used, but a typical limit is 1200°C (2200°F) on a continual basis.[2]

In summary, temperatures in both chambers should be maintained at high enough levels to ensure complete combustion of the waste but not so high that refractory damage or slagging of the ash occurs. A minimum temperature for the primary chamber in the range of 540° to 760°C (1000° to 1400°F) should be maintained to ensure pathogen kill, sterile ash, and good ash quality. The minimum temperature required for proper operation will depend on waste characteristics as well as the retention time of the ash in the primary chamber and consequently the incinerator design. To prevent clinker formation, the recommended upper bound primary chamber temperature is 980°C (1800°F). To assure complete combustion, yet conserve auxiliary fuel and prevent refractory damage, an operating range of 980° to 1200°C (1800° to 2200°F) is recommended for the secondary combustion chamber.

4.2.2.2 Charging Rate. An incinerator system is designed for a particular thermal input rate. The thermal input comes from the waste and, as necessary, the auxiliary fuel. Under ideal conditions, the incinerator operates under conditions of a constant thermal input. For

controlled-air incinerators, the thermal release from the "fuel" (the waste in the chamber) is controlled, to the extent possible, by controlling the available combustion air (the typical ranges for combustion air will be discussed in the next section). Additional control of the thermal input is obtained by controlling the quantity and frequency of waste charges to the incinerator. The charging process, thermal input, and combustion approaches a steady state condition as the waste homogeneity increases, the charge loads decrease in size, and the frequency of charges increase. Therefore, a charging scenario of more frequent charges of smaller volume is more desirable than one of a single large charge.[8]

4.2.2.2.1 Batch feed incinerators. By nature of their design, batch feed incinerators are intended to accept a single load of waste at the beginning of their incineration cycle; the heat release rate is controlled solely by controlling the size of the initial charge and the available air for combustion. The primary chamber acts as a fuel storage area. Manufacturers of batch operated incinerators recommend that the primary chamber be filled to capacity, but not overfilled or stuffed so full that the flame port to the secondary chamber or the ignition burner port assembly are blocked.[9] If wastes containing an unusually high volatile content are charged to the unit, a full load may contain enough volatiles that, even if the primary air is controlled, the capacity of the secondary combustion chamber will be exceeded. Therefore, it may be necessary to decrease the size of the charge to the incinerator. That is, volume of waste is an imperfect method for determining the thermal input to the incinerator. The incinerator chamber size is designed for a particular volume of waste with a particular Btu content. If the waste being charged is significantly higher in Btu content, even though the volume capacity of the chamber is not exceeded, the thermal capacity of the incinerator may be exceeded. Consequently, it will be necessary to decrease the thermal input of the batch charge by decreasing the volume input.

Regardless of the type, incinerators should never be overcharged above the manufacturer's specifications. In the case of batch feed incinerators where all charging occurs at the beginning of the incineration cycle, there may be a tendency to stuff that last bag of

waste into the incinerator so that no waste is left over for the next burn. This practice can lead to excessive emissions, incomplete combustion, and damage to the incinerator. Overcharging with waste adds more fuel to the incinerator than it can handle, may block the incinerator air ports, and damage the primary burner. Excessive fuel combined with an inadequate air supply causes excessive amounts of volatile material to be passed to the secondary chamber which cannot be handled effectively in the secondary chamber and results in high particulate matter emissions. Additionally if a large quantity of plastic material is charged, the excessive temperatures produced can cause refractory damage and clinker formation. Higher primary chamber temperatures also cause higher gas volumes and velocities which effectively reduces the secondary chamber retention time.

4.2.2.2.2 Intermittent-feed and continuous-duty incinerators. Intermittent- and continuous-duty, controlled-air incinerators are designed to accommodate semicontinuous charging. The primary design change for this type unit is that the charging system is set up with some type of a mechanical device (either manually or automatically operated) which allows the operator to safely add charges while the system is operating. The mechanical device is designed to protect the operator from exposure to the flame and heat of the primary combustion chamber. Additionally, the mechanical charging device may be designed to limit air in-leakage to the incinerator during charging to maintain control of the combustion air level. The primary difference between the "intermittent" and "continuous" duty units is not in the charging rate or operation, per se, but that the continuous-duty system has a means for continuously removing the ash generated by the waste. Consequently, this type unit can maintain continuous "steady state" operation. The intermittent unit can maintain continuous "steady-state" operation only for a limited time; once the ash in the incinerator builds up to an unacceptable level, the unit must be shutdown and the ash removed.

To approach a steady thermal input, manufacturers recommend that multiple charges be made at equally timed intervals. The recommended charge size is 10 to 25 percent of the rated capacity charged at 5 to 15 minute intervals.[10,11] The charging frequency may need to be adjusted

based upon variations in moisture content, volatile content, and overall Btu value. The procedures that the operator can use to monitor the charging rate and to make appropriate decisions is discussed in Section 4.4.

4.2.2.3 Primary and Secondary Combustion Air Rate and Combustion Gas Oxygen Concentration. For controlled-air units, the volatilization/combustion rate in the primary chamber is controlled by using combustion airflow rate to control the chamber temperature. The typical combustion air operating range for the ignition chamber is 30 to 80 percent of stoichiometric conditions.[1,2] Typically, about 20 percent of the total air requirement to the incinerator is supplied as underfire air to the ignition chamber.[2] The remainder of the air is supplied to the secondary mixing chamber.

Approximately 80 percent of the total combustion air required during incineration is supplied to the secondary combustion chamber. Typically, the total combustion air level is 140 to 200 percent excess air.[12,13] Measurement of the oxygen concentration provides a convenient way of determining and monitoring the excess-air level. Operating the incinerator at a total excess-air level in the range of 140 to 200 percent will result in stack gas oxygen concentrations in the range of 12 to 14 percent.

4.2.2.4 Combustion Chamber Pressure (Draft). A typical draft for controlled-air incinerators is in the range of -0.05 to -0.1 in. water column (w.c.). Excessive draft is not desirable because increased carryover of particulate matter to the secondary chamber can occur.

4.2.2.5 Burndown Period. After volatilization diminishes, sufficient time must be provided for the fixed carbon in the waste bed to combust.

For continuous-duty incinerators, there is no distinct burndown period since the burndown occurs continuously as the waste moves through the system during the "steady state" operation. However, on some continuous-duty incinerators with internal transfer rams, once the last load of waste is charged, each ram may go into a burndown mode sequentially where the rams' strokes are increased to push the waste from one hearth to the next. For example, the ram on the first or drying

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hearth will stroke at the same time intervals but will stroke several inches more on each stroke. During this period, the ash underfire air to this part of the hearth is shut off. On the last stroke, the ram is at the edge of the hearth, and all of the waste falls to the next hearth which then goes into its burndown mode, and so on. This burndown sequence is usually preset at the factory but can be changed by the manufacturer if ash quality is poor. On these units, the burndown sequence is normally in the range of 4 to 6 hours.[14]

For batch and intermittent-duty operations, there is a distinct burndown period associated with the operating cycle. During this period, the volatiles have been combusted, and the fuel remaining in the waste bed is slowly diminishing. In order to combust the fixed carbon remaining in the waste, a higher temperature is required and, therefore, more underfire air is introduced into the primary chamber.[10] As the burndown proceeds and the fuel is further diminished, the temperature slowly decreases. During burndown, a minimum temperature level (e.g., 1400°F) is maintained for a predetermined time period; auxiliary fuel may be required to maintain this temperature. It is difficult to recommend a required burndown period because it is somewhat experimental and will vary depending upon the waste composition and combustion air rate. According to one manufacturer, a rule of thumb for a trial burndown setting for an intermittent-duty, small capacity incinerator is 1 hour plus an additional 20 minutes for each hour of operation.[10] Therefore, a trial burndown setting for a unit that operated 6 hours would be (1 hour)+(6x20 minutes)= 3 hours. A typical burndown period for batch and intermittent units is in the range of 2 to 4 hours.[11,14]

4.2.3 Multiple-Chamber Incinerators

Traditionally, multiple-chamber units were designed specifically to burn pathological waste and contained a fixed (solid) hearth. Other multiple-chamber incinerators use a grate type of hearth. Combustion of medical waste containing significant quantities of fluids and/or infectious material is not recommended in multiple-chamber units with grates. Both type units employ large quantities of excess air for

combustion and will operate at similar temperature ranges. The operating parameters and ranges for a multiple-chamber incinerator are summarized in Table 4-2 and are briefly discussed below.

4.2.3.1 Primary and Secondary Chamber Temperatures. As discussed for controlled-air incinerators, the temperature in the primary chamber must be maintained at such a level as to assure pathogen kill. Most multiple-chamber incinerators operate on a batch or intermittent-duty basis. An extended burndown period is available to assure adequate ash burnout and sterilization of the waste. A minimum primary chamber temperature in the range of 540° to 760°C (1000° to 1400°F) is recommended. The upper operating range for the primary chamber should be established to prevent refractory damage. As previously mentioned for controlled-air units, sustained operation above 2200°F is generally not desirable.

Pathological wastes have a high moisture content and low volatile and fixed carbon content. For pathological wastes, continuous operation of an auxiliary burner is required to maintain the primary chamber temperature. To facilitate burndown of the pathological wastes, a minimum primary combustion chamber temperature of 1600°F is recommended.[15]

A minimum secondary chamber temperature of 1600°F for pathological incinerators is recommended in the Air Pollution Engineering Manual to assure complete combustion.[15] As discussed in Section 4.2.2.1 for controlled-air incinerators, a minimum temperature to prevent the discharge of potentially toxic products of incomplete combustion is required; a minimum secondary combustion chamber temperature of 980°C (1800°F) is recommended for multiple-chamber incinerators.

4.2.3.2 Charging Rate. Whether a multiple-chamber unit is incinerating red bag waste or pathological waste affects the charging rate and procedures because the volatile content, moisture content, and Btu value of these wastes are so different. An incinerator system is designed and sized for a particular thermal input rate. The thermal input comes from the waste and, as necessary, the auxiliary fuel. Unlike a controlled-air unit, the combustion rate in a multiple-chamber unit cannot be controlled by controlling the combustion air to the primary chamber. Therefore, the controlling factor for the combustion rate is essentially

TABLE 4-2. KEY INCINERATOR OPERATING PARAMETERS AND RECOMMENDED OPERATING RANGE: MULTIPLE-CHAMBER INCINERATOR

Parameter	Pathological waste	General refuse
Ignition chamber temperature, °F	1600 to 1800	1000 to 1400
Combustion (secondary) chamber temperature, °F	1800 to 2200	1800 to 2200
Charging rate	Single layer on hearth	10 to 25% of rated capacity at 5- to 15-min intervals
Ignition chamber combustion air (percent excess air)	80	150
Total combustion air (percent excess air)	120 to 200	250 to 300
Combustion gas oxygen concentration, percent	10 to 14	15 to 16
Ignition chamber draft, in. w.c.	-0.05 to -0.1	-0.05 to -0.1

the availability of fuel; i.e., the amount of waste charged when general refuse/red bag waste is being incinerated. The thermal input to the incinerator and the combustion approaches a steady-state condition as the waste homogeneity increases, the charge loads decrease in size, and the frequency of charges increase. Therefore, charging procedures using more frequent charges of smaller volume are more desirable than one single large charge. A charge rate of 10 to 15 percent of the rated capacity at regular intervals is recommended. Note that if a mechanical feeder is not used, the more frequently the charging door is opened, the greater the risk to the operator. Consequently, safety considerations make less frequent charging desirable, which contradicts the more frequent charging procedures desired from a thermal input standpoint. Thus, the objective should be to assure that the individual charges to the incinerator are not so large and infrequent that the capacity of the incinerator is exceeded by rapid volatilization of combustibles resulting in excess emissions. Consequently, charging frequency and load size will depend on waste characteristics and incinerator design.

Pathological wastes have a low Btu content and a low volatiles content. Consequently, rapid volatilization and rapid changes in heat release to the primary chamber are not a concern when charging pathological wastes. The primary chamber burner(s) provides(e) a steady heat input to the incinerator. Because of the high moisture and low volatile carbon content of pathological waste, the burner flame must impinge on or near the waste for efficient combustion to occur. Consequently, fresh pathological waste should not be charged into the incinerator until the previous waste charge has burned down almost completely. Completeness of burndown can be determined by inspection through a view port and examining the waste bed.

4.2.3.3 Primary and Secondary Chamber Combustion Air Levels. For multiple-chamber incinerators the primary chamber excess-air level is typically 150 percent or greater excess air. Overall excess-air levels for multiple-chamber incinerators are typically 250 to 300 percent.[15] This roughly corresponds to a combustion gas oxygen concentration of 15 to 16 percent. When incinerating pathological wastes, since the primary heat release is coming from the auxiliary burner, the combustion air can be

controlled at a lower level than for a typical multiple-chamber incinerator.

4.2.3.4 Chamber Pressures. A negative draft is maintained in the combustion chambers. A typical range for the ignition chamber draft is -0.05 to -0.1 in. w.c.[15]

4.2.4 Rotary Kiln Incinerators

Currently, there are relatively few rotary kiln incinerator installations at hospitals for incinerating hospital medical waste. Consequently, little information is available on the application of rotary kilns to this waste type. However, rotary kilns are a proven technology and have been used for a wide variety of industrial applications including hazardous waste incineration. The operating parameters identified below are based mainly on the application of rotary kilns to the incineration of hazardous waste because of the availability of information in this area.

4.2.4.1 Ignition and Combustion Chamber Temperatures. As discussed in Chapter 2, a rotary kiln incineration system consists of an inclined rotary kiln which serves to volatilize the waste and a secondary combustion chamber which completes the combustion process by burning the volatiles in the kiln off-gas. Temperatures in rotary kiln incinerators usually range from about 760° to 1670°C (1400° to 3000°F) depending on the types of waste being burned and on the location in the kiln.

In evaluating the application of rotary kiln incineration to hospital medical waste, it is likely that the kiln (primary chamber) and secondary chamber operating temperatures will be similar to those identified for other hospital medical waste incineration systems, i.e., a primary chamber temperature of 760°C (1400°F) and a secondary chamber temperature of 980°C(1800°F).

4.2.4.2 Charging Rate. Rotary kiln incinerators may be batch or continuously fed and have a feed capacity that ranges from 600 to 2,000 Kg/h (1,300 to 4,400 lb/h).

The waste throughput of a rotary kiln is determined both by the speed of rotation and by the incline angle (rake). Typically, rotary kilns rotate at a speed that ranges from 0.25 to 1.5 revolutions per minute and

are oriented at a rake of less than 3 percent (i.e., around 11° from horizontal). Both of these parameters may be adjusted depending on the throughput desired. However, once the rake is set, it is usually not altered. Assuming that all other operating parameters are in the normal operating ranges, incompletely burned material in the ash is an indication that waste is traveling through the kiln too quickly. The waste throughput may be reduced by reducing the speed of rotation of the kiln which in turn must include a corresponding decrease in the charging rate. Some experimentation with charge rates and speed of rotation may be required to obtain optimum ash quality and throughput.

4.2.4.3 Ignition and Combustion Chamber Air Levels. Based on information available on hazardous waste rotary kiln incinerators, the rotary kiln excess-air level ranges from 140 to 210 percent or greater, depending on the desired operating temperature and the heating value of the waste. When high aqueous wastes are being burned, lower excess-air rates may be needed to maintain adequate temperature. Secondary chamber excess-air levels are approximately 80 percent of the rotary kiln excess-air levels. For example, in a typical system operating at 820°C (1500°F) in the kiln and 980°C (1800°F) in the secondary chamber, approximately 160 to 170 percent excess air would be maintained in the secondary chamber compared to about 210 percent in the kiln. Manufacturers are now designing rotary kilns utilizing special kiln seals and air injection that operate with substoichiometric air levels in the kiln. Operating the kiln at substoichiometric air levels decreases the kiln size and reduces auxiliary fuel usage.[4]

4.3 WASTE FEED HANDLING

The physical and chemical properties of wastes and the effects of these properties on the incineration process were presented in Chapter 2. Furthermore, typical characteristics of hospital infectious wastes were presented and discussed. In most cases, the operator of an incinerator does not have control over the quantity or types of wastes which are transported to the incinerator for disposal. However, the operator does have control over two of the most important parameters--how

the waste is charged and at what rate. Waste charging procedures are specific to the type incinerator and the incinerator's mode of operation; proper charging procedures will be discussed in Section 4.4. In this section, some general concepts with regard to types of waste and handling of the wastes are discussed. Although the operator does not have control (or has very little control) over the waste which is to be incinerated, the operator must understand how waste composition affects operation of the incinerator and must learn to recognize problems related to waste composition or to identify significant changes in waste composition. The operator then can modify charging procedures, modify incinerator combustion parameters (if properly trained to make such adjustments), and/or notify the appropriate hospital administrators of continued waste related problems which are severely affecting incinerator operation. The remainder of this section addresses the following concerns:

1. Safe waste handling procedures; and
2. Wastes that should not be incinerated.

4.3.1 Proper Waste Handling

Infectious waste will be delivered to the incinerator area in "red bags." The primary concern is to avoid exposure to pathogens; consequently red bag wastes should be handled in a manner which maintains the integrity of the container. Proper procedures dictate that:

1. Sturdy containers are used;
2. Waste handling is minimized;
3. The waste storage area is secure if wastes are to be stored; and
4. Mechanical handling/loading systems are properly operated and maintained.

Plastic bags are the typical containers used for infectious waste. Tear-resistant bags that will maintain their integrity during the handling/transporting process should be used. The two main criteria used to evaluate bag durability are bag thickness and the ASTM dart test.[3,16] Some State regulations specify minimum bag requirements based on one of these two criteria.[3] For example, Massachusetts specifies a minimum bag thickness while California requires use of the ASTM dart test.[3] Even if

appropriate bag materials are used, overloading of bags, placement of sharp objects within the bags, or mishandling can result in tearing. "Sharps" (e.g., needles, broken glass) should be placed in special rigid sealed containers; these containers can then be placed in the red bag. The options that can be used if bag tearing is a problem include double bagging and the use of rigid containers to contain the bags. Rigid containers such as reuseable metal/plastic drums or disposable cardboard drums or boxes can be used to contain the individual plastic bags. If reusable containers are used, the plastic bag would be placed as a liner in the container (much like one might do at home for household garbage). When filled, the bag is sealed, and a lid is placed on the container. The container is then transported to the incineration area. Reuseable containers have some disadvantages in that they require additional handling and will need to be disinfected after each use.[1] Because the waste is to be incinerated, disposable cardboard cartons that can be loaded directly into the incinerator and disposed with the waste is a reasonable alternative. Use of disposable containers with mechanical charging systems also minimizes the potential for spillage in and contamination of the charging equipment during operation of the incinerator.

Another approach to enhancing integrity of the red bags is to use rigid carts, usually made of rigid plastic or of metal, to collect and transport the red bags. These rigid carts protect the waste bags from bumping, tears, etc.; the integrity of the bags is more easily maintained. Also, should a bag tear or break, the waste is contained, even if liquids are involved. Finally, handling of the waste can be minimized by the use of rigid carts. Once the red bags are placed in the cart, they need not be handled again until they are loaded directly into the incinerator or into the mechanical charging system for the incinerator. Since waste handling is minimized, the approach of keeping the wastes in the transport cart up until the time it is charged to the incinerator is preferred over the approach of unloading the waste to a storage area or charging pile on the floor. When rigid transport carts are used for large automated incineration systems, the waste may never need to be handled manually after collection. Charging systems are

available which will automatically lift and dump the contents of the collection transport carts into the charging hopper without handling of the waste by the operator.[8,17] Consequently, use of rigid type transport carts can be effective in minimizing waste handling.

To assure the integrity of the red bags, mechanical means of transporting the waste should not be used, except for final charging into the incinerator. For example, dumb-waiters, chutes or conveyors should not be used to transport the waste.[3] The mechanical charging systems for the incinerator should be designed and operated to minimize bag-breakage, spillage, and possible contamination. For example, trash compactors should not be used since when the bags are compacted, they will likely break open. Furthermore, compaction will affect the wastes' bulk/density (lb/ft^3) which will consequently affect the combustion process.[3]

The treatment of infectious waste as soon as possible after generation is preferable. However, because same-day treatment is not always possible, the incinerator operator may be responsible for waste storage. If the waste must be stored prior to incineration, four factors should be considered:

1. Maintaining container integrity and minimizing handling;
2. Storage temperature;
3. Storage duration; and
4. Location of the storage area.

The waste storage area should be a "secure" area, out of the way from normal hospital traffic and should have restricted access. Certainly, the area should be secure from public access. The storage area and/or the containers should be secure from rodents and vermin which can contract and transmit disease.

As temperature and storage time increases, decay occurs and unpleasant odors result. There is no unanimous opinion on acceptable storage temperature or times. The EPA Office of Solid Waste simply recommends that storage times be kept as short as possible.[3] Some States do regulate storage times. For example, Massachusetts allows infectious waste to be stored for 24 hours (1 day) at room temperature or for 72 hours (3 days) at refrigerated temperatures (34° to 45°F).[3]

Obviously, the level of control that the incinerator operator has over the items just discussed will vary with the situation and with the particular waste handling issue. That is, the operator may have little control over what strength red bag is used, but may have a great deal of control over whether red bags are removed from transport carts to a "charging floor" or whether the bags are simply loaded into the incinerator directly from the cart--thus eliminating handling each bag two more times.

The operator does, however, have control of personal protection items used. It is prudent that when handling infectious waste, an operator should always wear hard-soled shoes to avoid the potential for punctures and thick rubber gloves to resist cuts and punctures and to prevent direct contact with fluids. Safety precautions are discussed further in Chapter 9. The operator must remember that his/her safety is at stake and should bring deficiencies in waste handling practices (e.g., consistent tearing of bags due to poor bag quality) to the hospital administrator's attention.

4.3.2 Restricted Wastes

It is inappropriate to dispose of some wastes in a hospital waste incinerator unless special permits are obtained. Wastes which should not be incinerated, unless special permits are obtained include: (1) radioactive wastes, and (2) hazardous wastes regulated under the Resource Conservation and Recovery Act (RCRA).

Some State regulations or specific operating permits may dictate charging limits for certain types of wastes. For example, an operating permit may allow only up to 5 percent of the hourly charging rate to be human or animal parts (i.e., "pathological waste"). Obviously, the operator cannot tell whether the waste contains 4 percent or 5 percent of pathological wastes; nor should the operator ever open red bag wastes to examine the contents. Nonetheless, the operator must be aware of the regulations and must be attuned to spotting problem wastes, either by the obvious (e.g., gallon jugs of liquids, containers marked "radioactive") or by more subtle means (i.e., identifying large quantities of human/animal

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anatomical parts in the incinerator waste bed, while viewing the bed through a glass covered viewport.)

4.4 INCINERATOR OPERATION, CONTROL, AND MONITORING

The key operating parameters for incinerators were presented in Section 4.2. This section provides a summary of the operating procedures, parameters which can be automatically controlled, and monitoring techniques for incineration systems. The operation, monitoring, and control of these four "typical" systems are discussed:

1. Batch feed controlled air;
2. Intermittent-duty controlled air;
3. Continuous-duty controlled air; and
4. Multiple chamber.

The operation, control, and monitoring of rotary kilns is not presented here because very few units are used to incinerate hospital waste and detailed information regarding their operation was not available.

4.4.1 Batch Feed Controlled-Air Incinerator

This type incinerator typically is a small unit, up to 500 lb/h, but more typically less than 200 lb/h capacity. The incinerator is operated in a "batch mode" over a 12- to 24-h period which entails a single charge at the beginning of the cycle, followed by combustion, ash burnout, cooldown, and ash removal. The operating cycle from startup to shutdown is discussed in the following sections. Parameters which can be automatically controlled and monitoring techniques also are discussed.

4.4.1.1 Incinerator Operating Procedures.

4.4.1.1.1 Ash removal. Startup of the incinerator actually begins with removal of the ash generated from the previous operating cycle. The following are guidelines for good operating practice:[10]

1. In general, allowing the incinerator to cool overnight is sufficient for the operator to remove the ash safely. This cooling can take as long as 8 h.

2. The operator should open the ash cleanout door slowly both to minimize the possibility of damage to the door stop and seal gasket and to prevent ash from becoming entrained.

3. The operator should exercise caution since the refractory may still be hot and the ash may contain local hot spots, as well as sharp objects.

4. The ash and combustion chamber should not be sprayed with water to cool the chamber because rapid cooling from water sprays can adversely affect the refractory.

5. A flat blunt shovel, not sharp objects that can damage the refractory material, should be used for cleanup.

6. Avoid pushing ash into the underfire air ports.

7. Place the ash into a noncombustible heat resistant container, i.e., metal. Dampen the ash with water to cool and minimize fugitive emissions.

8. Once the ash has been removed and prior to closing the ash cleanout door, the operator should inspect the door seal gasket for frayed or worn sections. Worn seal gaskets should be replaced.

9. To prevent damage to the door seal gasket, the operator should close the ash cleanout door slowly and should not overtighten the door clamps. Overtightened door clamps may cause the seal gasket to permanently set and allow infiltration of outside air around the door face.

4.4.1.1.2 Waste charging. The operator may have the option of selecting which items are included in a particular charge. Waste properties which should be considered when the waste is segregated into charges include: (1) the heating value, (2) the moisture content, (3) the plastics content, and (4) the amount of pathological wastes. The heating value and moisture content of waste affects the performance of an incinerator. A charge of waste with a very high heating value may exceed the thermal capacity of the incinerator. The result is high combustion temperature, which can damage the refractory of the incinerator and can result in excessive emissions. Similarly, a charge of waste with a very high moisture content will not provide sufficient thermal input, and the charge will require the use of more auxiliary fuel than usual.

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Plastic items are an example of materials with high heating values. Large quantities of plastic, which may contain polyvinyl chloride, should be distributed through many waste charges, not concentrated in one charge, if possible. When sorting loads of waste to be incinerated, the operator should try to create a mixture of low, medium, and high heating value wastes in each charge, if possible, to match the design heat release rate of the incinerator. In general, lighter bags and boxes will contain high levels of low density plastics which burn very fast and very hot. Heavier containers may contain liquids (e.g., blood, urine, dialysis fluids) and surgical and operating room materials which will burn slowly. As a general rule for segregating waste into charges, it is best for the operator to mix light bags and heavy bags to balance the heating value of each charge. If several different types of waste, i.e., red-bag, garbage (cafeteria wastes), trash, are being charged to the incinerator, it is generally better to charge the incinerator with some of each waste, rather than all one type of waste. Special care should be taken to avoid overcharging the incinerator (beyond its intended use) with anatomical wastes.

Prior to initiating charging, operation of the combustion air blowers and ignition and secondary burners should be checked. Follow the manufacturers' recommendations. The proper operation of the primary and secondary burners is best achieved by observing the burner flame pattern through the viewports in the incinerator wall or in the burner itself. Some burners are equipped with one observation point to view the main flame and another to view the pilot flame. The flame pattern will likely vary with the type of burner. However, the length of the flame should be such that the flame touches the waste but does not impinge directly on the refractory floor or wall. Obviously, the absence of a flame indicates a problem with the burner or the system that controls the burner.

Most burners are equipped with a flame safeguard system that includes a flame detector that effectively cuts off the fuel (gas or oil) supply to the burner if a flame is not detected. When the burner is first started, the burner blower starts and when it reaches full speed, a purge timer starts. When the purge timer times out, the flame safeguard energizes the pilot relay that opens the pilot fuel supply and ignitor. When the pilot

lights, a flame detector (either an ultraviolet scanner [gas or oil] or flame rod circuit [gas only]) detects the flame and causes the main flame relay to activate the fuel supply to the main burner. The pilot then ignites the main burner. The flame detector continues to operate and shuts the burner down if the main burner fails. Additionally, if the air supply is lost both pilot and flame relays shut off the fuel supply. The pilot usually is ignited for no more than 15 seconds (interrupted pilot). If the main burner does not ignite during the period, the flame safeguard system shuts the entire system down.[18]

The incinerator is charged cold. Because these units generally are small, they are usually manually loaded. The waste is loaded into the ignition chamber, which is filled to the capacity recommended by the manufacturer. Typically, the manufacturer will recommend filling the incinerator completely, but not overstuffing the chamber. Overstuffing can result in blockage of the air port to the combustion chamber and in premature ignition of the waste and poor performance (i.e., excess emissions) during startup. Overstuffing also can result in blockage of the ignition burner port and damage to the burner. After charging is completed, the charge door seal gasket is visually checked for irregularities. The door is then slowly closed and locked. The charge door seal gasket should then be inspected for any gaps that would allow air infiltration into the primary chamber. Once operation is initiated, no further charges will be made until the next operating cycle is initiated, i.e., after cooldown and ash removal.

4.4.1.1.3 Waste ignition. Prior to ignition of the waste, the secondary combustion chamber is preheated to a predetermined temperature by igniting the secondary burner. A minimum secondary chamber temperature of 980°C (1800°F) is recommended prior to ignition of the waste. The manufacturer should be consulted regarding proper preheat procedures; improper preheat can result in refractory damage.

After the secondary chamber is preheated, the secondary combustion air blower is turned on to provide excess air for mixing with the combustion gases from the primary chamber.

The primary chamber combustion air blower is activated and the primary burner is ignited to initiate waste combustion. When the primary

chamber reaches a preset temperature (i.e., the minimum operating temperature for the primary chamber, see Table 4-1) and the waste combustion is self-sustaining, the primary burner is shutdown.

The primary combustion air and secondary combustion air are adjusted to maintain the desired primary and secondary chamber temperatures. (Typically this adjustment is automatic and can encompass switching from high to low settings or complete modulation over an operating range.)

During operation, the primary burner is reignited if the ignition chamber temperature falls below a preset temperature. Similarly, the secondary burner is reduced to its lowest firing level if the secondary chamber rises above a preset high temperature setting. Again, control of the burners, like the combustion air, is typically automated. A barometric damper on the stack is used to maintain draft. The incinerator chambers should both be maintained under negative draft.

4.4.1.1.4 Burndown. After the waste burns down and all volatiles have been released, the primary chamber combustion air level is increased to facilitate complete combustion of the fixed carbon remaining in the ash. The temperature in the primary chamber will continue to decrease. During the burndown period, the primary burner is used to maintain the primary chamber temperature at the predetermined minimum level of the operating range. The length of time required for the burndown period depends on the incinerator design, waste characteristics, and degree of burnout desired. A typical burndown period is 2 to 4 h.[14] When combustion is complete, the primary and secondary burners are shutdown.

Shutdown of the secondary burner which initiates the cooldown period usually is automatically determined by a preset length of time into the cycle.[9,11] The combustion air blowers are left operating to cool the chambers prior to subsequent ash removal. The blowers are shutdown when the chambers are completely cooled or prior to opening the ash door for ash removal. Cooldown typically lasts 5 to 8 h.[14]

The final step in the cycle is examination of ash burnout quality. Inspection of the ash is one tool the operator has for evaluating incinerator performance. The operator should look for fine gray ash with the consistency of ash found in the fireplace at home or in the barbeque grill. Ash containing large pieces of unburned material (other than

materials which are not combustible, such as cans) shows that incinerator performance is poor. It may be necessary to return these large pieces of material to the incinerator to be reburned because poor quality ash may be refused at landfills for disposal. Ash color also is an indicator of ash quality. White or gray ash indicates that a low percentage of carbon remains in the ash. Black ash indicates higher carbon percentages remaining. Although carbon remaining in the ash indicates that available fuel has not been used and combustion has not been complete, the fact that carbon remains in the ash is not in itself an environmental concern or an indicator that the ash is not sterile. Nonetheless, ash color can be used to assist the operator in evaluating burnout and incinerator performance.

4.4.1.1.5 Special considerations. If pathological waste is being burned, the ignition burner should be set to remain on until the waste is completely burned. Further, the volume of waste charged likely will need to be significantly reduced. The time required to burn an equivalent volume of Type 4 waste will be extended, since the waste contains high moisture and low volatile content. To destroy pathological waste efficiently, the waste must be directly exposed to the burner flame; consequently piling pathological waste in a deep pile (e.g., filling the entire chamber) will result in inefficient combustion.[15] If large volumes of pathological wastes are to be incinerated, an incinerator which is especially designed for pathological waste should be used.

4.4.1.2 Automatic Controls. Various levels of automatic controls are available for hospital incinerators, even for the smallest units sold. The smallest batch type units can be designed to use the same automatic control concepts and hardware for the key combustion control parameters (e.g., temperature and combustion air) as the larger continuous-duty incinerators.[19] The use of control systems allows key combustion parameters to be adjusted automatically based on data (e.g., temperature) from the incineration system. These automatic controls permit the combustion process to be more closely controlled.

For batch feed systems, parameters that can be automatically controlled include:

1. Charging frequency;
2. Combustion air rate;

3. Primary and secondary burner operation;

4. Temperature; and

5. Combustion, burndown, and cooldown cycle times.

4.4.1.2.1 Charging frequency. The charging frequency can be automatically controlled by providing an interlock system on the charging door. The interlock will prevent the charging door from being opened after the primary burner is ignited and will prevent additional charges to the batch system until after burndown and cooldown have been completed. The operation of the interlock can be set up in one of two ways. The interlock can be activated by a timer so that the door cannot be opened until after a preset time has elapsed (e.g., 24 hours). Alternatively, operation of the interlock can be based on temperature; the interlock is set to deactivate only after the proper temperature in the cool down cycle is attained. The latter approach truly controls operation of the unit in a manner that assures the incinerator will run through the complete charge, combustion, burnout, and cooldown cycle.

4.4.1.2.2 Combustion air rate. Combustion air rate can be automatically controlled by on/off settings, low/high settings, and full modulation of the flow over an entire operating range. The control settings can be activated based upon the value of a monitored parameter (e.g., temperature) or by a specified time in a cycle. Some manufacturers are now using different types of more advanced combustion air controls that sense parameters such as gas flow, opacity, oxygen concentration, and loading cycles to assure that adequate combustion air is available in the secondary chamber.[4]

4.4.1.2.3 Primary and secondary burner operation. Like the combustion air, the ignition and main combustion (secondary chamber) burners can be controlled over an entire operating range (i.e., modulated), at low/high levels, or in the on/off position. The settings can be based upon a monitored value (e.g., temperature) or as part of a timed sequence. The use of such settings in a control system is discussed in the following sections.

4.4.1.2.4 Temperature. Both the primary ignition and secondary combustion chamber temperatures can be automatically controlled. At least two levels of control are available. The first control approach is

designed to control temperature in each chamber by modulating the available combustion air to each chamber. In this type system, the temperature in each chamber is monitored, and the combustion air to each chamber is separately controlled based on feedback from the thermocouples. The combustion air is modulated continuously over a wide range in order to maintain the set point temperatures. Auxiliary burners are used as necessary to maintain minimum temperatures. Since instantaneous peaks in the combustion gases generated in the primary chamber can occur, some manufacturers recommend operating the secondary burner at all times (in a low fire position if heat is not required) to assure complete combustion of primary chamber gases.[4]

This type control system effectively controls the waste combustion rate in the primary chamber by controlling the combustion air. Controlling the combustion rate in the primary chamber subsequently limits the combustion rate in the secondary chamber. Controlling the secondary chamber combustion air controls that chamber's temperature by increasing or decreasing the excess-air level. The firing rate of the main combustion burner (secondary chamber) may be modulated upward or downward if low and high temperature set points are reached in the secondary chamber. Similarly, the ignition burner can be activated automatically if the primary chamber temperature falls below the minimum set point. This type system provides a true control of the key parameter, combustion temperature, by modulating the combustion air.

One manufacturer controls the combustion rate in the primary chamber and the temperature in the secondary chamber by monitoring the oxygen concentrations in each combustion chamber and using these data to control/adjust the combustion air levels.[20]

Review of manufacturers' information indicate that a second approach to automatically controlling the combustion process is used for batch type units.[9,11] In this approach, a series of timers are used to establish a timed sequence of events and the key process equipment (i.e., burners and combustion air) have high/low or on/off settings. The switching of the burners and combustion air from one setting to another is controlled by the timed sequence. Overrides for the timed sequence are typically provided to assure that minimum or maximum set point temperatures are not exceeded.

This type control system does not offer the same level of combustion control as the modulated system previously described. Instead of continuously modulating to achieve a specific set point (i.e., temperature), this type system utilizes on/off or low/high settings to maintain control between two set points.

4.4.1.2.5 Combustion, burndown, and cooldown cycle times. An automatic control sequence operating on a timer cycle typically is used to initiate and control the length of burndown and cooldown cycles. Table 4-3 presents an example timed control cycle for a batch operated incinerator.

4.4.1.3 Monitoring Operations. The monitoring of key operating parameters provides several benefits. First, monitoring provides the operator with information needed to make decisions on necessary combustion control adjustments. For example, continuous monitoring of the temperature and carbon monoxide level of the secondary combustion chamber effluent gas stream allows the operator to determine whether optimum combustion conditions are being maintained. Indications of an abnormally high CO level and low temperature can immediately be used to adjust the secondary burner rate to raise the combustion chamber temperature. Second, properly maintained monitoring records can provide useful information for identifying operating trends and potential maintenance problems. This historical information can be used to make decisions with respect to modifying standard operating procedures or control set points. For example, careful visual inspection of ash quality each day complemented by comments in a daily operator's log book can be used to track ash burnout patterns. If a gradual trend towards poor ash burnout becomes evident, identification of possible reasons and corrective actions can be initiated. Finally, monitoring generally is needed to satisfy regulatory requirements.

Monitoring can be divided into three broad categories:

1. Continuous monitoring--involves continuous instrumental measurement with continuous data recording; e.g., use of a temperature sensor with a strip chart recorder.

2. Continuous measurement--involves continuous instrumental measurement but requires the operator to monitor the data output manually; e.g., use of a temperature sensor with a digital meter display.

TABLE 4-3. EXAMPLE TIMED CONTROL CYCLE FOR BATCH MODE INCINERATOR

Cycle	Controlling parameter/level	Resulting automatic control action
1. Secondary combustion chamber preheat	Manual start	Secondary burner--High fire
2. Ignition	Combustion chamber temperature reaches 1100°F	Secondary combustion air-high level
		Primary combustion air--high level
		Primary burner on
3. Combustion	Primary chamber temperature reaches 1000°F	Primary burner off
	Secondary temperature reaches high set point, 2000°F	Secondary burner switches to low fire
	Secondary temperature reaches low set point, 1800°F	Secondary burner switches back to high fire
	(Burner will cycle as high/low set-points are reached)	
4. Burndown	5 hours from ignition	Primary air switched to high
	High primary temperature override	Primary air switched back to low
	1 hour after override activated	Primary air switched to high level
5. Cooldown	8 hours from ignition	Secondary burner shuts off
	16 hours from ignition; cycle completed	Combustion air blowers shut off

3. Manual monitoring--involves inspection by the operator on a noncontinuous basis, e.g., visual stack gas opacity readings.

All of these techniques can be used to monitor the operation of batch type incinerators. Continuous monitoring of operating parameters will, in most cases, provide more information than manual monitoring. For example, continuous opacity monitoring of stack gas opacity will provide opacity data for the entire operating period and will provide a permanent record of changes in opacity over the operating cycle and trends over time. On the other hand, visual inspection of the stack gas opacity will provide limited data, and a record will be available only if the observer records the result.

The following operating parameters can be monitored:

1. Charge rate;
2. Combustion gas temperature;
3. Condition of the waste bed and burner flame;
4. Combustion gas oxygen level;
5. Combustion gas carbon monoxide level;
6. Combustion gas opacity;
7. Auxiliary fuel usage; and
8. Ash quality.

The techniques for monitoring each of these parameters are briefly described in the following paragraphs.

Note that this section is not intended to recommend specific monitoring requirements, but is intended to present the key parameters which can be monitored and provide a brief description of how the parameters can be monitored and what useful information monitoring can provide. Chapter 6 further discusses actual instrumental monitoring methods.

4.4.1.3.1 Charge rate. The weight of each charge can be recorded in a log book. This procedure will help to indicate whether the rated capacity of the incinerator is being exceeded. Note that incinerators are designed for a specific thermal input. Since the heat value (Btu/lb) of wastes will vary, the weight of a charge is not a true indicator of whether the rated capacity is being exceeded. Variations in heating value in the waste will need to be considered in determining charge size.

Nonetheless, monitoring the weight of the charge will provide historical data which can be used to make systematic modifications to operating procedures, i.e., reduction of the charge rate by 20 percent to evaluate the effect on resolving poor burnout problems. Monitoring this parameter will require a scale or weigh bin which can be used to weigh individual waste bags or transport carts.

4.4.1.3.2 Combustion gas temperature. The combustion gas temperatures (primary and secondary) are critical operating parameters. These parameters typically are monitored continuously using thermocouples. Permanent strip chart (or data logger records) may be kept; for small units only meters without permanent recordkeeping typically are provided.

4.4.1.3.3 Condition of waste bed and burner flame. If viewports are provided in each chamber, the operator can view the flame pattern and the waste bed. Visual observation of the combustion process provides useful information on the burner operation (i.e., potential problems such as flame impingment on the refractory, or smoking of the secondary burner flame can be identified) and on the combustion process in general (i.e., quantity and condition of remaining waste charge can be identified).

Viewports should be sealed glass covered by blastgates. "Inspection doors" which open the chamber to atmosphere should not be used for viewing the combustion process because these pose safety problems and affect the combustion air control.

4.4.1.3.4 Combustion gas oxygen level. The combustion gas oxygen concentration is a direct measure of the excess-air level. Although this measurement is not essential, it provides real-time information about changing conditions in the combustion chamber. Typically, the oxygen level of the combustion gas exiting the secondary chamber is used to assure that excess air is always available for complete combustion. A continuous oxygen monitoring system typically is used (see Chapter 6). However, a portable instrumental measurement system also can be used occasionally for monitoring oxygen levels to confirm proper operation or to provide information necessary for adjusting combustion air dampers.

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4.4.1.3.5 Combustion gas carbon monoxide level. Carbon monoxide is a product of incomplete combustion; excessive levels indicate that a poor combustion condition exists. The CO concentration of the combustion chamber effluent can be monitored continuously to alert the operator to poor combustion conditions. An instrumental CO monitoring system generally is used for this procedure (see Chapter 6). Alternatively, a portable instrumental measurement system can be used to make occasional measurements of CO to monitor performance. As with the oxygen measurements, this approach often is used to check performance in conjunction with maintenance or adjustment of combustion control level settings.

4.4.1.3.6 Combustion gas opacity. Combustion gas opacity provides an indirect measurement of particulate matter concentration in the stack gas; hence opacity is an indicator of incinerator performance. As particulate concentration increases, so does the opacity. Continuous emission monitoring systems (CEMS) for measuring opacity (referred to as "transmissometers") are available (see Chapter 6). An alternative, and simpler monitoring technique, is visual observation of the stack emissions. The opacity of the stack gas can be determined accurately by a trained observer. Even an untrained observer can detect gross changes in stack gas opacity and can use visual observations to note combustion problems.

4.4.1.3.7 Fuel usage. Monitoring fuel usage provides historical data for identifying maintenance problems and for identifying the need for adjustments to control system settings to increase efficiency. Fuel usage can be monitored with a simple metering system. Fuel usage can than be determined by logging meter readings or continuously recording the metering system's output.

4.4.1.3.8 Ash quality. Ash quality is one indication of combustion performance. Visual inspection is the simplest means of determining ash quality and incinerator performance. For example, large pieces of uncombusted materials (e.g., paper) indicate very poor ash quality. The operator should inspect the ash visually and record comments on ash quality in a log book routinely.

For a more technical determination of ash quality, a chemical analysis of a sample of the ash can be conducted. The amount of combustible materials remaining in the ash can be determined by a laboratory test which subjects a sample of the ash to a combustion atmosphere and then determines the weight loss. This procedure measures the ash's "burnout" quality. A 100 percent "burnout" means no volatile or combustible materials remain in the ash; some incinerators are capable of 90 percent burnout.[21] Occasional checks of ash burnout are useful for monitoring performance of the incinerator.

4.4.2 Intermittent-Duty, Controlled-Air Incinerators

Intermittent-duty, controlled-air incinerators typically are used for "shift" type operation. The incinerator must be routinely shutdown for ash removal. Hence, there is a distinct operating cycle. The main feature which distinguishes this type incinerator from the batch incinerator is the charging procedures which are used. The charging system is designed to accommodate multiple charges safely throughout the operating cycle rather than rely on a single batch charge at the beginning of the operating cycle. Either manual or automated charging systems can be used.

4.4.2.1 Operation.

4.4.2.1.1 Ash removal. The residual ash from the previous operating cycle must be removed before a cycle can be initiated. Ash removal procedures are essentially the same as those described in Section 4.3 for batch mode incinerators.

4.4.2.1.2 Startup. Before the operator initiates startup, proper operation of the primary and secondary burners and combustion air blowers should be checked according to manufacturer's instructions. The following steps are conducted during startup:

1. The primary and secondary burner(s) are ignited, and preheat of the combustion chambers is initiated. The manufacturer should be consulted regarding proper preheat procedures, since improper preheat can damage the refractory.

2. The secondary chamber must reach a predetermined temperature (e.g., 1800°F) before the incinerator is ready for charging; and

3. After the predetermined secondary chamber temperature is attained, the primary and secondary combustion air blowers are activated. The incinerator is ready to be charged.

4.4.2.1.3 Waste charging. Stable combustion can be maintained most readily with a constant thermal input to the incinerator. Feeding too much waste in a charge causes the incinerator to overload. These overloads can result in poor burndown (because of waste pile buildup on the hearth) or can cause excessive emissions because the rapid generation of volatiles overloads the capacity of the secondary chamber. Feeding too little waste results in inadequate thermal input and consequent excessive auxiliary fuel use.[10] A charge frequency and quantity recommended by two manufacturers is 15 to 25 percent of the rated capacity (lb/h) at 10 to 15 minute intervals.[10,11] Another rule of thumb is to recharge the incinerator after the previous charge has been reduced by 50 to 75 percent in volume, determined by observation of the waste through the view ports or operating experience.[11] Charging volume and frequency will vary with waste composition, and the operator must use some judgment to determine appropriate rates.

The temperature profile of a combustion chamber is a picture of how the temperature in the chamber fluctuates during the course of the incineration process. The variations in temperature are shown on the strip or circular chart recorder that records the temperatures measured by the thermocouples in the combustion chambers. The temperature fluctuations are affected by the frequency of waste charging and the size of the charge. Insufficient or infrequent charging may cause the temperature to become too low and necessitates the use of auxiliary fuel to help maintain the desired set point temperature. Charging too much waste may cause a rapid increase in secondary combustion chamber temperature if the waste has a high volatile content. On the other hand, if the waste has a low Btu content or contains a lot of moisture, overcharging may have the effect of first decreasing the primary combustion chamber temperature (while the moisture is being volatilized) before a temperature increase is noted. Charging on a regular basis with

the same volume of waste in each charge helps to "flatten" the temperature variation and allow proper combustion while preventing refractory damage and excessive auxiliary fuel consumption. Monitoring the temperature profile of the combustion chambers will assist in determining the proper charging rates.

After the last charge of the day is completed, the incinerator is set to initiate the burndown cycle. The limiting factor on how long the charging period can be sustained without initiating the burndown cycle is the degree of ash buildup on the hearth. Typically the charging period is limited to 12 to 14 hours.[14]

4.4.2.1.4 Burndown. The burndown cycle is essentially the same as described for batch incinerators and is initiated after the last charge of the day is made. For intermittent-duty incinerators the burndown sequence can be initiated manually or may be initiated automatically. One manufacturer's control system is designed to include a control timer which is activated by the charging door.[11] Whenever the charging door is opened and then closed, the burndown timing cycle is initiated by resetting the burndown timer to a preset time-period, e.g., 5 hours (the actual length of the burndown time is determined by experience with waste stream).

4.4.2.1.5 Cooldown. The cooldown period is the same as for batch incinerators.

4.4.2.2 Automatic Controls. The parameters which can be controlled automatically for intermittent-duty controlled-air incinerators are essentially the same as those already discussed for the batch-operated incinerators. The automatic control techniques used also are essentially the same. Either timed sequences with high/low burner and air settings or control systems which have fully modulated burner and air controls that are continually adjusted based on control feedback (e.g., temperature) can be used. For intermittent-duty units, the charging rate can be controlled automatically if an automatic mechanical charging system is provided with the unit. Automatic control for a ram feed charger consists of a timing sequence which will initiate the charging sequence at regularly timed intervals. The size of the charge is controlled by the volume of the feed hopper. An override on the automatic feeder can be provided so that the control system will not allow a charge to be fed at the regular interval

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if certain conditions are not met. For example, if the primary chamber temperature exceeds a high level set point, the incinerator is not yet ready for another "fuel" charge and the charging cycle will not initiate.

4.4.2.3 Monitoring. The operating parameters that can be monitored for intermittent-duty incinerators are the same as those parameters discussed in Section 4.4.1.3 for batch incinerators. The same monitoring techniques generally apply. However, continuous monitoring and recording of the ignition and combustion chamber temperatures have added importance for intermittent-duty incinerators. The trends in these measured values are useful to the operator in determining the appropriate charging frequency and in adjusting the charging frequency as waste characteristics change. Similarly, the use of appropriate viewports has added significance in making decisions on charging frequency based upon appearance of the waste bed.

4.4.3 Continuous-Duty, Controlled-Air Incinerators

Continuous-duty incinerators have the capability of continuously removing the ash from the incinerator hearth. Consequently, the incinerator can be operated at a near-steady-state condition by continuously charging the unit at regularly timed intervals and similarly by removing the ash at regularly timed intervals.

4.4.3.1 Operation.

4.4.3.1.1 Startup. Startup procedures for continuous-duty incinerators are essentially the same as for the intermittent-duty incinerators. The chambers are first preheated before the initial charge is loaded to the incinerator. The manufacturer should be consulted regarding proper preheat procedures, since improper preheat can damage the refractory.

4.4.3.1.2 Charging. To approach steady state operation, consistently sized charges should be fed at regularly timed intervals. Practically speaking, continuous-duty incinerators are likely to be more automated than the types of units previously discussed. Continuous-duty incinerators will include a mechanical feed system, which may be fully automated so that charges are automatically fed at regularly timed intervals.

During operation, the waste bed/ash bed is typically moved through the incinerator by one of two methods. In the first method, the waste bed is continually pushed towards the back end of the chamber when each new waste charge is pushed into the incinerator by the feed ram. In the second method, where the incinerator hearth is exceptionally long, the hearth is built in a stepped fashion, and special ash rams are provided for pushing the ash from one step to the next step. Ultimately, in both systems, the ash is pushed off the hearth into an ash discharge chute.

During operation, the operator must assure that the ash is being removed from the system. For manual ash removal systems, an ash bin must be emptied routinely. The ash bin is located inside a sealed chamber at the end of the ash discharge chute or is directly sealed to the combustion chamber ash discharge chute. For fully automated ash systems, the ash is mechanically removed by a rake or conveyor from a water quench pit located at the end of the ash discharge chute. For these systems, the operator need only monitor the ash discharge system to assure that no mechanical problems have developed and to assure that the quench pit water level is maintained.

4.4.3.1.3 Shutdown. Shutdown of the incinerator involves stopping the charging process and maintaining temperatures in the combustion chamber until the remaining waste burns down to ash and is finally discharged from the system in the normal manner.

4.4.3.2 Automatic Controls. The parameters which can be controlled automatically for this type unit are essentially the same as those for the intermittent duty unit. However, when separate ash transfer rams are a part of the system, ash removal may also be automatically controlled. If the waste feed system is on an automatically timed sequence, the ash removal system likely will be integrated into the timed sequence.

The operating controls for the parameters discussed in Section 4.2.2 are more likely to be fully automated for continuous-duty incinerators than for batch units, simply because of the size and frequency of use of the units. Automated controls relieve the operator from the burden of continuously making adjustments.

4.4.3.3 Monitoring. The operating parameters that can be monitored for continuous-duty incinerators are the same as those parameters

discussed in Section 4.4.2.3 for intermittent-duty incinerators. The use of automatic/mechanical feed systems simplifies the monitoring of waste feed charge frequency (and consequently volume). A recording indicator can be installed that indicates how frequently the waste feed charge system is activated. This information can be used to provide a rough estimate of the charging rate (lb/h) for the unit and also may be helpful in diagnosing other operational problems, such as reasons for temperature excursions.

4.4.4 Multiple-Chamber Incinerators

Typically, multiple-chamber incinerators are used to burn pathological waste. However, other medical waste including red bag waste are sometimes burned in these units; when burning red bag waste special precautions should be taken during charging to assure the incinerator's capacity is not exceeded. Typical applications of multiple-chamber incinerators include batch or intermittent operation; continuous-duty operation automatic ash removal is atypical. Operation of these units is discussed briefly below.

4.4.4.1 Operation.

4.4.4.1.1 Ash removal. The residual ash from the previous operating cycle must be removed before a cycle can be initiated. Ash removal procedures are essentially the same as those described in Section 4.4.1.1.1 for batch mode controlled-air incinerators.

4.4.4.1.2 Startup. Startup of the excess-air incinerator is similar to startup for the batch-mode, controlled-air incinerators. The secondary chamber is first preheated to a predetermined chamber temperature. The incinerator is then charged with the waste.

4.4.4.1.3 Charging. Multiple-chamber incinerators may be either batch or intermittent duty and may be charged manually or with a mechanical loading device. Because of the significant difference in heat contents between pathological waste and red bag waste and because incinerators are designed to burn a waste with a specific heat input, the proper charging (addition of fuel) procedures are different for different wastes.

Pathological waste has a low heat content, a high moisture content, and a low percentage of volatiles. Consequently, it must be constantly exposed to the auxiliary burner(s') flame(s) to be combusted. The following proper pathological waste charging procedures are recommended:

1. The waste should be placed on the hearth in an even layer that provides maximum exposure to the burner(s) flame(s). The waste should not be deeply piled.

2. Recharging the incinerator should not be done until considerable reduction in volume (greater than 75 percent) of the previous charge has occurred.

3. When recharging the incinerator:

a. Turn off the primary burner (some units may have an interlock system that automatically turns the burner off when the charge door is opened);

b. Place the fresh charge in a single layer on the hearth so that the burner(s) impinge on the waste; and

c. Close the charge door before restarting the primary burner.

The heat content of red bag waste will be variable depending on the contents of the bag. Proper operation of the incinerator dictates that: (1) sufficient waste should be charged to the unit to sustain the desired temperature without excessive use of the primary burner; and (2) to maintain the primary chamber temperature below the upper limit and to prevent emissions, the charge rate should not exceed the capacity of the incinerator at any time. Obviously, if the incinerator was designed for pathological waste, then a significantly smaller red bag waste charge should be made than is typically made of pathological waste. The following guidelines are recommended for charging red bag waste into a multiple-chamber incinerator:

1. Use of frequent, small batches rather than one large batch. The objective is to avoid causing a rapid release of volatile compounds that exceeds the combustion capacity of the incinerator. The frequency and size of each charge will be determined by the incinerator being operated and the type of waste. A recommended procedure is to charge about 1/10 the rated capacity (lb/h) every 6 minutes.

2. Keep a fairly consistent waste bed in the incinerator. The incinerator should not be jammed full, nor should it be empty.

3. Avoid "stuffing and burning" in the incinerator; that is, do not fill the incinerator chamber to full capacity, floor to ceiling, ignite the waste, and allow the incinerator to operate unattended.

4. When recharging the incinerator:

a. Turn the primary burner off (some units may have an interlock system that automatically turns the burner off when the charge door is opened);

b. The partially burned waste from the previous charges should be pushed towards the back of the hearth with a rake; and

c. The new waste charge should be fed to the front end of the hearth (near the charge door). This procedure allows good exposure of the partially combusted waste to the overfire air and allows a good flame from the waste bed to be maintained. On the other hand, if cold, newly charged waste is thrown on top of the existing waste bed it partially smothers the burning bed which can result in increased emissions.

5. If the incinerator has a grate, it is important that the entire grate be covered with a waste bed.

4.4.4.1.4 Operation. When burning pathological waste, the primary burner is operated throughout the combustion cycle and thermal output should be relatively constant without rapid fluctuations. The primary chamber combustion air is preset to maintain a constant excess-air level, and primary chamber temperature is controlled by modulating the primary burner. Since the pathological waste does not contain large amounts of combustible volatiles, secondary chamber combustion settings also will remain relatively constant. The combustion air damper settings and burner settings necessary to attain the desired secondary chamber temperature and excess-air levels are set and normally do not need to be adjusted. Temperature control normally is achieved only by modulating the primary burner settings.[15]

Modulating the primary burner does not offer the same degree of control over temperature as the adjustment of air supply. If a multiple-chamber incinerator was overcharged with red bag waste, modulation of the primary burner (or even shutdown of the burner) would not reduce the

temperature because once ignited, the red bag waste will continue to burn out of control with the large excess-air level carrying excessive unburned material to the secondary chamber. In such a scenario, the secondary chamber would be unable to respond to such a high carryover of volatiles. Therefore, while red bag waste may be burned in a multiple-chamber incinerator, the potential exists for high temperatures that may damage the unit and for high emissions if the unit is overcharged. Some multiple-chamber units may have an automatically modulated air supply system that adds air if the temperature rises (cools the combustion process) or restricts air if the temperature falls. However, the large excess-air level in the primary chamber will still produce carryover of particulate matter to the secondary chamber. Therefore, multiple-chamber incinerators are better suited to burn pathological waste than they are to burn red bag waste because of the relatively stable and constant heat output of pathological waste and the fact that pathological waste combustion is controlled entirely by the firing of the primary burner (i.e., pathological waste cannot sustain combustion without the primary burner and will not burn out of control as the red bag waste can).

4.4.4.1.5 Burndown. There is no burndown period in the operation of multiple-chamber incinerators. The degree of burnout achieved is dictated by the length of time that the primary burner is left in operation after the last charge. After complete destruction of the waste has been achieved (as noted by visual observation through a viewport), the primary burner is shut down. The secondary burner is not shut off until all smoldering from residual material on the hearth in the primary chamber has ceased.[15]

4.4.4.1.6 Cooldown. After all smoldering in the ignition chamber has ceased, the secondary burner is shut down, and the incinerator allowed to cool.

4.4.4.2 Automatic Controls. The primary operating parameters which are automatically controlled are the primary and secondary chamber temperatures. Control of the temperatures is achieved by modulating the burner rates. The primary and secondary combustion air levels typically are not automatically controlled, but are preset. Incinerator draft typically is controlled by a barometric damper. Charging rate also is not likely to be controlled automatically in this application.[15]

4.4.4.3 Monitoring. The same operating parameters that are monitored on controlled-air incinerators can be manually or continuously monitored during operation of the multiple-chamber unit.

4.5 ADD-ON AIR POLLUTION CONTROL SYSTEMS

Key operating parameters and procedures for wet scrubbers, fabric filters, and dry scrubbers are discussed in this section. Addition of an air pollution control system (APCS) to a hospital waste incinerator increases the number of operating parameters the operator must control, monitor, and adjust. Furthermore, addition of an APCS to an incinerator significantly modifies how at least one important incinerator operating parameter is controlled; this parameter is the incinerator draft. Operation of the APCS will require use of an induced draft (ID) fan to provide the necessary airflow through the system. Natural draft control will no longer be applicable; gas flow through the system will be controlled by the ID fan.

4.5.1 Wet Scrubbers[22-24]

4.5.1.1 Key Operating Parameters. All wet scrubbers utilize a liquid scrubbing media to remove pollutants from the incinerator exhaust gas stream. Actual collection of the pollutant in the liquid is primarily through impaction for particulates and absorption for acid gases. The liquid/gas (L/G) ratio is an important parameter for all wet scrubbers. The appropriate L/G ratio varies with scrubber type. Venturi scrubbers require a relatively low L/G ratio with 7 to 10 gallons per thousand actual cubic feet (gal/Macf) recommended.[22] This low L/G ratio is acceptable because venturi scrubbers rely on high energy pressure drops to create high gas velocities, turbulence, and lots of small water droplets for the collection of fine particulate matter by impaction. Therefore, pressure drop (ΔP) and L/G ratio are the two key performance parameters for venturi scrubbers. Packed-bed scrubbers, however, rely on creating large surface areas of gas to liquid interface for collection of gaseous pollutants through absorption. Large pressure drops are not required by

packed-bed scrubbers. However, relatively large L/G ratios are required to adequately cover the packing media and create a large wetted surface. The L/G ratio is the key performance parameter for packed-bed scrubbers used for acid gas control with 10 to 15 gal/Macf recommended.[23] Spray towers also require a L/G ratio of 5 to 20 gal/Macf.[23] While these are the most important key performance parameters, there are several key parameters for each scrubber type that can be monitored and adjusted by the operator to achieve the desired performance of the unit. Table 4-4 lists the key parameters and identifies typical operating ranges for venturi scrubbers, packed-bed scrubbers, spray towers, and mist eliminators for application to hospital waste incineration systems.

Control of scrubber liquor pH is important to minimize corrosion from acid or alkaline conditions. A scrubber liquor pH range of 5.5 to 7.0 is recommended.[22] A pH in this range represents neutral water. A lower pH indicates acidic water which can cause corrosion. Higher pH values may result in scaling.

Turbidity of the scrubber liquor feed also is an important operating parameter with regard to maintaining particulate matter control efficiencies. High turbidity (a measure of the dissolved and suspended solids in the liquid) can result in increased particulate matter emissions and pluggage of nozzles.

Proper design and operation of the mist eliminator system is necessary for maintaining particulate matter control efficiencies. Scrubber system design sometimes includes a clean water spray for rinsing mesh pad eliminators and maintaining performance.

4.5.1.2 Scrubber Operation. Proper operation of a scrubber requires that the operator (1) establish a fixed liquid flow rate to the scrubbing section, (2) initiate gas flow through the system by starting a fan, and (3) set up the liquid recirculation system so that suspended and dissolved solids buildup does not create operating problems. Once the system has been started and operation has stabilized, little additional operator attention will be needed. Operators should refer to the instruction manual provided by the scrubber manufacturer for adjustment of site-specific operating conditions.

TABLE 4-4. WET SCRUBBER PERFORMANCE PARAMETERS FOR HOSPITAL WASTE INCINERATORS[22-24]

Parameter	Typical range[a]	Units of measure	Operating range[b]
Venturi scrubbers			
Pressure drop	15-60	in. w.c.	20-50
Liquid feed rate[c]	>35	gal/min	
Liquid-to-gas ratio	4-10	gal/Macf	7-10
Liquid feed pressure	20-60	psi	20-60
Liquid feed turbidity	1-10	Percent suspended solids	0-3
Gas flow rate[c]	>5,000	acfm	
Liquid feed pH	5-10	pH	5.5-7.0
Packed-bed scrubbers			
Pressure drop	1-5	in. w.c.	
Liquid feed rate[c]	>5	gal/min	
Liquid feed pH	5.5-7.0	pH	5.5-7.0
Liquid-to-gas ratio	10-30	gal/Macf	15-25
Liquid feed pressure	20-60	psi	30-60
Gas flow rate[a]	>5,000	acfm	
Liquid feed turbidity	1-10	Percent suspended solids	1-3
Spray towers			
Pressure drop	0.5-3.0	in. w.c.	1-3
Liquid-to-gas rate	5-20	gal/macf	5-20
Mist eliminator			
Pressure drop	1-3	in. w.c.	1-3
Liquid feed rate[c]	>5	gal/min	
Liquid feed pressure	20-60	psi	30-60
Liquid-to-gas ratio	1-6	gal/Macf	2-3
Liquid turbidity	0-3	Percent suspended solids	0-0.5
Gas flow rate[c]	>5,000	acfm	
Liquid feed pH	5-10	pH	7

[a]The typical range is the range of operating parameters that can exist on a broad range of source categories.
[b]The operating range is the range of operating parameters specified by manufacturers for combustion sources similar to hospital waste incinerators.
[c]Values, or range of values, are dependent on the size of the scrubber system.

4.5.1.2.1 Scrubber Startup. The scrubber should be started prior to charging waste feed to the incinerator but not necessarily prior to preheat. The specific manufacturer's startup instructions should be followed. The following procedures in sequence are typical during startup of a scrubbing system to insure proper operation:

1. Turn on the liquid recirculation system or liquid supply(s) to the scrubber(s) and mist eliminator.

2. Adjust the liquid flow rates to those specified in the instructions supplied by the scrubber manufacturer.

3. If the induced draft or forced draft fan feeding the scrubbing system has a damper installed at its inlet or outlet, close the damper.

4. Start the induced draft or forced draft fan.

5. If the system is equipped with a damper, gradually open the damper until the proper gas flow rate is established.

6. Again recheck the liquid flow rate(s) and adjust as necessary.

7. Check the differential pressure across the scrubber and compare with the design pressure drop specified in the operating manual. If the differential pressure is too low across the scrubber, either the liquid rate is too low or the gas flow rate is too low. To correct this condition, either increase the gas flow rate by opening a damper, or increase the liquid flow rate to the scrubber. If the scrubber is a venturi unit with an adjustable throat, the pressure can be increased by decreasing the throat area.

8. Initiate the liquid bleed to treatment or disposal as specified in the manufacturer's manual. If the bleed is taken by an overflow from the recirculation tank, the flow rate at this point is established by the rate at which makeup water is introduced to the recirculation tank. The manufacturer's manual should show the anticipated water evaporation rate in the scrubbing system. If, as an example, the evaporation rate is 1 gallon per minute, and if you wish to establish a bleed rate of 1 gallon per minute, it will be necessary to feed 2 gallons per minute of total water to the recirculation tank. The bleed rate is determined by the rate at which the solids buildup in the scrubbing system. These solids can be either suspended or dissolved solids or both. A scrubber is capable of handling a maximum of 3 percent (weight) suspended solids, and it is

suggested that the dissolved solids not exceed 10 percent (weight).[22] Based on design data, a recommended bleed rate from the system should be provided by the manufacturer. The operator should combine this figure with the evaporation figures to give a total recommended makeup water rate to the recirculation tank if an overflow type bleed system is used. If a bleed system is provided from a slip stream off the pump feeding the venturi scrubber, liquid makeup is normally provided by a level control device in the recirculation tank. The flow rate required will be the same as the flow rate required for the overflow bleed system. However, it is only necessary to insure that adequate water supply is available to the level control device on a continuous basis.

4.5.1.2.2 Scrubber shutdown. To shut the system down without overloading the fan or causing any damage to the scrubbing equipment, the following procedures in sequence are typical:

1. Shut off the induced draft or forced draft fan feeding the scrubbing system.
2. Wait until the fan impeller has stopped rotation and then shut off the scrubbing water recirculation pump.
3. Shut off the makeup water supply system.

4.5.1.3 Automatic Control. Key operating parameters which may be automatically controlled for a scrubber system include:

1. Venturi pressure drop;
2. Scrubber liquid flow rate;
3. Scrubber liquid pH; and
4. Gas flow rate.

The venturi pressure drop is the key performance parameter for venturi scrubbers and the scrubber system can be designed to monitor this parameter and provide automatic control based on adjustment of the venturi throat.

For venturis, packed beds, and spray towers, the scrubber liquid flow rate is a key parameter. This parameter usually remains constant during operation but, nonetheless, can be designed for automatic flow rate control.

When caustic materials are added to the scrubber liquid, control of scrubber liquid pH is necessary to prevent damage to the scrubber

equipment. A pH meter is used to monitor the pH of the liquid. The output of the meter is used to control the amount of caustic material added to the scrubber sump.

Gas flow rate through the system can be controlled automatically by monitoring and adjusting fan rpm for a variable speed fan, or by monitoring and controlling fan static pressure using a damper for a constant rpm fan. Gas flow rate is controlled to maintain the desired draft in the incinerator combustion chambers, as well as the desired pressure drop across the scrubber.

4.5.1.4 Monitoring. Scrubber parameters which can be monitored by the operator include:

1. Venturi pressure drop;
2. Scrubber liquid flow rate;
3. Scrubber liquid pH;
4. Fan static pressure, rpm, or amperage; and
5. Gas inlet temperature.

The first four items listed were discussed in the section above with regard to using these parameters for automatic system control. Gas inlet temperature is of interest to the operator because excessive temperatures can damage the pollution control equipment, especially in systems where fiber reinforced plastic materials are used. A thermocouple is used to monitor the gas inlet temperature.

4.5.2 Fabric Filters[25-27]

4.5.2.1 Key Operating Parameters. The key operating parameters for fabric filter control systems are summarized in Table 4-5. To prevent damage to the system the gas temperature must be maintained in a range between the dewpoint of the gas and the upper temperature limit of the fabric. The upper operating temperature of the fabric will depend on the fabric type; the manufacturer should be consulted regarding the upper temperature limit.

The pressure drop across the system for pulse jet baghouses typically is maintained within a range of 5 to 9 in. w.c.[25] Pressure drop gives an indication of filter cake formation. Filter cake formation is dependent

TABLE 4-5. KEY OPERATING PARAMETERS FOR FABRIC FILTER CONTROL SYSTEMS

Parameter	Operating range[26]
Upper gas temperature, °F	Below upper limit for fabric[a]
Lower gas temperature, °F	Above dewpoint[b]
Pressure drop, in. w.c.	5-9
Cleaning air pressure, psig	60-100

[a]The upper temperature limit will be dependent on fabric type. Consult manufacturer.
[b]The gas temperature usually is maintained above 300°F.

on the effectiveness of the bag cleaning cycle. The frequency and dwell of bag cleaning must be set to maintain the desired pressure drop. The cleaning pressure must be maintained at sufficient pressure to properly clean the bags; the desired range is 60 to 100 psig.[25]

4.5.2.2 Operation of Fabric Filters. While the performance of a fabric filter is dependent on proper design and the timely detection of upset conditions, proper operation and preventive maintenance procedures dictate satisfactory long-term performance. This section discusses general operating procedures that can minimize unexpected malfunctions and improve the performance of the fabric filter. Preventive maintenance practices are discussed in Chapter 5. Proper operating procedures are important during startup, normal operation, shutdown, and emergency conditions.

4.5.2.2.1 Startup Procedures. Prior to operation of new fabric filters, a complete check of all components is recommended including the cleaning system, the dust-discharge system, and the isolation dampers and fans. Clean, ambient air should be passed through the system to confirm that all bags are properly installed. New bags are prone to abrasion if subjected to high dust loadings and full-load gas flows, particularly during the initial startup before new bags have the benefit of a dust buildup cake to protect the fibers from abrasion or to increase their resistance to gas flow. Full gas flow at high dust loadings can allow the particulate matter to impinge on the fabric at high velocity and result in abrasion that may shorten bag life. In addition, the dust may penetrate so deeply into the fabric that the cleaning system cannot remove it, and a "permanent" pressure drop results. Bag abrasion may be prevented by either (1) initially operating the incinerator at a low throughput and reduced gas volume to allow the dust cake to build gradually or (2) precoating the bags to provide a protective cake before the incinerator exhaust is introduced. The baghouse manufacturer should be consulted regarding proper startup procedures and acceptable precoat materials.

The fabric filter should not be operated at temperatures approaching the dewpoint of water and/or the hydrochloric acid formed by the combustion of chlorinated plastics because if the dewpoint is reached, serious operating problems may arise. Warm moist gas that is introduced into a cool or cold fabric filter will cause condensation on the bags or

on the fabric filter shell. Condensation can cause a condition known as "mudded" bags where the bags are blinded by dust and moisture. The acid dewpoint depends on the amount of moisture and acidic material in the gas stream. Condensation of acid can cause corrosion of the fabric filter components, sticky particulate and cake-release problems, and acid attack on some fabrics. Preheating the fabric filter to a temperature above the acid dewpoint will prevent condensation and enhance fabric filter performance. Since the incinerator goes through a warmup period using natural gas or fuel oil burners prior to waste combustion, the problems associated with condensation of water or hydrochloric acid are unlikely to occur.

Unstable combustion during startup can cause some carbon carryover, which may result in a sticky particulate. This situation creates the potential for fires in the fabric filter when a combustion source and an adequate oxygen supply are available. Therefore, during startup, the fabric filter hoppers that collect the particulate should be emptied continually. More importantly, unstable combustion conditions during startup should be minimized by going through proper incinerator startup procedures.

4.5.2.2.2 Normal operating procedures. Under normal conditions, operation of the fabric filter is straightforward. The operator has to do very little other than monitor the key parameters, as discussed later in Section 4.5.2.4. Combustion gas flow rate through the system must be maintained at the level necessary to maintain negative draft in the combustion chambers.

4.5.2.2.3 Shutdown procedures. The top priority during shutdown of a fabric filter is avoiding dewpoint conditions. Bag cleaning and hopper emptying are lower-priority items.

When processes operate on a daily cycle, the last operation of the day should be to purge moisture and acidic materials from the fabric filter without passing through the dewpoint. In the case of a hospital waste incinerator, the operator should leave the secondary chamber burner on for a few minutes after combustion is completed to remove moisture from the fabric filter. Ambient air could then be drawn through the system to purge the remaining combustion products.

After shutdown, the fabric filter should be allowed to go through a complete bag cleaning cycle. This procedure will help prevent blinding of the bags. Additionally, continuing to operate the hopper discharge system while the cleaning system is in operation will minimize the potential of hopper pluggage.

When emergency conditions are encountered such as high temperatures, spark detection, or other process upsets, the fabric filter is usually bypassed to prevent damage to the system. If a fire occurs in the hopper, the addition of water under oxygen-starved conditions is not advisable because the water will hydrolyze forming hydrogen and causing the potential for an explosion inside the fabric filter. Both the fabric filter manufacturer and insurance carrier should be contacted whenever a known potential for fires/explosions exists.

Other process failures may necessitate only temporary bypassing of the fabric filter, and operation can be restored in a matter of minutes. In these cases, the fabric filter generally does not have to be shut down completely and purged. If the upset cannot be corrected within a reasonable amount of time, however, shutdown and the subsequent startup of the fabric filter may then be necessary to prevent dewpoint problems.

It is important to note that bypassing the fabric filter during startup, soot blowing, or an emergency may not be acceptable to the applicable regulatory agency. Such occurrences should be investigated and addressed during the design stages of development.

4.5.2.3 Automatic Controls. Operating parameters which are controlled automatically for fabric filter control systems include the bag cleaning cycle and the ash removal system.

The combustion gas flow rate through the system also can be controlled automatically. Control is achieved by adjusting fan rpm's (variable speed fans) or fan static pressure by way of a damper. Proper gas flow through the system must be maintained to assure sufficient negative draft in the combustion chambers. Reduction of the gas stream temperature to the fabric filter typically is achieved by passing the combustion gases through a waste heat boiler. Temperature monitoring systems are available that will cause automatic bypass of the fabric filter under high temperature conditions.

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4.5.2.4 Monitoring. A well-designed and maintained fabric filter should provide adequate control of particulate matter emissions. Parameters that can be monitored to maintain optimum performance include opacity, pressure drop, fan motor amperage, and temperature.

Opacity readings can help to determine the presence of pinholes and tears in bags and, in some cases, the general location of the bag failure. These visible emissions are usually the first indicator of poor fabric filter performance. The failed bags should be replaced as necessary.

The pressure drop across the fabric filter is another indicator of poor performance. A high pressure drop outside the normal operating range may indicate inadequate cleaning of the fabric, bag blinding, or excessive gas volume through the system. In some cases, the pressure drop before and after cleaning increases steadily as the bags age. Excessively low pressure drop may indicate inadequate filter cake formation resulting from too frequent cleaning.

When used in conjunction with the pressure drop across the fabric filter, measurement of fan motor amperage also can provide an indication of the gas flow rate. In general, an increase in current combined with an increase in pressure drop indicates an increase in gas volume, and a decrease in amperage reflects a decrease in gas volume. These changes, however, must be normalized for temperature (density) changes because temperature influences the energy required to move the gas through the system.

High-temperature operations such as hospital waste incinerators should be equipped with continuous strip chart recorders and high-temperature alarms. The high-temperature alarms should provide some margin for corrective action, i.e., set points of 50° to 75°F below the high temperature limit of the fabric. The temperature alarm/recorder also may be connected to an automatic damper system to control the temperature or to bypass the fabric filter. Although some differential between the maximum temperature and the alarm activation must be provided, the temperature set point should not be so low that the alarm is continually activated. The temperature indicator also will monitor against excessively low temperatures and dewpoint problems.

4.5.3 Spray Dryers[7,28]

4.5.3.1 Key Operating Parameters. The key parameters that are necessary for effective operation of a spray dryer are slurry feed rate, slurry sorbent content, and the outlet gas wet and dry bulb temperatures. Effective operation of a spray dryer system requires that adequate sorbent is provided in the slurry for reaction with the acid gases and that all slurry moisture is evaporated in a time frame that allows for reaction with the acid gases. Drying that is too rapid can reduce acid gas collection efficiency. Drying that is too slow will result in solids buildup on the sides of the reaction vessel that will further impede drying. The liquid slurry feed rate and sorbent content should be balanced with the hot flue gas volume and acid gas content to ensure the desired removal of acid gases and the timely evaporation of all water. The recommended slurry sorbent content is 5 to 20 percent by weight solids. The slurry moisture added to the flue gas serves to cool and increase the moisture content of the gas stream. The difference between the wet bulb and dry bulb temperatures gives an indication of the saturation of the gas stream and the potential for evaporation of the slurry moisture. As the slurry feed rate is increased, the wet bulb and dry bulb temperature difference will decrease. The recommended wet bulb/dry bulb outlet gas temperature difference (for Municipal Solid Waste Systems) is 30° to 80°C (90° to 180°F).[28]

4.5.3.2 Spray Dryer Operation. The design specifications for the dry scrubber should identify the sorbent-to-water ratio for the mix tank. The sorbent content should be set at a level that will provide ample sorbent for the range of acid gas concentration expected to occur. Proper operation of the dry scrubber requires that the operator adjust the slurry flow rate to the atomizer in the reaction vessel to maintain an acceptable wet bulb/dry bulb temperature difference. If the wet bulb/dry bulb temperature difference is too low, the slurry feed should be decreased.

4.5.3.2.1 Spray dryer startup. Startup of a spray dryer should follow procedures that ensure evaporation of all slurry moisture in the reaction vessel and that prevent condensation of moisture in the fabric filter. One method of ensuring evaporation and prevention of condensation in the fabric filter is to use auxiliary fuel firing in the incinerator to bring the exhaust gas temperature up to the normal operating range before injecting the slurry. Slurry injection should be initiated before charging the incinerator with waste feed material. An alternative method would be to gradually increase the slurry feed rate during startup to maintain a 90° to 180°F wet bulb/dry bulb temperature differential.

4.5.3.2.2 Spray dryer shutdown. Proper shutdown procedures for spray dryers should ensure that no liquid moisture remains in the spray dryer or that condensation in the fabric filter does not cause bag blinding or corrosion. Slurry remaining in the system after shutdown can cause solids buildup. Also, the reaction products resulting from the neutralization of the acid gases include highly corrosive salts such as NaCl and $CaCl_2$. After the waste material in the incinerator has been combusted, auxiliary fuel firing should be used to maintain temperatures above saturation until all sorbent is purged from the system. To prevent bag blinding and reaction product salt corrosion that could occur in the presence of condensation, the fabric filter should go through a complete cleaning cycle to remove the filter cake after shutdown of the incinerator and spray dryer.

4.5.3.3 Automatic Control. The most important key parameter from a control standpoint is the slurry feed rate. The slurry feed rate determines the amount of sorbent available for acid gas collection (along with the sorbent content of the slurry) and the outlet gas wet bulb/dry bulb temperatures. Slurry feed rate can be automatically controlled in response to monitoring of HCl outlet gas concentration or wet bulb/dry bulb temperature. In less complex systems, the slurry sorbent content is fixed and the slurry feed is automatically increased or decreased in response to the outlet gas temperatures. Under conditions of low inlet HCl concentrations these systems will use excessive amounts of sorbent. More complex systems are available that automatically adjust the sorbent feed to the slurry mix tank in response to HCl concentration and slurry feed rate to the atomizer in response to outlet gas temperatures.

4.5.3.4 Monitoring. Spray dryer parameters which can be monitored by the operator include:

1. Sorbent feed to the mix tank;
2. Slurry feed rate to the atomizer;
3. Gas inlet temperature;
4. Gas outlet wet bulb and dry bulb temperature; and
5. HCl and SO_2 outlet gas concentrations.

The most important parameters are the outlet gas HCl concentration which indicates the performance of the unit and the outlet gas wet bulb/dry bulb temperatures which determine evaporation rate. As explained earlier, the evaporation rate is important to ensure that adequate absorption time is available for acid gas removal and that all moisture is evaporated prior to leaving the reaction vessel.

4.5.4 Dry Injection

4.5.4.1 Key Operating Parameters. The key operating parameters for a dry injection system are the sorbent injection rate and the particle size of the sorbent. The sorbent injection rate should provide adequate sorbent for neutralization of the acid gases and is dependent on the acid gas content of the flue gas. The sorbent feed rate for dry injection systems is usually three to four times the stoichiometric requirements.[27]

The acid gas/sorbent reaction requires that the acid gas come in physical contact with the surface of the solid sorbent particles. To maximize the efficiency of the collection process it is necessary to maximize the surface area of the sorbent material. Because the surface area-to-volume ratio increases with decreasing particle size, acid gas removal efficiency increases with the decreasing particle size of the sorbent. Generally, the sorbent feed should have a particle size where 90 percent by weight will pass through a 325 mesh screen.[28]

4.5.4.2 Dry Injection Operation. Dry injection systems are relatively simple to operate compared to spray drying systems. The particle size of the sorbent should be specified to the supplier. To ensure that the particles do not agglomerate prior to injection, the airflow rate in the pneumatic transfer line should be set and maintained

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at the manufacturer's specified rate. Proper airflow in the pneumatic line will fluidize the sorbent particles and prevent agglomeration. Sorbent injection rates for dry injection systems, as stated above, are usually three to four times stoichiometric requirements. The large amount of extra sorbent can handle moderate variations in inlet acid gas concentrations. For systems that are not equipped with outlet acid gas continuous monitors, the sorbent injection rate can be set at a constant level or varied with flue gas flow rate. If the system is equipped with an outlet monitor for HCl, the sorbent injection can be varied as needed.

4.5.4.2.1 Dry injection startup. There are no special considerations for dry injection startup. At startup of the incinerator, sorbent injection can be initiated.

4.5.4.2.2 Dry injection shutdown. The only special concern for shutdown of a dry injection system is to put the fabric filter through a cleaning cycle after sorbent injection is stopped. This prevents possible blinding from condensation and reaction product salt damage to the fabric filter components.

4.5.4.3 Automatic control. Dry injection systems can be equipped with outlet gas HCl continuous monitors. The sorbent injection rate can be controlled automatically based on the outlet HCl concentration.

4.5.4.4 Monitoring. Dry injection system parameters which can be monitored by the operator include:

1. Sorbent injection rate;
2. Pneumatic transfer line airflow rate;
3. Flue gas flow rate; and
4. HCl and SO_2 outlet gas concentrations.

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5.0 MAINTENANCE

Efficient operation of a hospital waste incinerator and any associated air pollution control device requires an aggressive preventive maintenance (PM) program. Effective maintenance will prolong the service life of the equipment, reduce the frequency of upset conditions and air pollution episodes, and save the hospital money by avoiding costly repairs. Information on the types and frequency of equipment inspections and maintenance procedures for incinerators, wet scrubbers, and fabric filters is provided in this chapter. The information provided represents only general guidance and should not be substituted for the equipment manufacturer's recommended maintenance schedule. Recordkeeping, which is an important part of a PM program is mentioned briefly below and is discussed more fully in Chapter 8. Records of maintenance activities can help pinpoint problems and show trends in maintenance activities that may increase the life of the equipment and minimize emissions.

5.1 HOSPITAL WASTE INCINERATORS

Typically, the incinerator operator does not perform PM but makes hourly and daily inspections to ensure proper operation of the incinerator and its air pollution control device and the identification of potential problems. The hospital's maintenance department performs PM on the incinerator on a set schedule and corrects any potential problems identified by the operator. At some hospitals, the maintenance department performs PM on a work order system.[1] In practice, minimizing the number of PM items per work order ensures that PM is performed properly and with less downtime.[1]

Because of the diversity in both size and design of hospital waste incinerators, specific recommendations on PM practices and frequency that would be applicable to all units are impossible to make. Also, as noted above, the manufacturer's or vendor's recommended PM schedule for a particular unit should be followed, and the information presented here should only be used to supplement, not replace, that schedule. In general, however, PM activities for any hospital waste incinerator involve

inspection, cleaning, and lubrication of incinerator components on a regular basis. Table 5-1 presents a typical PM program for a hospital waste incinerator. Note that both the components listed on the table for maintenance and the maintenance frequency will vary depending on the type and amount of waste being incinerated and the type of incinerator used. The sections below discuss the items on Table 5-1 in greater detail and are organized according to hourly/daily maintenance, weekly/biweekly maintenance, and monthly/semiannual maintenance.

5.1.1 Hourly/Daily Maintenance

The hourly maintenance activities described in Table 5-1 are simple inspections that are applicable to large, continuous-feed incinerators. These large units may be equipped with a water quench pit and an ash removal conveyor system that continuously removes ash from the incinerator.[2] The operator must routinely replenish the water in the quench pit because water is constantly removed by evaporation and by the ash removal system.[2,3] The water quench pit is used to quench or extinguish the hot ash as it is removed from the incinerator and to provide an air seal for the ash removal conveyor.[3] Therefore, it is essential that sufficient water be available. In addition, the operator should check the ash removal conveyor system frequently to remove any debris that could cause it to jam.[3] Small, batch-feed incinerators will likely have neither a water quench pit nor an automatic ash removal conveyor system.

Daily maintenance activities involve checking the operation of any opacity, oxygen, and CO monitors. These monitors indicate whether the operating/combustion conditions of the incinerator are within an acceptable range; for some units, the oxygen monitor may also be used to control the combustion air rate. Before the incinerator is started up, the opacity monitor and the CO monitor should read 0 percent opacity and 0 parts per million (ppm), respectively. The oxygen monitor should read about 21 percent oxygen (ambient air). If these monitors are equipped to conduct for daily calibration checks, the calibration checks should be conducted and the calibration values noted to assure that they are in the

TABLE 5-1. TYPICAL MAINTENANCE INSPECTION/CLEANING/LUBRICATION SCHEDULE FOR A HOSPITAL WASTE INCINERATOR[4]

Activity frequency	Incinerator component	Procedure
Hourly	Ash removal conveyor	Inspect and clean as required
	Water quench pit	Inspect water level and fill as required
Daily	Opacity monitor	Check operation of the opacity monitor and check exhaust for visible emissions
	Oxygen monitor	Check operation of the oxygen monitor
	Thermocouples	Check operation of the thermocouples
	Underfire air ports	Inspect and clean as required
	Limit switches	Inspect for freedom of operation and potential obstructing debris
	Door seals	Inspect for wear, closeness of fit, and air leakage
	Ash pit/internal dropout sump	Clean after each shift on batch units that do not have continuous ash conveyor cleaning system
Weekly	Heat recovery boiler tubes	Inspect and clean as required. (Clean weekly for 6 weeks to determine optimum cleaning schedule.)
	Blower intakes	Inspect for accumulations of lint, debris; clean as required
	Burner flame rods (gas-fired units)	Inspect and clean as required
	U.V. scanner flame sensors	Inspect and clean as required
	Swing latches and hinges	Lubricate
	Hopper door support pins	Lubricate
	Ram feeder carriage wheels	Lubricate
	Heat recovery induced-draft fans	Inspect and clean fan housing as required. Check for corrosion and V-belt drives and chains for tension and wear
Biweekly	Hydraulic systems	Check hydraulic fluid level and add the proper replacement fluid as required. Investigate sources of fluid leakage
	Ash removal conveyor bearings	Lubricate
	Fuel trains and burners	Inspect and clean as required. Investigate sources of fuel leakage as required
	Control panels	Inspect and clean as required. Keep panel securely closed and free of dirt to prevent electrical malfunction
Monthly	External surface of incinerator and stack	Inspect external "hot" surfaces. White spots or discoloration may indicate loss of refractory

(continued)

TABLE 5-1. (continued)

Activity frequency	Incinerator component	Procedure
Monthly continued	Refractory	Inspect and repair minor wear areas with plastic refractory material
	Internal ram faces	Inspect for wear. These stainless steel faces may wear out and may require replacement in 1 to 5 years depending on service
	Upper/secondary combustion chamber	Inspect and vacuum any particulate matter that has accumulated on the chamber floor
	Large combustion air blowers and heat recovery induced draft fans (those fans whose bearings are not sealed)	Lubricate
	Hydraulic cylinder clevis and trunnion attachments to all moving components	Lubricate
	Burner pilots	Inspect and adjust as required
Semi-annually	Hot external surfaces	Inspect and paint with high-temperature paint as required
	Ambient external surfaces	Inspect and paint with equipment enamel as required
	Chains	Inspect and brush clean as required. Lubricate

proper range. If not, maintenance personnel should be informed. An additional check for the opacity monitor is to observe the stack emissions and compare the observation to the opacity monitor reading. For example, if the opacity monitor, which normally reads below 5 percent, reads 25 percent, and a simple check of the exhaust stack shows an opacity of 0 percent, then something is wrong with the opacity monitor.

The thermocouples that indicate the temperature of the primary and secondary chambers should also be checked daily.[4] It is essential that these thermocouples be operating properly because the temperature monitored by these thermocouples typically is the parameter that controls the combustion airflow into the incinerator (controlled-air units) and burner operation.[2] The temperature readings should be ambient prior to incinerator startup. A thermocouple problem may be indicated if the operator notices a significant change in startup conditions, i.e., if significantly more auxiliary fuel is required than normal, or if it takes significantly longer to heat the incinerator than normal.[4] Also, a noticeable change in response time of the thermocouple is an indication of problems. Unfortunately, there is no simple way to check the accuracy of a thermocouple; either the thermocouple must be removed and tested or a second thermocouple must be inserted in a second thermocouple port, if available.

The remaining daily maintenance activities involve inspection for slagging and plugging (underfire air ports); inspection for obstructing debris (e.g., limit switches on charging doors, charging rams, hopper doors, etc.); inspection of door seals for wear, closeness of fit, and air leakage; and cleaning the ash from the hearth on batch and intermittent-duty incinerators.[4] The underfire air ports must be kept clean so that the proper amount of underfire air can reach the burning waste in a well distributed manner. Limit switches must be kept clear of debris because they control the proper adjustment of the charging door and the ram feeder (if installed).[2] Proper functioning of charging door and hopper/ram limit switches is essential because these switches ensure that the doors are fully opened/closed at the proper times and help prevent excessive air in-leakage to the incinerator during charging and operation.[2] Improperly sealed doors, which result in excessive air leakage, will not only affect

incinerator operation, but also may result in more severe maintenance requirements (damage to seals or warpage due to excessive heat), as well as causing a fire/safety hazard. Finally, the ash typically is allowed to cool overnight and is removed from the hearth on batch and intermittent-duty incinerators the day after the burn.[1]

5.1.2 Weekly/Biweekly Maintenance[4]

Some of the large hospital waste incinerators (20 to 25 tons waste/d) may employ a waste heat recovery boiler to produce steam for use in the hospital. When first installed, the heat recovery boiler tubes should be cleaned weekly. The first indication of fouled tubes on the gas side will be the gradual increase of boiler outlet gas temperature. All blower intakes and the heat recovery induced-draft fan housing should be inspected weekly and cleaned as required. The burner flame rods (gas-fired units) or ultraviolet scanner flame sensors (other units) should also be inspected weekly and cleaned as required. The swing latches and hinges, the hopper door support pins, and the ram feed carriage wheels should all be lubricated weekly.

The biweekly maintenance items include the inspection of the fuel trains, burners, and control panels. These pieces of equipment should also be cleaned as required. Any sources of fuel leakage should be investigated. The hydraulic fluid level should be checked on all hydraulic systems, and the appropriate replacement fluid should be added as needed. Only the fluid recommended by the manufacturer should be used because other fluids may damage the hydraulic seals. The ash removal conveyor bearings on large incinerators should be lubricated biweekly.

5.1.3 Monthly/Semiannual Maintenance[4]

On a monthly basis, the incinerator operator should inspect the external hot surfaces of both the incinerator vessels and stack for white spots or other discoloration that may indicate a loss of refractory inside. Additionally, whether white spots are evident or not, the refractory lining inside the incinerator should be inspected for wear

areas and any buildup of ash or metal oxides such as calcium, potassium, and sodium. Any minor wear areas in the refractory should be repaired using plastic refractory material. The metal oxides can cause a marked decrease in the softening temperature of the refractory that effectively reduces the operating temperature range. Any ash and metal oxide buildup should be washed off only after the incinerator has cooled to avoid damaging the refractory if the temperature of the wash water is significantly different from that of the refractory.

Large incinerators may be equipped with internal ash rams that push burning waste from one hearth to the next. The rams typically are made of refractory material with the exception of the front face of the ram, which is made of stainless steel. These stainless steel ram faces should be inspected for wear and damage each month initially until an optimum inspection schedule can be established. The ram faces may last from 1 year to 5 years depending upon the type of service in which they are used.

In controlled-air incinerators, the primary chamber is operated at less than stoichiometric air (starved-air) conditions, which minimizes the amount of fly ash carryover to the secondary (excess-air) chamber. However, in multiple-chamber (excess-air) designs, carryover of fly ash to the secondary chamber should be expected; the carryout of carryover will depend on the amount of excess air at which the primary chamber is operating. Therefore, a monthly inspection and cleaning schedule for the secondary chamber is appropriate for multiple-chamber units but may be unnecessary for controlled-air units. Manufacturers of controlled-air units specify vacuuming ash from the secondary chamber at least every 6 months. Therefore, an effective cleaning schedule for these units may be every 3 to 4 months until an optimum cleaning schedule can be established.

Large fans (those that do not have sealed bearings) and the hydraulic cylinder clevis and trunnion attachments should be lubricated monthly. Lastly, the burner pilots should be inspected and adjusted as required.

The semiannual maintenance activities include the inspection of all hot external surfaces, all ambient external surfaces, and any conveyor chains. All external surfaces should be cleaned; high-temperature paint

should be applied to hot surfaces, and equipment enamel should be applied to ambient surfaces as required. The chains should be brushed clean if necessary and lubricated.

5.2 WET SCRUBBERS[5-7]

Table 5-2 presents a typical maintenance inspection, cleaning, and lubrication schedule for a wet scrubber. As with incinerators, the frequency with which these activities take place will depend on a number of variables including the size and complexity of the scrubber, the number of hours per day it operates, and the volume and pollutant concentration of the exhaust gas it handles. In addition, not all of the maintenance activities listed in Table 5-2 will be required at each scrubber installation. The type and frequency of maintenance activities will depend in large part on the scrubber vendor's recommendations and the experience of personnel with the unit.

5.2.1 Daily/Weekly Maintenance

The daily maintenance activities described in Table 5-2 are simple inspections that are applicable to all scrubbers. Most of these inspections involve checking various components for proper operation and fluid leakage. These inspections should be carried out after the scrubber has been started up and prior to startup of batch-feed incinerators so that any necessary repairs can be made before the scrubber has to control emissions. Scrubbers controlling continuous-feed incinerators should be inspected while both units are in operation.

Failure of components such as the scrubber liquid pump and variable throat activator (on venturi scrubbers) will cause the scrubber to be ineffective in controlling emissions from the incinerator. In such cases, the incinerator may have to be shut down depending on both the severity of the problem and any State regulations concerning operation of the incinerator without its attendant air pollution control device. Liquid leakage from these components also can have a detrimental effect on the performance of wet scrubbers. The sources of such leaks should be investigated and repaired as required.

TABLE 5-2. TYPICAL MAINTENANCE INSPECTION/CLEANING/LUBRICATION SCHEDULE FOR A WET SCRUBBER

Inspection frequency	Component	Procedure
Daily	Scrubber liquid pump	Check for proper operation and leakage. Investigate sources of fluid leakage and repair as required.
	Variable throat activator	Check for proper operation and leakage.
	Scrubber liquid lines	Check for leakage. Repair as required.
	Mist eliminator pressure lines	Check for leakage. Repair as required.
	Reagent feed system	Check for leakage. Repair as required.
	Fan	Check for vibration and proper operation.
	Fan bearings	Check for abnormal noise.
	Fan belt[a]	Check for abnormal noise.
Weekly	Fan	Check oil level, oil color, oil temperature, and lubricate.
	Scrubber liquid pump	Check oil level and lubricate pump motor bearings.
	Damper air purge system	Check for proper operation.
Monthly	Duct work	Inspect for leakage.
	Fan and motor bearings	Inspect for leaks, cracks, and loose fittings.
	Fan blades and internal housing	Inspect for material buildup and clean as required. Inspect for abrasion and corrosion and repair as required.
	Drain chain drive mechanism	Check chain tension, sprocket wear and alignment, and oil level.
	Pipes and manifolds	Inspect for plugging/leaking and clean/repair as required.
	Dampers	Check for leakage.
	Spray bars	Inspect for nozzle wear and plugging and clean as required.
	Pressure gauges	Check for accuracy.
	Main body of scrubber	Inspect for material buildup and clean as required. Inspect for abrasion and corrosion and repair as required.
Semi-annually	Fan, pump, motor, and drag chain bearings and gear reducers	Inspect clearances and wear, pitting, and scoring. Inspect for leaks, cracks, and loose fittings.
	Flowmeters	Check for accuracy.
	Damper drive mechanism	Check for proper operation and alignment.
	Damper seals, bearings, blades, blowers	Check for wear and leakage.

[a]Check fan belt tension whenever fan is out of service.

Fans in wet scrubber service operate under substantially more severe conditions than those serving dry systems because humid conditions enhance the possibility of condensation of acids on the fan and fan housing. In the case of hospital waste incinerators, scrubbers and fans are likely to experience hydrochloric acid mist as a result of the combustion of chlorinated plastic material. Therefore, acid-resistant materials should be used in the construction of the scrubber interior and more frequent cleaning of the fan system serving the scrubber should be practiced. Unusual noise or vibration from any part of the fan system, including the bearings or belt, may indicate that replacement is necessary.

The weekly maintenance items include more inspections of components. The fan and the scrubber liquid pump oil levels should be checked and adjusted as appropriate. Additionally, the fan oil temperature and color should be checked. Temperature or color readings that are outside of the manufacturer's recommended ranges may indicate excessive wear and/or contamination of the oil. Both the fan and scrubber liquid pump bearings should be lubricated weekly.

5.2.2 Monthly/Semiannual Maintenance

The monthly maintenance activities consist of additional inspections and appropriate corrective actions as required. Clogged pipes, manifolds, and spray nozzles can hinder the proper operation of the scrubber. The pressure drop of the scrubber will be lower than normal if plugging is experienced. The pressure drop is a critical indicator of scrubber performance in removing particulate from the incinerator exhaust, and the pressure gauges should be checked and calibrated for accuracy. Some regulations may require a minimum pressure drop to be achieved across the venturi to assure a minimum pollutant removal efficiency. Therefore, it is important that the pressure gauges operate properly.

The main body of the scrubber, fan blades, and internal fan housing are subject to buildup of particulate matter that can adversely affect both scrubber and fan performance. These components should be inspected and cleaned monthly. In addition, these components should be inspected for any abrasion caused by particulate matter or corrosion caused by hydrochloric acid mist that might adversely affect performance.

Fan and motor bearings should be inspected for leaks, cracks, and loose fittings. Dampers and ductwork should be checked for any air leakage. Leakage of air can cause condensation of moisture and acid gases due to the introduction of cool ambient air. Also, a large number of leaks in the ductwork will cause the induced-draft fan to pull more air, and the incinerator operator will have less control over the air introduced into the incinerator. The drag chain drive mechanism used on some automatic ash removal systems should be inspected for wear, chain tension, and sprocket alignment. The oil level also should be checked on this component and adjusted as required.

The semiannual maintenance activities include inspections of all bearings on fans, pumps, motors, and gear reducers for leaks, cracks, and loose fittings. Additionally, the clearances and any wear, pitting, or scoring should be checked on these components. The flow meters on the scrubber should be checked for accuracy. State regulations, in addition to requiring a pressure drop, also may require a specific water flow rate. Therefore, the flow meters should operate properly. The damper drive mechanism should be checked for proper operation and alignment; and the damper seals, bearings, blades, and blowers should be inspected for wear and leakage.

5.3 MAINTENANCE OF FABRIC FILTERS[8,9]

Although the frequency and components of a PM program for a fabric filter system will depend on the type of system and the vendor's recommendations, the major components should be inspected on a routine basis, and any needed maintenance should be performed. The following sections describe the daily, weekly, monthly/quarterly, and semiannual/annual inspections/maintenance that are recommended. A specific PM program should be established based on the manufacturer's recommendations. Table 5-3 presents a typical maintenance inspection, cleaning, and lubrication schedule for a fabric filter.

TABLE 5-3. TYPICAL MAINTENANCE INSPECTION/CLEANING/LUBRICATION SCHEDULE FOR A FABRIC FILTER SYSTEM[8,9]

Inspection frequency	Component	Procedure
Daily	Stack	Check exhaust for visible dust.
	Manometer	Check and record fabric pressure loss and fan static pressure. Watch for trends.
	Compressed air system	Check for air leakage (low pressure). Check valves.
	Collector	Observe all indicators on control panel and listen to system for properly operating subsystems.
	Damper valves	Check all isolation, bypass, and cleaning damper valves for synchronization and proper operation.
	Rotating equipment and drives	Check for signs of jamming, leakage, broken parts, wear, etc.
	Dust removal system	Check to ensure that dust is being removed from the system.
Weekly	Filter bags	Check for tears, holes, abrasion, proper fastening, bag tension, dust accumulation on surface or increases and folds.
	Cleaning system	Check cleaning sequence and cycle times for proper valve and timer operations. Check compressed air lines including oilers and filters. Inspect shaker mechanisms for proper operation.
	Hoppers	Check for bridging or plugging. Inspect screw conveyor for proper operation and lubrication.
Monthly	Shaker mechanism	Inspect for loose bolts.
	Fans(s)	Check for corrosion and material buildup and check V-belt drives and chains for tension and wear.
	Monitor(s)	Check accuracy of all indicating equipment.
Quarterly	Inlet plenum	Check baffle plate for wear; if appreciable wear is evident, replace. Check for dust deposits.
	Access doors	Check all gaskets.
	Shaker mechanisms	Tube type--(tube hooks suspended from a tubular assembly): inspect nylon bushings in shaker bars and clevis (hanger) assembly for wear.
		Channel shakers--(tube hooks suspended from a channel bar assembly): inspect drill bushings in tie bars, shaker bars, and connecting rods for wear.
Semiannually	Motors, fans, etc.	Lubricate all electric motors, speed reducers, exhaust and reverse-air fans, and similar equipment.
Annually	Collector	Check all bolts and welds. Inspect entire collector thoroughly, clean, and touch up paint where necessary.

5.3.1 Daily Inspection/Maintenance

At least twice per shift (and perhaps as often as every 2 hours), plume opacity (visual inspection of stack outlet) and pressure drop should be checked. Sudden changes in these values along with those of temperature and gas volume may indicate a problem. For example, the failure or partial failure of the cleaning system generally will cause a relatively rapid increase in pressure drop in most systems. Timely identification, location, and correction of this problem can minimize operating problems and long-term effects on bag life. Although identification and subsequent correction of relatively minor problems have little effect on fabric life, some minor problems tend to turn into major failures. The ability to perform on-line maintenance depends on the design of the control equipment.

Routine checks of the fabric filter include pressure drop (and patterns if a ΔP indicator and recorder are used), plume opacity at the outlet, dust discharge operation, and external checks (i.e., visual inspection) of the cleaning system operation. Other factors that can be checked include temperature (range) and fan motor current. If a check of these factors reveals a sudden change, maintenance should be scheduled as soon as possible.

5.3.2 Weekly Inspection/Maintenance

The extent of the weekly maintenance program depends greatly on access and design of the fabric filter. Where possible, quick visual inspections should be conducted; however, not all systems or processes are amenable to this type of review. A weekly lubrication schedule should be established for most moving parts. Manometer lines should be blown clear, and temperature monitors should be checked for proper operation.

When a fabric filter is the air pollution control device of choice for a hospital waste incinerator, it is almost always a pulse-jet fabric filter. The following items should be checked weekly. On the dirty side of the tubesheet, bags should be checked for relatively thin and uniform exterior deposits. Bags also should be checked for bag-to-bag contact

(points of potential bag wear). On the clean side of the tubesheet, each row of bags should be examined for leakage or holes. Deposits on the underside of the blowpipes and on the tubesheet may indicate a bag failure. The cleaning system should be activated (the inspector should use hearing protection), and each row of bags should fire with a resounding "thud." The blowpipes should remain secured, and there should be no evidence of oil or water in the compressed air supply. The surge tank or oil/water separator blowdown valve should be opened to drain any accumulated water. Misaligned blowpipes should be adjusted to prevent damage to the upper portion of the bag. The compressed air reservoir should be maintained at about 90 to 120 psi.

On a weekly basis, the dust removal system including hopper and screw conveyor should be inspected to make sure that dust is being removed from the system by checking the conveyor for jamming, pluggage, wear and broken parts, etc. Problems with the conveyor system are indicated when the conveyor appears to be moving but no dust is dropping into the dust storage container, when the conveyor does not move, or when the conveyor makes unusual sounds.

5.3.3 Monthly/Quarterly Inspection/Maintenance

Requirements for monthly or quarterly maintenance and inspection for fabric filters are very site specific. Clear-cut schedules cannot be established for such items as bag replacement and general maintenance of the fabric filter. Some items, however, may warrant quarterly or monthly inspections, depending on site-specific factors. Items to be checked include door gaskets and airlock integrity to prevent excessive in-leakage (both air and water) into the enclosure. Any defective seals should be replaced. Baffles or blast plates should be checked for wear and replaced as necessary, as abrasion can destroy the baffles. Some facilities prefer to use fluorescent dye to check the integrity of the bags and bag seals. Any defective bags should be replaced, and leaking seals should be corrected.

Bag failures tend to occur shortly after installation and near the end of a bag's useful life. A record of bag failures and replacements is

invaluable for identifying recurrent problems and indicating when the end of bag life has been reached. Initial bag failures usually occur because of installation errors or bag manufacturing defects. When new bags are installed, a period with few or no bag failures is normally expected unless serious design or operation problems exist. As the bags near the end of their useful life, however, the number of bag failures may increase dramatically. When weighed against factors such as downtime for rebagging, the cost of new bags, and the risk of limited incinerator operating time as the result of keeping the old bags in service, the most economical approach may be to replace all the bags at one time to eliminate or minimize failure rate.

In some cases, bags can be washed or drycleaned and reused, e.g., when dewpoint limits are approached or the bags are blinded in some manner. Although cleaning may shorten bag life somewhat, cleaning may still be more economical than replacement if more than half a bag's "normal" life expectancy remains.

5.3.4 Semiannual/Annual Inspection/Maintenance

Some motors and packaged blowers are supplied with sealed bearings and, therefore, require no lubrication. Semiannual fabric filter system maintenance activities include the lubrication of the following components having nonsealed bearings: all electric motors, speed reducers, exhaust and reverse air fans, and similar equipment.

Annual maintenance activities include checking the tightness and fit of all bolts and welds on the fabric filter. Additionally, the unit should be cleaned and painted as appropriate.

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6.0 CONTROL AND MONITORING INSTRUMENTATION

6.1 OPERATING PARAMETERS THAT SHOULD BE MONITORED

Proper operation of incinerators depends to a large extent on certain operating parameters that are commonly monitored to provide necessary information to properly control the process. These usually consist of:

1. Temperature;
2. Pressure;
3. Oxygen;
4. CO;
5. Opacity; and
6. Charge rate.

Although all of the above parameters provide useful information, many hospital incinerators monitor only temperature and pressure. The other parameters listed are sometimes monitored on larger incinerators or if regulatory agencies require that monitoring be conducted (e.g., opacity). The temperature and oxygen level are key parameters, and incinerators are normally designed to monitor one or both of these parameters to provide the necessary information for automatic control of combustion air input and auxiliary fuel rates. In order to maintain the desired draft in the incinerator, control loops may be used to adjust incinerator draft by means of barometric dampers or the induced draft fan. The other parameters provide additional information that operators can use to maintain proper operation (e.g., charge rate, oxygen levels).

Proper operation of wet scrubber systems is dependent on several operating parameters that are commonly monitored, usually consisting of:

1. Pressure and pressure drop;
2. Scrubber liquid flow;
3. Scrubber liquid pH;
4. Temperature.

For venturi scrubbers, pressure drop is normally monitored and automatically controlled to a fixed level by adjusting the venturi throat. For venturi's and packed beds, the scrubber liquid flow is usually established at a constant rate and is not automatically controlled

during operation. For both types of scrubbers, control of pH is necessary to prevent damage to the scrubber equipment. Most scrubbers are designed to monitor and control pH automatically. Gas flow and temperature are often monitored to provide operators with additional information useful in maintaining proper operation by indicating potential problems and the need to make manual adjustments. Other instrumentation and control often includes an automatic liquid level control for the scrubber liquid sump, and a temperature switch/solenoid valve to activate an emergency quench spray and/or an emergency bypass stack.

For fabric filters, the key operating parameter which typically is monitored is pressure drop across the bags. Temperature also is monitored to assure that the temperature does not decrease below the dewpoint or increase to a level which will cause bag damage.

The next section describes the typical instrumentation used to monitor/control these key parameters and briefly discusses its proper use and operation.

6.2 TYPICAL INSTRUMENTATION

6.2.1 Temperature Sensors

Thermocouples are used to monitor temperatures in the combustion chambers and the air pollution control system. The thermocouples are always enclosed in a thermowell to protect the small thermocouple wires and the critical thermocouple junction from direct exposure to the combustion gases and entrained dust particles, etc. Thermocouples are usually located near the exit of the combustion chamber to provide a representative temperature reading away from the flame zone, which can otherwise cause erratic temperature readings as well as damage to the thermocouple. Thermowells may extend several inches past the inner wall of the refractory into the gas stream, or may extend only to the depth of the refractory. Thermowells that extend past the refractory provide a more accurate measure of the gas temperature and respond more quickly to temperature changes; however, this type also may be subject to dust and slag buildup, which can slow response to temperature changes. Generally,

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thermocouples also are located upstream of the air pollution control system to provide a warning or control mechanism for high temperature excursions that could damage control equipment.

The different types of thermocouples are identified by the metal used for the thermocouple junction wires. The most common types are listed in Table 6-1. Replacement thermocouples must always be the same type as the original because the receiver to which a thermocouple is connected is designed to receive the signal from a specific type of thermocouple. Thermocouples generate a small millivolt signal that increases with increasing temperature, but the amount of voltage for a given temperature is different for each type of thermocouple. It is important to realize that thermocouples operate on the basis of a junction between two different metals that generates only a small millivolt signal. Consequently, any wiring connections from the thermocouple to the receiver or any interfering electrical signals can affect the resulting temperature reading. This sensitivity necessitates the special shielding of the wire in electrical conduit.

Although thermocouples typically are very reliable, they can fail or give erroneous readings. For example, the thermocouple junction or wire may break after long exposure to high temperatures. However, a thermocouple can give erroneous readings for reasons that are not as obvious as a broken junction or wire. For example, if mechanical vibration abrades the insulation and one of the thermocouple wires comes into contact with the metal wall of the thermowell or other grounded metal surface, an erroneous temperature reading will likely result. As noted earlier, faulty thermocouple readings may also be the result of external conditions; for example, excessive dust buildups around a thermowell can insulate it from the gas stream and result in erroneously low temperature readings. To have the ability to compare readings to identify a faulty thermocouple, dual thermocouples are often used at nearby locations in the incinerator chamber. The second thermocouple enables continued monitoring of temperatures while the faulty thermocouple is being checked or replaced.

Periodic replacement of thermocouples, and checking the physical integrity of the thermowell and any outer dust buildup, is probably the

TABLE 6-1. THERMOCOUPLE TYPES

Type	Materials	Upper temp., °F
J	Iron/Constantan	1400
E	Chromel/Constantan	1650
K	Chromel/Alumel	2300
S	Pt 10% Rhodium/Pure Pt	2650
R	Pt 13% Rhodium/Pure Pt	2650
B	Pt 30% Rhodium/Pt 6% Rhodium	3100

best maintenance procedure. Because it is not practical to perform a high temperature calibration of the thermocouple, only periodic replacement ensures that a properly operating thermocouple is in place. The receiver should be checked periodically using calibrated equipment that produces a known millivolt signal equivalent to a specific temperature reading for a particular type of thermocouple. The generated signal can be applied to the thermocouple leads to check that the receiver's output produces the correct "temperature" reading.

Close monitoring of temperatures is essential to good incinerator operation. It is essential, therefore, to identify possible thermocouple problems because the temperature signal is usually the primary measurement used for the automatic control of auxiliary fuel burners and combustion air input. Any problem with the thermocouple temperature reading can cause the automatic control system to make inappropriate changes in the controlled variable in an attempt to maintain the desired (setpoint) temperature.

6.2.2 Pressure

The incinerator draft is measured in units of gauge static pressure, but it is actually a measure of the differential pressure (ΔP) between the inside of the chamber and the outside air. Monitoring of ΔP can be done with a common U-tube manometer, but for incineration systems, a differential pressure gauge (e.g., Magnehelic®) or a differential pressure transmitter typically is used. All of these instruments use the same basic method to monitor incinerator draft. One side (the high-pressure side) of the instrument is always open to the ambient air; the other (low-pressure) side is connected by tubing or piping to the incinerator.

These types of pressure monitors also are used to measure differential pressure across an air pollution control system (e.g., venturi scrubber throat or fabric filter baghouse). For this application, the low-pressure side is connected to a pressure tap in the ductwork downstream from the control device and the high-pressure side is connected upstream from the control device.

A differential pressure transmitter contains a diaphragm with two tubes connected on each side of the diaphragm; the diaphragm moves or deflects as a result of changes in pressure. The transmitter is designed so that any change or deflection causes a change in an electrical output signal from the transmitter. The electrical signal is sent to the monitor in the control room that indicates the incinerator draft or the pressure differential across the air pollution control system.

Several problems can cause faulty incinerator draft readings. Transmitters used to measure ΔP are sensitive devices that can be damaged by excessive vibration or sudden shocks. The severe hot and dirty conditions in the incinerator may also cause problems such as pluggage in the tubing and its connections. When faulty incinerator pressure readings are suspected, several procedures for correcting them can be used. Air can be blown through the tubing to clear any pluggage, and a known ΔP can be applied to the transmitter to check its response and span. Disconnecting any instrumentation should be done by experienced instrumentation personnel and must be coordinated with the operator so that the appropriate instrument can be put on manual control. For example, if the incinerator's automatic control system maintains incinerator draft via a damper on the ID fan inlet duct, disconnecting the pressure tap would probably cause the ID fan to increase flow in an effort to maintain the draft setpoint, thereby upsetting the temperature and other process operating parameters.

6.2.3 Oxygen Concentration[1]

Some incinerators may be equipped with oxygen analyzers to monitor the oxygen concentration in the combustion gases from the secondary combustion chamber to help ensure that adequate oxygen is available for proper combustion (i.e., that the excess-air level is sufficient). In some incinerators, the oxygen levels measured by the monitor are used to control air feed rates for control of the combustion process. In essence, lower waste feed rates require lower air feed rates in order to maintain essentially constant temperature and constant percent oxygen in the combustion gases, so long as the characteristics of the waste feed are the

same. However, if the composition of the feed changes (i.e., its heating value changes), more or less air will be needed to maintain the same temperature and oxygen content in the combustion gases. Thus, the oxygen content is a useful parameter to monitor and is an important control parameter if the incinerator is set up to control based on oxygen level rather than temperature.

Oxygen monitors may be of two types: in situ or extractive. In situ merely means that the analyzer's sensor is mounted in direct contact with the gas stream. In an extractive system, the gas sample is continuously withdrawn (extracted) from the gas stream and directed to the analyzer which may be located several feet or several hundred feet away.

Extractive analyzers include a conditioning system to remove dust and moisture from the gas sample; thus, the oxygen concentration measurement is on a dry basis. In situ analyzers, on the other hand, do not include a conditioning system, and the oxygen concentration measurement is on a "wet basis." For the same gas stream, the oxygen measurement obtained with an in situ analyzer will be slightly lower than that obtained with an extractive analyzer. For example, a typical combustion gas stream that contains 10 percent water vapor will yield a reading of 8 percent oxygen using an in situ analyzer and a reading of 10 percent oxygen using an extractive analyzer.

Regardless of the type of analyzer, the location of the sampling point is very important to ensure that a representative sample is obtained. The monitoring point may be in the stack, the combustion chamber exit, or other locations within the process (e.g., duct between air pollution control system and the stack). In most cases, the intent is to monitor the combustion gases at the exit of the combustion chamber and that, in fact, is where the sampling point is often located. One of the main problems related to sampling location that can occur is obtaining a nonrepresentative sample due to in-leakage of air. For example, substantial air in-leakage can occur through emergency stack dampers. Any such in-leakage affects the analyzer reading if the sample point is downstream of the in-leakage. However, there are practical limitations with regard to locating oxygen monitors. The in situ sensor or probe for extracting the sample must be located in an environment consistent with

the monitor's design. High temperatures, particulate concentrations, and acid gas concentrations can have adverse effects on the monitoring system resulting in operational and/or maintenance problems.

Oxygen analyzers are capable of good accuracy (±1 percent of full scale) as long as the actual gas to be sampled reaches the analyzer (no pluggage or in-leakage of air), the conditioning system (if one is present) is operating properly, and the instrument is calibrated. Electrocatalytic in situ monitors have rapid response times (i.e., seconds). The response times for polarographic and paramagnetic extractive analyzers are slower (several seconds to a minute). Extractive systems inherently involve longer response times, usually on the order of 1 to 2 minutes, depending on the sampling rate and the volume of the sampling line and conditioning system.

Problems with oxygen analyzer systems may be difficult to discern since they commonly are associated with slowly developing pluggage in the system, or small air in-leaks, etc. The extractive systems should be checked daily by the operators, and maintained and calibrated on a weekly basis by the incinerator instrument personnel.

6.2.3.1 <u>In Situ Oxygen Analyzers</u>. In situ analyzers provide rapid response to changes in the oxygen content of the gas because the sensor is in direct contact with the gas stream. In most cases, the sensing element is enclosed in a sintered stainless steel tube, which allows the gas to permeate through the tube but prevents particles in the gas stream from entering. Most in situ oxygen analyzers are equipped with connections so that zero gas (nitrogen) or calibration gas (air) can be flushed through the permeable tube and in contact with the sensing element. Flushing provides a means of zeroing and spanning the analyzer, and also creates reverse flow of gas through the permeable tube that helps to remove dust particles that eventually will clog the tube and slow the detector's response time. Even so, the tube periodically must be removed for cleaning or replaced if warranted.

Most in situ oxygen analyzers are of the electrocatalytic type, sometimes referred to as fuel-cell analyzers. Operation of these analyzers is based upon an electron flow created by reaction of oxygen with a solid zirconium oxide electrolyte. Consequently, manufacturers

recommend that the sensing element be replaced after several months of service.

6.2.3.2 Extractive Oxygen Analyzers.

Extractive analyzers always involve a "conditioning system" for removal of water, dust, and sometimes other constituents that would interfere with operation of the analyzer. An example extractive system is illustrated in Figure 6-1. The moisture knockout for removal of water vapor and the normal connections for zeroing and calibrating the analyzer are shown.

The integrity of the sample line and the conditioning system is crucial to obtaining a representative sample and accurate results. Any in-leakage of air can drastically distort the reading. As shown in Figure 6-1, the extractive system requires a pump to draw the sample gas continuously through the sample line, conditioning system, and analyzer. Most systems include a small rotameter (flowmeter) which shows that sample gas is flowing through the system. This flowmeter is always one of the first items that should be checked if any problem is suspected because loss of flow will occur if the pump fails or the system is plugged. However, even if the flow rate is correct, the measured gas concentration will not be correct if there is any problem with in-leakage of air.

Two types of extractive oxygen analyzers, paramagnetic and polarographic analyzers, are available in addition to the electrocatalytic type described previously for in situ analyzers. Paramagnetic analyzers measure the oxygen concentration as the strength of a magnetic field in which oxygen molecules are present. Oxygen molecules are somewhat unique in displaying a permanent magnetic moment (paramagnetism), allowing oxygen concentration to be differentiated from the stack gas sample. Calibration is performed by monitoring an inert gas such as nitrogen (zero) and a gas of known oxygen concentration (span). A potential problem with this type of analyzer is its susceptibility to paramagnetic molecules other than oxygen. Nitrogen oxide and nitrogen dioxide in particular display a high degree of paramagnetism (about one-half that of oxygen), but their concentration is usually low compared to that of oxygen.

Polarographic analyzers monitor oxygen concentration by allowing oxygen to pass through a selective, semipermeable membrane and react at an

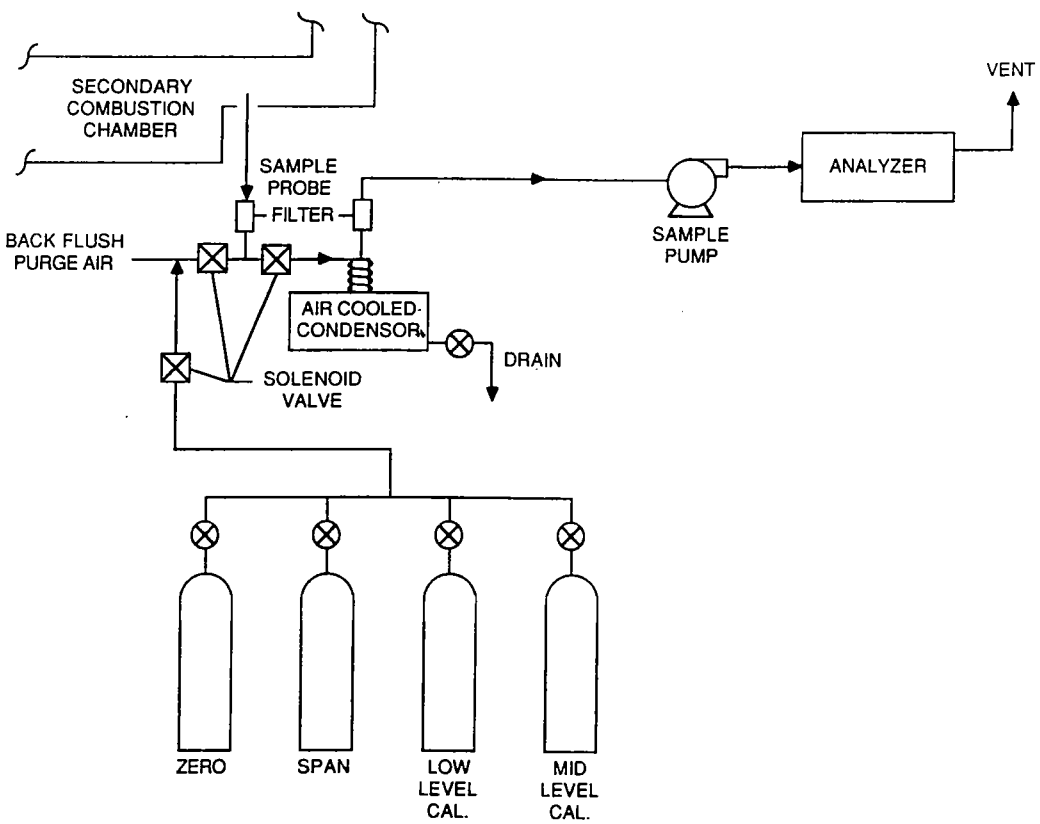

Figure 6-1. Schematic of an extractive monitoring system.

electrode in an oxidation-reduction reaction. Measuring the current produced by the reaction indicates the oxygen concentration. Improper conditioning of the sample gas is a potential problem with these analyzers, since moisture and particles will hinder performance of the semipermeable membrane. Calibration is performed by zeroing with an oxygen-free gas (nitrogen) and spanning with a gas of known oxygen concentration (e.g., air). Furthermore, these monitors contain a liquid electrolyte that has a limited life span and must be replaced at regular intervals.

6.2.4 Carbon Monoxide[1]

Carbon monoxide (CO) analyzers are used to measure emissions of CO and indicate whether proper combustion conditions are being maintained. Carbon monoxide analyzers typically are not part of the automatic process control system. In general, a problem with CO levels (i.e., high level) indicates some other problem in the process and its control system (e.g., feed rate or temperature).

Location of the CO sampling point may vary, although it is most commonly in the stack or at the exit of the combustion chamber. As with oxygen monitors, CO analyzers can be affected by upstream in-leakage of air, but usually not as dramatically as oxygen monitors.

Carbon monoxide analyzers also may be in situ or extractive, but by far the most common type is extractive. Both types are based on the principle that CO will absorb specific wavelengths of light in the infrared region. They are therefore referred to as nondispersive infrared (NDIR) analyses.

In situ CO monitors involve an infrared signal that is transmitted across the duct or stack to a receiver or reflector on the opposite side. The change in the signal, due to absorbence by CO, is processed by the analyzer system and output as an equivalent CO concentration. In situ CO monitors are difficult to calibrate directly because the duct cannot be filled with a gas of known concentration. Therefore, calibration is performed using an optical filter that can be moved into the signal path, or a calibration gas that can be put through a separate cell through which the infrared signal can be sent.

In most cases, in situ systems are installed at a location in a stack after pollution control devices have removed most of the particulate matter because solid particles also absorb the IR signal. Water vapor and carbon dioxide also may interfere with the signal. Because all these interferences can be removed by a sample conditioning system, the extractive systems are more commonly used.

Much of the previous discussion on extractive oxygen systems applies to extractive CO systems. In fact, the same extraction/conditioning system often is used for both monitors. Daily checks of the system should be made by the operator, with weekly maintenance and calibration by the instrument personnel.

Currently, there are no specific EPA performance requirements for CO analyzers on hospital incinerators. However, EPA is developing guidelines for CO monitors that are required on hazardous waste incinerators permitted under the Resource Conservation and Recovery Act (RCRA).

6.2.5 Opacity[1,2]

Like CO monitors, opacity monitors or transmissometers are used as indicators of proper operation rather than as a part of the automatic control system and almost always are located in the stack or in the ducting to the stack downstream of air pollution control devices. The operating principle for these transmissometers involves measurement of the absorbence of a light beam across the stack or duct. Consequently, they are not applicable in saturated wet streams downstream of wet scrubbers unless the gas has been reheated to vaporize any water droplets.

Transmissometers involve a light source directed across the stack and a detector, or reflector, on the opposite side. The amount of light absorbed or scattered is a function of the particles in the light path, path length (duct diameter), and several other variables that are considered in the design and installation. Figure 6-2 depicts a typical transmissometer.

The lenses on the light source and the detector must be kept clean of any buildup of dust. For this reason, the systems often include air blowers and filters that continuously blow clean air past the lenses to

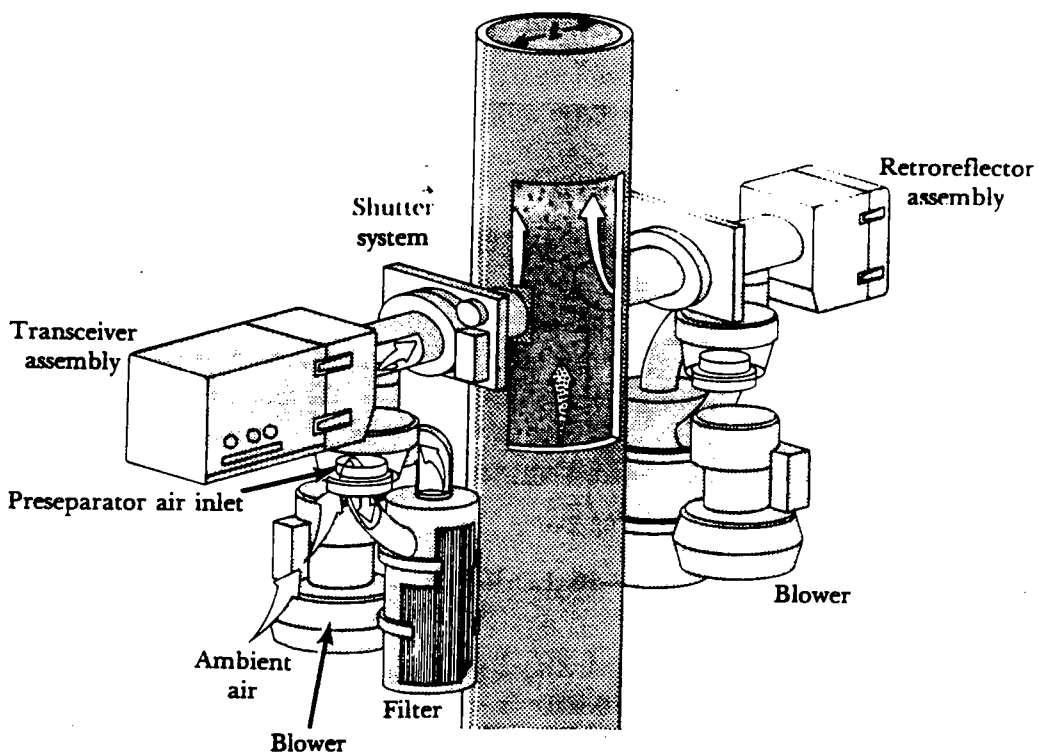

Figure 6-2. Typical transmissometer installation for measuring opacity.[1]

prevent contact with the gas and dust in the stack (see Figure 6-2). These blowers and filters should be checked and cleaned regularly but often are neglected because of their location on the stack.

The EPA has promulgated performance specifications for opacity monitoring systems that are required at some types of plants as summarized in Table 6-2. The calibration procedure for this performance specification, or normal checking of the instrument, is based on filters having known light absorbence that can be placed in the light path. Some systems automatically calibrate on a regular schedule that is evident to the operator because it usually activates a high opacity alarm or a spike on the opacity recorder.

6.2.6 Charge Rate

The amount of waste charged into the incinerator and the charging frequency are important operating variables for an incinerator. Some incinerators may be equipped with systems that weigh the amount of each charge and automatically record this weight, but, at most facilities, the amount charged is based on operator experience and hopper charge size and is not closely monitored. Thus, operator experience is relied upon to avoid overcharging (stuffing), which may decrease temperature, increase emissions (CO), and cause poor burnout. Undercharging will require excessive auxiliary fuel usage.

For mechanically charged systems, the charging frequency is often automatically set by the system at preselected time intervals. As long as the loader fills the charging hopper to a certain level within this time interval, the charging rate will be maintained constant by the control system, unless the charging frequency is changed by the operator. Altering the charging frequency is sometimes necessary when the characteristics or composition of the waste has changed. For example, if a charge contains large amounts of plastic or other high heating value material, temperatures may rise rapidly. Thus, the operator may decide to delay the next charge until the system can again handle another charge. For mechanical systems, a recorder can be set up to indicate the frequency of changes automatically, i.e., when a charge is fed to the incinerator.

TABLE 6-2. PERFORMANCE SPECIFICATIONS FOR OPACITY MONITORS[3]

Parameter	Specifications
Calibration error[a]	≤3 percent opacity
Response time	≤10 seconds
Conditioning period[b]	≤168 hours
Operational test period[b]	≤168 hours
Zero drift (24-hour)[a]	≤2 percent opacity
Calibration drift (24-hour)[a]	≤2 percent opacity
Data recorder resolution	≤0.5 percent opacity

[a]Expressed as the sum of the absolute value of the mean and the absolute value of the confidence coefficient.
[b]During the conditioning and operational test periods, the CEMS must not require any corrective maintenance, repair, replacement, or adjustment other than that clearly specified as routine and required in the operation and maintenance manuals.

Having a charging record available is useful for monitoring and troubleshooting problems and for determining whether adjustments to the charging procedures are necessary.

Operator judgment and experience are usually key to proper control of charging rate; pressure on the operator to increase the charging rate when the amount of accumulated waste has increased cannot be allowed to compromise proper incinerator operating conditions.

6.2.7 Scrubber Liquor pH

There are two types of pH sensors: immersion (dip-type) and flow-through. The immersion sensor is merely inserted into a tank and can be removed for maintenance and calibration. A flow-through sensor depends upon a continuous flow in the sample line. Both have advantages and disadvantages. The immersion sensor is easier to operate and maintain. Performance can also be improved by locating the sensor in a special sampling tank, by using redundant sensors, and by frequent cleaning and calibration. The flow-through pH sensor is prone to wear and abrasion. Redundant sensors are also desirable for the flow-through type but are not easy to provide.

The pH measurement probe consists of a pH measuring electrode, a reference electrode, and a high input impedance meter. The voltage of the pH electrode varies with the pH of the solution it is in contact with, while the reference electrode delivers a constant voltage. The difference between the two voltages is measured by the impedance meter, allowing pH of the system to be monitored. Such a system is susceptible to signal loss and noise, making it desirable to locate the preamp, controller, or signal conditioning unit as close to the electrodes as possible.

Calibration of a pH monitoring system is performed through the use of known pH buffer solutions. Typically, pH 7 is used for calibration, although pH 4 and pH 10 may also be used, depending upon the expected ranges of scrubber operation. For greatest accuracy, buffer solutions should be selected that are close to expected pH values.

The pH monitoring system electrodes may become fouled over time by dirt, particulate matter, and bacteria. This fouling can damage or

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inhibit correct electrode operation, introducing drift and inaccuracy in the unit's calibration. To maintain reliability, electrodes can be boiled in a solvent or cleaned with a built-in ultrasonic device. Calibration checks usually are necessary every few weeks.

Control systems for pH meters range in complexity from simple ON/OFF types to more sophisticated proportional controllers. In an ON/OFF type, as pH goes out of range, a valve opens and neutralizing reagent is added until the pH is corrected. Proportional controllers add an amount of neutralizing reagent in proportion to deviation of pH from the setpoint, which provides much smoother control. The exact type of controller necessary for the system is based upon individual needs, but typically a proportional controller is used.

The pH measurement probe should be placed at a representative location within the system. Turbulent flow is needed to ensure a well-mixed solution and to limit dead time (reaction time of the controller) to 30 seconds or less. Excessive dead time will cause the system to overshoot the pH setpoint continually as the controller is unable to react quickly enough and continues to add neutralizing reagent beyond the desired pH. Dead time can be reduced by locating the pH probe a short distance downstream from where the reagent is added.

6.3 REFERENCES FOR CHAPTER 6

1. U. S. EPA. Continuous Air Pollution Source Monitoring Systems Handbook, EPA 625/6-79-005. June 1979.

2. Jahnke, J. APTI Course SI:476A, Transmissometer Systems Operation and Maintenance, an Advanced Course. EPA 450/2-84-004. U. S. Environmental Protection Agency, Research Triangle Park, N.C. September 1984. p. 6-9.

3. Code of Federal Regulations, Title 40 Part 60 (40 CFR 60), Appendix B, Performance Specification 1. Specifications and Test Procedures for Opacity Continuous Emission Monitoring Systems in Stationary Sources.

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7.0 OPERATIONAL PROBLEMS AND SOLUTIONS

This section describes potential operational problems associated with hospital waste incinerators, wet scrubbers, and fabric filters; discusses the cause of the problems; and discusses possible solutions to the problems. Unfortunately, some operational problems are the result of deficiencies in design, fabrication, and/or installation of the equipment. Deficiencies in incinerator design are usually the result of insufficient information on the waste characteristics and/or quantity. The following paragraphs assume that the incinerator and its air pollution control system have been properly designed, fabricated, and installed and do not address any deficiencies in these areas. It is recommended that purchasers of hospital waste incinerators and air pollution control systems consult with reputable manufacturers. In many cases, these companies can provide complete turnkey service that includes evaluation of the purchaser's needs, proper design of the incinerator based on waste characteristics, proper design of the air pollution control device based on expected combustion exhaust gas characteristics, fabrication of the incinerator with appropriate quality control, installation and shakedown of the entire system, and operator training.

7.1 OPERATIONAL PROBLEMS AND SOLUTIONS ASSOCIATED WITH HOSPITAL WASTE INCINERATORS

Incinerator operational problems include excessive stack emissions in the form of white or black smoke, smoke leakage from the charging door or other openings, excessive auxiliary fuel usage, and incomplete burnout of the waste. These operational problems can be minimized through proper operation of the incinerator together with an effective preventive maintenance program.

7.1.1 Excessive Stack Emissions--Controlled-Air Units[1,2]

The proper operation of controlled air incinerators results in relatively low emission rates. Excessive emission rates can usually be attributed to one of the following causes:

1. High setpoint for the secondary burner temperature is not high enough;

2. Excessive negative draft in the primary chamber;

3. Excessive infiltration air (from charging door);

4. Excessive underfire air in the primary chamber;

5. Operating at too high a primary chamber temperature;

6. Overcharging;

7. Problem wastes; and

8. Inadequate secondary combustion air.

7.1.1.1 Black Smoke. The appearance of black smoke indicates the presence of unburned carbonaceous material. Dense black smoke is caused because incomplete combustion is occurring. Incomplete combustion is due to insufficient amounts of combustion air for the quantity of volatiles/soot present and is usually the result of overcharging the unit charging of a highly volatile material or operating the primary chamber at too high a temperature. The following steps may assist in eliminating black smoke:

1. Check/increase secondary chamber combustion air;

2. Check/decrease underfire air (if necessary); this should result in reducing the primary chamber operating temperature;

3. Check/increase secondary chamber temperature.

Should these steps fail to eliminate the black smoke, evaluate the composition of the material remaining to be charged. Highly combustible materials (i.e., rubber, plastics, etc.) that are charged in too great a proportion to the other refuse will result in a combustion rate which is too rapid for the incinerator to handle. These materials may be charged in very small quantities and in relatively small pieces along with general refuse. If such materials must be burned frequently, experimentation as to the quantity that may be charged along with other materials may be necessary. Generally, highly combustible materials must be charged at less than 10 percent by weight of the total charge. If the waste contains a significant amount of plastics, then reducing the primary chamber temperature (to the 540° to 650°C [1000° to 1200°F] range) may assist in reducing emissions. Operating the primary chamber at too high a temperature can cause the plastics to rapidly volatilize.

7.1.1.2 White Smoke. The appearance of a steady stream of white smoke from the stack indicates the presence of small aerosols in the effluent gas. There are several causes for this problem. Either excess air is entering the incinerator causing entrainment of micron-sized particles or the secondary chamber is operating at too low a temperature (i.e., too much air) causing premature cooling of the combustion gases. The following steps may assist in eliminating white smoke:

1. Check to see that the secondary burner is operating and that secondary chamber temperature is above 1200°F.
2. Check/decrease underfire air.
3. Decrease secondary air.
4. If all the secondary burner capacity is not being used, gradually increase the operating rate of the burner until full capacity is reached.

If adjustment of the combustion parameters fail to stop the issuance of white smoke, examine the material to be charged. Possibly the white smoke is the result of finely divided noncombustible mineral material present in the waste charge which is being carried out the stack. Paper sacks that contain pigments or other metallic oxides, and minerals such as calcium chloride, generate fine inorganic particulate which cause white smoke.

The appearance of a white plume (other than a condensing water vapor plume) a short distance away from the stack probably indicates that hydrogen chloride is condensing. Unfortunately, there is no incinerator adjustment that will solve this problem. One solution is to reduce the amount of chlorinated waste incinerated in each load. This option is often impractical because the waste is mixed together in packages and, therefore, cannot be separated. Probably the best solution is to eliminate chlorinated plastics from use in the hospital or to install an acid gas scrubbing system.

7.1.2 Excessive Stack Emissions--Multiple-Chamber Units

Excessive emission rates from multiple-chamber units can usually be attributed to one of the following causes:

1. High setpoint for the secondary burner temperature is not high enough;
2. Excessive draft in the primary chamber;
3. Overcharging;
4. Problem wastes;
5. Inadequate secondary combustion air; and
6. Operating at too high a primary chamber temperature.

7.1.2.1 Black Smoke. The appearance of black smoke indicates the presence of unburned carbonaceous material. Dense black smoke is caused by incomplete combustion as a result of insufficient amounts of combustion air for the quantity of volatiles/soot present. Black smoke is often the result of overcharging of the incinerator or of too large an amount of highly volatile materials in the waste charged.

Steps which can be taken to eliminate black smoke include:

1. Decrease the charging rate;
2. Increase the secondary combustion air; and
3. Reduce the percentage of highly volatile materials in the waste feed; and
4. Reduce the primary chamber operating temperature.

7.1.2.2 White Smoke. The appearance of a steady stream of white smoke from the stack indicates the presence of small aerosols in the effluent gas. Steps which can be taken to eliminate white smoke include:

1. Check to see that the secondary burner is operating. If all the secondary burner capacity is not being used, increase the operating rate of the burner to full capacity; and
2. Decrease the secondary and/or primary air in order to increase the secondary temperature.

The appearance of a white plume (other than a condensing water vapor plume) a short distance away from the stack probably indicates that hydrogen chloride is condensing. No incinerator adjustment will solve this problem.

7.1.3 Leakage of Smoke From Primary Chamber

The leakage of smoke through charging doors or other openings indicates that a positive pressure differential exists in the primary chamber. Positive pressure can be caused by excessive combustion air, by excessive charging of a highly volatile material, by too high a primary chamber operating temperature, or by too much hot ash being discharged to a wet sump all at one time. The following steps may help eliminate leakage of smoke:

1. Check/decrease underfire air (controlled-air units);
2. Decrease feed rate;
3. Adjust ash discharge ram cycle; and
4. Adjust draft control (damper or ID fan) setpoints.

If a positive pressure persists, operation of the incinerator draft control system (draft monitor, barometric damper, induced draft fan) should be checked.

7.1.4 Excessive Auxiliary Fuel Usage[1]

For controlled-air units, improper underfire air distribution, excessive air infiltration, or improper setting of the underfire and secondary combustion air levels can result in excessive fuel usage. If the underfire air distribution in the primary chamber is incorrect or if there is excessive air inleakage, even a substoichiometric air/fuel mixture, which generates combustible gases for maintaining the secondary combustion chamber temperature, will not exist in the primary chamber. Instead, the waste bed will completely burn in some areas and not burn at all in other areas. The gases conveyed to the secondary chamber will already be fully oxidized, and auxiliary fuel will be necessary to maintain the secondary chamber temperature.[2]

Another cause of excessive auxiliary fuel usage is that the incinerator is not consistently charged. If the incinerator is not receiving enough heat input in the form of waste to maintain its temperature set-points, then the unit will supply its own heat in the form of auxiliary fuel, i.e., natural gas or oil. Consistent charging of waste

at regular timed intervals at a rate near 100 percent of the incinerator's design capacity will reduce the amount of auxiliary fuel required and will enhance the incinerator's performance. It is best to charge waste in batches which are 10 to 15 percent of rated capacity. Therefore, if a unit is rated at 500 pounds of waste per hour, then the unit should be charged at 6-minute intervals with charges of approximately 50 pounds each. The following actions may assist in reducing auxiliary fuel usage:

1. Charge waste at regularly timed intervals at a rate consistent with 100 percent of the design (thermal input) capacity;
2. Check/reduce secondary combustion air levels;
3. Check primary combustion air levels and distribution;
4. Check charging door seals and other seals for air leakage (controlled-air units); and
5. Check the fuel trains and burners for fuel leakage.

7.1.5 Incomplete Burnout--Poor Ash Quality

The causes of incomplete burnout include primary burner malfunction, insufficient primary chamber combustion air or poor underfire air distribution, overcharging the incinerator with waste, and charging too much wet waste. As with other operational problems, the causes of incomplete burnout can be minimized by proper operation of the incinerator and an effective preventive maintenance program.

7.1.5.1 Primary Burner Malfunction. Primary burner malfunction causes incomplete burnout because the primary chamber temperature will not be maintained and because the flame is insufficient to ignite the waste and keep it burning. Primary burner malfunction may arise due to burner power loss, burner pluggage, failure of the flame safeguard, or leaking fuel trains. Each of these problems can be eliminated by preventive maintenance performed on a regular basis as outlined in Section 5.1. If the primary burner should fail, the following steps are recommended:

1. Check power supply to the primary burner;
2. If power is available, check burners for pluggage and clean as required;

3. Check the operation of the burner safeguard system as outlined in the owner's manual; and

4. Check fuel trains and burner assembly for fuel leakage and repair as required.

7.1.5.2 Insufficient Underfire Air (Controlled-Air Units). In a controlled-air incinerator, insufficient underfire air can cause the combustion process to stop completely. Primary causes of the lack of combustion air are an improper underfire air setting, clinker buildup around the underfire air ports, and air ports clogged with ash or slag from previous charges. Clinker buildup around primary chamber air ports is usually the result of too much air, resulting in local hot spots that cause the ash to soften, agglomerate, and then harden as clinker during the cool down cycle. Some manufacturer utilize steam injection into the ash bed to facilitate burnout of fixed carbon in the ash bed and at the same time help prevent hot spots and clinker formation.[3] Maintaining proper air levels and air distribution through all underfire air ports is important. Proper operation and preventive maintenance can prevent these problems. If poor burnout occurs, the following items should be checked:

1. Check underfire air ports for ash pluggage and rod out as required;

2. Check around the underfire air ports for clinker buildup and clean as required; and

3. Check underfire air setting and adjust to the proper setting (increase) as required.

7.1.5.3 Waste Charging. Charging of waste into the incinerator should be performed as described in the vendor's literature. Two conditions to be avoided that can cause incomplete burnout are overcharging the incinerator and charging too much wet waste as part of a charge.

These problems may be encountered with the so called "stuff-and-burn" type batch units operating on a timed-cycle. When the incinerator is overcharged and tightly packed with waste, the combustion air cannot circulate freely through the compacted waste, thereby inhibiting combustion. When incinerating wet waste, the waste must first be dried by evaporating the moisture in the waste; if the batch contains a large fraction of wet waste, insufficient time for complete combustion may be a

problem. Both of these conditions should be prevented by not overcharging the incinerator or by increasing the burnout cycle time.

For intermittent-duty, controlled-air, and multiple-chamber incinerators, reduction of the charge rate may improve the ash burnout quality. The burndown period also can be increased in an attempt to improve burnout.

For continuous-duty incinerators, reducing the waste feed charge rate will increase the residence time of the solids in the primary chamber and may help to improve ash burnout quality.

7.2 OPERATIONAL PROBLEMS AND SOLUTIONS ASSOCIATED WITH WET SCRUBBERS[4,5]

The performance of a wet scrubber system is dependent on the key operating parameters discussed in Chapter 4, on effective preventive maintenance, and on the integrity of the scrubber components. Premature failure of these components will lead to increased costs, extended downtime of the system, and/or operation in temporary noncompliance. The main problems experienced by wet scrubber systems include corrosion, scaling, and erosion. An effective preventive maintenance program can minimize these problems by correcting malfunctions, observing trends in maintenance activities and making modifications to prolong equipment life, and correcting minor problems before they become costly, time consuming repairs. The following sections describe the problems, identify affected equipment, and recommend solutions.

7.2.1 Corrosion

Corrosion of wet scrubber components is the result of absorption of sulfur dioxide, sulfur trioxide, or hydrochloric acid gas from the dirty gas to the scrubbing liquid. The resulting acidic conditions cause corrosion of the wet scrubber system if it is made of carbon steel. Wet scrubbers controlling hospital waste incinerators are likely to experience corrosion from hydrochloric acid as a result of combustion of chlorinated plastics. The types of equipment that are likely to be subject to corrosion include scrubbers, absorbers, fans, dampers, ductwork, and

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exhaust stack. If the scrubbing liquid is recirculated (i.e., the system does not use once-through water), the importance of maintaining the pH of the scrubbing liquid above the level at which carbon steel is attacked cannot be stressed enough. An appropriate pH of 6 or greater is usually maintained through additions of alkaline reagents such as soda ash, lime, or limestone. The operation of the pH monitor used to control the rate of alkaline addition should be checked on at least a daily basis to minimize short-term low pH excursions.

Corrosion also can be a problem in the pumps, pipes, valves, tanks, and feed preparation areas in slurry service. Slurry tanks and associated feed preparation equipment should be checked daily for leaks. Equipment temporarily removed from slurry service should be thoroughly flushed. Typically, slurry pumps are disassembled at least annually to verify lining integrity and to detect wear and corrosion or other signs of potential failure. Bearings and seals are checked but not necessarily replaced. Pipelines also must be periodically disassembled or tested in other ways (e.g., hand-held nuclear and ultrasonic devices) both for solids deposition and for wear. Valves must be serviced routinely, especially control valves.

The solution to corrosion problems in wet scrubber systems is to maintain the pH of the scrubbing liquid by the following:

1. Check the proper operation of the pH monitor that controls alkaline additions daily;

2. Check the alkaline addition system for leaks daily and repair as required; and

3. Perform regular preventive maintenance on pumps, pipes, valves, and tanks to minimize and correct corrosion problems.

7.2.2 Scaling

Scaling is a common problem that arises in scrubber components in wet service such as mist eliminators, fans, dampers, and ductwork. Scale deposits in mist eliminators can cause nonuniform flow and plugging. Fans in wet service can develop vibrations as a result of scale deposition on the fan blades. Dampers may become stuck in place.

The best solution to scaling and/or plugging is an effective preventive maintenance program. Observation of the differential pressure across the mist eliminator can alert personnel to scaling problems. Periodic cleaning of equipment can minimize scaling problems.

7.2.3 Erosion

Erosion is a common problem associated with scrubber components in dry service such as fans, dampers, and ductwork. Erosion is also a problem for scrubber spray nozzles due to the suspended solids recovered in the scrubbing liquid from the dirty gas. For fans in dry service, fan vibration may be caused by erosion of fan blades. In such cases, the fan blades may have to be replaced. Erosion may cause holes in the ductwork. These holes must be repaired to prevent air in-leakage.

Scrubber spray nozzles are extremely susceptible to erosion and pluggage problems due to the high velocities of the liquid stream and the suspended solids within the stream. Pluggage and erosion in the spray nozzles can be determined by observing the spray angle. If the spray angle has become enlarged, then the nozzle orifice probably has been enlarged by erosion. Conversely, if the spray angle has decreased or if a distinct spray pattern is no longer achieved, then the nozzle orifice probably is partially or completely plugged. The potential for erosion of the scrubber components is directly related to the percent suspended solids. The greater the recirculation flow rate relative to the makeup and purge (blowdown) flow rates, the greater the potential for buildup of solids. Infrequent purging also can cause high solids buildup.

Erosion in dry service components is to be expected. Effective preventive maintenance and equipment replacement when required are the best solutions.

Erosion in scrubber spray nozzles and other scrubber components may be prevented by proper operation and maintenance as follows:

1. Rod out spray nozzles on a regular basis to prevent plugging;
2. Purge the system frequently to prevent solids buildup; and
3. Adjust the recirculation rate as appropriate.

7.3 OPERATIONAL PROBLEMS AND SOLUTIONS ASSOCIATED WITH FABRIC FILTERS[6]

The two main operational problems associated with fabric filters are high opacity and high pressure drop. Well designed, operated, and maintained fabric filters will generally have a very low opacity (between 0 to 5 percent), and the pressure drop will fall within a general operating range for the particular fabric filter type (5 to 9 in. w.c. for pulse-jet fabric filters). Opacity and/or pressure drop deviations from the baseline values are good indicators of fabric filter performance deterioration. Higher or lower than normal inlet temperatures can cause opacity and pressure drop problems. The inlet temperature should be monitored continuously. The following sections describe each operational problem, the cause, and possible solutions.

7.3.1 Opacity

Large fabric filter installations may have an opacity monitor coupled with a strip-chart recorder. Typically, smaller installations have no opacity monitor and must rely on visible emission observations. In any event, opacity measurements are useful in determining trends in the performance of the fabric filter. Typically, the opacity plume of a properly operated and maintained filter will be very low, except when a condensible plume is present (even in this case the condensing plume should be detached). In general, high opacity is a good indicator of fabric failure. A consistently elevated opacity level relative to the baseline level is an indication of major leaks and tears in the filter bags. A puffing, intermittent opacity observed after cleaning that is higher than the baseline opacity level is a good indication of pinhole leaks in the filter bags. The factors that cause fabric failure include improper filter bag installation, high temperature, chemical degradation, and bag abrasion.

Improper installation of filter bags can result in leaks around seals, improper bag tensioning, and damage to the bags. Lack of training of maintenance personnel in filter bag replacement and poor access to the fabric filter housing are contributing factors to improper installation.

High temperatures are the result of process malfunction(s) upstream of the fabric filter. Therefore, in the fabric filter design phase, a fabric must be chosen on the basis of expected temperature range with an adequate margin for error. High temperature breaks the polymer chains in most commercially available fabrics causing loss of strength and reduced bag life. High temperature attacks the finish on fiberglass bags causing increased bag abrasions. In general, high temperatures shorten bag life considerably. High enough temperatures can cause filter bags to ignite. Some installations may have an alarm system to warn of high temperature excursions and a bypass system to prevent damage to the filter bags. Such a system may be appropriate should the cooling system prior to the fabric filter fail. Sparks may also be a problem with a combustion source such as a hospital waste incinerator. A spark arrestor can help eliminate the potential for sparks in the fabric filter.

Chemical degradation of the filter bags occurs as the result of acid gas condensation. In addition to specification of a temperature range for filter bags, a chemical resistance rating must also be specified for the fabric. In the case of hospital waste incinerators, fabric should have good chemical resistance to hydrochloric acid due to combustion of chlorinated plastics. Additionally, operation at a high enough temperature to prevent acid gas condensation will reduce chemical degradation.

Filter bag abrasion can be caused by contact between a bag and another surface (e.g., another bag or the walls of the fabric filter) or by the impact of higher-than-average gas volumes and particulate loading on the bags. Bag abrasion can also be a problem when the fabric filter experiences a high pressure drop. Usually, when bag abrasion is a problem, the greatest abrasion occurs within 18 to 24 inches from the bottom of the bags. A blast plate or diffuser will redirect the larger particles away from the bags and reduce bag abrasion.

While the only solution to the problem of high opacity is replacement of the failed filter bags, it can be prevented by the following:

1. Train maintenance personnel in the proper installation of replacement filter bags;

2. Design fabric filters for ease in bag replacement;

3. Choose filter bag fabric with an appropriate operating temperature range and chemical resistance rating;

4. Blast plates or diffusers are recommended for those facilities experiencing severe bag abrasion;

5. Monitor inlet temperature--an alarm and bypass system may be installed to prevent filter bag damage from high temperature excursions;

6. Install a spark arrestor to prevent sparks and fire inside the fabric filter; and

7. Install a bypass/alarm system to prevent damage to filter bags during high temperature excursions.

7.3.2 Pressure Drop

The pressure drop across a fabric filter is an important indicator of performance. An increase in pressure drop indicates greater resistance to flow and can be a symptom of a high air-to-cloth ratio or an increase in dust cake thickness due to condensation or cleaning system failure.

The air-to-cloth ratio is a design parameter that is determined during the fabric filter design phase. In the pulse-jet baghouses used to control emissions from hospital waste incinerators, the air-to-cloth ratio and therefore pressure drop are relatively high (5 to 9 in. w.c.). Bag abrasion and/or fugitive emissions may result if the pressure drop is too high (10 to 14 in. w.c.).

Condensation of moisture on filter bags is caused by temperatures in the fabric filter below the dewpoint. "Mudding" or blinding of the bags increases the resistance to flow and occurs because the cleaning system cannot remove the dust. Condensation can be prevented by preheating the fabric filter during the startup operation and by purging moist gases from the unit prior to shutdown. During operation it is critical to maintain the operating temperature above the dewpoint of the gas stream at all times.

Cleaning system failures in pulse-jet systems are usually the result of worn or undersized compressors, and failed solenoids and/or timers. Compressor problems are indicated by a low compressed-air pressure. Because of the low pressure the system cannot clean the bags properly and

an increased pressure drop across the fabric filter results due to dust cake buildup. Compressor capacity may be a problem and should be checked against the needs of other systems the compressor serves. Routine preventive maintenance can prevent premature failure of the compressor and can prevent worn compressor seals from passing oil into the fabric filter and blinding the filter bags. Both reduced compressed-air pressure and bag blinding can cause an increase in pressure drop.

Failure of solenoids and or timers can prevent the filter bags from being cleaned at all. These sytems require clean, dry mountings to operate properly. Solenoid failures affect the only row of filter bags that the solenoid services, while timer failures tend to affect most, if not all, of the fabric filter system.

An additional problem is that associated with the pulse pipe that discharges the compressed air into the bags. Pulse pipes may sometimes be damaged by the force of the compressed air causing ineffective cleaning and pressure drop increase, improper pipe alignment that may blow holes in the filter bags, or a loose pipe that may damage the interior of the fabric filter. The sound of a loose pulse pipe is unmistakable because it moves whenever compressed air is fired into the pipe.

An increase in pressure drop may indicate operation and maintenance problems that may be corrected. However, blinded bags resulting from condensation or the accidental discharge of compressor oil into the fabric filter will likely have to be replaced. An increase in pressure drop can be prevented by the following:

1. Preheat the fabric filter prior to process operation;
2. Purge the fabric filter of moist air prior to shutdown;
3. Always maintain the temperature of the gas entering the fabric filter above its dewpoint;
4. Perform preventive maintenance of the compressor system and solenoid/timer system;
5. Make necessary repairs to pulse pipes as required; and
6. Adjust the cleaning cycle to shorten the cycle between cleanings.

7.4 REFERENCES FOR CHAPTER 7

1. McRee, R. Operation and Maintenance of Controlled-Air Incinerators. Ecolaire Environmental Control Products. Undated.

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5. U. S. Environmental Protection Agency. Wet Scrubber Inspection and Evaluation Manual. EPA-340/1-83-022. (NTIS PB85-149375). September 1983.

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8.0 RECORDKEEPING

Recordkeeping is an integral part of an equipment operation and maintenance (O&M) program. The purpose of recordkeeping is to document major O&M events and to collect historical data on key operating parameters. The objective of recordkeeping is to prevent premature failure of equipment, increase the life of the equipment, and to minimize emissions. Recordkeeping allows facility and regulatory agency personnel to track performance, to evaluate trends, to identify potential problem areas, and to determine appropriate solutions. The magnitude and scope of recordkeeping activities will depend on a combination of factors, including personnel availability and training, size and sophistication of the equipment, and the level of maintenance required. Only records of key performance parameters and activities should be maintained to avoid accumulation of unnecessary information.

The following information should be readily available to O&M personnel: (1) the manufacturer's equipment specification and instruction manuals, (2) compliance emission tests, (3) operating permits, (4) operating logs, and (5) maintenance activities log. The operating history provided by this information is useful in evaluating current and future performance, maintenance trends, and operating characteristics. A spare parts inventory also should be maintained with periodic updates so that parts can be obtained and installed in a timely manner. A recommended spare parts inventory typically is supplied with the equipment manufacturers' O&M manuals. Whether a facility maintains an extensive or minimal parts inventory is dependent on the available space for parts storage and whether the facility has a service agreement with the equipment vendor.

8.1 MANUFACTURER'S SPECIFICATIONS AND LITERATURE

The manufacturer's information is the foundation of a recordkeeping program. A copy of the information and literature supplied by the incinerator and air pollution control device manufacturers should be easily accessible for use and review by personnel responsible for O&M. This literature includes the manufacturer's design specifications,

performance guarantee, piping and instrumentation diagram, process flowsheet, material balance information for normal and maximum design conditions, and an instruction manual for O&M.

The O&M manuals discuss the theory and design of the equipment; operating procedures for startup, shutdown, normal operation, and troubleshooting; maintenance procedures; and a recommended spare parts list. The guarantee or warranty provisions in the contract are conditioned on the proper care and treatment of the equipment as specified in the O&M instruction manual.

8.2 COMPLIANCE EMISSION TEST RECORDS[1]

Records of initial compliance test results and records of incinerator process and air pollution control device operating conditions during the compliance test form the baseline information against which subsequent operating data are compared. The baseline period normally occurs soon after shakedown of new equipment and represents conditions when the control device is operating in compliance with applicable regulations. Comprehensive baseline test results and equipment operating data establish the relationship between operating conditions and emission levels for a specific process/air pollution control device combination. Once this relationship exists, operating personnel and regulatory groups can use subsequent measurements of the same parameters to compare against baseline conditions and thereby identify excursions from acceptable performance.

8.3 OPERATING RECORDS[1-3]

There is a practical limit to the operating parameters that should be routinely checked and to the frequency with which the data are logged. Table 8-1 presents a list of recommended operating parameters for incinerators, wet scrubbers, fabric filters, and continuous emission monitors that should be monitored and logged on a regular basis. However, the decision on which operating parameters will be monitored and recorded and with what frequency is largely site-specific. This decision depends on the size and complexity of the equipment, the number of hours per day

TABLE 8-1. RECOMMENDED OPERATING PARAMETERS THAT SHOULD BE INCLUDED IN OPERATING LOGS FOR INCINERATORS, WET SCRUBBERS, FABRIC FILTERS, AND CONTINUOUS EMISSION MONITORS

A. Incinerator Operating Parameters

1. Charging rate/frequency
2. Primary combustion chamber temperature
3. Secondary combustion chamber temperature
4. Incinerator draft
5. Exhaust gas O_2 concentration
6. Auxiliary fuel feed rate

B. Wet Scrubber Operating Parameters

1. Gas temperature, inlet and outlet
2. Static pressure drop, total
3. Static pressure drop, mist eliminator
4. Liquor feed rate
5. Liquor pH
6. Water makeup rate
7. Fan(s) current, rpm
8. Nozzle pressure
9. Solids content of liquor

C. Fabric Filter Operating Parameters

1. Gas temperature, inlet and outlet
2. Static pressure drop, total
3. Cleaning cycle frequency

D. Continuous Emission Monitors

1. CO emission concentration, ppm
2. Opacity of emissions, percent

that it operates, and the availability of personnel. The greater the frequency of data gathering, the more sensitive the operators will be to equipment operational problems. However, as the amount of data increases, the effort required to collect and manipulate the data also increases. The optimal frequency of data gathering may be every 4 hours (twice per shift). If sudden and dramatic changes in performance occur, if the source is highly variable (such as an incinerator), or if the air pollution control device operation is extremely sensitive, shorter monitoring intervals, such as once per hour, are required.

In addition to the numerical values of the operating parameters, a checklist should be included to confirm operation of fans, limit switches, burners, ram feeders, pumps, nozzles, and the other general physical considerations that can adversely influence performance.

8.4 MAINTENANCE RECORDS[2]

Maintenance records provide an operating history of equipment. They can indicate what equipment has failed, where, when, and how often; what kinds of problems are typical; what actions were taken; and, over time, the efficacy of the remedial actions. These records can be used in conjunction with a spare parts inventory to maintain and update a current list of available parts and the costs of these parts.

The work order system is one way to keep useful maintenance records. This system would be administered by the engineer in charge of the proper O&M of the incinerator. Whenever maintenance is required, the engineer will issue a work order to the appropriate department (e.g., maintenance) detailing the work to be performed. Additionally, the work order form should include the following information to assure both good communication between departments and prompt completion of the work: a work order number, the date of the work request, the name of the person requesting the work and his/her department, the department to which the work order is sent, any special equipment required, any special precautions that should be taken, a signature block for the person performing the work, and the date of completion of the work. The format of the work order form is variable as long as it fits the needs of the

particular hospital. The engineer, upon return of the completed work order, may check the satisfactory performance of the work requested. When properly designed and used, this system provides information on the suspected problem, the problem actually found, the corrective action taken, time and parts required, and any additional pertinent information. Additionally, such a system can also be used to ensure that the monthly, quarterly, and semiannual routine preventive maintenance is performed. In developing a work order maintenance log system, facility personnel should consult both the schedules in Chapter 5.0 and the manufacturer's recommended maintenance schedule. The work order system may involve the use of triplicate carbon forms or it may be computerized. Triplicate carbons provide a copy of the work order to the engineer (requestor), the department performing the work, and the hospital administration. These copies would become part of the O&M log. Daily and weekly preventive maintenance activities should be included as part of the routine operation of the incinerator and associated air pollution control device. Preventive maintenance activities and schedules for incinerators, wet scrubbers, and fabric filters are discussed more fully in Chapter 5.0.

Another approach is to use a log book in which a summary of maintenance activities is recorded. Although not as flexible as a work order system (e.g., copies of individual work orders can be sent to appropriate departments), it does provide a centralized record and is probably better suited for the small facility.

8.4.1 Retrieval of Records[2]

A computerized storage and retrieval system is ideal for recordkeeping. A computer can manipulate and retrieve data in a variety of forms and also may be useful in identifying trends. A computerized system is not for everyone, however. The larger the data set to be handled, the more likely it is that a computer can help to analyze and sort data. Sorts might include a history of maintenance activities and identification of recurring operating problems that might indicate a need for more frequent maintenance or inspections. For a small source that presents few problems and that has a manageable set of operating parameters to be monitored, a computer system may not be cost effective.

Retention time is also a site-specific variable. If records are maintained only to meet a regulatory requirement and are not used or evaluated, they can probably be disposed of at the end of the statutory limitation (typically 2 years). It can be argued that these records should not be destroyed because if the equipment fails prematurely, the data preserved in the records could be used to troubleshoot the problem. In some cases, records going back 10 to 12 years have been kept to track the performance, cost, and system response to various situations and the most effective ways to accomplish remedial actions. These records serve as a learning tool to optimize performance and minimize emissions, which is the underlying purpose of recordkeeping. Some of these records may be kept throughout the life of the equipment. After several years, however, summaries of O&M activities are more desirable than the actual records themselves. These can be created concurrently with the daily O&M records for future use. If needed, actual data can then be retrieved for further evaluation.

8.5 REFERENCES FOR CHAPTER 8

1. U. S. Environmental Protection Agency. Wet Scrubber Inspection and Evaluation Manual. EPA-340/1-83-022. (NTIS PB85-149375). September 1983.

2. U. S. Environmental Protection Agency. Operation and Maintenance Manual for Electrostatic Precipitators. EPA 625/1-85-017. September 1985.

3. U. S. Environmental Protection Agency. Operation and Maintenance Manual for Fabric Filters. EPA/625/1-86/020. June 1986.

9.0 SAFETY GUIDELINES

This section provides general safety guidelines in the O&M of hospital incinerators and associated air pollution control devices. The information presented here is intended to supplement safety information provided by manufacturers and/or safety standards established by individual hospitals. There are two primary concerns with respect to the operator's safety. The first concern is the potential for exposure to pathogens during handling of infectious waste. The second concern is the prevention of injury due to the general hazards normally associated with industrial equipment such as incinerators and air pollution control devices.

9.1 PREVENTION OF INFECTION DURING WASTE HANDLING[1]

The major risk of infection to an operator is from puncture wounds caused by contaminated objects such as surgical instruments, needles, and broken glass. Most, if not all, hospitals are using special rigid, secure containers to prevent injury from infected sharp objects. Nonetheless, to prevent possible injury which could result in infection, safety rules which should be followed include:

1. Minimize the handling of red bag waste;
2. Keep red bag wastes in a secure location prior to incineration;
3. <u>Never</u> open red bags to inspect the contents; and
4. Follow procedures which maintain the integrity of the red bag waste. If breakage/spillage of red bag waste occurs, then handling procedures must be changed. The use of double bags, stronger bags, rigid carts, or cardboard containers to contain the red bag waste should be instituted. The hospital administration should be contacted if there are continued problems with bag integrity;
5. Wear thick rubber gloves when handling red bag wastes;
6. Wear hard-soled rubber shoes when handling waste and working in the area around the incinerator; and
7. Wear safety glasses.

9.2 EQUIPMENT SAFETY PROCEDURES[2-5]

General safety procedures to prevent injury when working around the incinerator and air pollution control equipment include:

1. Containers of flammable liquids or explosives should never be fed into the incinerator;

2. The incinerator charging door should not be opened if the incinerator is under positive pressure, if the ignition burner is on, or if other conditions recommended by the manufacturer are not met (i.e., minimum time between charges). Always exercise caution when opening the charging door. Wearing safety glasses, the operator should stand behind the door, open the door several inches and pause, then open the door fully;

3. Never open cleanout ports to view into the incinerator during operation;

4. Never enter the chambers of mechanical ram feeders, ash conveyors, or the incinerator without first turning off all power sources and assuring that the units are "locked out." If a chamber must be entered, after locking the unit out, make sure a second person is standing by;

5. Observe caution around all moving belts, hydraulic cylinders, and doors;

6. For systems requiring manual ash removal, exercise extreme caution when removing the ash. Do not enter the incineration chamber to remove the ash. Instead, use the mechanical ash ram or conveyor (if available) or rakes or shovels with handles of sufficient length to reach the back of the incinerator ash compartment. When using rakes or shovels, use caution so as not to damage the incinerator refractory;

7. Wear proper personal safety equipment when operating the incinerator and removing/handling the ash to prevent burns, cuts, punctures, or eye injury. Proper safety equipment includes gloves, hard-soled rubber shoes, and safety glasses;

8. Avoid direct contact with the hot surfaces of the incinerator chamber, heat recovery equipment, ductwork, and stack;

9. The scrubber liquor from wet scrubbers likely will be caustic. Avoid contact with the liquid and wear eye protection near and around the scrubber;

10. Venturi scrubbers operate at high positive pressures. Be cautious of leaks in the scrubber vessel, ductwork, or piping;

11. Entry into fabric filters other than for maintenance should be avoided. Only persons who have been properly trained should enter fabric filters, and they should be alert to the following hazards ad necessary precautions.

(a) Before personnel enter the unit, the filter bags should be thoroughly cleaned and dust dislodged and discharged from the hopper by mechanical vibration to prevent fugitive emissions and dust inhalation. Hopper doors should only be opened when the unit (including fan and hopper evacuation systems such as screws and drag chains) has been shut down.

(b) Oxygen deficiency as is common in incinerator combustion gases makes fabric filter entry especially dangerous. Purging of the unit does not always replace the exhaust gases with ambient air. Inspectors should know the dangers associated with oxygen deficiency.

(c) Explosion is possible in a confined space such as a fabric filter. Ventilation/purging prior to entry is recommended.

(d) Exposure to toxic chemicals in the collected dust is another danger of fabric filter entry. A quantitative assessment of the expected compounds in the dust and threshold dose levels should be made prior to entry. Proper personnel protection equipment such as respirators should be worn.

12. Eye protection, hearing protection, long sleeved shirts, and gloves should be worn during fabric filter inspection. Inspectors also should be cognizant of heat/thermal stress associated with the length of time required for inspection/repairs. Because of the dusty, humid conditions and limited access, thermal effects may be severe.

9.3 FIRE SAFETY[6]

Fire safety is particularly important when working around incinerators due to the nature of the high temperature combustion process. The areas in which the operator should exercise caution include: waste storage, waste charging to the incinerator, and ash removal.

The location of the waste storage area relative to the incinerator is an important consideration regarding fire safety. Waste should be stored away from the incinerator and ash storage areas such that access to the unit is not blocked and premature ignition of the stored waste from stray sparks or burning flyash is eliminated.

Charging of the waste into the incinerator has a particularly high fire hazard associated with it because of the potential exposure of high temperature and flaming conditions to the operator and surrounding building areas. When charging manually charged incinerators, the operator should exercise extreme caution. A fire safety feature that should be included on manually loaded incinerators is an interlock system that shuts off the primary chamber burner(s) when the charging door is opened. Some systems shut off the underfire air when the charge door opens. The charge door should operate freely and be free of any sharp edges or projections that could catch or hang up waste materials and cause spillage. When charging automatically charged incinerators, a potential fire hazard exists when waste material (particularly plastics) adheres to the hot charging ram. If these materials do not drop from the ram during its loading cycle, they may ignite and be carried back into the charging hopper where the remaining waste will become ignited. Automatic loading systems usually have automatic safety systems activated by a flame scanner that spray water to quench the hot ram face and any flames and/or automatic systems that reinitiate a loading sequence to charge the burning waste into the incinerator.

Handling of ash is another area where the operator should exercise extreme caution regarding fire safety. Manual ash removal involves removing ash with rakes and shovels followed by a water quench. Because the ash may contain hot spots, the operator should wear proper personal

safety equipment including gloves, hard-soled rubber shoes, and safety glasses. Water quenching should occur only after removing the ash from the incinerator to prevent damage to the incinerator refractory. Automatic ash removal systems quench the ash as it is removed from the incinerator and dump the quenched ash into ash carts. Quenched ash should be stored in a fire rated area in a location isolated from stored waste materials.

9.4 REFERENCES FOR CHAPTER 9

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5. U. S. Environmental Protection Agency. Air Pollution Source Inspection Safety Procedures: Student Manual, EPA-340/1-85-002a. September 1985.

6. Doucet, L. Fire Protection Handbook, National Fire Protection Association Waste Handling Systems and Equipment. Chapter 12.

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10.0 GLOSSARY

ABSORPTION.[3] The process by which gas molecules are transferred to (dissolved in) a liquid phase.

ACID GASES.[4] Corrosive gases formed during combustion of chlorinated or halogenated compounds, e.g., hydrogen chloride (HCl).

ACTUAL CUBIC FEET PER MINUTE (acfm).[3] A gas flow rate expressed with respect to temperature and pressure conditions.

AERODYNAMIC DIAMETER.[4] The diameter of a unit density sphere having the same aerodynamic properties as an actual particle. It is related to the physical diameter according to the equation below:

$$d_{pa} = d_p(\rho C)^{1/2}$$

where:

d_{pa} = aerodynamic diameter
d_p = physical diameter
ρ = particle density
C = Cunningham correction factor

AIR, DRY.[4] Air containing no water vapor.

ASH.[5] The noncombustible inorganic residue remaining after the ignitionof combustible substances.

ATOMIZATION.[4] The reduction of liquid to a fine spray.

BAG BLINDING. The loading, or accumulation, of filter cake to the point where capacity rate is diminished.

BAROMETRIC SEAL.[1] A column of liquid used to hydraulically seal a scrubber, or any component thereof, from the atmosphere or any other part of the system.

BOTTOM ASH.[5] The solid material that remains on a hearth or falls through the grate after incineration is completed.

BURN RATE.[4] The total quantity of waste that is burned per unit of time that is usually expressed in pounds of waste per hour.

BURNDOWN PERIOD. The period of time in an incinerator's operating cycle during which no additional waste is charged to the incinerator and the primary combustion chamber temperature is maintained above a minimum temperature (using auxiliary burners as necessary) to facilitate the solid phase combustion of the waste bed.

CHARGE RATE.[4] Quantity of waste material loaded into an incinerator over a unit of time but which is not necessarily burned. Usually expressed in pounds of waste per hour.

CLINKERS.[5] Hard, sintered, or fused pieces of residue formed in an incinerator by the agglomeration of ash, metals, glass, and ceramics.

COCURRENT OR CONCURRENT.[4] Flow of scrubbing liquid in the same direction as the gas stream.

COLLECTION EFFICIENCY.[1] The ratio of the weight of pollutant collected to the total weight of pollutant entering the collector.

COMBUSTION.[4] A thermal process in which organic compounds are broken down into carbon dioxide (CO_2) and water (H_2O).

CONDENSATION.[1] The physical process of converting a substance from the gaseous phase to the liquid phase via the removal of heat and/or the application of pressure.

CONTROLLED AIR INCINERATION.[5] Incineration utilizing two or more combustion chambers in which the amounts and distribution of air to each chamber are controlled. Partial combustion takes place in the first zone (chamber) and subsequent zones are used to complete combustion of the volatilization gases.

COOLDOWN PERIOD. The period of time at the end of an incinerator's operating cycle during which the incinerator is allowed to cool down. The cooldown period follows the burndown period.

CROSSFLOW.[4] Flow of scrubbing liquid normal (perpendicular) to the gas stream.

CYCLONE.[4] A device in which the velocity of an inlet gas stream is transformed into a confined vortex from which inertial forces tend to drive particles to the wall.

DAMPER.[2] An adjustable plate installed in a duct to regulate gas flow.

DEHUMIDIFY.[1] To remove water vapor from a gas stream.

DEMISTER.[4] A mechanical device used to remove entrained water droplets from a scrubbed gas stream.

DENSITY.[2] The ratio of the mass of an object to the volume of the object.

DIFFUSION (AEROSOL).[4] Random motion of particles caused by repeated collisions of gas molecules.

DRAFT.[1] A gas flow resulting from pressure difference; for example, the pressure difference between an incinerator and the atmosphere, which moves the products of combustion from the incinerator to the atmosphere. (1) Natural draft: the negative pressure created by the difference in density between the hot flue gases and the atmosphere. (2) Induced draft: the negative pressure created by the vacuum action of a fan or blower between the incinerator and the stack. (3) Forced draft: the positive pressure created by the fan or blower, which supplies the primary or secondary air.

DUST.[2] Solid particles less than 100 micrometers created by the breakdown of larger particles.

DUST LOADING.[2] The weight of solid particulate suspended in an airstream (gas). Usually expressed in terms of grains per cubic foot, grams per cubic meter, or pounds per thousand pounds of gas.

ENDOTHERMIC.[4] A chemical reaction that absorbs heat from its surroundings. For example: $C+H_2O+heat \rightarrow CO+H_2$

ENTRAINMENT.[3] The suspension of solids, liquid droplets, or mist in a gas stream.

EXOTHERMIC.[4] A chemical reaction that liberates heat to its surroundings. Combustion is an exothermic reaction. For example: $C+O_2 \rightarrow CO_2+heat$

FEEDBACK CONTROL.[3] An automatic control system in which information about the controlled parameter is fed back and used for control of another parameter.

FIXED CARBON.[4] The nonvolatile organic portion of waste.

GRID.[1] A stationary support or retainer for a bed of packing in a packed bed scrubber.

HEADER.[1] A pipe used to supply and distribute liquid to downstream outlets.

HEAT RELEASE RATE.[4] The energy released over a unit of time during combustion. Calculated as the heating value (Btu/pound)xburn rate (pound/hour). Usually expressed as Btu/hour (Btu/h).

HEATING VALUE.[4] The amount of heat that is released when a material is combusted usually expressed as Btu/lb.

HUMIDITY, ABSOLUTE.[2] The weight of water vapor carried by a unit weight of dry air or gas.

HUMIDITY, RELATIVE.[2] The ratio of the absolute humidity in a gas to the absolute humidity of a saturated gas at the same temperature.

INCINERATOR.[4] A thermal device which combusts organic compounds using heat and oxygen.

INDUCED DRAFT FAN.[3] A fan used to move a gas stream by creating a negative pressure.

INERTIA.[4] Tendency of a particle to remain in a fixed direction, proportional to mass and velocity.

LIQUID-TO-GAS RATIO.[3] The ratio of the liquid (in gallons per minute) to the inlet gas flow rate (in acfm).

LIQUOR.[1] A solution of dissolved substance in a liquid (as opposed to a slurry, in which the materials are insoluble).

MAKEUP WATER.[3] Water added to compensate for water losses resulting from evaporation and water disposal.

MIST ELIMINATOR.[3] Equipment that removes entrained water droplets downstream from a scrubber.

OPACITY.[4] Measure of the fraction of light attenuated by suspended particulate.

PACKED-BED SCRUBBER.[3] Equipment using small plastic or ceramic pieces, with high surface area to volume ratios for intimate gas/liquid contact for mass transfer.

PARTICLE.[4] Small discrete mass of solid or liquid matter.

PARTICLE SIZE.[4] An expression for the size of liquid or solid particle usually expressed in microns.

PARTICULATE EMISSION.[4] Fine solid matter suspended in combustion gases carried to the atmosphere. The emission rate is usually expressed as a concentration such as grains per dry standard cubic feet (gr/dscf) corrected to a common base, usually 12 percent CO_2.

PARTICULATE MATTER.[4] As related to control technology, any material except uncombined water that exists as a solid or liquid in the atmosphere or in a gas stream as measured by a standard (reference) method at specified conditions. The standard method of measurement and the specified conditions should be implied in or included with the particulate matter definition.

PATHOGENIC. Waste material capable of causing disease.

PATHOLOGICAL WASTE. Waste material consisting of anatomical parts.

PENETRATION.[4] Fraction of suspended particulate that passes through a collection device.

pH.[1] A measure of acidity-alkalinity of a solution.

PRESSURE DROP.[3] The difference in static pressure between two points due to energy losses in a gas stream.

PRESSURE, STATIC.[4] The pressure exerted in all directions by a fluid; measured in a direction normal (perpendicular) to the direction of flow.

PROXIMATE ANALYSIS.[4] The determination of the amounts of volatile matter, fixed carbon, moisture, and noncombustible (ash) matter in any given waste material.

PYROLYSIS. The chemical destruction of organic materials in the presence of heat and the absence of oxygen.

QUENCH.[1] Cooling of hot gases by rapid evaporation of water.

REAGENT.[3] The material used in a scrubbing system to react with the gaseous pollutants.

RED BAG WASTE. As used in this document, red bag waste refers to infectious waste; the name comes from the use of red plastic bags to contain the waste and to clearly identify that the waste should be handled as infectious.

RESIDENCE TIME. Amount of time the combustion gases are exposed to mixing, temperature, and excess air for final combustion.

SATURATED GAS.[1] A mixture of gas and vapor to which no additional vapor can be added, at specified conditions.

SIZE DISTRIBUTION.[4] Distribution of particles of different sizes within a matrix of aerosols; numbers of particles of specified sizes or size ranges, usually in micrometers.

SLURRY.[1] A mixture of liquid and finely divided insoluble solid materials.

SMOKE.[4] Small gasborne particles resulting from incomplete combustion; particles consist predominantly of carbon and other combustible material; present in sufficient quantity to be observable independently of other solids.

SPECIFIC GRAVITY.[1] The ratio between the density of a substance at a given temperature and the density of water at 4°C.

SPRAY NOZZLE.[1] A device used for the controlled introduction of scrubbing liquid at predetermined rates, distribution patterns, pressures, and droplet sizes.

STANDARD CUBIC FEET PER MINUTE (scfm).[3] A gas flow rate expressed with respect to standard temperature and pressure conditions.

STARVED-AIR INCINERATION. Controlled air incineration in which the primary chamber is maintained at less than stoichiometric air conditions.

STOICHIOMETRIC AIR. The theoretical amount of air required for complete combustion of waste to CO_2 and H_2O vapor.

STUFF AND BURN. A situation in which the charging rate is greater than burning rate of the incinerator.

VAPOR.[4] The gaseous form of substances that are normally in the solid or liquid state and whose states can be changed either by increasing the pressure or by decreasing the temperature.

VOLATILE MATTER. That portion of waste material which can be liberated with the application of heat only.

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16. ABSTRACT

The primary objective of this document is to identify the operation and maintenance (O&M) procedures that should be practiced on hospital medical waste incinerators and associated air pollution control equipment to minimize air emissions. Proper O&M, in addition to reducing air emissions, improves equipment reliability and performance, prolongs equipment life, and helps to ensure proper ash burnout. This document provides general guidance on proper O&M procedures with the intention of identifying good operating practices. The document is intended as a technical guide for use by Federal, State, and local agency personnel, hospital waste management personnel, and hospital incinerator operators.

The document presents background information on hospital medical waste incineration systems including a summary of combustion principles and descriptions of the types of incinerators typically used for hospital medical wastes. Background information on add-on air pollution control systems also is presented. Key operating parameters and good operating practices for the incineration and air pollution systems are identified and discussed. General guidance on maintenance of the systems also is provided. Common operating problems, their possible causes, and possible solutions to the problems are presented. Other topics discussed include control and monitoring instrumentation, recordkeeping procedures, and safety.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
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Sanford, North Carolina

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EMISSION TEST REPORT

VOLUME 1

Central Carolina Hospital
Sanford, North Carolina

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1. INTRODUCTION

Under Section 11008 of the Medical Waste Tracking Act of 1988 (MWTA), the United States Environmental Protection Agency (EPA) must prepare a series of reports to Congress that provide information concerning the characterization of medical wastes, treatment and disposal technologies, and an assessment of the impact of medical waste on human health and the environment. The MWTA specifically requires that incineration methods be evaluated to determine their advantages and disadvantages, including their ability to render a medical waste non-infectious or less infectious, and unrecognizable.

The Office of Solid Waste (OSW) is responsible for implementation of the MWTA and for managing the various studies that are required to prepare the report to Congress. One of the basic needs in the evaluation of incineration as a treatment technology is a characterization of emissions and ash from existing MWI's. These data are required to assess the actual potential impacts on health and the environment from existing sources that do not have advanced combustion controls or air pollution control devices.

Therefore, OSW and the Office of Air Quality Planning and Standards (OAQPS) are working jointly to perform additional studies at typical existing medical waste incinerator (MWI) facilities. The emission test program described in this report is one of the studies.

The MWI facility at Central Carolina Hospital in Sanford, North Carolina, was selected for emissions testing because it is typical of many existing units in which pathological wastes are burned with a secondary chamber gas retention time of 0.3 to 0.4 seconds, and with no add-on emission control equipment (see Figure 1-1). Other factors in the selection were that the proximity to Research Triangle Park (RTP), North Carolina minimized travel expenditures and because the hospital administration had expressed an interest in cooperating with the EPA in the emission test program.

1.1 TEST OBJECTIVES

The objectives of the testing program at the Central Carolina Hospital MWI were:

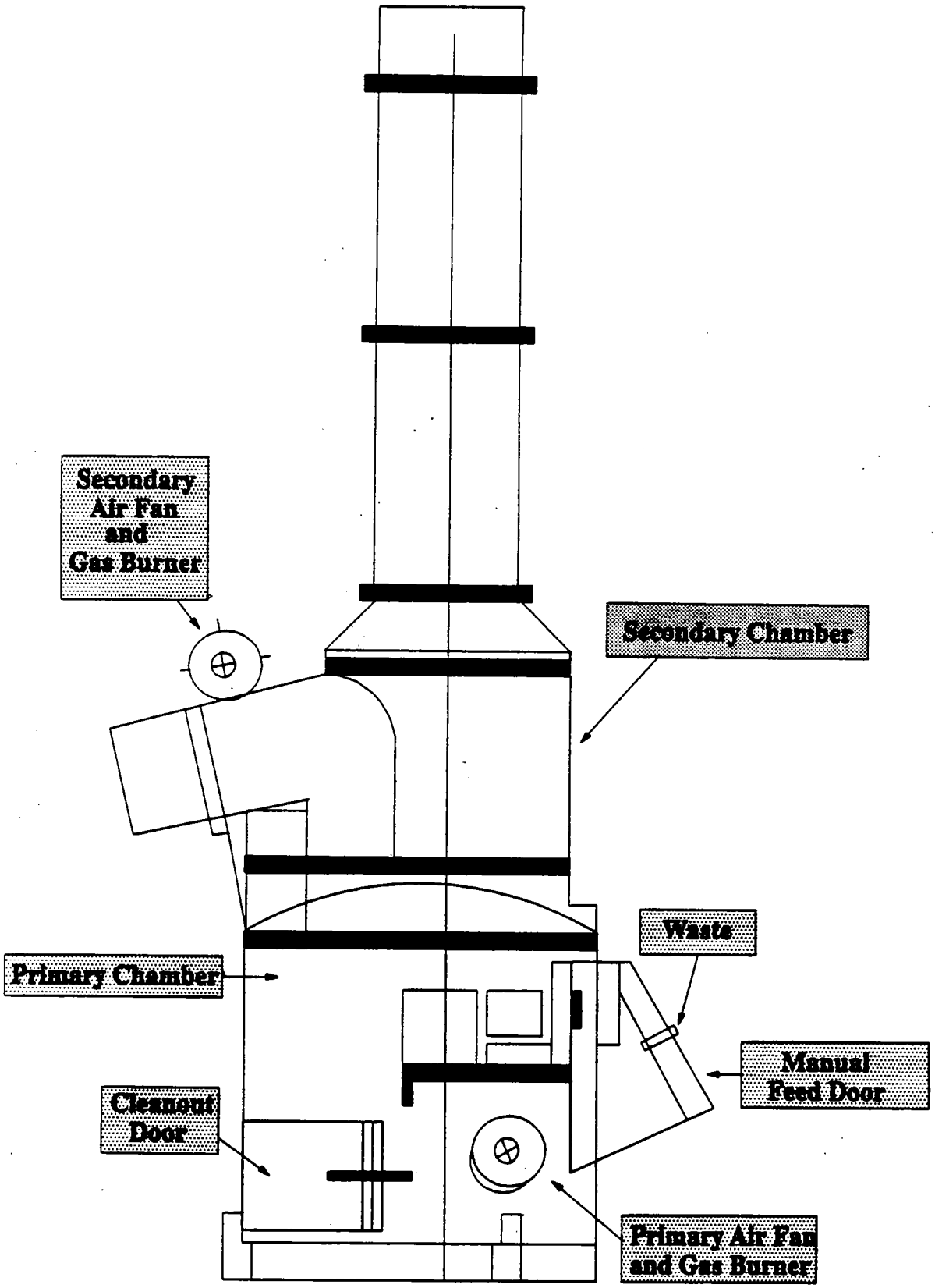

Figure 1-1. AMI Central Carolina Hospital Incinerator

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- To obtain emission data from a facility that is not equipped with air pollution control devices and is typical of the existing population of medical waste incinerators.

- To collect data and evaluate the impact of incinerator operation variations on the emissions and ash as a factor in the overall effectiveness of incineration as a treatment method.

The measurements that were performed at this facility provided data to:

- Determine the mass emission rates of particulate matter (PM), selected metals, carbon monoxide (CO), total hydrocarbons (THC), sulfur dioxide (SO_2), nitrogen oxides (NO_x), hydrogen chloride (HCl), and polychlorinated dibenzo-p-dioxins (CDD) and polychlorinated dibenzofurans (CDF).

- Determine, if possible, the microorganism destruction efficiencies based on a surrogate indicator organism that is spiked into the incinerator feed during each test run.

- Determine the degree of combustion (burnout) of the wastes based on residual carbon, or loss on ignition (LOI), of the bottom ash that is collected for each test day.

- Determine the relationship, if any, between visible emissions and other emissions, such as PM.

The measurements described above were repeated at three operating conditions while the incinerator was burning hospital wastes (including red bag waste) to evaluate the effect of waste feed rate, charging frequency, and secondary chamber temperature on the emissions. These conditions were:

- Condition 1 - 100 percent pathological wastes at a charge rate of 100 pounds per hour (lb/hr) with a 15 minute charge cycle (25 lb/charge) and a secondary chamber temperature setpoint between 1800°F and 1900°F.

- Condition 2 - A mix of pathological and red bag waste typically burned at this facility (between 5 and 10 percent pathological waste) at a charge rate of 250 lb/hr (manufacturer's rating) with a 15 minute charge cycle and a 1600°F secondary chamber temperature setpoint.

- Condition 3 - 100 percent pathological wastes at a charge rate of 160 lb/hr with a 15 minute charge cycle (40 lb/charge) and a 1600°F secondary chamber temperature setpoint.

(These conditions were revised from those listed in the final test plan.)

Key process operating variables including flue gas oxygen (O_2), carbon dioxide (CO_2), primary and secondary chamber temperatures, and the amount and frequency of waste charging were monitored and recorded to document the operating conditions during each test.

The test program included an internal quality control program. The goal of the quality assurance/quality control (QA/QC) activities was to ensure that the results are of known precision and accuracy, and that they are complete, representative and comparable.

1.2 BRIEF SITE DESCRIPTION

AMI Central Carolina Hospital is located in Sanford, North Carolina. The MWI at this facility is a Consumat Model C-75P. It has a rated capacity of 175 lb/hr of Type IV (pathological) waste. A plan view of the facility is shown in Figure 1-1. Two natural gas-fired auxiliary burners in the primary chamber are used to maintain a preset minimum combustion temperature. Primary chamber temperatures normally vary between 1200°F and 1600°F. The unit is charged manually by operating a large refractory-lined charging door that opens at the front of the primary chamber. It is designed for 8 to 12 hours of operation each day, and ashes must be removed manually after cooldown.

The secondary chamber on this unit is sized for a design gas retention time of about 0.3 to 0.4 seconds. A gas-fired auxiliary burner in the secondary chamber is activated automatically when the temperature falls below a preset level, normally 1600°F. Setpoint and actual temperatures in each chamber are displayed on a dial in the control panel. There is no add-on air pollution control device on this MWI. The stack is about 16 to 18 feet high and has no sampling ports. The unit is located outside, at the rear of the hospital.

There is a full time operator for the AMI Central Carolina Hospital MWI. The typical hours of operation are from 7:00 a.m. to 3:00 p.m. A burn down period of

5 hours on gas-firing is timed by the control panel. The gas is then extinguished and the incinerator is allowed to cool. The ash is typically removed from the incinerator from 7:00 a.m. to 8:00 a.m., and stored in 30 gallon metal cans. Two to five cans are filled each day.

Waste materials are collected by the hospital housekeeping staff. Waste is collected from all patient contact areas, including patient rooms, examination rooms, operating and recovery rooms, and laboratories. Included in the waste stream are waste drugs and chemicals; patient contact items such as disposable garments, dressings, disposable surgical tools and sharps and diagnostic devices; and human and animal tissue. Pathological waste is generally from 5 to 10 percent of the total waste weight.

Non-red bag wastes are collected by the housekeeping staff and placed in standard 30 gallon plastic trash bags, which are twist tied. The bags are transported via plastic bin type carts from the collection area to the incinerator area. Red bag wastes bags can be and are mixed with the other bags. The hospital incinerator operator hand feeds the bags through the incinerator feed door.

The combustion process utilized to incinerate wastes in this type of incinerator is known as controlled or "starved" air incineration. The unit is designed with two separate chambers (a primary chamber and a secondary chamber) in which controlled amounts of combustion air and combustible material are admitted. The lower chamber, known as the primary air ignition chamber, is operated at below stoichiometric or air starved conditions when operating on mixed medical waste (dry mode). Excess air conditions exist when the unit is operated on pathological waste (wet mode). A gas-fired pilot burner is used to drive moisture and volatiles from the wastes, and initiate the ignition of the fixed carbon portion of the waste material. Limited amounts of underfire air are admitted through ports in the lower chamber so that combustion of the fixed carbon matter can be sustained. Heat input from the gas burner is modulated to keep the lower chamber temperature within a certain range and to maintain the oxidation of fixed carbon at varying levels of waste moisture only when burning pathological waste (wet mode).

The volatile matter is vaporized in the lower chamber and passes into the secondary combustion chamber. A second gas-fired burner is used to ignite the

combustible gases and maintain secondary chamber temperatures within a specified temperature range. In the secondary chamber, excess air is supplied to achieve more complete combustion of the volatile matter and entrained solids by providing an adequate oxygen supply and turbulent mixing.

Detailed descriptions of the MWI facility, its operation, the waste and waste handling procedures are given in Section 3.

1.3 EMISSIONS MEASUREMENT PROGRAM

This section provides an overview of the emissions measurement program conducted at Central Carolina Hospital. Included in this section are summaries of the test matrix, sampling locations, sampling methods, and laboratory analysis. Greater detail on these topics is provided in the sections that follow.

1.3.1 Test Matrix

The sampling and analytical matrix for this test program is presented in Table 1-1. Sampling locations are shown in Figure 1-2. Both manual emissions tests and continuous emission monitors (CEM) were employed for the Central Carolina Hospital MWI test program. In addition to flue gas sampling, incinerator bottom ash and ash quality pipe samples were also taken. Each of the tests are briefly described in Sections 1.3.3 and 1.3.4.

1.3.2 Sampling Locations

The stack gas sampling was conducted at a series of three sets of double ports in the stack wall. The double ports were located 90° from each other. The top-most ports were used for microbial survivability emission tests. The middle set of ports was used for PM/metals tests as well as CDD/CDF tests. The bottom set of ports was used for halogen emission tests and for the CEM probes. Incinerator ash was sampled every day. Ash was completely removed from the incinerator every day, screened through 1/2" mesh, and placed in the bulk ash containers where it was sampled to obtain a representative sample.

1.3.3 Sampling Methods

Total PM emissions along with a series of 11 toxic metals [lead (Pb), chromium (Cr), cadmium (Cd), mercury (Hg), nickel (Ni), arsenic (As), beryllium (Be), antimony

TABLE 1-1. AMI CENTRAL CAROLINA HOSPITAL MWI TEST MATRIX

Sample Location	Number of Runs	Sample Type	Sample Method	Sample Duration	Analysis Method	Laboratory
Stack	9	Particulates/Metals (Pb, Cr, Cd, Be, Hg, Ni, As, Sb, Ag, Ba, Tl)	EPA Method 5/Combined Metals Train	4 hours	Gravimetric Atomic Adsorption/ICAP	Radian
Stack	9	CDD/CDF	EPA Method 23 and GC/MS Method 8290	4 hours	Mass Spectrometry and High Resolution MS for CDD/CDF	Triangle Labs, Inc.
Stack	25[a]	HCl/HBr/HF	EPA Method 26	1 hour[a]	Ion Chromatography	Radian
Stack	18[b]	Indicator Spores	Draft EPA Method	2 hours[b]	Microbial Draft Method	RTI
Stack	9[c]	SO_2	EPA Method 6C	Continuous[c]	UV Analyzer CEM	Radian
Stack	9[c]	O_2 /CO_2	EPA Method 3A	Continuous[c]	Zirconium Oxide Cell/ NDIR CEM	Radian
Stack	9[c]	NO_x	EPA Method 7E	Continuous[c]	Chemiluminescence CEM	Radian
Stack	9[c]	CO	EPA Method 10	Continuous[c]	NDIR CEM	Radian
Stack	9[c]	THC	EPA Method 25A	Continuous[c]	FID CEM	Radian
Stack	9[c]	HCl	CEM	Continuous[c]	NDIR CEM	Radian
Stack	9[d]	Opacity	EPA Method 9	4 hour[d]	Visual	Radian
Incinerator	9	Incinerator Ash	Representative Composite Sample	1 day	LOI, Carbon, Metals	Radian
	9		Representative Composite Sample	1 day	Dioxins	Triangle Labs, Inc.
	9		Representative Composite Sample	1 day	Microbial Draft Method	RTI
Incinerator	54	Indicator Spore Pipes	Manual	1 day	Microbial Draft Method	RTI

[a]3 one-hour runs per test day (2 runs out of 27 planned were not completed).
[b]2 one-hour 45 minute runs per test day.
[c]Continuous during test periods.
[d]Four-hour run concurrent with particulate/metals run.

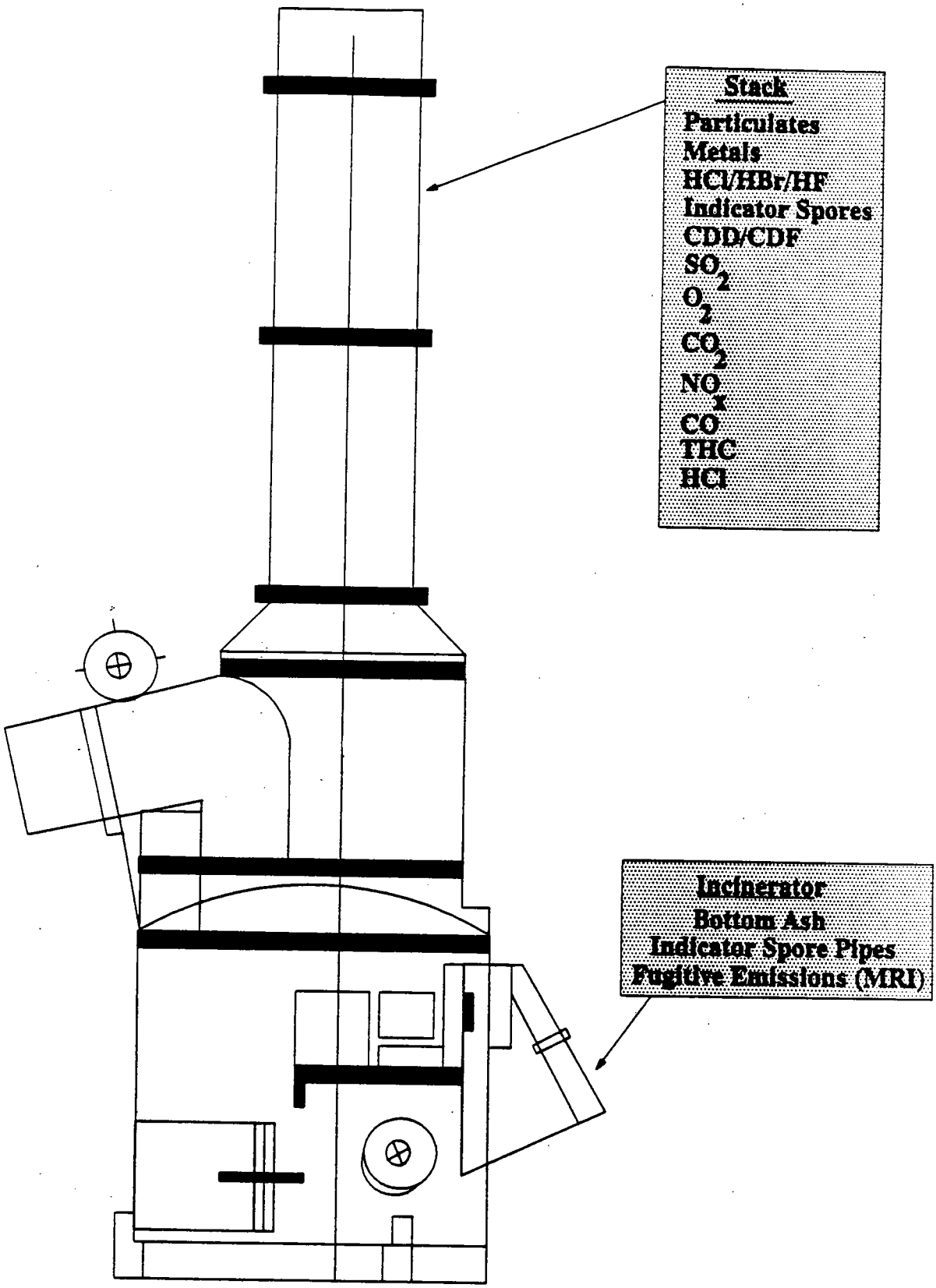

Figure 1-2. Sampling Locations at the AMI Central Carolina Hospital MWI

(Sb), barium (Ba), silver (Ag), and thallium (Tl)], were determined using a single sample train. Particulate loading on the filter and front half (nozzle/probe, filter holder) rinse was determined gravimetrically. Metals analyses were then completed on the filter front half rinses and back half impinger catches using atomic absorption (AA) and inductively coupled argon plasma (ICAP) techniques. Flue gas samples for CDD/CDF were collected using EPA Method 23. Flue gas was extracted isokinetically and CDD/CDF was collected on the filter, on a chilled adsorbent trap, and in the impingers. The analysis was completed using High Resolution Gas Chromatography (HRCG) coupled with High Resolution Mass Spectrometry (HRMS) detection.

Hydrogen chloride, hydrogen bromide (HBr), and hydrogen fluoride (HF) concentrations in the stack gas were determined using EPA Method 26. Gas was extracted from the stack and passed through a acidified collection solution which stabilized the respective halogen ions (Cl^-, Br^-, F^-). The quantity of ions collected was then determined using ion chromatography (IC) analyses.

Three types of microbial survivability tests were completed on the incinerator. These tests were intended to evaluate the effectiveness of the MWI in destroying indicator organisms in the waste. This was achieved by direct ash sampling and by spiking the incinerator with surrogate indicator spores encased in insulated double-pipe containers. Indicator spore spikes were loaded onto material commonly found in the medical waste stream and then charged into the incinerator to determine the ability of the indicator organisms to survive in the combustion gases and the incinerator bottom ash. Flue gas testing for spore emissions was conducted simultaneously with the other emissions testing. The next day following the daily burn cycle, ash samples and pipe samples were recovered and subsequently analyzed for spore viability. Direct ash sampling and pipe sampling was conducted daily when the ash was removed manually from the incinerator. Flue gas samples were collected isokinetically and passed through a circulating phosphate buffer solution. Following the test, the buffer solution samples were analyzed for viable spores using culturing, identification, and quantification techniques outlined in the EPA draft method "Microbial Survivability Test for Medical Waste Incinerator Emissions." Ash samples and pipe samples were analyzed as outlined

in the EPA draft method "Microbial Survivability Test for Medical Waste Incinerator Ash."

Visual opacity measurements were also taken continuously during the particulate test periods. A certified observer documented incinerator stack gas opacity by following EPA Method 9 protocol.

Gaseous emissions (NO_x, CO, SO_2, THC, and HCl) were measured using CEMs continuously during the day. The diluent gases (O_2, CO_2) were measured using CEMs at all times when tests were being performed so that the emission results could be normalized to a reference O_2 or CO_2 basis. The O_2 and CO_2 results were also used for flue gas molecular weight calculations for stack gas flow rate calculations.

Ash was sampled manually and mixed to provide a representative composite sample. Samples were taken for analysis as follows: LOI, carbon, toxic metals, dioxins, and microbial analysis. An archive sample was also saved for each test condition. Indicator spore pipes were charged at regular intervals into the incinerator and recovered manually for microbial analysis. Detailed descriptions of the sampling and analytical procedures are provided in Section 5.

1.3.4 Laboratory Analyses

All manual flue gas tests were sent out for extensive laboratory analyses. Samples from CDD/CDF emission tests were analyzed for tetra-octa CDD/CDF isomers by Triangle Laboratories, Inc (Triangle). Ash samples were also analyzed by Triangle for these analytes. Analytical procedures followed EPA Method 23 protocols (Analytical Method 8290X). This technique incorporates High Resolution Gas Chromatography/High Resolution Mass Spectrometry (HRGC/HRMS) analytical procedures.

Samples from particulate matter/metals emission tests were analyzed by Radian's Perimeter Park (PPK) laboratory. Analytical procedures were completed using Inductively Coupled Argon Plasma Spectroscopy (ICAPS), Graphite Furnace Atomic Absorption Spectroscopy (GFAAS), and Cold Vapor Atomic Absorption Spectroscopy (CVAAS). Incinerator ash was also analyzed for metals content using these techniques. Particulate matter was analyzed using gravimetric techniques following EPA Method 5 guidelines. Samples from halogen emission tests were analyzed by Radian's PPK

laboratory. Quantities of chloride, bromide, and fluoride ions in the impinger solutions were determined using IC techniques.

Microbial survivability samples from the emissions tests and the ash and pipe tests were analyzed for viable spores of Bacillus stearothermophilus (B. stearothermophilus) by Research Triangle Institute (RTI). Impinger samples (emissions), ash, and pipe samples were cultured and enumerated using analytical techniques recently developed specific for this test method. This protocol is given in the EPA draft methods "Microbial Survivability Test for Medical Waste Incinerator Emissions" and "Microbial Survivability Test for Medical Waste Incinerator Ash.

The incinerator ash was analyzed by McCoy Labs for volatile matter (LOI) by Standard Methods of Water and Wastes, Method 209G, and for carbon content by ASTM Method D 3178-84.

1.4 QUALITY ASSURANCE/QUALITY CONTROL (QA/QC)

All flue gas testing procedures followed comprehensive QA/QC procedures as outlined in the Central Carolina MWI test plan and EPA reference methods. A full description of the resulting QA parameters is given in Section 6.

All post-test leak check criteria were met for all four manual sampling trains. The allowable isokinetic QC range of ±10 percent of 100 percent was met for all CDD/CDF, PM/Metals and Microbial emissions test runs. All post-test dry gas meter calibration checks were within 5 percent of the full calibration factor. Field blanks (FB) results showed no contamination in the CDD/CDF MM5; sample however, the toluene FB had relatively high concentrations. The halogen FB showed virtually no contamination; however, the PM/metals FB had high levels of arsenic, chromium, and nickel. Also the front half analysis for metals Run 10 has not been completed at this time. Final toluene rinses of the CDD/CDF samples collected only a small portion of the total MM5 catch.

From an analytical QA perspective, all analyses were completed under a strict QA/QC regimen. The CDD/CDF MM5 analytical protocol was varied to accommodate the expected high organic loading of the Runs 2, 4, and 8 (Condition 2) MM5 samples.

The manual flue gas test data reflected variation from run to run as indicated by the coefficient of variation (CV) analyses. Overall pooled CVs ranged from 64.4 percent for CDD/CDF flue gas concentrations to 65.0 percent for metals flue gas concentrations. The overall pooled CV for the CEM data was 159 percent. These values reflect a strong variability in process operation.

1.5 DESCRIPTION OF REPORT CONTENTS

Section 1 of this report provides an introduction to the medical waste testing program conducted at Central Carolina Hospital in Sanford, North Carolina. This section includes the test objective, a brief site description, an overview of the emissions measurement program, a brief overview of the QA/QC program, and this description of the report contents.

Section 2 gives a summary of the test results. Included in the contents of this section are the emissions test log, CDD/CDF results, toxic metals results, PM/visible emissions results, halogen results, CEM results, ash LOI and carbon results, and microbial survivability results.

Section 3 details the process and operation of the Central Carolina incinerator and gives process results. Included in the process results are the waste feed rates and incineration chamber temperatures.

Section 4 provides a detailed description and drawings of the sample locations.

Section 5 presents detailed descriptions of sampling and analytical procedures. The descriptions that are covered in this section are the CDD/CDF testing method, the PM and toxic metals testing method, microbial survivability testing methods, the manual halogen emissions testing method, EPA Methods 1 through 4, CEM methods, the visible emissions method, particle size distribution tests, and process sampling procedures.

Section 6 provides details of the QA/QC procedures used on this program and the QC results. Included in this section is a summary of QA/QC objectives, QC procedures for the manual flue gas sampling methods, QC procedures for the ash and

pipe (microbial) sampling, analytical QC procedures and QA parameters, and CEM QC procedure and QA parameters.

Appendices containing the actual field data sheets and computer data listings are contained in a separate volume.

2. SUMMARY OF RESULTS

This section provides results of the emissions test program conducted at the Central Carolina Hospital MWI from September 20 to October 2, 1990. Included in this section are results of manual tests conducted for CDD/CDF, toxic metals, PM, visible emissions, halogens, and microbial survivability. This section also contains the results of continuous emissions monitoring for O_2, CO_2, CO, NO_x, SO_2, THC, and HCl gases as well as particle size distribution (PSD) results.

2.1 EMISSIONS TEST LOG

Ten tests were conducted over a 13 day period. A probe liner for the CDD/CDF sampling train broke during Run 7 and the entire run was invalidated and repeated (samples from other sampling trains for Run 7 were not analyzed). Table 2-1 presents the emissions test log. This table shows the test date, run number, test type, run times and port change times for all the stack testing conducted during this program.

2.2 CDD/CDF RESULTS

2.2.1 Overview

Nine 4-hour CDD/CDF emission test runs were completed at Central Carolina Hospital during the September 1990 test program. Three runs were completed under each of three test conditions. Testing protocol followed EPA Method 23 which requires a final sample recovery rinse with toluene to be analyzed separately from the rest of the sample. Because this data was not incorporated into the final emission results, it will be presented with the sampling QA parameters in Section 6.2.1.

As well as flue gas samples, daily ash samples were also taken. Each ash sample was also analyzed for tetra through octa CDD/CDF isomers.

The following sections report CDD/CDF emissions test results in Section 2.2.2 and incinerator ash CDD/CDF concentrations in Section 2.2.3.

2.2.2 CDD/CDF Emission Results

Tables 2-2 through 2-5 present the average emission parameters for each of the three test conditions. Data from each individual test run are presented in Tables 2-6 through 2-12. Emission tests analyses were targeted for the tetra through octa 2378

TABLE 2-1. EMISSIONS TEST LOG;
CENTRAL CAROLINA HOSPITAL (1990)

DATE	LOCATION	RUN NUMBER	OPERATING CONDITION[a]	TEST TYPE	RUN TIME	PORT CHANGES
9/20/90	Stack	1	1	Toxic Metals	14:00–18:18	16:10–16:18
9/20/90	Stack	1	1	CDD/CDF	14:00–18:18	16:10–16:18
9/20/90	Stack	1A	1	HCl	14:09–15:09	
9/20/90	Stack	1B	1	HCl	15:21–16:21	
9/20/90	Stack	1C	1	HCl	16:35–17:35	
9/20/90	Stack	1A	1	Spore	13:58–15:58	
9/20/90	Stack	1B	1	Spore	15:58–17:58	
9/21/90	Stack	2	2	Toxic Metals	09:46–13:57	11:47–11:58
9/21/90	Stack	2	2	CDD/CDF	09:45–13:57	11:45–11:57
9/21/90	Stack	2A	2	HCl	09:53–11:43	
9/21/90	Stack	2B	2	HCl	12:23–14:36	
9/21/90	Stack	2A	2	Spore	09:43–11:28	
9/21/90	Stack	2B	2	Spore	11:28–13:43	
9/22/90	Stack	3	1	Toxic Metals	09:47–14:00	11:47–12:00
9/22/90	Stack	3	1	CDD/CDF	09:45–14:00	11:45–12:00
9/22/90	Stack	3A	1	HCl	09:53–11:53	
9/22/90	Stack	3B	1	HCl	12:22–13:22	
9/22/90	Stack	3C	1	HCl	13:35–14:35	
9/22/90	Stack	3A	1	Spore	09:43–11:43	
9/22/90	Stack	3B	1	Spore	11:43–13:43	
9/23/90	Stack	4	2	Toxic Metals	11:40–15:47	13:40–13:47
9/23/90	Stack	4	2	CDD/CDF	11:40–15:47	13:40–13:47
9/23/90	Stack	4A	2	HCl	11:42–12:42	
9/23/90	Stack	4B	2	HCl	12:52–13:52	
9/23/90	Stack	4C	2	HCl	14:03–15:03	
9/23/90	Stack	4A	2	Spore	11:38–13:40	
9/23/90	Stack	4B	2	Spore	13:40–15:40	
9/24/90	Stack	5	3	Toxic Metals	11:45–15:52	13:45–13:52
9/24/90	Stack	5	3	CDD/CDF	11:45–15:52	13:45–13:52
9/24/90	Stack	5A	3	HCl	11:54–12:54	
9/24/90	Stack	5B	3	HCl	13:17–14:17	
9/24/90	Stack	5C	3	HCl	14:29–15:29	
9/24/90	Stack	5A	3	Spore	11:44–13:44	
9/24/90	Stack	5B	3	Spore	13:44–15:44	

a Condition 1: 100 percent pathological wastes (100 lb/hr, 15 min. cycle, 1800–1900°F)
Condition 2: Pathological/red bag waste mix (250 lb/hr, 15 min. cycle, 1600°F)
Condition 3: 100 percent pathological wastes (160 lb/hr, 15 min. cycle, 1600°F)

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TABLE 2-1. EMISSIONS TEST LOG (continued);
CENTRAL CAROLINA HOSPITAL (1990)

DATE	LOCATION	RUN NUMBER	OPERATING CONDITION[a]	TEST TYPE	RUN TIME	PORT CHANGES
9/25/90	Stack	6	3	Toxic Metals	10:10-14:15	12:10-12:15
9/25/90	Stack	6	3	CDD/CDF	10:10-14:15	12:10-12:15
9/25/90	Stack	6A	3	HCl	10:22-11:22	
9/25/90	Stack	6B	3	HCl	11:33-12:33	
9/25/90	Stack	6C	3	HCl	12:41-13:41	
9/25/90	Stack	6A	3	Spore	10:08-12:08	
9/25/90	Stack	6B	3	Spore	12:08-14:08	
9/26/90	Stack	7 b	1	Toxic Metals	10:00-14:06	12:00-12:06
9/26/90	Stack	7 b	1	CDD/CDF	10:00-14:06	12:00-12:06
9/26/90	Stack	7A b	1	HCl	10:06-11:06	
9/26/90	Stack	7B b	1	HCl	11:17-12:17	
9/26/90	Stack	7C b	1	HCl	12:27-13:27	
9/26/90	Stack	7A b	1	Spore	09:58-11:58	
9/26/90	Stack	7B b	1	Spore	11:58-13:58	
9/27/90	Stack	8	2	Toxic Metals	13:45-17:50	15:45-15:50
9/27/90	Stack	8	2	CDD/CDF	13:45-17:50	15:45-15:50
9/27/90	Stack	8A	2	HCl	13:51-14:51	
9/27/90	Stack	8B	2	HCl	15:01-16:01	
9/27/90	Stack	8C	2	HCl	16:12-17:12	
9/27/90	Stack	8A	2	Spore	13:43-15:44	
9/27/90	Stack	8B	2	Spore	15:44-17:56	
9/28/90	Stack	9	3	Toxic Metals	11:00-15:05	13:00-13:05
9/28/90	Stack	9	3	CDD/CDF	11:00-15:05	13:00-13:05
9/28/90	Stack	9A	3	HCl	11:11-12:11	
9/28/90	Stack	9B	3	HCl	12:22-13:22	
9/28/90	Stack	9C	3	HCl	13:32-14:32	
9/28/90	Stack	9A	3	Spore	10:58-12:58	
9/28/90	Stack	9B	3	Spore	12:58-14:58	
10/02/9	Stack	10	1	Toxic Metals	10:15-14:21	12:15-12:21
10/02/9	Stack	10	1	CDD/CDF	10:15-14:21	12:15-12:21
10/02/9	Stack	10A	1	HCl	10:26-11:26	
10/02/9	Stack	10B	1	HCl	11:38-12:38	
10/02/9	Stack	10C	1	HCl	12:47-13:47	
10/02/9	Stack	10A	1	Spore	10:13-12:13	
10/02/9	Stack	10B	1	Spore	12:13-14:13	

a Condition 1: 100 percent pathological wastes (100 lb/hr, 15 min. cycle, 1800-1900°F)
Condition 2: Pathological/red bag waste mix (250 lb/hr, 15 min. cycle, 1600°F)
Condition 3: 100 percent pathological wastes (160 lb/hr, 15 min. cycle, 1600°F)

b Run 7 data were invalidated due to an incomplete data set (CDD/CDF sampling probe broke during run)

TABLE 2-2. AVERAGE CDD/CDF STACK GAS CONCENTRATIONS FOR EACH TEST CONDITION; CENTRAL CAROLINA HOSPITAL (1990)

CONGENER	CONCENTRATION a (ng/dscm, as measured)		
	CONDITION 1	CONDITION 2	CONDITION 3
DIOXINS			
2378 TCDD	0.26	11.7	0.38
Other TCDD	22.5	242	23.9
12378 PCDD	0.85	47.01	0.94
Other PCDD	19.1	311	18.2
123478 HxCDD	0.80	45.5	0.58
123678 HxCDD	1.35	53.4	0.89
123789 HxCDD	2.49	98.6	1.58
Other HxCDD	16.6	410	10.8
1234678-HpCDD	8.27	249	4.75
Other HpCDD	9.89	270	5.51
Octa-CDD	10.4	259	6.21
Total CDD	92.5	2,000	73.8
FURANS			
2378 TCDF	1.43	32.2	1.75
Other TCDF	73.6	934	67.2
12378 PCDF	2.14	149	2.03
23478 PCDF	5.27	184	3.28
Other PCDF	58.7	2367	38.1
123478 HxCDF	8.44	474	4.26
123678 HxCDF	3.74	294	2.21
234678 HxCDF	7.33	233	3.03
123789 HxCDF	0.24	18.4	0.15
Other HxCDF	25.0	1614	13.5
1234678-HpCDF	13.4	681	6.71
1234789-HpCDF	2.23	86.9	0.94
Other HpCDF	12.0	500	5.15
Octa-CDF	14.6	285	5.82
Total CDF	228	7,850	154
Total CDD+CDF	321	9,850	228

a dscm = dry standard cubic meter. Standard conditions are defined as 1 atm and 68°F.

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TABLE 2-3. CDD/CDF STACK GAS CONCENTRATIONS ADJUSTED TO 7% OXYGEN FOR EACH TEST CONDITION; CENTRAL CAROLINA HOSPITAL (1990)

CONGENER	CONCENTRATION (ng/dscm, adjusted to 7 percent O2)		
	CONDITION 1	CONDITION 2	CONDITION 3
DIOXINS			
2378 TCDD	0.72	29.35	0.97
Other TCDD	64.6	613	60.3
12378 PCDD	2.41	118	2.37
Other PCDD	54.6	782	46.0
123478 HxCDD	2.27	115	1.46
123678 HxCDD	3.83	135	2.25
123789 HxCDD	7.07	248	4.01
Other HxCDD	47.4	1034	27.4
1234678-HpCDD	23.3	631	12.1
Other HpCDD	27.9	683	14.0
Octa-CDD	29.4	661	15.8
Total CDD	264	5,050	187
FURANS			
2378 TCDF	4.06	80.1	4.40
Other TCDF	210	2324	169
12378 PCDF	6.06	373	5.13
23478 PCDF	14.9	461	8.29
Other PCDF	167	5906	96.0
123478 HxCDF	24.0	1189	10.8
123678 HxCDF	10.6	736	5.61
234678 HxCDF	20.9	585	7.70
123789 HxCDF	0.67	46.1	0.38
Other HxCDF	71.0	4045	34.2
1234678-HpCDF	38.2	1716	17.1
1234789-HpCDF	6.32	219	2.41
Other HpCDF	34.2	1262	13.1
Octa-CDF	41.5	728	14.9
Total CDF	650	19,700	389
Total CDD+CDF	914	24,700	576

a dscm = dry standard cubic meter. Standard conditions are defined as 1 atm and 68°F.

TABLE 2-4. AVERAGE CDD/CDF STACK GAS EMISSIONS FOR EACH TEST CONDITION; CENTRAL CAROLINA HOSPITAL (1990)

CONGENER	EMISSIONS (ug/hr)		
	CONDITION 1	CONDITION 2	CONDITION 3
DIOXINS			
2378 TCDD	0.41	18.6	0.64
Other TCDD	36.7	387	39.7
12378 PCDD	1.38	75.6	1.56
Other PCDD	31.1	499	30.3
123478 HxCDD	1.30	73.3	0.96
123678 HxCDD	2.20	85.9	1.48
123789 HxCDD	4.05	159	2.63
Other HxCDD	27.1	658	18.0
1234678-HpCDD	13.4	402	7.90
Other HpCDD	16.1	435	9.18
Octa-CDD	16.9	416	10.3
Total CDD	151	3,210	123
FURANS			
2378 TCDF	2.32	51.2	2.91
Other TCDF	120	1481	112
12378 PCDF	3.48	240	3.38
23478 PCDF	8.56	296	5.45
Other PCDF	95.5	3,799	63.44
123478 HxCDF	13.7	764	7.09
123678 HxCDF	6.08	473	3.69
234678 HxCDF	11.9	374	5.05
123789 HxCDF	0.39	29.6	0.25
Other HxCDF	40.6	2,598	22.5
1234678-HpCDF	21.8	1,097	11.2
1234789-HpCDF	3.63	140	1.57
Other HpCDF	19.6	805	8.57
Octa-CDF	23.8	457	9.71
Total CDF	371	12,600	256
Total CDD+CDF	522	15,800	379

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TABLE 2-5. AVERAGE CDD/CDF 2378 TOXIC EQUIVELENT STACK GAS CONCENTRATIONS ADJUSTED TO 7 PERCENT O2 FOR EACH TEST CONDITION; CENTRAL CAROLINA HOSPITAL (1990)

CONGENER	2378-TCDD a TOXIC EQUIV. FACTOR	2378 TOXIC EQUIVALENCIES (ng/dscm, @ 7 percent O2) b		
		CONDITION 1	CONDITION 2	CONDITION 3
DIOXINS				
2378 TCDD	1.000	0.719	29.348	0.967
Other TCDD	0.000	0.000	0.000	0.000
12378 PCDD	0.500	1.203	59.161	1.183
Other PCDD	0.000	0.000	0.000	0.000
123478 HxCDD	0.100	0.227	11.505	0.146
123678 HxCDD	0.100	0.383	13.457	0.225
123789 HxCDD	0.100	0.707	24.807	0.401
Other HxCDD	0.000	0.000	0.000	0.000
1234678-HpCDD	0.010	0.233	6.310	0.121
Other HpCDD	0.000	0.000	0.000	0.000
Octa-CDD	0.001	0.029	0.661	0.016
Total CDD		3.50	145	3.06
FURANS				
2378 TCDF	0.100	0.406	8.014	0.440
Other TCDF	0.000	0.000	0.000	0.000
12378 PCDF	0.050	0.303	18.642	0.257
23478 PCDF	0.500	7.471	230.514	4.143
Other PCDF	0.000	0.000	0.000	0.000
123478 HxCDF	0.100	2.405	118.859	1.081
123678 HxCDF	0.100	1.063	73.562	0.561
234678 HxCDF	0.100	2.089	58.528	0.770
123789 HxCDF	0.100	0.067	4.612	0.038
Other HxCDF	0.000	0.000	0.000	0.000
1234678-HpCDF	0.010	0.382	17.155	0.171
1234789-HpCDF	0.010	0.063	2.195	0.024
Other HpCDF	0.000	0.000	0.000	0.000
Octa-CDF	0.001	0.041	0.728	0.015
Total CDF		14.3	533	7.50
Total CDD+CDF		17.8	678	10.6

a North Atlantic Treaty Organization, Committee on the Challenges of Modern Society. Pilot Study on International Information Exchange on Dioxins and Related Compounds: International Toxicity Equivalency Factor (I-TEF) Methods of Risk Assessment for Complex Mixtures of Dioxins and Related Compounds. Report No.176, August 1988.

b ng/dscm = nanogram per dry standard cubic meter. Standard conditions defined as 1 atm. and 68øF.

TABLE 2-6. CDD/CDF STACK GAS CONCENTRATIONS AND EMISSIONS RATES AT CONDITION 1; CENTRAL CAROLINA HOSPITAL (1990)

	CONCENTRATION a (ng/dscm, as measured)				EMISSIONS (ug/hr)			
CONGENER	RUN 1	RUN 3	RUN 10	AVERAGE	RUN 1	RUN 3	RUN 10	AVERAGE
DIOXINS								
2378 TCDD	0.22	(0.419)	(0.130)	0.26	0.34	(0.688)	(0.208)	0.41
Other TCDD	6.17	54.5	6.77	22.5	9.73	89.5	10.8	36.7
12378 PCDD	0.52	1.61	0.42	0.85	0.82	2.64	0.68	1.38
Other PCDD	5.45	44.9	6.84	19.1	8.61	73.7	11.0	31.1
123478 HxCDD	0.34	1.57	0.49	0.80	0.53	2.58	0.79	1.30
123678 HxCDD	0.52	2.55	0.99	1.35	0.82	4.19	1.58	2.20
123789 HxCDD	1.10	4.89	1.48	2.49	1.74	8.03	2.37	4.05
Other HxCDD	5.12	35.4	9.45	16.6	8.07	58.1	15.1	27.1
1234678-HpCDD	2.93	14.6	7.30	8.27	4.63	23.9	11.7	13.4
Other HpCDD	3.52	17.9	8.21	9.89	5.56	29.4	13.2	16.1
Octa-CDD	3.45	18.7	9.13	10.4	5.45	30.6	14.6	16.9
Total CDD	29.3	197	51.2	92.5	46.3	323	82.1	151
FURANS								
2378 TCDF	0.72	2.73	0.85	1.43	1.14	4.47	1.36	2.32
Other TCDF	24.7	165	30.9	73.6	38.9	271	49.5	120
12378 PCDF	1.10	3.95	1.37	2.14	1.74	6.48	2.20	3.48
23478 PCDF	2.11	10.4	3.31	5.27	3.32	17.0	5.31	8.56
Other PCDF	23.5	125	27.4	58.7	37.1	205	44.0	95.5
123478 HxCDF	2.59	18.2	4.55	8.44	4.08	29.8	7.29	13.7
123678 HxCDF	1.35	7.55	2.33	3.74	2.12	12.39	3.73	6.08
234678 HxCDF	1.66	15.65	4.69	7.33	2.61	25.7	7.51	11.9
123789 HxCDF	0.06	0.45	0.20	0.24	0.10	0.75	0.32	0.39
Other HxCDF	7.98	51.5	15.4	25.0	12.6	84.5	24.7	40.6
1234678-HpCDF	3.31	28.4	8.49	13.4	5.23	46.6	13.6	21.8
1234789-HpCDF	0.41	4.40	1.87	2.23	0.65	7.23	2.99	3.63
Other HpCDF	2.38	24.8	8.81	12.0	3.76	40.8	14.1	19.6
Octa-CDF	2.00	29.0	12.9	14.6	3.16	47.6	20.6	23.8
TOTAL CDF	73.9	487	123	228	117	800	197	371
TOTAL CDD+CDF	103	684	174	321	163	1,120	279	522

a ng/dscm = nanogram per dry standard cubic meter. Standard conditions are defined as 1 atm and 68° F.

( ) = estimated maximum possible concentration. [ ] = minimum detection limit

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TABLE 2-7. CDD/CDF STACK GAS CONCENTRATIONS AND EMISSIONS RATES AT CONDITION 2; CENTRAL CAROLINA HOSPITAL (1990)

	CONCENTRATION a (ng/dscm, as measured)				EMISSIONS (ug/hr)			
CONGENER	RUN 2	RUN 4	RUN 8	AVERAGE	RUN 2	RUN 4	RUN 8	AVERAGE
DIOXINS								
2378 TCDD	7.27	19.2	8.54	11.7	10.8	30.9	14.2	18.6
Other TCDD	171	341	215	242	254	549	357	387
12378 PCDD	22.6	75.1	43.4	47.0	33.6	121	72.0	75.6
Other PCDD	150	503	280	311	223	810	465	499
123478 HxCDD	21.5	64.6	50.5	45.5	32.0	104	83.8	73.3
123678 HxCDD	25.4	82.3	52.5	53.4	37.8	133	87.2	85.9
123789 HxCDD	45.1	156.4	94.2	98.6	67.3	252	156	159
Other HxCDD	209	614	406	410	312	990	674	658
1234678-HpCDD	120	335	292	249	180	540	485	402
Other HpCDD	126	365	318	270	188	589	528	435
Octa-CDD	156	254	366	259	233	409	608	416
Total CDD	1,050	2,810	2,130	2,000	1,570	4,530	3,530	3,210
FURANS								
2378 TCDF	22.1	70.8	3.86	32.2	32.9	114	6.41	51.2
Other TCDF	659	1991	151	934	982	3210	250	1481
12378 PCDF	63.5	288	96.5	149	94.6	465	160	240
23478 PCDF	88.3	341	123	184	132	550	205	296
Other PCDF	1015	4596	1491	2367	1512	7409	2476	3799
123478 HxCDF	189	831	403	474	282	1339	670	764
123678 HxCDF	114	524	244	294	169	844	406	473
234678 HxCDF	111	372	214	233	166	600	356	374
123789 HxCDF	7.88	32.5	14.8	18.4	11.7	52.5	24.6	29.6
Other HxCDF	649	2809.6	1382.9	1613.8	967	4529	2297	2598
1234678-HpCDF	301	1058	684	681	449	1706	1137	1097
1234789-HpCDF	45.5	128	87.4	86.9	67.8	206	145	140
Other HpCDF	242	743	516	500	361	1197	856	805
Octa-CDF	210	324	322	285	313	523	535	457
TOTAL CDF	3,720	14,100	5,730	7,850	5,540	22,700	9,520	12,600
TOTAL CDD+CDF	4,770	16,900	7,860	9,850	7,110	27,300	13,100	15,800

a ng/dscm = nanogram per dry standard cubic meter. Standard conditions are defined as 1 atm and 68° F.

( ) = estimated maximum possible concentration

TABLE 2-8. CDD/CDF STACK GAS CONCENTRATIONS AND EMISSIONS RATES AT CONDITION 3; CENTRAL CAROLINA HOSPITAL (1990)

	CONCENTRATION a (ng/dscm, as measured)				EMISSIONS (ug/hr)			
CONGENER	RUN 5	RUN 6	RUN 9	AVERAGE	RUN 5	RUN 6	RUN 9	AVERAGE
DIOXINS								
2378 TCDD	0.25	(0.074)	0.83	0.38	0.41	(0.125)	1.37	0.64
Other TCDD	19.7	3.77	48.1	23.9	32.6	6.38	80.0	39.7
12378 PCDD	0.66	0.23	1.92	0.94	1.09	0.39	3.19	1.56
Other PCDD	12.4	3.87	38.4	18.2	20.5	6.56	63.9	30.3
123478 HxCDD	0.42	0.19	1.12	0.58	0.69	0.32	1.87	0.96
123678 HxCDD	0.63	0.32	1.72	0.89	1.04	0.55	2.86	1.48
123789 HxCDD	1.29	0.61	2.84	1.58	2.13	1.03	4.73	2.63
Other HxCDD	8.25	3.93	20.3	10.8	13.6	6.65	33.8	18.0
1234678-HpCDD	4.31	2.12	7.80	4.75	7.14	3.59	13.0	7.90
Other HpCDD	4.66	2.49	9.39	5.51	7.71	4.22	15.6	9.18
Octa-CDD	5.98	2.56	10.1	6.21	9.90	4.33	16.8	10.3
Total CDD	58.6	20.2	143	73.8	96.9	34.1	237	123
FURANS								
2378 TCDF	1.18	0.29	3.77	1.75	1.96	0.49	6.27	2.91
Other TCDF	44.7	9.77	147	67.2	74.0	16.6	245	112
12378 PCDF	1.43	0.54	4.13	2.03	2.36	0.91	6.87	3.38
23478 PCDF	2.44	0.94	6.45	3.28	4.03	1.60	10.72	5.45
Other PCDF	22.1	8.31	84.0	38.1	36.6	14.1	140	63.4
123478 HxCDF	3.17	1.62	8.00	4.26	5.24	2.74	13.3	7.09
123678 HxCDF	1.64	0.81	4.20	2.21	2.71	1.37	6.98	3.69
234678 HxCDF	2.26	1.28	5.56	3.03	3.74	2.17	9.24	5.05
123789 HxCDF	0.11	0.06	0.27	0.15	0.19	0.10	0.45	0.25
Other HxCDF	9.28	4.62	26.6	13.5	15.4	7.82	44.3	22.5
1234678-HpCDF	6.19	2.86	11.08	6.71	10.2	4.84	18.4	11.2
1234789-HpCDF	0.80	0.57	1.46	0.94	1.32	0.97	2.42	1.57
Other HpCDF	4.63	2.32	8.50	5.15	7.66	3.93	14.1	8.57
Octa-CDF	4.18	4.51	8.76	5.82	6.91	7.64	14.6	9.71
TOTAL CDF	104	38.5	320	154	172	65.2	532	256
TOTAL CDD+CDF	163	58.7	462	228	269	99.3	769	379

a ng/dscm = nanogram per dry standard cubic meter. Standard conditions are defined as 1 atm and 68° F.

() = estimated maximum possible concentration

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TABLE 2-9. CDD/CDF STACK GAS CONCENTRATIONS AND 2378 TOXIC EQUIVALENT STACK GAS CONCENTRATIONS ADJUSTED TO 7 PERCENT O2 FOR CONDITION 1; CENTRAL CAROLINA HOSPITAL (1990)

CONGENER	CONCENTRATION a (ng/dscm, adjusted to 7 percent O2)				2378-TCDD b TOXIC EQUIV. FACTOR	2378 TOXIC EQUIVALENCIES (ng/dscm, adjusted to 7 percent O2)			
	RUN 1	RUN 3	RUN 10	AVERAGE		RUN 1	RUN 3	RUN 10	AVERAGE
DIOXINS									
2378 TCDD	0.59	(1.221)	(0.349)	0.72	1.000	0.588	(1.221)	(0.349)	0.719
Other TCDD	16.7	159	18.2	64.6	0.000	0.000	0.000	0.000	0.000
12378 PCDD	1.40	4.68	1.14	2.41	0.500	0.700	2.342	0.568	1.203
Other PCDD	14.7	131	18.3	54.6	0.000	0.000	0.000	0.000	0.000
123478 HxCDD	0.91	4.58	1.32	2.27	0.100	0.091	0.458	0.132	0.227
123678 HxCDD	1.40	7.43	2.65	3.83	0.100	0.140	0.743	0.265	0.383
123789 HxCDD	2.99	14.3	3.97	7.07	0.100	0.299	1.425	0.397	0.707
Other HxCDD	13.8	103	25.3	47.4	0.000	0.000	0.000	0.000	0.000
1234678-HpCDD	7.93	42.5	19.6	23.3	0.010	0.079	0.425	0.196	0.233
Other HpCDD	9.52	52.2	22.0	27.9	0.000	0.000	0.000	0.000	0.000
Octa-CDD	9.33	54.4	24.5	29.4	0.001	0.009	0.054	0.024	0.029
Total CDD	79.3	574	137	264		1.91	6.67	1.93	3.50
FURANS									
2378 TCDF	1.96	7.94	2.27	4.06	0.100	0.196	0.794	0.227	0.406
Other TCDF	66.7	482	82.9	210	0.000	0.000	0.000	0.000	0.000
12378 PCDF	2.99	11.51	3.69	6.06	0.050	0.149	0.575	0.184	0.303
23478 PCDF	5.69	30.2	8.89	14.9	0.500	2.847	15.120	4.446	7.471
Other PCDF	63.6	365	73.6	167	0.000	0.000	0.000	0.000	0.000
123478 HxCDF	7.00	52.9	12.2	24.0	0.100	0.700	5.295	1.220	2.405
123678 HxCDF	3.64	21.99	6.24	10.6	0.100	0.364	2.199	0.624	1.063
234678 HxCDF	4.48	45.6	12.6	20.9	0.100	0.448	4.561	1.258	2.089
123789 HxCDF	0.17	1.32	0.53	0.67	0.100	0.017	0.132	0.053	0.067
Other HxCDF	21.6	150	41.4	71.0	0.000	0.000	0.000	0.000	0.000
1234678-HpCDF	8.96	82.8	22.8	38.2	0.010	0.090	0.828	0.228	0.382
1234789-HpCDF	1.12	12.8	5.01	6.32	0.010	0.011	0.128	0.050	0.063
Other HpCDF	6.44	72.4	23.6	34.2	0.000	0.000	0.000	0.000	0.000
Octa-CDF	5.41	84.5	34.5	41.5	0.001	0.005	0.085	0.035	0.041
Total CDF	200	1,420	330	650		4.83	29.7	8.32	14.3
Total CDD+CDF	279	1,990	468	914		6.73	36.4	10.3	17.8

a ng/dscm = nanogram per dry standard cubic meter. Standard conditions are defined as 1 atm and 68° F.

b North Atlantic Treaty Organization, Committee on the Challenges of Modern Society. Pilot Study on International Information Exchange on Dioxins and Related Compounds: International Toxicity Equivalency Factor (I-TEF) Methods of Risk Assessment for Complex Mixtures of Dioxins and Related Compounds. Report No. 176, August 1988.

[ ] = minimum detection limit. ( ) = estimated maximum possible concentration.

TABLE 2-10. CDD/CDF STACK GAS CONCENTRATIONS AND 2378 TOXIC EQUIVALENT STACK GAS CONCENTRATIONS ADJUSTED TO 7 PERCENT O2 FOR CONDITION 2; CENTRAL CAROLINA HOSPITAL (1990)

CONGENER	CONCENTRATION a (ng/dscm, adjusted to 7 percent O2)				2378-TCDD b TOXIC EQUIV. FACTOR	2378 TOXIC EQUIVALENCIES (ng/dscm, adjusted to 7 percent O2)			
	RUN 2	RUN 4	RUN 8	AVERAGE		RUN 2	RUN 4	RUN 8	AVERAGE
DIOXINS									
2378 TCDD	19.4	46.4	22.2	29.3	1.000	19.385	46.438	22.221	29.348
Other TCDD	455	825	560	613	1.000	0.000	0.000	0.000	0.000
12378 PCDD	60.2	182	113	118	0.500	30.097	90.952	56.434	59.161
Other PCDD	399	1,217	728	782	0.000	0.000	0.000	0.000	0.000
123478 HxCDD	57.2	157	131	115	0.100	5.724	15.654	13.138	11.505
123678 HxCDD	67.6	199	137	135	0.100	6.764	19.940	13.667	13.457
123789 HxCDD	120	379	245	248	0.100	12.039	37.868	24.513	24.807
Other HxCDD	558	1,487	1,056	1,034	0.000	0.000	0.000	0.000	0.000
1234678-HpCDD	321	812	760	631	0.010	3.214	8.116	7.601	6.310
Other HpCDD	337	885	827	683	0.000	0.000	0.000	0.000	0.000
Octa-CDD	417	614	952	661	0.001	0.417	0.614	0.952	0.661
Total CDD	2,810	6,800	5,530	5,050		77.6	220	139	145
FURANS									
2378 TCDF	59.0	171	10.1	80.1	0.100	5.897	17.141	1.005	8.014
Other TCDF	1,757	4,822	392	2,324	0.000	0.000	0.000	0.000	0.000
12378 PCDF	169	698	251	373	0.050	8.468	34.894	12.565	18.642
23478 PCDF	236	826	321	461	0.500	117.839	413.220	160.483	230.514
Other PCDF	2,707	11,130	3,881	5,906	0.000	0.000	0.000	0.000	0.000
123478 HxCDF	505	2,011	1,049	1,189	0.100	50.502	201.144	104.931	118.859
123678 HxCDF	303	1,268	636	736	0.100	30.301	126.808	63.576	73.562
234678 HxCDF	297	901	558	585	0.100	29.689	90.078	55.816	58.528
123789 HxCDF	21.0	78.8	38.5	46.1	0.100	2.102	7.880	3.853	4.612
Other HxCDF	1,731	6,804	3,600	4,045	0.000	0.000	0.000	0.000	0.000
1234678-HpCDF	803	2,562	1,781	1,716	0.010	8.029	25.624	17.812	17.155
1234789-HpCDF	121	310	227	219	0.010	1.214	3.096	2.275	2.195
Other HpCDF	647	1,798	1,342	1,262	0.000	0.000	0.000	0.000	0.000
Octa-CDF	560	785	838	728	0.001	0.560	0.785	0.838	0.728
Total CDF	9,920	34,200	14,900	19,700		255	921	423	533
Total CDD+CDF	12,700	41,000	20,500	24,700		332	1140	562	678

a ng/dscm = nanogram per dry standard cubic meter. Standard conditions are defined as 1 atm and 68° F.

b North Atlantic Treaty Organization, Committee on the Challenges of Modern Society. Pilot Study on International Information Exchange on Dioxins and Related Compounds: International Toxicity Equivalency Factor (I-TEF) Methods of Risk Assessment for Complex Mixtures of Dioxins and Related Compounds. Report No. 176, August 1988.

[ ] = minimum detection limit. ( ) = estimated maximum possible concentration.

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TABLE 2-11. CDD/CDF STACK GAS CONCENTRATIONS AND 2378 TOXIC EQUIVALENT STACK GAS CONCENTRATIONS ADJUSTED TO 7 PERCENT O2 FOR CONDITION 3; CENTRAL CAROLINA HOSPITAL (1990)

CONGENER	CONCENTRATION a (ng/dscm, adjusted to 7 percent O2)				2378-TCDD b TOXIC EQUIV. FACTOR	2378 TOXIC EQUIVALENCIES (ng/dscm, adjusted to 7 percent O2)			
	RUN 5	RUN 6	RUN 9	AVERAGE		RUN 5	RUN 6	RUN 9	AVERAGE
DIOXINS									
2378 TCDD	0.66	(0.198)	2.04	0.97	1.000	0.657	(0.198)	2.045	0.967
Other TCDD	51.7	10.1	119	60.3	0.000	0.000	0.000	0.000	0.000
12378 PCDD	1.73	0.62	4.74	2.37	0.500	0.867	0.310	2.372	1.183
Other PCDD	32.5	10.4	95.0	46.0	0.000	0.000	0.000	0.000	0.000
123478 HxCDD	1.10	0.51	2.78	1.46	0.100	0.110	0.051	0.278	0.146
123678 HxCDD	1.64	0.86	4.25	2.25	0.100	0.164	0.086	0.425	0.225
123789 HxCDD	3.38	1.62	7.03	4.01	0.100	0.338	0.162	0.703	0.401
Other HxCDD	21.6	10.5	50.2	27.4	0.000	0.000	0.000	0.000	0.000
1234678-HpCDD	11.3	5.67	19.3	12.1	0.010	0.113	0.057	0.193	0.121
Other HpCDD	12.2	6.66	23.2	14.0	0.000	0.000	0.000	0.000	0.000
Octa-CDD	15.7	6.84	24.9	15.8	0.001	0.016	0.007	0.025	0.016
Total CDD	154	54	353	187		2.26	0.87	6.04	3.06
FURANS									
2378 TCDF	3.10	0.77	9.32	4.40	0.100	0.310	0.077	0.932	0.440
Other TCDF	117	26.1	364	169	0.000	0.000	0.000	0.000	0.000
12378 PCDF	3.74	1.44	10.2	5.13	0.050	0.187	0.072	0.511	0.257
23478 PCDF	6.39	2.52	15.9	8.29	0.500	3.194	1.260	7.974	4.143
Other PCDF	57.9	22.2	207.7	96.0	0.000	0.000	0.000	0.000	0.000
123478 HxCDF	8.30	4.32	19.8	10.8	0.100	0.830	0.432	1.979	1.081
123678 HxCDF	4.29	2.16	10.4	5.61	0.100	0.429	0.216	1.039	0.561
234678 HxCDF	5.93	3.42	13.7	7.70	0.100	0.593	0.342	1.374	0.770
123789 HxCDF	0.30	0.16	0.67	0.38	0.100	0.030	0.016	0.067	0.038
Other HxCDF	24.3	12.3	65.8	34.2	0.000	0.000	0.000	0.000	0.000
1234678-HpCDF	16.2	7.65	27.4	17.1	0.010	0.162	0.076	0.274	0.171
1234789-HpCDF	2.10	1.53	3.60	2.41	0.010	0.021	0.015	0.036	0.024
Other HpCDF	12.1	6.21	21.0	13.1	0.000	0.000	0.000	0.000	0.000
Octa-CDF	11.0	12.1	21.7	14.9	0.001	0.011	0.012	0.022	0.015
Total CDF	273	103	791	389		5.77	2.52	14.2	7.50
Total CDD+CDF	427	157	1,140	576		8.03	3.39	20.3	10.6

a ng/dscm = nanogram per dry standard cubic meter. Standard conditions are defined as 1 atm and 68° F.

b North Atlantic Treaty Organization, Committee on the Challenges of Modern Society. Pilot Study on International Information Exchange on Dioxins and Related Compounds: International Toxicity Equivalency Factor (I-TEF) Methods of Risk Assessment for Complex Mixtures of Dioxins and Related Compounds. Report No. 176, August 1988.

[ ] = minimum detection limit. ( ) = estimated maximum possible concentration.

TABLE 2-12. CDD/CDF EMISSIONS SAMPLING AND FLUE GAS PARAMETERS; CENTRAL CAROLINA HOSPITAL (1990)

	Test Condition 1			
Run No.	1	3	10	Average
Date	9/20/90	9/22/90	10/02/90	
Total Sampling Time (min.)	240	240	240	NA
Average Stack Temperature (°F)	753	734	697	728
Carbon Dioxide Concentration (%V)	3.14	3.07	3.37	3.19
Oxygen Concentration (%V)	15.8	16.1	15.7	15.9
Average Sampling Rate (dscfm)	0.426	0.421	0.417	0.422
Standard Metered Volume, Vm (dscm)	2.897	2.862	2.837	2.87
Stack Moisture (%V)	9.42	9.24	7.61	8.76
Volumetric Flow Rate (acfm)	2359	2431	2311	2367.28
Volumetric Flow Rate (dscfm)	929	966	943	946.07
Volumetric Flow Rate (dscmm)	26.3	27.4	26.7	26.8
Percent Isokinetic	101	95.7	97.2	NA
	Test Condition 2			
Run No.	2	4	8	Average
Date	9/21/90	9/23/90	9/27/90	
Total Sampling Time (min.)	240	240	240	NA
Average Stack Temperature (°F)	813	773	750	779
Carbon Dioxide Concentration (%V)	3.76	4.01	3.86	3.88
Oxygen Concentration (%V)	15.7	15.2	15.6	15.5
Average Sampling Rate (dscfm)	0.385	0.407	0.434	0.409
Standard Metered Volume, Vm (dscm)	2.61	2.77	2.95	2.78
Stack Moisture (%V)	7.60	6.93	6.71	7.08
Volumetric Flow Rate (acfm)	2293	2405	2404	2367
Volumetric Flow Rate (dscfm)	877	949	978	934
Volumetric Flow Rate (dscmm)	24.8	26.9	27.7	26.5
Percent Isokinetic	96.3	94.3	97.6	NA
	Test Condition 3			
Run No.	5	6	9	Average
Date	9/24/90	9/25/90	9/28/90	
Total Sampling Time (min.)	240	240	240	NA
Average Stack Temperature (F)	748	727	735	736
Carbon Dioxide Concentration (%V)	3.46	3.4	3.67	3.51
Oxygen Concentration (%V)	15.6	15.7	15.3	15.5
Average Sampling Rate (dscfm)	0.423	0.437	0.445	0.435
Standard Metered Volume, Vm (dscm)	2.87	2.97	3.02	2.96
Stack Moisture (%V)	7.60	8.08	8.83	8.17
Volumetric Flow Rate (acfm)	2415	2424	2432	2424
Volumetric Flow Rate (dscfm)	974	997	979	983
Volumetric Flow Rate (dscmm)	27.6	28.2	27.7	27.8
Percent Isokinetic	95.4	96.9	99.9	NA

NA = Not Applicable

substituted CDD/CDF isomers. Results are presented for each isomer as well as for each tetra octa homologue total (Total CDD, Total CDF). All CDD/CDF results have been formatted to three significant figures.

Average CDD/CDF stack gas concentrations for each test condition are presented in Table 2-2. Stack gas concentrations of all target CDD/CDF congeners were detected during each test condition throughout the program. However, flue gas concentrations from Condition 2 (250 lbs/hr-medical waste) were substantially higher than for either of the other conditions. The average 2378 TCDD concentration for Condition 2 was 11.7 ng/dscm compared to 0.26 and 0.38 for Conditions 1 and 3, respectively. The Total CDD/CDF concentrations for Condition 2 was 9,850 ng/dscm compared to 321 and 228 ng/dscm for Conditions 1 and 3, respectively.

Average oxygen concentrations for the 3 conditions varied by only 0.9 percent by volume (see Section 2.7). Therefore, relative corrected flue gas concentrations for each condition are proportionately similar to the uncorrected values. Corrected 2378 TCDD flue gas concentrations for Conditions 1, 2, and 3 were 0.72, 29.35, and 0.97 ng/dscm at 7 percent 0_2, respectively. Total CDD/CDF corrected concentrations for the above conditions were 914, 24,700, and 576 ng/dscm at 7 percent O_2, respectively.

Average CDD/CDF emission rates for each condition are shown in Table 2-4. Average emissions of 2378 TCDD for Conditions 1, 2, and 3 were 0.41, 18.6, and 0.64 ug/hr, respectively. Average Total CDD/CDF emissions for Conditions 1, 2, and 3 were 522, 15,800, and 379 μg/hr, respectively.

Table 2-5 presents average corrected CDD/CDF gas concentrations in 2378 Toxic Equivalents. The concentration of each congener corrected to 7 percent O_2 was multiplied by its respective Toxic Equivalency Factor (TEF) to determine 2378 Toxic Equivalents. The TEF's used in this report are the international TEF (I-TEF) developed by the North Atlantic Treaty Organization Committee of the Challenges of Modern Society (NATO/CCMS(1)).were developed by EPA.(1) The average 2378 Toxic Equivalent Concentrations for Total CDD/CDF for Conditions 1, 2, and 3 were 17.8, 678, and 10.6 ng/dscm at 7 percent O_2, respectively.

Table 2-6 gives both the CDD/CDF stack gas concentrations and emission rates for each test run in Condition 1. Tables 2-7 and 2-8 give similar information for Conditions 2 and 3, respectively. Non-detected results are presented in brackets (i.e., [1.023]) and other values classified as estimated maximum possible concentration (EMPC) are presented in parenthesis. The EMPCs represent analytical results which have a signal to noise ratio above 2.5:1, but do not meet all of the qualitative identification criteria. These values are included in all averages and summations. Non-detected values are considered to be zero in calculating averages and summations. Condition 1 was made up of Runs 1, 3, and 10, whereas Conditions 2 and 3 were made up of Runs 2, 4, and 8 and Runs 5, 6, and 9, respectively.

Table 2-9 presents both the CDD/CDF stack gas concentration corrected to 7 percent O_2 and the 2378 Toxic Equivalent Concentrations for each run in Condition 1. Tables 2-10 and 2-11 give similar information for Conditions 2 and 3, respectively.

The CDD/CDF sampling and flue gas parameters for each run are shown in Table 2-12. Information on sample rates, sample gas volumes, O_2/CO_2 concentrations, moisture content, stack gas flow, and other parameters are given.

2.2.3 CDD/CDF Ash Results

Incinerator ash was completely removed from the incinerator every morning following a test day. The ash was passed through a one-half inch mesh sieve to remove large pieces of glass, metal, or other large objects. The sifted ash was stored in a pre-cleaned stainless steel drum and allowed to cool. Daily composite ash samples were then taken using a 4 foot sample thief. Three daily ash samples from each run from a given condition were composite into a single ash sample per Condition.

Ash samples were analyzed for the same CDD/CDF isomers that the flue gas samples were analyzed for. Average ash CDD/CDF concentrations for each condition are presented in Table 2-13.

Average ash CDD/CDF concentrations are given in units of parts-per-billion by weight (ppb.wt). Ash 2378 TCDD Toxic Equivalencies are also presented. As was the case with CDD/CDF flue gas emissions, ash from Condition 2 had the highest concentration of congeners. The 2378 TCDD concentration for Conditions 1, 2, and 3

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TABLE 2-13. CDD/CDF AVERAGE ASH RESULTS FOR EACH CONDITION; CENTRAL CAROLINA HOSPITAL HOSPITAL (1990)

CONGENER	COND 1 ASH (ppb.wt)	COND 2 ASH (ppb.wt)	COND 3 ASH (ppb.wt)	2378-TCDD b TOXIC EQUIV. FACTOR	COND 1 TEF (ppb.wt)	COND 2 TEF (ppb.wt)	COND 3 TEF (ppb.wt)
DIOXINS							
2378 TCDD	0.030	0.120	(0.010)	1.00000	0.030	0.120	(0.0100)
Other TCDD	1.070	13.080	0.350	0.00000	0.000	0.000	0.000
12378 PCDD	0.110	0.630	0.030	0.50000	0.055	0.315	0.015
Other PCDD	1.190	18.970	0.550	0.00000	0.000	0.000	0.000
123478 HxCDD	0.120	0.810	0.040	0.10000	0.012	0.081	0.004
123678 HxCDD	0.110	1.400	0.050	0.10000	0.011	0.140	0.005
123789 HxCDD	0.350	2.500	0.100	0.10000	0.035	0.250	0.010
Other HxCDD	1.120	26.090	0.490	0.00000	0.000	0.000	0.000
1234678-HpCDD	0.620	10.800	0.270	0.01000	0.006	0.108	0.003
Other HpCDD	0.780	14.900	0.380	0.00000	0.000	0.000	0.000
Octa-CDD	0.830	12.500	0.360	0.00100	0.001	0.013	0.000
Total CDD	6.330	101.800	2.630		0.150	1.027	0.047
FURANS							
2378 TCDF	7.100	9.900	1.700	0.10000	0.710	0.990	0.170
Other TCDF	22.700	32.900	4.100	0.00000	0.000	0.000	0.000
12378 PCDF	0.830	1.400	0.160	0.05000	0.042	0.070	0.008
23478 PCDF	2.500	4.000	0.650	0.50000	1.250	2.000	0.325
Other PCDF	24.570	37.800	5.890	0.00000	0.000	0.000	0.000
123478 HxCDF	6.000	10.300	1.700	0.10000	0.600	1.030	0.170
123678 HxCDF	1.200	3.200	0.360	0.10000	0.120	0.320	0.036
234678 HxCDF	3.300	7.500	1.200	0.10000	0.330	0.750	0.120
123789 HxCDF	0.030	(0.180)	0.010	0.10000	0.003	(0.0180)	0.001
Other HxCDF	8.570	19.800	2.430	0.00000	0.000	0.000	0.000
1234678-HpCDF	6.000	15.600	2.100	0.01000	0.060	0.156	0.021
1234789-HpCDF	0.210	1.300	0.090	0.01000	0.002	0.013	0.001
Other HpCDF	2.590	8.400	1.010	0.00000	0.000	0.000	0.000
Octa-CDF	1.300	8.000	0.550	0.00100	0.001	0.008	0.001
Total CDF	86.9	160	22.0		3.118	5.355	0.852
Total CDD+CDF	93.2	262	24.6		3.268	6.382	0.900

a [ ] = minimum detection limit

( ) = estimated maximum possible concentration

b North Atlantic Treaty Organization, Committee on the Challenges of Modern Society. Pilot Study on International Information Exchange on Dioxins and Related Compounds: International Toxicity Equivalency Factor (I-TEF) Methods of Risk Assessment for Complex Mixtures of Dioxins and Related Compounds. Report No. 176, August 1988.

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were 0.03, 0.12 and 0.010 ppb, respectively. Total CDD/CDF concentrations for the three conditions were 93.2, 262, and 24.6 ppb, respectively. The total CDD/CDF TEF concentrations for the three conditions were 3.27, 6.38, and 0.90 ppb wt., respectively.

2.3 TOXIC METALS RESULTS

2.3.1 Data Reduction Overview

A single sampling train was used to determine emission rates of a series of 11 metals (Sb, As, Ba, Be, Cd, Cr, Pb, Hg, Ni, Ag, and Tl) and PM. Three sampling runs were performed under each of the three test conditions in order to assure representative test results. Sampling locations, methods, and QA/QC are discussed in Sections 4, 5, and 6, respectively. The average metals concentrations and emission rates for each test condition are summarized in Table 2-14. The results for each individual run are presented in Tables 2-15 through 2-17. Concentrations at dry, standard conditions, and concentrations adjusted to 7 percent O_2 are shown.

The values reported in Tables 2-14 through 2-17 include the respective detection limits for metals which were not detected in the samples. Since the samples were analyzed in three separate fractions (see Section 5 for details), guidelines for mathematically handling detection limits were required. The guidelines used for this report are:

- If a metal was detected in one or more fractions of the sample train but not in all fractions, only the detected values were used to determine total sample mass (non detects = zero).
- If a metal was not detected in any fractions of a sample train, the lowest detection limit reported for an individual fraction was used as the overall sample detection limit.

For the purpose of calculating average results:

- If a metal was detected in one or more of the test runs but not in all, only those runs for which a detected result was obtained were used in calculating the average. Runs where the metal was not detected were not included for averaging.

TABLE 2-14. AVERAGE METALS STACK GAS CONCENTRATIONS AND EMISSION RATES AT EACH CONDITION; CENTRAL CAROLINA HOSPITAL (1990)

TEST CONDITION		1 a	2	3
RUN NUMBERS		1,3,10	2,4,8	5,6,9
Antimony	(ug/dscm)	51.9	237	22.8
	(ug/dscm @7% O2)	142	612	59.0
	(g/hr)	0.078	0.368	0.037
Arsenic	(ug/dscm)	16.1	4.29	33.5
	(ug/dscm @7% O2)	43.9	11.1	83.3
	(g/hr)	0.026	0.007	0.056
Barium	(ug/dscm)	8.43	33.5	11.5
	(ug/dscm @7% O2)	23.9	86.2	29.7
	(g/hr)	0.013	0.052	0.019
Beryllium	(ug/dscm)	[0.080]	0.442	[0.075]
	(ug/dscm @7% O2)	[0.222]	1.11	[0.196]
	(g/hr)	[0.0001]	0.001	[0.0001]
Cadmium	(ug/dscm)	89.5	21.3	7.91
	(ug/dscm @7% O2)	260	55.0	20.5
	(g/hr)	0.130	0.033	0.013
Chromium	(ug/dscm)	8.74	14.1	71.61
	(ug/dscm @7% O2)	25.0	36.3	190
	(g/hr)	0.013	0.022	0.112
Lead	(ug/dscm)	234	726	119
	(ug/dscm @7% O2)	663	1878	307
	(g/hr)	0.356	1.12	0.197
Mercury	(ug/dscm)	22.5	3.08	69.6
	(ug/dscm @7% O2)	60.3	7.96	182
	(g/hr)	0.034	0.005	0.115
Nickel	(ug/dscm)	10.0	10.0	112
	(ug/dscm @7% O2)	29.2	25.8	298
	(g/hr)	0.014	0.016	0.177
Silver	(ug/dscm)	[1.312]	5.516	[1.230]
	(ug/dscm @7% O2)	[3.634]	14.233	[3.189]
	(g/hr)	[0.002]	0.008	[0.002]
Thallium	(ug/dscm)	2.34	[2.116]	[2.005]
	(ug/dscm @7% O2)	6.34	[5.428]	[5.196]
	(g/hr)	0.004	[0.003]	[0.003]

a Condition 1 averages do not include Run 10, front half, and therefore are biased low.

NOTE: Values enclosed in brackets represent the minimum detection limits for compounds not detected in the samples. Detection limits are only presented if the compound was not detected in any of the three test runs.

TABLE 2-15. METALS STACK GAS CONCENTRATIONS AND EMISSION RATES FOR CONDITION 1;
CENTRAL CAROLINA HOSPITAL (1990)

DATE		09/20/90	09/22/90	10/02/90	
TIME		14:00-18:18	09:47-14:00	10:15-14:21	
RUN NUMBER		RUN 1	RUN 3	RUN 10	
O2 CONCENTRATION (%V)		15.8	16.1	15.7	
FLOW RATE (dscmm)		27.1	24.1	25.0	AVERAGE
Antimony	(ug/dscm)	20.8	32.3	103	51.9
	(ug/dscm @7% O2)	56.3	94.1	275	142
	(g/hr)	0.034	0.047	0.154	0.078
Arsenic	(ug/dscm)	43.7	4.20	0.48	16.1
	(ug/dscm @7% O2)	118	12.2	1.30	43.9
	(g/hr)	0.071	0.006	0.001	0.026
Barium	(ug/dscm)	8.82	16.2	0.275	8.43
	(ug/dscm @7% O2)	23.9	47.2	0.737	23.9
	(g/hr)	0.014	0.023	0.000	0.013
Beryllium	(ug/dscm)	[0.076]	[0.084]	[0.080]	[0.080]
	(ug/dscm @7% O2)	[0.206]	[0.245]	[0.215]	[0.222]
	(g/hr)	[0.0001]	[0.0001]	[0.0001]	[0.0001]
Cadmium	(ug/dscm)	5.94	173	[0.197]	89.5
	(ug/dscm @7% O2)	16.1	504	[0.529]	260
	(g/hr)	0.010	0.250	[0.000]	0.130
Chromium	(ug/dscm)	5.87	19.84	0.509	8.74
	(ug/dscm @7% O2)	15.9	57.8	1.37	25.0
	(g/hr)	0.010	0.029	0.001	0.013
Lead	(ug/dscm)	189	279	[0.116]	234
	(ug/dscm @7% O2)	512	814	[0.311]	663
	(g/hr)	0.308	0.404	[0.000]	0.356
Mercury	(ug/dscm)	1.60	[0.316]	43.3	22.5
	(ug/dscm @7% O2)	4.32	[0.921]	116	60.3
	(g/hr)	0.003	[0.000]	0.065	0.034
Nickel	(ug/dscm)	[0.763]	10.0	[0.801]	10.0
	(ug/dscm @7% O2)	[2.063]	29.2	[2.149]	29.2
	(g/hr)	[0.001]	0.014	[0.001]	0.014
Silver	(ug/dscm)	[1.249]	[1.376]	[1.310]	[1.312]
	(ug/dscm @7% O2)	[3.378]	[4.010]	[3.515]	[3.634]
	(g/hr)	[0.002]	[0.002]	[0.002]	[0.002]
Thallium	(ug/dscm)	2.34	[2.254]	[2.111]	2.34
	(ug/dscm @7% O2)	6.34	[6.568]	[5.665]	6.34
	(g/hr)	0.004	[0.003]	[0.003]	0.004

Note: Run 10 Values do not include the front half catch and therefore are biased low

Values enclosed in brackets represent the minimum detection limits for compounds not detected in the samples. Detection limits are included in the averages unless otherwise indicated.

TABLE 2-16. METALS STACK GAS CONCENTRATIONS AND EMISSION RATES FOR CONDITION 2;
CENTRAL CAROLINA HOSPITAL (1990)

DATE		09/21/90	09/23/90	09/27/90	
TIME		09:46-13:57	11:40-15:47	13:45-17:50	
RUN NUMBER		2	4	8	
O2 CONCENTRATION (%V)		15.69	15.16	15.56	
FLOW RATE (dscmm)		24.45	26.26	27.04	AVERAGE
Antimony	(ug/dscm)	265	164	282	237
	(ug/dscm @7% O2)	706	398	733	612
	(g/hr)	0.388	0.259	0.457	0.368
Arsenic	(ug/dscm)	6.40	3.81	2.65	4.29
	(ug/dscm @7% O2)	17.1	9.23	6.90	11.1
	(g/hr)	0.009	0.006	0.004	0.007
Barium	(ug/dscm)	40.3	31.4	28.9	33.5
	(ug/dscm @7% O2)	108	76.1	75.1	86.2
	(g/hr)	0.059	0.049	0.047	0.052
Beryllium	(ug/dscm)	[0.083]	0.446	0.437	0.442
	(ug/dscm @7% O2)	[0.221]	1.08	1.14	1.11
	(g/hr)	[0.0001]	0.001	0.001	0.001
Cadmium	(ug/dscm)	20.8	17.5	25.8	21.3
	(ug/dscm @7% O2)	55.4	42.4	67.1	55.0
	(g/hr)	0.030	0.028	0.042	0.033
Chromium	(ug/dscm)	16.3	12.9	13.1	14.1
	(ug/dscm @7% O2)	43.6	31.2	34.1	36.3
	(g/hr)	0.024	0.020	0.021	0.022
Lead	(ug/dscm)	891	500	786	726
	(ug/dscm @7% O2)	2380	1210	2050	1880
	(g/hr)	1.31	0.787	1.28	1.12
Mercury	(ug/dscm)	4.02	2.14	[0.266]	3.08
	(ug/dscm @7% O2)	10.7	5.19	[0.692]	7.96
	(g/hr)	0.006	0.003	[0.0004]	0.005
Nickel	(ug/dscm)	5.34	5.28	19.4	10.0
	(ug/dscm @7% O2)	14.2	12.8	50.5	25.8
	(g/hr)	0.008	0.008	0.031	0.016
Silver	(ug/dscm)	7.11	3.93	[1.258]	5.52
	(ug/dscm @7% O2)	19.0	9.51	[3.275]	14.2
	(g/hr)	0.010	0.006	[0.002]	0.008
Thallium	(ug/dscm)	[2.180]	[2.106]	[2.062]	[2.116]
	(ug/dscm @7% O2)	[5.816]	[5.100]	[5.367]	[5.428]
	(g/hr)	[0.003]	[0.003]	[0.003]	[0.003]

Note:

Values enclosed in brackets represent the minimum detection limits for compounds not detected in the samples. Detection limits are not included in the averages unless otherwise indicated.

TABLE 2-17. METALS STACK GAS CONCENTRATIONS AND EMISSION RATES FOR CONDITION 3;
CENTRAL CAROLINA HOSPITAL (1990)

DATE		09/24/90	09/25/90	09/28/90	
TIME		11:45-15:52	10:10-14:15	11:00-15:05	
RUN NUMBER		5	6	9	
O2 CONCENTRATION (%V)		15.60	15.70	15.28	
FLOW RATE (dscmm)		27.49	25.90	28.21	AVERAGE
Antimony	(ug/dscm)	22.0	21.0	25.6	22.8
	(ug/dscm @7% O2)	57.6	56.1	63.3	59.0
	(g/hr)	0.036	0.033	0.043	0.037
Arsenic	(ug/dscm)	3.78	4.90	91.7	33.5
	(ug/dscm @7% O2)	9.92	13.1	227	83.3
	(g/hr)	0.006	0.008	0.155	0.056
Barium	(ug/dscm)	9.00	13.5	11.9	11.5
	(ug/dscm @7% O2)	23.6	36.0	29.4	29.7
	(g/hr)	0.015	0.021	0.020	0.019
Beryllium	(ug/dscm)	[0.075]	[0.078]	[0.073]	[0.075]
	(ug/dscm @7% O2)	[0.197]	[0.209]	[0.181]	[0.196]
	(g/hr)	[0.0001]	[0.0001]	[0.0001]	[0.0001]
Cadmium	(ug/dscm)	5.11	9.72	8.91	7.91
	(ug/dscm @7% O2)	13.4	26.0	22.0	20.5
	(g/hr)	0.008	0.015	0.015	0.013
Chromium	(ug/dscm)	14.1	189	11.5	71.6
	(ug/dscm @7% O2)	37.1	506	28.4	190
	(g/hr)	0.023	0.294	0.019	0.112
Lead	(ug/dscm)	125	75.6	157	119
	(ug/dscm @7% O2)	329	202	389	307
	(g/hr)	0.207	0.117	0.266	0.197
Mercury	(ug/dscm)	69.6	[0.273]	[0.215]	69.6
	(ug/dscm @7% O2)	182	[0.730]	[0.532]	182
	(g/hr)	0.115	[0.0004]	[0.0004]	0.115
Nickel	(ug/dscm)	12.2	292	33.3	112
	(ug/dscm @7% O2)	32.0	780	82.4	298
	(g/hr)	0.020	0.454	0.056	0.177
Silver	(ug/dscm)	[1.226]	[1.277]	[1.188]	[1.230]
	(ug/dscm @7% O2)	[3.215]	[3.414]	[2.938]	[3.189]
	(g/hr)	[0.002]	[0.002]	[0.002]	[0.002]
Thallium	(ug/dscm)	[2.010]	[2.057]	[1.947]	[2.005]
	(ug/dscm @7% O2)	[5.272]	[5.499]	[4.816]	[5.196]
	(g/hr)	[0.003]	[0.003]	[0.003]	[0.003]

Note:

Values enclosed in brackets represent the minimum detection limits for compounds not detected in the samples. Detection limits are not included in the averages unless otherwise indicated.

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- If the metal was not detected in any of the three runs, then the average results was reported as not detected at the average detection limit.

This approach assumes that it is most likely that an element would be found in the train fraction with the lowest detection limit; therefore, the minimum detection limit for the entire train is based on the lowest fraction detection limit.

The ash samples were analyzed for the same series of metals as were the emissions test sample. These results will be reported in Section 2.3.3.

2.3.2 Metals Emission Results

Table 2-14 presents the metals emission parameters averaged for each condition. Concentrations at standard conditions, concentrations corrected to 7 percent O_2, and emission rates are shown. No condition consistently had higher emission rates of all metals. Average emissions of antimony, barium, beryllium, lead, and silver were highest for Condition 2. Emissions of cadmium and thallium were highest during Condition 1 and emissions of arsenic, chromium, mercury, and nickel were highest during Condition 3. Lead had the highest emission rates of all metals under each condition at 0.356, 1.12, and 0.197 g/hr for Conditions 1, 2, and 3, respectively. Beryllium, silver, and thallium were not detected in two out of the three test conditions.

Table 2-15 presents the metals emission results for Condition 1 (100 lb/hr pathological waste, 15 minute cycle, 1800-1900°F secondary setpoint). The results for Run 10 do not include the front half catch (probe rinses, filter). The results for this run should therefore be considered suspect low. Lead had the highest emission rates during Runs 1 and 3 at 0.308 and 0.404 g/hr, respectively. Arsenic emissions during run 1 were substantially higher than those from run 3 with values of 0.071 and 0.006 g/hr, respectively.

The metals emission results for Condition 2 (250 lb/hr-medical waste, 15 minute cycle) are presented in Table 2-16. Lead showed the highest metals flue gas concentrations of 891, 500, and 786 μg/dscm (1.31, 0.787, and 1.28 g/hr) for Runs 2, 4, and 8, respectively.

Table 2-17 presents the metals emission results for Condition 3 (160 lb/hr pathological waste, 15 minute cycle). Emission rates of nickel during Run 6 at 0.454 g/hr were higher than any other metals. Arsenic emissions during Run 9 at 0.155 g/hr were substantially higher than for Runs 5 and 6 (0.006 and 0.008 g/hr), respectively.

A summary of the ratio by weight of metals to PM is presented in Table 2-18. Metals to PM ratios are given in units of milligrams of metal to grams of PM collected by the sampling train. The range of values were 0.001 mg beryllium per gram of PM during run 4 to 8.092 mg lead per gram of PM during Run 3.

Table 2-19 presents a summary of the amounts of metals collected in each of the sample fractions from each run. The front half fraction includes the acetone probe/filter holder rinse, nitric acid (HNO_3) probe/filter holder rinse, and the filter itself. The back half fraction included the HNO_3/hydrogen peroxide (H_2O_2) impinger contents (Impingers 1 and 2), and the third fraction consisted of the potassium permanganate ($KMnO_4$) impinger contents analyzed only for mercury. Except for thallium (Run 1), silver (Runs 2 and 4) and mercury, (Run 5), the higher proportion of most metals was collected in the front half fractions. The above metals had higher catches in the Impingers 1 and 2 fractions. Laboratory analytical results for each sample fraction are presented in detail in Appendix E.2.

Sampling and flue gas parameters for the metals and PM runs are shown in Table 2-20. Total sampling times, sample volumes, and isokinetic results for each sampling run are presented. Appendix C.2 contains a complete listing of these and additional sampling and flue gas parameters for each run. The field data sheets are contained in Appendix A.2.

2.3.3 Metals In Ash

A sample of the incinerator bottom ash was collected after each sampling run (the following day) to determine metals concentrations in the ash. The metals of interest were the same as those sampled for in the flue gas. Concentrations of the metals in the ash were determined by extracting the metals from 1 gram of ash in 100 ml of extraction fluid. The analyses were then completed as discussed in Section 5.

TABLE 2-18. RATIO OF METALS TO PARTICULATE MATTER; CENTRAL CAROLINA HOSPITAL (1990)

METALS/PARTICULATE RATIO (mg metal per gram of particulate)												
TEST CONDITION	CONDITION 1				CONDITION 2				CONDITION 3			
RUN NUMBER	1	3	10	AVERAGE	2	4	8	AVERAGE	5	6	9	AVERAGE
Antimony	0.592	0.936	2.896	1.475	1.709	0.187	1.320	1.072	0.657	0.401	0.579	0.546
Arsenic	1.244	0.122	0.014	0.460	0.041	0.004	0.012	0.019	0.113	0.093	2.075	0.761
Barium	0.251	0.469	0.008	0.243	0.260	0.036	0.135	0.144	0.269	0.257	0.269	0.265
Beryllium	ND	ND	ND	ND	ND	0.001	0.002	0.001	ND	ND	ND	ND
Cadmium	0.169	5.013	ND	2.591	0.134	0.020	0.121	0.092	0.153	0.186	0.202	0.180
Chromium	0.167	0.575	0.014	0.252	0.105	0.015	0.061	0.061	0.423	3.612	0.260	1.432
Lead	5.392	8.092	ND	6.742	5.755	0.568	3.686	3.336	3.749	1.442	3.561	2.918
Mercury	0.046	0.000	1.222	0.422	0.026	0.002	ND	0.014	2.082	ND	ND	2.082
Nickel	ND	0.290	ND	0.290	0.034	0.006	0.091	0.044	0.365	5.573	0.754	2.231
Silver	ND	ND	ND	ND	0.046	0.004	ND	0.025	ND	ND	ND	ND
Thallium	0.067	ND	ND	0.067	ND	ND	ND	ND	ND	ND	ND	ND

ND = Metal not detected in the flue gas.

TABLE 2-19. METALS AMOUNTS IN FLUE GAS SAMPLES BY SAMPLE FRACTION; CENTRAL CAROLINA HOSPITAL (1990)

CONDITION 1									
	RUN 1			RUN 3			RUN 10		
METAL	FRONT HALF	IMPINGERS 1,2	IMPINGER 3,4 b	FRONT HALF	IMPINGERS 1,2	IMPINGER 3,4 b	FRONT HALF	IMPINGERS 1,2	IMPINGER 3,4 b
Antimony	60	[6.900]		76.5	8.05		NC	282	
Arsenic	126	[0.430]		11.0	[0.440]		NC	1.33	
Barium	25.0	0.433		41.8	0.544		NC	0.755	
Beryllium	[0.500]	[0.220]		[0.500]	[0.220]		NC	[0.220]	
Cadmium	16.2	0.92		452	0.871		NC	[0.540]	
Chromium	14.6	2.33		48.0	3.92		NC	1.4	
Lead	546	[3.200]		731	[3.300]		NC	[0.320]	
Mercury	[2.400]	[6.500]	4.61	[2.400]	[6.000]	[0.826]	NC	119	[0.550]
Nickel	[5.000]	[2.200]		26.2	[2.200]		NC	[2.200]	
Silver	[8.200]	[3.600]		[8.200]	[3.600]		NC	[3.600]	
Thallium	[14.00]	6.76		[14.00]	[5.900]		NC	[5.800]	
CONDITION 2									
	RUN 2			RUN 4			RUN 8		
METAL	FRONT HALF	IMPINGERS 1,2	IMPINGER 3,4 b	FRONT HALF	IMPINGERS 1,2	IMPINGER 3,4 b	FRONT HALF	IMPINGERS 1,2	IMPINGER 3,4 b
Antimony	655	49.0		412	47.8		748	58.0	
Arsenic	15.8	1.23		8.93	1.75		6.80	0.780	
Barium	106.0	1.19		85.8	2.18		80.2	2.39	
Beryllium	[0.500]	[0.220]		1.25	[0.220]		1.25	[0.220]	
Cadmium	55.2	[0.540]		49.0	[0.540]		73.8	[0.540]	
Chromium	40.0	3.45		27.0	9.05		32.8	4.68	
Lead	2370	[3.200]		1400	[3.300]		2250	[3.300]	
Mercury	[2.400]	[6.700]	10.7	6.00	[5.900]	[0.670]	[2.400]	[6.100]	[0.760]
Nickel	14.2	[2.200]		14.8	[2.200]		55.5	[2.200]	
Silver	[8.200]	18.9		[8.200]	11.0		[8.200]	[3.600]	
Thallium	[14.00]	[5.800]		[14.00]	[5.900]		[14.00]	[5.900]	
CONDITION 3									
	RUN 5			RUN 6			RUN 9		
METAL	FRONT HALF	IMPINGERS 1,2	IMPINGER 3,4 b	FRONT HALF	IMPINGERS 1,2	IMPINGER 3,4 b	FRONT HALF	IMPINGERS 1,2	IMPINGER 3,4 b
Antimony	64.5	[7.000]		59.2	[6.900]		77.5	[7.000]	
Arsenic	11.1	[0.440]		13.8	[0.430]		278	[0.440]	
Barium	26.0	0.435		33.2	4.76		34.8	1.20	
Beryllium	[0.500]	[0.220]		[0.500]	[0.220]		[0.500]	[0.220]	
Cadmium	15.0	[0.540]		26.0	1.41		27.0	[0.540]	
Chromium	41.5	[1.100]		532.0	1.41		33.5	1.30	
Lead	368	[3.300]		213	[3.200]		477	[3.300]	
Mercury	4.80	113	86.5	[2.400]	[6.400]	[0.770]	[2.400]	[6.100]	[0.650]
Nickel	35.8	[2.200]		823	[2.200]		101	[2.200]	
Silver	[8.200]	[3.600]		[8.200]	[3.600]		[8.200]	[3.600]	
Thallium	[14.00]	[5.900]		[14.00]	[5.800]		[14.00]	[5.900]	

a Values enclosed in brackets represent minimum detection limits for elements not detected in the samples.

b Impingers 3 & 4 analyzed for mercury content only.

NC = Analysis not completed at this time.

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TABLE 2-20. METALS AND PM EMISSIONS SAMPLING AND FLUE GAS PARAMETERS
CENTRAL CAROLINA HOSPITAL (1990)

	TEST CONDITION 1			
RUN NUMBER	1	3	10	AVERAGE
DATE	09/20/90	09/22/90	10/02/90	
Total Sampling Time (min.)	240	240	240	NA
Average Sampling Rate (dscfm)	0.42	0.39	0.40	0.40
Metered Volume (dscf)	101.81	92.41	97.02	97.08
Metered Volume (dscm)	2.883	2.617	2.748	2.749
Average Stack Temperature (°F)	751.5	759.0	749.4	753.3
O2 Concentration (%V)	15.8	16.1	15.7	15.9
CO2 Concentration (%V)	3.1	3.1	3.4	3.2
Stack Gas Moisture (%V)	9.4	9.9	8.1	9.1
Volumetric Flow Rate (dscfm)	956.00	850.54	882.08	896.21
Volumetric Flow Rate (dscmm)	27.07	24.09	24.98	25.38
Percent Isokinetic	97.0	98.9	100	NA
	TEST CONDITION 2			
RUN NUMBER	2	4	8	AVERAGE
DATE	09/21/90	09/23/90	09/27/90	
Total Sampling Time (min.)	240	240	240	NA
Average Sampling Rate (dscfm)	0.39	0.41	0.42	0.41
Metered Volume (dscf)	93.92	98.89	101.01	97.94
Metered Volume (dscm)	2.660	2.801	2.861	2.774
Average Stack Temperature (°F)	809.4	778.9	766.3	784.9
O2 Concentration (%V)	15.7	15.2	15.6	15.5
CO2 Concentration (%V)	3.76	4.0	3.9	3.9
Stack Gas Moisture (%V)	8.4	7.8	6.8	7.7
Volumetric Flow Rate (dscfm)	863.34	927.14	954.69	915.05
Volumetric Flow Rate (dscmm)	24.45	26.26	27.04	25.91
Percent Isokinetic	99.1	97.1	96.3	NA
	TEST CONDITION 3			
RUN NUMBER	5	6	9	AVERAGE
DATE	09/24/90	09/25/90	09/28/90	
Total Sampling Time (min.)	240	240	240	NA
Average Sampling Rate (dscfm)	0.43	0.42	0.45	0.43
Metered Volume (dscf)	103.67	99.55	106.98	103.40
Metered Volume (dscm)	2.936	2.819	3.030	2.928
Average Stack Temperature (°F)	746.4	724.6	770.9	747.3
O2 Concentration (%V)	15.6	15.7	15.3	15.5
CO2 Concentration (%V)	3.5	3.4	3.7	3.5
Stack Gas Moisture (%V)	8.3	8.6	9.0	8.6
Volumetric Flow Rate (dscfm)	970.52	914.65	996.12	960.43
Volumetric Flow Rate (dscmm)	27.49	25.90	28.21	27.20
Percent Isokinetic	97.3	99.1	97.8	NA

NA = Not Applicable

The metals in ash results are shown in Table 2-21 for each test condition. Barium was the most prevalent metal found in the ash from all test conditions at 2,630, 7,260, and 245 mg/kg for Conditions 1, 2, and 3, respectively. All metals except silver were detected in at least 1 of the samples. Analytical results of the ash analyses are contained in Appendix E.2.

2.4 PARTICULATE MATTER/VISIBLE EMISSIONS

2.4.1 Particulate Matter Results

Particulate matter emissions were determined from the same sampling train used for metals analysis. Before metals analysis, PM collected on the filter and in the front half acetone rinse (probe, nozzle, filter holder) was analyzed gravimetrically. The PM stack gas concentrations and emission rates for each sampling run, as well as averages for each test condition are presented in Table 2-22. Uncorrected concentrations and concentrations adjusted to 7 percent O_2 are shown. Test Condition 2 had the highest concentrations and emission rates (0.182 gr/dscf and 1.439 lb/hr) while Test Condition 1 had the lowest (0.015 gr/dscf and 0.118 lb/hr). A brief summary of the sampling and flue gas parameters for the PM runs is given in Table 2-20 and Appendix C.2 presents a detailed listing of the parameters for each sampling run. The results of the gravimetric analyses are presented in Appendix E.2.

2.4.2 Visible Emissions

The opacity of emissions from the stack were determined visually by a qualified observer following EPA Method 9 protocol. Observations were recorded during the full duration of each PM/metals sampling run.

Opacity observations were recorded at 15 second intervals to the nearest 5 percent. Opacity for each run was determined by grouping the 15-second field observations into set of 24 (6 minutes) consecutive observations and then calculating the average percent opacity of each set. An average percent opacity for each run was also calculated as well as a test condition average. A summary of the observations is presented in Table 2-23. Test Conditions 1 and 3 both had an average percent opacity of 0 and Test Condition 2 had an average percent opacity of 13.

TABLE 2-21. METALS IN ASH CONCENTRATIONS;
CENTRAL CAROLINA HOSPITAL (1990)

Test Condition	1	2	3
Run No.'s	1,3,10 (mg/kg)	2,4,8 (mg/kg)	5,6,9 (mg/kg)
Antimony	9.60	19.2	[6.4]
Arsenic	11.7	45.5	[4.0]
Barium	2630	7260	245
Beryllium	1.60	4.10	1.00
Cadmium	3.30	1.20	[0.50]
Chromium	30.4	26.7	8.30
Lead	78.4	232	[15.7]
Mercury	[0.039]	0.0450	[0.039]
Nickel	7.20	15.1	[2.0]
Silver	[3.3]	[3.3]	[3.3]
Thallium	72.7	1820	410

a Values enclosed in brackets represent minimum detection limits for elements not dectected in the samples.

E.3

TABLE 2-22. PARTICULATE MATTER CONCENTRATIONS AND EMISSIONS RESULTS; CENTRAL CAROLINA HOSPITAL (1990)

DATE	SAMPLING CONDITION	RUN NUMBER	TIME	FLUE GAS CONCENTRATION				FLUE GAS EMISSION RATE	
				(grains/dscf)	(grains/dscf @7% O2)	(grams/dscm)	(grams/dscm @7% O2)	(lb/hr)	(kg/hr)
09/20/90	1	1	14:00-18:18	0.015	0.042	0.035	0.095	0.126	0.057
09/22/90	1	3	09:47-14:00	0.015	0.044	0.035	0.101	0.110	0.050
10/02/90	1	10	10:15-14:21	0.015	0.042	0.035	0.095	0.117	0.053
			AVERAGES:	0.015	0.043	0.035	0.097	0.118	0.053
09/21/90	2	2	09:46-13:57	0.068	0.181	0.155	0.413	0.501	0.227
09/23/90	2	4	11:40-15:47	0.384	0.931	0.879	2.129	3.054	1.385
09/27/90	2	8	13:45-17:50	0.093	0.243	0.213	0.555	0.763	0.346
			AVERAGES:	0.182	0.451	0.416	1.033	1.439	0.653
09/24/90	3	5	11:45-15:52	0.015	0.038	0.033	0.088	0.122	0.055
09/25/90	3	6	10:10-14:15	0.023	0.061	0.052	0.140	0.179	0.081
09/28/90	3	9	11:00-15:05	0.019	0.048	0.044	0.109	0.165	0.075
			AVERAGES:	0.019	0.049	0.043	0.112	0.155	0.070

TABLE 2-23. PERCENT OPACITY OBSERVATIONS SUMMARY; CENTRAL CAROLINA HOSPITAL (1990)

	TEST CONDITION 1		
RUN NUMBER	1	3	10
DATE	09/20/90	09/22/90	10/02/90
TIME	14:00-18:18	09:47-14:00	10:15-14:21
Range of Individual Observations (% opacity) (a)	0-5	0-5	0-10
Range of Set Averages (% opacity) (b)	0	0-1	0-1
Run Average (% opacity) (c)	0	0	0
Test Conditions Average (% opacity)		0	
	TEST CONDITION 2		
RUN NUMBER	2	4	8
DATE	09/21/90	09/23/90	09/27/90
TIME	09:46-13:57	11:40-15:47	13:45-17:50
Range of Individual Observations (% opacity)	0-100	0-100	0-80
Range of Set Averages (% opacity)	0-23	0-71	0-21
Run Average (% opacity)	5	28	6
Test Conditions Average (% opacity)		13	
	TEST CONDITION 3		
RUN NUMBER	5	6	9
DATE	09/24/90	09/25/90	09/28/90
TIME	11:45-15:52	10:10-14:15	11:00-15:05
Range of Individual Observations (% opacity)	0-25	0-25	0-25
Range of Set Averages (% opacity)	0-1	0-3	0-2
Run Average (% opacity)	0	0	0
Test Conditions Average (% opacity)		0	

a Individual observations recorded at 15 second intervals, to the nearest five percent

b A set is composed of 24 consecutive individual observations.

c The run average is calculated by averaging the set averages in a run, or averaging all the individual observations.

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2.5 HALOGEN GAS EMISSIONS

Hydrogen chloride (HCl), HF, and HBr, incinerator stack gas concentrations were manually sampled following EPA Method 26 procedures. In this method, flue gas was extracted from the stack and passed through acidified water. The HCl solubilizes and forms chloride (Cl^-) ions in acidified water. Ion chromatography was used to detect the Cl^-, bromide (Br^-), and fluoride (F^-) ions present in the sample. Three test runs were performed at each of the three operating conditions described previously.

2.5.1 Halogen Gas Emissions Results

Table 2-24 presents a summary of the average HCl, HF, and HBr test results with concentrations reported on a ppmV and ppmV corrected to 7 percent O_2 basis. Conditions 1 and 3 had similar average HCl concentrations at 45.1 and 43.7 ppmV, respectively. The Condition 2 average was 593 ppmV HCl. When compared to the HCl gas concentrations, substantially lower amounts of HF and HBr were found. Average HF concentrations for Conditions 1, 2, and 3 were 2.15, 9.96, and 1.28 ppmV, respectively. Average HBr concentrations were 0.20, 0.55, and 0.16 ppmV for the above conditions, respectively.

Table 2-25 presents the HCl results for each run performed under each condition. Three "sub-runs" were conducted during each day's overall test interval (i.e, 1A, 1B, and 1C). Concentrations as well as emission rates are presented. Emission rates used an average of the stack gas flows determined from the PM/Metals and CDD/CDF sampling trains. The HCl concentrations ranged from 19.4 ppmV for Run 1A to 943 ppmV for Run 8C. The corresponding HCl emission rates were 47.1 and 2,347 g/hr, respectively.

Table 2-26 presents the HF emissions results for all test runs. Certain values in this table are enclosed in parenthesis, denoting them as "maximum estimated concentration." These numbers were flagged by the analytical laboratory as estimates because they were less than five times the detection limit. These values are included in all averages. Run 2B had a concentration substantially higher than the rest of the runs at 23.7 ppmV, respectively. The range of concentrations for the other runs was 0.755 to 10.7 ppmV for Runs 1A and 8A, respectively. Emissions rates ranged from 1.006 to 29.1 g/hr.

TABLE 2-24. SUMMARY OF HALOGEN ACID TESTING RESULTS; CENTRAL CAROLINA HOSPITAL (1990)

TEST RUN NUMBER	HCl CONCENTRATION		HF CONCENTRATION		HBr CONCENTRATION	
	(ppmv)	(ppmv @7% O2)	(ppmv)	(ppmv @7% O2)	(ppmv)	(ppmv @7% O2)
AVERAGE 1	32.1	84.1	(1.17)	(3.07)	0.21	0.54
AVERAGE 3	65.3	186	3.11	8.96	0.21	0.60
AVERAGE 10	38.1	99.0	2.16	5.64	0.19	0.49
AVERAGE COND 1	45.1	123	1.76	4.87	0.20	0.54
AVERAGE 2	487	1,277	16.2	46.6	0.47	1.15
AVERAGE 4	647	1,583	5.75	13.44	0.47	1.09
AVERAGE 8	644	1,753	7.95	20.06	0.71	1.88
AVERAGE COND 2	593	1,537	9.96	26.7	0.55	1.37
AVERAGE 5	37.6	100	(1.431)	(3.771)	[0.032]	[0.084]
AVERAGE 6	31.1	81.2	(0.942)	(2.46)	(0.158)	(0.412)
AVERAGE 9	62.3	153	(1.456)	(3.58)	0.17	0.42
AVERAGE COND 3	43.7	111	0.00	0.00	0.16	0.42

[ ] = Minimum Detection Limit

TABLE 2-25. SUMMARY OF HCl RESULTS FOR EACH CONDITION; CENTRAL CAROLINA HOSPITAL (1990)

TEST RUN NUMBER	MEASURED CONCENTRATIONS				EMISSION RATE (g/hr)
	(mg/dscm)	(mg/dscm @7% O2)	(ppmv)	(ppmv @7% O2)	
RUN 1A	29.4	79.3	19.4	52.3	47.1
RUN 1B	54.1	135	35.7	88.9	86.6
RUN 1C	62.3	169	41.1	111	99.8
AVERAGE	48.6	128	32.1	84.1	77.8
RUN 2A	802	1,764	529	1,164	1,186
RUN 2B	674	2,109	444	1,391	996
RUN 2C	NA	NA	NA	NA	NA
AVERAGE	738	1,936	487	1,277	1,091
RUN 3A	101	278	66.8	184	156
RUN 3B	96.7	285	63.8	188	149
RUN 3C	NA	NA	NA	NA	NA
AVERAGE	99.0	282	65.3	186	153
RUN 4A	327	715	216	471	521
RUN 4B	1,276	3,068	841	2,024	2,033
RUN 4C	1,342	3,415	885	2,253	2,138
AVERAGE	981	2,399	647	1,583	1,564
RUN 5A	49.7	131	32.8	86.4	82.0
RUN 5B	48.1	117	31.7	77.1	79.4
RUN 5C	73.1	206	48.2	136	121
AVERAGE	57.0	151	37.6	100	94.1
RUN 6A	47.8	125	31.5	82.2	77.6
RUN 6B	43.3	111	28.6	73.1	70.3
RUN 6C	50.5	134	33.3	88.2	82.0
AVERAGE	47.2	123	31.1	81.2	76.6
RUN 8A	630	1,334	416	880	1,035
RUN 8B	868	2,436	572	1,607	1,424
RUN 8C	1,430	4,201	943	2,771	2,347
AVERAGE	976	2,657	644	1,753	1,602
RUN 9A	120	283	79.1	187	201
RUN 9B	60.0	141	39.6	93.0	101
RUN 9C	104	271	68.4	179	174
AVERAGE	94.5	232	62.3	153	159
RUN 10A	97.0	252	64.0	166	150
RUN 10B	40.0	97.9	26.4	64.6	62.0
RUN 10C	36.1	100.5	23.8	66.3	56.0
AVERAGE	57.7	150.1	38.1	99.0	89.5

NA = Not Applicable (Runs not completed)

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TABLE 2-26. SUMMARY OF HF RESULTS FOR EACH CONDITION; CENTRAL CAROLINA HOSPITAL (1990)

TEST RUN NUMBER	MEASURED CONCENTRATIONS				EMISSION RATE (g/hr)
	(mg/dscm)	(mg/dscm @7% O2)	(ppmv)	(ppmv @7% O2)	
RUN 1A	(0.628)	(1.695)	(0.755)	(2.038)	(1.006)
RUN 1B	(1.075)	(2.678)	(1.292)	(3.218)	(1.721)
RUN 1C	(1.216)	(3.288)	(1.462)	(3.954)	(1.947)
AVERAGE	0.97	2.55	1.17	3.07	1.56
RUN 2A	7.23	15.9	8.69	19.1	10.7
RUN 2B	19.7	61.7	23.7	74.2	29.1
RUN 2C	NA	NA	NA	NA	NA
AVERAGE	13.5	38.8	16.2	46.6	19.9
RUN 3A	(1.825)	(5.013)	(2.194)	(6.027)	(2.817)
RUN 3B	3.35	9.90	4.03	11.9	5.18
RUN 3C	NA	NA	NA	NA	NA
AVERAGE	2.59	7.45	3.11	8.96	4.00
RUN 4A	7.17	15.7	8.61	18.8	11.4
RUN 4B	2.98	7.17	3.58	8.62	4.75
RUN 4C	4.21	10.7	5.06	12.9	6.71
AVERAGE	4.79	11.2	5.75	13.4	7.63
RUN 5A	(0.835)	(2.202)	(1.004)	(2.648)	(1.379)
RUN 5B	(1.296)	(3.149)	(1.558)	(3.786)	(2.141)
RUN 5C	(1.439)	(4.057)	(1.730)	(4.878)	(2.377)
AVERAGE	1.19	3.14	1.43	3.77	1.97
RUN 6A	(0.734)	(1.914)	(0.882)	(2.300)	(1.192)
RUN 6B	(0.670)	(1.715)	(0.805)	(2.061)	(1.088)
RUN 6C	(0.948)	(2.510)	(1.140)	(3.018)	(1.539)
AVERAGE	0.78	2.05	0.94	2.46	1.27
RUN 8A	8.89	18.8	10.7	22.6	14.6
RUN 8B	6.96	19.5	8.37	23.5	11.4
RUN 8C	3.99	11.7	4.79	14.1	6.54
AVERAGE	6.61	16.7	7.95	20.1	10.9
RUN 9A	(0.939)	(2.220)	(1.129)	(2.669)	(1.576)
RUN 9B	(1.279)	(3.008)	(1.538)	(3.617)	(2.146)
RUN 9C	(1.416)	(3.707)	(1.702)	(4.455)	(2.376)
AVERAGE	1.21	2.98	1.46	3.58	2.03
RUN 10A	3.32	8.63	3.99	10.4	5.15
RUN 10B	(0.955)	(2.337)	(1.148)	(2.809)	(1.481)
RUN 10C	(1.117)	(3.111)	(1.343)	(3.741)	(1.732)
AVERAGE	1.80	4.69	2.16	5.64	2.79

NA = Not Applicable (runs not completed)

( ) = Maximum estimated concentration

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Table 2-27 presents the HBr emission results for all test runs. Hydrogen bromide was detected in the flue gas in 19 out of 25 test runs. Detected concentrations ranged from 0.18 to 0.76 ppmV for Runs 10A and 8C, respectively. Corresponding emission rates were 0.96 to 4.21 g/hr.

2.5.2 HCl CEM-Manual Comparison

Continuous emissions monitoring was performed to measure HCl in addition to other gas concentrations. The average HCl CEM concentrations calculated over the duration of the PM/Metals, CDD/CDF, and Microbial Survivability emissions test runs are presented in Section 2.7. The following paragraphs and Table 2-28 present HCl CEM data averaged over the same time period as each manual halogen "sub-run." A direct comparison can then be made between the CEM HCl data and the manual HCl data.

The results show generally good agreement between the manual and CEM concentrations. The CEM values in 7 out of 18 runs were within 30 percent of the manual values. Eleven out of 18 runs were within 40 percent. Only did Run 10 exhibit deviations greater than 100 percent. Recent state-of-the art HCl CEM sampling and instrument methods were employed during this test program. Especially important hardware developments included the use of a high temperature in-stack probe which allowed for fast, accurate responses to extreme and quick changes in stack gas HCl concentrations.

Additional agreement may have been gained if more post-test HCl calibrations could have been performed. The HCl CEM calibrations needed to be completed at the same stack gas temperature as during the test. However, following several tests, the incinerator went into a burn down mode (decrease in temperature) before final calibrations could be performed. Post-test calibrations may have revealed slight calibration drift which could be incorporated into data drift corrections for more accurate data.

For the purpose of determining the most accurate HCl flue gas concentrations, data generated by the EPA test protocol (EPA Method 26) should be used.

TABLE 2-27. SUMMARY OF HBr RESULTS AT EACH CONDITION; CENTRAL CAROLINA HOSPITAL (1990)

TEST RUN NUMBER	MEASURED CONCENTRATIONS				EMISSION RATE (g/hr)
	(mg/dscm)	(mg/dscm @7% O2)	(ppmv)	(ppmv @7% O2)	
RUN 1A	0.69	1.85	0.20	0.55	1.10
RUN 1B	0.73	1.82	0.22	0.54	1.17
RUN 1C	0.66	1.78	0.20	0.53	1.05
AVERAGE	0.69	1.82	0.21	0.54	1.11
RUN 2A	2.32	5.11	0.69	1.52	3.43
RUN 2B	0.85	2.65	0.25	0.79	1.25
RUN 2C	NA	NA	NA	NA	NA
AVERAGE	1.58	3.88	0.47	1.15	2.34
RUN 3A	0.66	1.82	0.20	0.54	1.02
RUN 3B	0.74	2.20	0.22	0.65	1.15
RUN 3C	NA	NA	NA	NA	NA
AVERAGE	0.70	2.01	0.21	0.60	1.09
RUN 4A	1.80	3.93	0.53	1.17	2.86
RUN 4B	2.02	4.85	0.60	1.44	3.22
RUN 4C	0.89	2.26	0.26	0.67	1.41
AVERAGE	1.57	3.68	0.47	1.09	2.50
RUN 5A	[0.108]	[0.285]	[0.032]	[0.084]	[0.178]
RUN 5B	[0.109]	[0.265]	[0.032]	[0.078]	[0.180]
RUN 5C	[0.108]	[0.305]	[0.032]	[0.090]	[0.178]
AVERAGE	[0.108]	[0.285]	[0.032]	[0.084]	[0.179]
RUN 6A	(0.530)	(1.382)	(0.158)	(0.412)	(0.861)
RUN 6B	[0.109]	[0.279]	[0.032]	[0.082]	[0.177]
RUN 6C	[0.111]	[0.294]	[0.033]	[0.087]	[0.180]
AVERAGE	0.53	1.38	0.16	0.41	0.86
RUN 8A	2.10	4.43	0.62	1.32	3.44
RUN 8B	2.48	6.96	0.74	2.07	4.07
RUN 8C	2.57	7.54	0.76	2.24	4.21
AVERAGE	2.38	6.31	0.71	1.88	3.91
RUN 9A	0.63	1.49	0.19	0.44	1.06
RUN 9B	[0.113]	[0.266]	[0.034]	[0.080]	[0.190]
RUN 9C	(0.521)	(1.364)	(0.155)	(0.406)	(0.874)
AVERAGE	0.58	1.43	0.17	0.42	0.96
RUN 10A	0.62	1.60	0.18	0.48	0.96
RUN 10B	0.73	1.80	0.22	0.53	1.14
RUN 10C	(0.541)	(1.507)	(0.161)	(0.448)	(0.839)
AVERAGE	0.63	1.64	0.19	0.49	0.98

NA = Not applicable (runs not completed)

[ ] = Minimum detection limit; ( ) = maximum estimated concentration

TABLE 2-28. COMPARISON OF MANUAL AND CEM HCl RESULTS; CENTRAL CAROLINA HOSPITAL (1990)

TEST RUN NUMBER	MANUAL HCl RESULTS		CEM HCl RESULTS	
	(ppmV/ dry)	(ppmV @7% O2)	(ppmV/ dry)	(ppmV @7% O2) a
RUN 1A	19.4	52.3	NC	NC
RUN 1B	35.7	88.9	NC	NC
RUN 1C	41.1	111	42.7	120
AVERAGE	32.1	84.1	NA	NA
RUN 2A	529	1164	548	1279
RUN 2B	444	1391	397	1253
RUN 2C	NC	NC	NC	NC
AVERAGE	487	1277	473	1266
RUN 3A	66.8	184	93.8	284
RUN 3B	63.8	188	18.6	60.0
RUN 3C	NC	NC	32.7	123
AVERAGE	65.3	186	NA	NA
RUN 4A	216	471	NC	NC
RUN 4B	841	2024	625	1441
RUN 4C	885	2253	659	1633
AVERAGE	647	1583	NA	NA
RUN 5A	32.8	86.4	NC	NC
RUN 5B	31.7	77.1	39.9	89.3
RUN 5C	48.2	136	31.0	81.0
AVERAGE	37.6	99.8	NA	NA
RUN 6A	31.5	82.2	NC	NC
RUN 6B	28.6	73.1	41.5	107
RUN 6C	33.3	88.2	55.2	148
AVERAGE	31.1	81.2	NA	NA
RUN 8A	416	880	NC	NC
RUN 8B	572	1607	351	1006
RUN 8C	943	2771	594	1737
AVERAGE	644	1753	NA	NA
RUN 9A	79.1	187	NC	NC
RUN 9B	39.6	93.0	74.2	179
RUN 9C	68.4	179	65.1	185
AVERAGE	62.3	153	NA	NA
RUN 10A	64.0	166	NC	NC
RUN 10B	26.4	64.6	84.9	225
RUN 10C	23.8	66.3	55.2	181
AVERAGE	38.1	99.0	NA	NA

a Averages of corrected 30 second readings

NC = Run not completed.

NA = Averages not valid for comparisons.

2.6 CEM RESULTS

Three test runs were performed at each of three operating conditions while the incinerator was burning hospital waste. Continuous emissions monitoring was performed using an extractive sample system and instrument methods to measure NO_x, CO, SO_2, THC, and HCl concentrations. The diluent gases (O_2, CO_2) were measured using CEMs at all times so that the emission results could be normalized to a reference 7 percent O_2. Concentrations of NO_x, SO_2, CO, CO_2, and O_2 were measured on a dry basis with the sample stream conditioned as shown in Figure 5-16. Concentrations of HCl using a separate monitor were measured using a dilution probe system and were on a wet basis. The THC concentrations were also monitored on a wet basis, but did not employ the dilution probe system. All CEM data were recorded as 30-second averages over each sampling interval, a copy of which are included in Appendix D.

The 30-second CEM values were averaged over the sampling interval for each test run. Both actual and values corrected to 7 percent O_2 are summarized in Tables 2-29 and 2-30. Actual concentrations are presented as they were measured (NO_x, SO_2, CO, CO_2, and O_2-dry; THC and HCl-wet). All values corrected to 7 percent O_2 are presented on a dry basis. Each 30-second CEM reading was corrected to 7 percent O_2 based on the corresponding O_2 value. Averages of the corrected values were then calculated. For HCl and THC, stack gas moisture determined from the average of the PM/Metals and CDD/CDF sampling trains was used for the corrections. Overall averages are presented for each CEM parameter under each of the three incinerator operating conditions.

Average O_2 concentrations varied by only 0.9 percent by volume during the 9 test runs, ranging from 15.2 to 16.1 percent/dry. The average percent O_2 values for each set of tests was 15.9 (Condition 1), 15.5 (Condition 2), and 15.5 (Condition 3). The CO_2 concentrations varied inversely with the O_2 concentrations at 3.19, 3.88, and 3.51 percent by volume (%V) for Conditions 1 through 3, respectively. The CO_2 run averages ranged from 3.07 to 4.01 percent by volume over the nine test runs.

Average CO concentrations ranged from 14.9 ppmV to 42.1 ppmV under Condition 1, with the overall average concentration at 29.2 ppmV. For the second

TABLE 2-29. CONTINUOUS EMISSIONS MONITORING TEST AVERAGES FOR O2, CO2, CO, and HCl; CENTRAL CAROLINA HOSPITAL (1990)

DATE	RUN NUMBER/ MANUAL TEST TYPE	CONDITION	TEST TIME a	MOISTURE	OXYGEN (%vol.dry)	CO2 (%vol.dry)	CO actual (ppmV,dry)	CO corrected b (ppmV,dry) @7% O2	HCL c actual (ppmV,wet)	HCL c corrected d (ppmV,dry) @7% O2
09/20/90	1	1	14:00 - 18:18	9.39	15.8	3.14	42.1	119	107	305
09/22/90	3	1	9:47 - 14:00	9.57	16.1	3.07	14.9	40.6	33.6	110
10/02/90	10	1	10:15-14:21	7.88	15.7	3.37	30.6	81	64.6	143
	AVERAGE			8.95	15.9	3.19	29.2	80.2	68.4	186
09/21/90	2	2	9:45 - 13:57	7.98	15.7	3.76	132	407	413	1273
09/23/90	4	2	11:43 - 15:47	7.35	15.2	4.01	1187	2780	568	1480
09/27/90	8	2	13:45 - 17:50	6.78	15.6	3.87	181	453	445	1350
	AVERAGE			7.37	15.5	3.88	500	1213	475	1368
09/24/90	5	3	11:45 - 15:52	7.96	15.6	3.46	37.6	104	33.9	90.3
09/25/90	6	3	10:10 - 14:15	8.29	15.7	3.40	65.3	196	45.8	138
09/28/90	9	3	11:00 - 15:05	8.93	15.3	3.67	36.1	107	55.6	164
	AVERAGE			8.39	15.5	3.51	46.3	136	45.1	131

a For metals/CDD/CDF runs.
b Averages are corrected to 7% oxygen (corrected value = actual * (13.9 /(20.9 - O2)). 30 second values were corrected and then averaged.
c HCl concentrations were determined by manual methods as well. A comparison of CEM vs. manual results is presented in Section 2.6.
d Averages are corrected to 7% oxygen and for moisture, where the corrected value = actual * 13.9/(20.9 - O2) * (1/(1 - moist). Thirty second values were corrected and then averaged.

TABLE 2-30. CONTINUOUS EMISSIONS MONITORING TEST AVERAGES FOR O2, SO2, NOx, and THC; CENTRAL CAROLINA HOSPITAL (1990)

DATE	RUN NUMBER	CONDITION	TEST TIME a	MOISTURE (%volume)	OXYGEN (%vol.dry)	SO2 actual (ppmV,dry)	SO2 corrected b (ppmV,dry)	NOX actual mV,d	NOX corrected b (ppmV,dry)	THC actual (ppm C,wet)	THC corrected c (ppm C, dry)
09/20/90	1	1	14:00-18:18	9.39	15.8	40.2	106	132	340	7.15	23.0
09/22/90	3	1	9:47-14:00	9.57	16.1	42.1	119	109	289	9.84	32.3
10/02/90	10	1	10:15-14:21	7.88	15.7	31.4	80.7	125	313	2.52	7.74
	AVERAGE			8.95	15.9	37.9	102	122	314	6.50	21.0
09/21/90	2	2	9:45-13:57	7.98	15.7	15.0	37.2	79.9	208	23.0	82.7
09/23/90	4	2	11:40-15:47	7.35	15.2	18.2	44.2	62.9	143	60.2	183
09/27/90	8	2	13:45-17:50	6.78	15.6	19.0	47.0	73.7	195	30.0	91.3
	AVERAGE:			7.37	15.5	17.4	42.8	72.2	182	37.7	119
09/24/90	5	3	11:45-15:52	7.96	15.6	51.5	134	150	384	3.79	11.7
09/25/90	6	3	10:10-14:15	8.29	15.7	51.1	135	153	402	5.63	17.9
09/28/90	9	3	11:00-15:05	8.93	15.3	43.1	108	165	397	3.62	11.7
	AVERAGE:			8.39	15.5	48.6	126	156	394	4.35	13.8

a Time is for metals and CDD/CDF runs.
b SO2 and NOx are corrected to 7.0% oxygen, where the corrected value = actual * 13.9/(20.9 - O2).
c THC is corrected to 7.0% oxygen and corrected for moisture where the corrected value = actual * 13.9/(20.9 - O2) * 1/(1 - moist).

NOTE: For all CEM Data, 30 second values were corrected and then averaged.

condition, the CO run averages ranged from 132 ppmV to 1187 ppmV, with an overall average CO concentration of 500 ppmV. For the third condition, the CO run averages ranged from 36.1 ppmV to 65.3 ppmV, with the overall average for this condition being 46.3 ppmV.

The average NO_x concentrations varied from 62.9 ppmV to 165 ppmV over the nine test runs. Averages for Condition 1 ranged from 109 to 132 ppmV, with an overall average of 122 ppmV. Averages for Condition 2 ranged from 62.9 to 79.9 ppmV, with an overall average of 72.2 ppmV, and the Condition 3 range was 150 to 165 ppmV, with the average value being 156 ppmV.

The SO_2 run averages for each condition ranged from 31.4 to 42.1 ppmV for Condition 1, 15.0 to 19.0 ppmV for Condition 2, and 43.1 to 51.5 ppmV for Condition 3. The condition averages were 37.9 ppmV, 17.4 ppmV, and 48.6 ppmV SO_2 for Conditions 1 through 3, respectively.

Average THC concentrations varied from 2.52 to 60.2 ppmV-wet over the nine runs. The average THC for each condition ranged from 2.52 to 9.84 ppmV for Condition 1, 23.0 to 60.2 ppmV for Condition 2, and 3.62 to 5.63 ppmV for Condition 3. The Condition 1 average was 6.50 ppmV, the Condition 2 average was 37.7 ppmV, and the Condition 3 average was 4.35 ppmV.

2.7 CEM BURN DOWN RESULTS

After the daily test run was completed, combustion gas concentrations were continuously analyzed and recorded during a "burn down" period by the CEMS. At this time no waste was fed to the incinerator. The primary and secondary chambers operated under burn down set point routines. Two days of burn down conditions were monitored with all CEM analyzers operational. Concentrations of O_2, CO_2, SO_2, NO_x, CO, HCl, and THC were monitored. The 30-second CEM averages were reported in ppm or percent by volume as measured and also corrected to 7 percent O_2.

Table 2-31 reports the burn down CEM data. Burn down parameters were measured after test Run 6 (9/25/90) and Run 10 (10/2/90). Oxygen values were 17.5 and 17.7 percent by volume for these two runs. Carbon dioxide values were 2.14 and 1.92, respectively. The CO concentrations were 8.5 and 6.2 ppmV dry and NO_x values

TABLE 2-31. CEM BURN DOWN AVERAGES
CENTRAL CAROLINA HOSPITAL (1990)

DATE	RUN NUMBER	COND.	BURNDOWN TEST TIME a	OXYGEN (%vol.dry)	SO2 actual (ppmV,dry)	SO2 corrected b (ppmV,dry)	NOX actual (ppmV,dry)	NOX corrected b (ppmV,dry)	THC actual (ppm C, wet)	THC corrected c (ppm C, dry)
09/25/90	6	3	14:15-17:28	17.5	26.1	92.6	62.8	217	1.1	3.1
10/02/90	10	1	14:22-17:35	17.7	7.10	24.6	38.5	154	0.0	0.0

				CO2 (%vol.dry)	CO actual (ppmV,dry)	CO corrected b (ppmV,dry) @7% O2	HCL c,d actual (ppmV,wet)	HCL c,d corrected (ppmV,dry) @7% O2
09/25/90	6	3	14:15-17:28	2.14	8.5	31.4	16.6	67.9
10/02/90	10	1	14:22-17:35	1.92	6.2	24.5	31.1	141

a Time is for approximate burndown period.

b Thirty-second CEM averages were corrected to 7% oxygen (corrected value = actual * (13.9 /(20.9 - O2)).

c THC and HCl is corrected to 7% oxygen and corrected for moisture where the corrected value = actual * 13.9/(20.9 - O2) / (1 - moist)). Moistu assumed to be the same as during the test run conducted on the same day.

d HCl concentrations were determined by manual methods as well. A comparison of CEM vs. manual results is presented in Section 2.5. HCl calibrations were performed at different stack gas temperatures than the burndown stack temperatures thereby affecting the sampling rate/dilution ratio which may have affected the HCl accuracy.

were 62.8 and 38.5 ppmV dry, respectively. The THC average concentrations were below 2 ppm for both runs.

2.8 ASH LOSS-ON-IGNITION AND CARBON CONTENT RESULTS

This section presents results of laboratory analyses of ash samples collected daily. During the test period, ash was removed manually from the incinerator each morning, screened through 1/2-inch mesh, weighed and placed in 35-gallon metal cans. After the ash was allowed to cool, samples were taken manually and composited to obtain a representative sample. Portions were taken from the composite sample for the various analyses, including one sample which was analyzed for moisture content, LOI, and carbon content.

Samples were collected for three replicate tests at the three different incinerator operating conditions (total of 9 runs).

Table 2-32 presents a summary of the ash analysis results. The moisture content of the samples ranged from 0.27 percent for Run 10 (Test Condition 1) to 44.26 percent for Run 8 (Test Condition 2). The average moisture values for each test condition are shown. The lowest value shown was for Condition 1 (0.33 percent) and the highest value for Condition 2 (27.10 percent). The ash from Runs 4, 8, and 6 were cooled down in the incinerator using a water spray. This was done in order to allow the ash to be removed and the next test run to be started. Ash moisture values for these runs reflect the presence of this additional water.

Loss-on-ignition results varied from 17.8 percent for Run 10 (Condition 1) to 78.0 percent for Run 8 (Condition 2). Average values for each test condition ranged from 22.2 percent for Condition 1 to 53.2 percent for Condition 2.

Carbon content in the ash samples varied from 9.77 percent for Run 10 (Condition 1) to 35.7 percent for Run 8 (Condition 2). Average values for each test condition showed a low value of 14.2 percent for Condition 1 and a high value of 27.4 percent for Condition 2.

TABLE 2-32. SUMMARY OF ASH CARBON CONTENT, LOI AND MOISTURE RESULTS; CENTRAL CAROLINA HOSPITAL (1990)

CONDITION a	TEST DATE	TEST NUMBER	SAMPLE DATE	MOISTURE (%)	L.O.I. (%)	TOTAL LOSS (%)	CARBON (%)
PRE TEST 1	PRE TEST	NA	9/20/90	28.55	62.68	73.34	18.12
PRE TEST 2	PRE TEST	NA	9/20/90	15.83	58.88	65.39	28.25
			AVERAGE	22.19	60.78	69.37	23.19
1	9/20/90	1	9/21/90	0.41	29.66	24.17	15.03
1	9/22/90	3	9/23/90	0.30	19.19	19.48	17.87
1	10/02/90	10	10/03/90	0.27	17.80	18.02	9.77
			AVERAGE	0.33	22.22	20.56	14.22
2	9/21/90	2	9/22/90	2.12	45.72	46.87	30.17
2	9/23/90	4	9/24/90	34.92 b	35.90	58.28	16.39
2	9/27/90	8	9/25/90	44.26 b	78.02	87.75	35.70
			AVERAGE	27.10	53.21	64.30	27.42
3	9/24/90	5-MC c	9/25/90	3.16	23.64	26.05	20.36
3	9/24/90	5-MF	9/25/90	0.64	23.79	24.28	22.80
3	9/25/90	6-MC	9/26/90	30.03 b	40.39	50.29	21.85
3	9/25/90	6-MF	9/26/90	0.47	32.45	32.77	16.66
3	9/28/90	9	9/29/90	1.13	27.63	28.45	20.41
			AVERAGE	7.09	29.58	32.37	20.42

a CONDITIONS:
(1) '100 lb/hr., 1800-1900° F, 25 lb/15 min.
(2) 250 lb/hr., 1600° F, 62.5 lb/15 min.
(3) 160 lb/hr., 1600° F, 40 lb/15 min.

b For these runs, a water spray was used to extinguish the fire in order to allow ash to be removed.

c MF = Fine Ash (sifted through 1/2" mesh) MC = Course Ash (would not pass through 1/2" mesh). Course and fine ash comparison was only completed during Runs 5 and 6 to examine any relative differences in properties.

2.9 MICROBIAL SURVIVABILITY RESULTS

This section provides the background and test matrix for microbial survivability testing and presents the test results for microbial survivability in emissions, in ash and in ash quality pipes.

2.9.1 Background and Test Matrix

One of the objectives of this test program was to further develop testing methods to determine microbial survivability in incinerator processes. As part of the MWI test program at Central Carolina Hospital, testing was conducted to determine microbial survivability based on a surrogate indicator organism that was spiked into the incinerator feed during each test run. The surrogate indicator organism used was a type of soil spore known as Bacillus stearothermophilus. This organism as chosen because it survives at high temperatures and it is easy to culture and identify. Also, it is non-pathogenic and is not commonly found in medical waste streams.

Two types of testing were performed. The first test method was aimed at determining microbial survivability in the combustion gases (emissions) and the bottom ash. For these tests, a known quantity of B. stearothermophilus in solution was absorbed onto materials commonly found in the medical waste stream (i.e., gauze, paper, bandages, etc.) and introduced into the incinerator at regular intervals. Simultaneous emissions testing was conducted at the incinerator stack following the EPA draft method "Microbial Survivability Test for Medical Waste Incinerator Emissions." This testing was performed concurrently with other emissions testing (PM/Metals, CDD/CDF, halogens, and CEMs). Spiked waste was charged into the incinerator four times during a 4-hour test run (essentially once per hour). Ash samples were taken daily each morning following the previous days' test run when the incinerator was cleaned manually. The ash was sampled and analyzed as described in the EPA Draft Method "Microbial Survivability Test for Medical Waste Incinerator Ash" (Appendix K).

The second Microbial Survivability test method utilized freeze dried spores encased in double pipes which were insulated. These tests were performed as a comparison to the direct ash method. Two sizes of pipes were used during this test program to determine if pipe size was a determining factor in microbial survivability.

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Large pipes samples (6 in. x 2.0 in. diameter) were compared to small pipes (6 in. x 1.25 in. diameter). Three spiked pipes sets (1 large, 1 small) were charged daily at nearly even intervals: (1) the first charge of the day, (2) midday, and (3) last charge of the day.

Complete details of the microbial spiking, recovery and analysis procedures are given in Section 5.3.

Three triplicate runs were performed at the three different incinerator operating conditions for a total of nine runs. Four medical waste (wet spore) spikes and three pipe samples (dry spore) spikes were added during each run. One run was performed daily.

Table 2-33 summarizes the spore spiking times and quantities as well as waste feed and total ash quantities.

2.9.2 Overall Microbial Survivability

By comparing the number of spores spiked to the incinerator with the number of viable spores exiting in both the stack gas and incinerator ash, an overall microbial survivability value can be determined as follows:

$$MS = \left(\frac{S_e + A_e}{S_s}\right) \times 100$$

MS	=	spore microbial survivability (wet)
S_e	=	Number of viable spores exiting the stack
A_e	=	Number of viable spores detected in the incinerator ash
S_s	=	Number of viable spores spiked in the waste feed

This is an adaptation of the destruction efficiency (DE) calculation presented in the reference test protocol which calculates DE based only on stack emissions and a separate DE based on spores in ash. By combining the two DE estimates a more complete estimate of Microbial Survivability (1 - DE) is obtained. The total number of spores in the ash was calculated by multiplying the number of spores found in 1 gram of ash by the total weight of ash removed from the incinerator per day. The values presented in

TABLE 2-33. SUMMARY OF INCINERATOR FEED AMOUNTS AND ASH GENERATION PER RUN; CENTRAL CAROLINA HOSPITAL (1990)

RUN NUMBER	DATE	CONDITION	WET SPORE SPIKES a		DRY SPORE (PIPE) SPIKES a		TOTAL WASTE FEED (lbs) AND TYPE	TOTAL ASH WEIGHT (lbs)
			TIMES	AMOUNTS (TOTAL SPORES)	TIMES	AMOUNTS (TOTAL SPORES)		
1	09/20/90	1	14:00	1.5E+12	14:00	5.2E+06	21.2	503.4
			15:15	1.5E+12	16:15	5.2E+06	PATHOLOGICAL	
			16:00	1.5E+12	16:00	5.2E+06		
			17:00	1.5E+12				
2	09/21/90	2	09:45	1.5E+12	09:45	5.2E+06	139	1015.8
			11:00	1.5E+12	12:03	5.2E+06	MEDICAL	
			12:03	1.5E+12	15:45	5.2E+06		
			12:45	1.5E+12				
3	09/22/90	1	09:45	1.5E+12	09:45	5.2E+06	22.4	649.5
			11:00	1.5E+12	12;15	5.2E+06	PATHOLOGICAL	
			12:00	1.5E+12	14:30	5.2E+06		
			13:00	1.5E+12				
4	09/23/90	2	11:40	1.5E+12	11:40	5.2E+06	172.7	905.3
			12:45	1.5E+12	14:15	5.2E+06	MEDICAL	
			13:45	1.5E+12	17:15	5.2E+06		
			14:45	1.5E+12				
5	09/24/90	3	11:45	1.5E+12	11:45	5.2E+06	45.1	674.6
			12:40	1.5E+12	13:45	5.2E+06	PATHOLOGICAL	
			13:45	1.5E+12	15:50	5.2E+06		
			14:40	1.5E+12				

TABLE 2-33. SUMMARY OF INCINERATOR FEED AMOUNTS AND ASH GENERATION PER RUN; (continued)
CENTRAL CAROLINA HOSPITAL (1990)

RUN NUMBER	DATE	CONDITION	WET SPORE SPIKES a		DRY SPORE (PIPE) SPIKES a		TOTAL WASTE FEED (lbs) AND TYPE	TOTAL ASH WEIGHT (lbs)
			TIMES	AMOUNTS (TOTAL SPORES)	TIMES	AMOUNTS (TOTAL SPORES)		
6	09/25/90	3	10:10 11:15 12:10 13:15	1.5E+12 1.5E+12 1.5E+12 1.5E+12	10:10 12:10 14:15	5.2E+06 5.2E+06 5.2E+06	411.4 PATHOLOGICAL	697.2
8	09/27/90	2	13:45 14:45 15:56 16:45	1.5E+12 1.5E+12 1.5E+12 1.5E+12	13:45 16:15 18:00	5.2E+06 5.2E+06 5.2E+06	137.3 MEDICAL	727.3
9	09/29/90	3	11:00 12:00 13:00 14:00	1.5E+12 1.5E+12 1.5E+12 1.5E+12	11:00 13:15 15:53	5.2E+06 5.2E+06 5.2E+06	77 PATHOLOGICAL	867.2
10	10/02/90	1	10:15 11:15 12:15 13:15	1.5E+12 1.5E+12 1.5E+12 1.5E+12	10:15 12:15 14:30	5.2E+06 5.2E+06 5.2E+06	17.2 PATHOLOGICAL	453.5

NOTE:
Condition 1 = 100 lb/hr; 1800-1900°F; 25 lb/15 min
Condition 2 = 250 lb/hr; 1600°F; 62.5 lb/15 min
Condition 3 = 160 lb/hr; 1600°F; 40 lb/15 min

a Spike amounts were taken from the confirmation analysis results (see Tables 6-24 and 6-25).

this section were taken from a "quantitative summary" performed on the raw analytical data by the analytical laboratory. These results are included in the analytical results shown in Appendix E.3, and calculations are shown in Appendix F.

Table 2-34 presents the overall survivability of the indicator spores. Four test run results had viable spores found in the stack gas. Spores were found in several isolated ash aliquots; however, definitive quantitative results could not be provided and all test run results were assigned no spores detected. For those runs in which positive Microbial Survivability values could be calculated, the numbers ranged from survivability for 3.1×10^{-5} percent Run 6 to $>2.6 \times 10^{-4}$ percent for Run 8. Flue gas microbial survivability and ash microbial survivability are further discussed in the following sections. All microbial survivability calculations are shown in Appendix F.

2.9.3 Microbial Survivability in Emissions

Microbial Survivability in emission tests were conducted to quantify the number of viable spores exiting the stack during the test run. The formulas used for calculating the number of viable spores existing in the stack, S_e is calculated as shown in Appendix F, and in the EPA draft method in Appendix K.

Each test run for viable spore emissions was actually made up of 2 "sub-runs" (A and B). Each sub-run sample was collected for 120 minutes through one of the 2 sample ports. An approximate 1.5 liter sample of impinger collection solution was generated for each sub-run. These sub-run samples were recovered in a disinfected mobile laboratory, sealed and sent to the analytical laboratory where they were combined into one sample for each test run.

For each run performed, 9 aliquots were prepared for analysis: three 10 ml aliquots, three 100 ml aliquots, and 3 equal aliquots of a remaining filterable amount of sample. Both a first and second count on each aliquot were performed. The first count was conducted after approximately 24 hours incubation, and the second after approximately a 48 hour incubation period. Additional research showed that the spore count did not increase after the 48-hour count incubation period. Therefore, all values presented here are from the second (typically a 48-hour) count.

TABLE 2-34. OVERALL MICROBIAL SURVIVABILITY;
CENTRAL CAROLINA HOSPITAL (1990)

RUN NO.	FEED RATE/ FREQUENCY/TYPE (lb/hr/min)	TOTAL NUMBER OF WET SPORES SPIKED TO INCINERATOR a	NUMBER INDICATOR SPORES EXITING THE STACK b	NUMBER OF INDICATOR SPORES IN ASH c	SPORE SURVIVABILITY (%) d	MICROBIAL LOG REDUCTION f
1	100/15-P	6.0E+12	<3.84E+04	<9.6E+05	<1.7E-05	>6.8
3	100/15-P	6.0E+12	~13.8E+06	<1.0E+06	~2.3E-04	~5.7
10	100/15-P	6.0E+12	<3.22E+04	<3.9E+03	<6.0E-07	>8.2
2	250/15-M	6.0E+12	<4.36E+04	<6.3E+06	<1.1E-04	>6.0
4	250/15-M	6.0E+12	<4.31E+04	<7.8E+06	<1.3E-04	>5.9
8	250/15-M	6.0E+12	>15.5E+06 e	<6.2E+06	>2.6E-04	<5.6
5	160/15-P	6.0E+12	<13.5E+06	<1.0E+04	<2.3E-04	>5.6
6	160/15-P	6.0E+12	~18.5E+05	<1.9E+06	~3.1E-05	~6.5
9	160/15-P	6.0E+12	~6.94E+06	<1.8E+04	~1.2E-04	~5.9

a Four 500 ml wet spore aliquots were spiked during each test run. This value represents the total spores spiked/test run as determined by the confirmation count (see Table 6-24).

b Values taken from repetitive analytical runs as detailed in Appendix E.3. Detection limits are presented in Table 2-35.

c Detection liits are presented in Table 2-37.

d Calculated using (number spores in flue gas + number of spores in ash/number wet spores spiked) x 100. If spores were not detected in either fraction, the non-detected values were used in calculation. Otherwise non-detects were considered zero.

e Maximum value could not be determined for this flue gas sample (see Appendix E.3).

f MLR = log(spiked spores) - log(stack spores + ash spores)

P = Pathological Waste M = Medical Waste

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Table 2-35 presents the Microbial Survivability in Emissions test results. There were four test runs where viable spores were determined to be present in the flue gas (Runs 3, 8, 6, and 9).

The Microbial Survivability sampling and flue gas parameters are shown in Table 2-36.

2.9.4 Microbial Survivability in Ash

Incinerator ash was completely removed from the incinerator every day and stored in a pre-cleaned, disinfected stainless steel drum. A composite ash sample was then taken from the drum using a sample thief and deposited in a sterilized, amber glass sample bottles. The composite samples were then submitted to the laboratory for filtering culturing, and enumeration of B. stearothermophilus.

Microbial Survivability in ash for the Central Carolina MWI tests are presented in Table 2-37. Three ash aliquots of approximately one gram were prepared from each sample. Six serial dilutions were prepared on each ash aliquot and triple plated. B. stearothermophilus colonies were found in several of the cultures. However, because repetitive analyses of these aliquots did not consistently reveal B. stearothermophilus colonies, the final values were determined to be <100 spores per gram of ash. (Several samples had no spores detected at all, ND, and were assigned <0.5 spores per gram of ash). A quantitative summary of the analytical data used to compile this data is shown in Appendix E.3.

2.9.5 Microbial Survivability in Pipes

Three pipe samples were loaded into the incinerator during each test day. The pipes were recovered the following morning during ash removal. After allowing the pipes to cool, the inner containers were removed from the outer containers and sent to the laboratory for analysis. The entire contents of the pipe were rinsed, filtered, and cultured.

Microbial Survivability in pipes is presented in Table 2-38. Results ranged from not-detected to too numerous to count (TNTC). The TNTC results were assigned a value of greater than 200 spores (>200). All runs except Run 6 showed some spore survivability in the pipe samples.

TABLE 2-35. VIABLE SPORE EMISSIONS;
CENTRAL CAROLINA HOSPITAL (1990)

RUN NUMBER	FEED RATE/ FREQUENCY/TYPE (lb/hr/min)	NUMBER OF INDICATOR SPORES IN ALIQUOT (spores/100 ml)	NUMBER OF INDICATOR SPORES IN SAMPLE (spores)	CONCENTRATION OF INDICATOR SPORES IN FLUE GAS (spores/dscm)	NUMBER OF INDICATOR SPORES EXITING STACK DURING TEST PERIOD (spores)
1	100/15-P	ND	ND	ND	<3.84E+04
3	100/15-P	~200	~8785	~2183	~13.8E+06
10	100/15-P	ND	ND	ND	<3.22E+04
2	250/15-M	ND	ND	ND	<4.36E+04
4	250/15-M	ND	ND	ND	<4.31E+04
8	250/15-M	>200 a	>9761	>2572	>15.5E+06
5	160/15-P	<200 b	<8378	<2289	<13.5E+06
6	160/15-P	~30	~1166	~271	~18.5E+05
9	160/15-P	~100	~4567	~1120	~6.94E+06

NOTE: Values taken from averages of repetitive analytical runs as presented in the analytical quantitative summary in Appendix E.3
All calculations are shown in Appendix F.
ND = Not Detected. Detection limits were determined to be 0.5 spores/100ml (1 spore/100 ml aliquot / 2).

a Maximum value could not be determined for this flue gas sample (see Appendix E.3).
b One aliquot out of nine repitions resulted in "Too Numerous To Count" (TNTC), and, therefore, was assigned the above detection limit.

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TABLE 2-36. INDICATOR SPORE EMISSIONS SAMPLING AND FLUE GAS PARAMETERS; CENTRAL CAROLINA HOSPITAL (1990)

RUN NUMBER:	1A	1B	AVERAGE	3A	3B	AVERAGE	10A	10B	AVERAGE
Total Sampling Time (min.)	120	120	NA	120	120	NA	120	120	NA
Average Stack Temperature (°F)	644	796	720	688	741	714	693	745	719
Carbon Dioxide Concentration (%V)	3.08	3.26	3.17	3.25	3.1	3.175	3.51	3.28	3.395
Oxygen Concentration (%V)	15.7	15.6	15.7	15.8	16.2	16.0	15.4	16.0	15.7
Average Sampling Rate (dscfm)	0.592	0.600	0.596	0.589	0.596	0.592	0.611	0.594	0.603
Standard Metered Volume,Vm(std) (dscm)	2.011	2.039	2.025	2.000	2.025	2.012	2.077	2.019	2.048
Stack Moisture (%V)	9.39	9.39	9.39	9.57	9.57	9.57	7.88	7.88	7.88
Volumetric Flow Rate (acfm)	2180	2472	2326	2279	2349	2314	2381	2358	2370
Volumetric Flow Rate (dscmm)	26.7	26.6	26.7	26.6	26.2	26.4	27.5	26.1	26.8
Percent Isokinetic	95.2	96.9	NA	95.1	96.1	NA	95.4	96.3	NA

RUN NUMBER:	2A	2B	AVERAGE	4A	4B	AVERAGE	8A	8B	AVERAGE
Total Sampling Time (min.)	105	135	NA	120	120	NA	120	120	NA
Average Stack Temperature (°F)	848	757	802	707	706	706	770	708	739
Carbon Dioxide Concentration (%V)	4.40	3.41	3.91	4.22	4.01	4.12	4.17	3.59	3.88
Oxygen Concentration (%V)	14.5	16.3	15.4	14.85	15.16	15.005	15.09	15.98	15.535
Average Sampling Rate (dscfm)	0.592	0.544	0.568	0.555	0.574	0.565	0.560	0.557	0.558
Standard Metered Volume,Vm(std) (dscm)	1.760	2.081	1.921	1.885	1.952	1.919	1.904	1.891	1.897
Stack Moisture (%V)	7.98	7.98	7.98	7.35	7.35	7.35	6.78	6.78	6.78
Volumetric Flow Rate (acfm)	2604	2177	2391	2141	2238	2190	2268	2056	2162
Volumetric Flow Rate (dscmm)	27.3	24.6	26.0	25.2	26.3	25.7	25.7	24.5	25.1
Percent Isokinetic	93.1	93.6	NA	94.8	92.2	NA	93.8	95.9	NA

RUN NUMBER:	5A	5B	AVERAGE	6A	6B	AVERAGE	9A	9B	AVERAGE
Total Sampling Time (min.)	120	120	NA	120	120	NA	120	120	NA
Average Stack Temperature (°F)	687	761	724	672	796	734	729	764	746
Carbon Dioxide Concentration (%V)	3.48	3.44	3.46	3.34	3.5	3.42	3.79	3.58	3.685
Oxygen Concentration (%V)	15.5	15.7	15.6	15.6	15.7	15.7	15.0	15.5	15.3
Average Sampling Rate (dscfm)	0.580	0.500	0.540	0.648	0.620	0.634	0.611	0.589	0.600
Standard Metered Volume,Vm(std) (dscm)	1.965	1.695	1.830	2.202	2.107	2.154	2.076	2.001	2.038
Stack Moisture (%V)	7.96	7.96	7.96	8.29	8.29	8.29	8.93	8.93	8.93
Volumetric Flow Rate (acfm)	2186	2024	2105	2414	2507	2461	2345	2232	2289
Volumetric Flow Rate (dscmm)	26.2	22.8	24.5	29.4	27.5	28.4	26.8	24.8	25.8
Percent Isokinetic	95.0	92.6	NA	94.7	95.2	NA	97.9	100.3	NA

NA = Not applicable.

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TABLE 2-37. VIABLE SPORES IN ASH;
CENTRAL CAROLINA HOSPITAL (1990)

RUN NUMBER	CONCENTRATION OF INDICATOR SPORES IN ASH (spores/g ash)	NUMBER OF INDICATOR SPORES EXITING INCINERATOR IN ASH
1	<100	<9.6E+05
3	<100	<1.0E+06
10	ND	<3.9+03
2	<100	<6.3E+06
4	<100	<7.8E+06
8	<100	<6.2E+06
5	ND	<1.02E+04
6	<100	<1.9E+06
9	ND	<1.75E+04

Note: Values were taken from the average of replicate analyses as presented in the analytical quantitative summary in Appendix E.3.

ND = Not Detected. Detection limits for these samples were determined to be 0.5 spores / gram ash(1 spore/g ash/2). All calculations are shown in Appendix F.

Detection limits for all other samples were determined to be 1 spore/1 ml filtration or 100 spores/g ash.

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TABLE 2-38. VIABLE SPORES IN PIPES; CENTRAL CAROLINA HOSPITAL (1990)

RUN NUMBER	SAMPLE ID	LOADING ORDER	PIPE SIZE	APPROXIMATE TEMPERATURE RANGE (deg F)	NUMBER OF INDICATOR SPORES DETECTED (spores)
1	CCH-085	2	L	1750 - 2000	14
	CCH-086	3	L	1750 - 2000	3
	CCH-087	2	S	2000 - 2200	0
	CCH-088	3	S	2000 - 2200	1
	CCH-089	1	L	1750 - 2000	20
	CCH-090	1	S	1500 - 1750	>200
2	CCH-096	3	S	1750 - 2000	>1
	CCH-097	2	S	750 - 1000	>32
	CCH-098	1	S	750 - 1000	20
	CCH-099	3	L	750 - 1000	>20
	CCH-100	2	L	1250 - 1500	3
	CCH-101	1	L	750 - 1000	7
3	CCH-154	3	L	1750 - 2000	0
	CCH-155	3	S	1750 - 2000	>1
	CCH-156	2	L	1500 - 1750	0
	CCH-157	2	S	1750 - 2000	1
	CCH-158	1	S	1750 - 2000	4
	CCH-159	1	L	1750 - 2000	5
4	CCH-175	1	L	1500 - 1750	0
	CCH-176	3	S	1750 - 2000	2
	CCH-177	3	L	1500 - 1750	4
	CCH-178	2	S	1250 - 1500	3
	CCH-179	2	L	1000 - 1250	0
	CCH-180	1	S	750 - 1000	0
5	CCH-193	3	L	1500 - 1750	>200
	CCH-194	3	S	750 - 1000	0
	CCH-195	2	L	750 - 1000	>200
	CCH-196	1	L	750 - 1000	>166
	CCH-197	2	S	1250 - 1500	79
	CCH-198	1	S	750 - 1000	0

NA = Not available at this time

L = Large (2.25" diameter); S = Small (1.5 " diameter)

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TABLE 2-38. VIABLE SPORES IN PIPES (continued);
CENTRAL CAROLINA HOSPITAL (1990)

RUN NUMBER	SAMPLE ID	LOADING ORDER	PIPE SIZE	APPROXIMATE TEMPERATURE RANGE (deg F)	NUMBER OF INDICATOR SPORES DETECTED (spores)
6	CCH-280	NA	L	NA	0
	CCH-281	NA	S	NA	0
	CCH-282	NA	L	NA	0
	CCH-283	NA	S	NA	0
	CCH-284	NA	L	NA	0
	CCH-285	NA	S	NA	0
8	CCH-292	NA	S	NA	1
	CCH-293	NA	L	NA	17
	CCH-294	NA	L	NA	0
	CCH-295	NA	L	NA	2
	CCH-296	NA	S	NA	0
	CCH-297	NA	S	NA	0
9	CCH-304	NA	L	NA	0
	CCH-305	NA	S	NA	1
	CCH-306	NA	L	NA	0
	CCH-307	NA	L	NA	0
	CCH-308	NA	S	NA	1
	CCH-309	NA	S	NA	0
10	CCH-378	NA	L	NA	0
	CCH-379	NA	L	NA	1
	CCH-380	NA	S	NA	0
	CCH-381	NA	L	NA	0
	CCH-382	NA	S	NA	0
	CCH-383	NA	S	NA	0

NA = Not available at this time
L = Large (2.25" diameter); S = Small (1.5 " diameter)

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As part of the microbial survivability in pipes method development, a single pipe's temperature was measured and recorded during four test runs (Runs 7 through 10). A large pipe (2 in. ID) containing no spores was configured with a thermocouple placed through a hole drilled in one of the capped ends. The pipe was placed in the incinerator and internal pipe temperatures were measured and manually recorded. Temperatures varied considerably. A general range was from 500 to 1500°F. However, no data analysis has been completed (averages, standard deviation, etc.). All pipe temperature data is listed in Appendix B.4.

2.10 PARTICLE SIZE DISTRIBUTION RESULTS

Six PSD test runs were conducted during the Central Carolina Hospital MWI test program. An eight stage MK III cascade impactor sampling device was used (See Section 5.9 for PSD Method). Following a test, the impactor was inspected to determine if there was adequate particle loading on each of the filter stages. A properly loaded impactor has distinct particulate "piles" under each stage's acceleration jets (holes). An underloaded impactor is evidenced by clean, undisturbed filters while an over-loaded impactor has particulate piles which overlap and appear to have "broken-up" (re-entrainment). An assessment of the quality of particulate loading was made by the recovery technician with observations noted on the PSD field data sheets (See Appendix A.6). Of those six PSD runs, the first two did not meet recovery QC objectives and therefore are not included in these results (Raw Field Data and Analytical data are shown in Appendix A.6 and E.5). The test results for PSD Runs 3 through 6 will be reported in the following section.

The PSD Runs 3 and 4 were conducted on September 26, 1990 during test No. 7. Other results from this test No. were not reported due to an invalidated CDD/CDF run (See Section 2.2). Test No. 7 was conducted during Condition 2 (250 lbs/hr, 15 minute long cycle, 1600°F). The PSD Runs 5 and 6 were conducted on September 28, 1990 and October 2, 1990 under Conditions 3 and 1, respectively.

Tables 2-39 and 2-40 report the results from PSD Runs 3 and 4 (Condition 2), respectively. Approximately 70 percent of the particulate was less than 8.8 um.

TABLE 2-39. PSD RUN 3 RESULTS (TEST NO 7);
CENTRAL CAROLINA HOSPITAL (1990)

FLUE GAS AND SAMPLING PARAMETERS	
Total Sampling Time (min.)	2.5
Average Stack Temperature (°F)	1122.00
Average Sampling Rate (dscfm)	0.2960
Standard Metered Volume, Vm(std) (dscf)	0.7320
Standard Metered Volume, Vm(std) (dscm)	0.021
Stack Moisture (%V)	6.8100
Percent Isokinetic	111.0
Date	09/26/90

STAGE	Dp50 (microns)	NET WEIGHT (grams)	MASS FRACTION	MASS FRACTION LESS THAN	INTERVAL GEOMETRIC MIDPOINT (microns)	dM/dlog DP (gr/dscf)	CONCENTRATION (gr/dscf)
Prelim & 1	13.2	0.06236	0.1978	0.8022*	25.7	2.1019	1.2161
2	8.65	0.03040	0.0964	0.7057	10.7	3.2332	0.5928
3	5.65	0.03014	0.0956	0.6101	6.99	3.1749	0.5877
4	3.99	0.03238	0.1027	0.5074	4.75	4.1935	0.6314
5	2.37	0.03334	0.1058	0.4016	3.08	2.8803	0.6501
6	1.37	0.02838	0.0900	0.3116	1.80	2.3096	0.5533
7	0.866	0.03056	0.0970	0.2146	1.09	3.0046	0.5959
8	0.588	0.03127	0.0992	0.1154	0.714	3.6283	0.6097
Back-up		0.03639	0.1154	0.0000*	0.054	0.3426	0.7095
Total		0.31521	1.0000				

* These values assume top end and bottom end dp50s of 50 and .005 um.

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TABLE 2-40. PSD RUN 4 RESULTS (TEST NO 7);
CENTRAL CAROLINA HOSPITAL (1990)

FLUE GAS AND SAMPLING PARAMETERS	
Total Sampling Time (min.)	15
Average Stack Temperature (°F)	773
Average Sampling Rate (dscfm)	0.305
Standard Metered Volume, Vm(std) (dscf)	4.57
Standard Metered Volume, Vm(std) (dscm)	0.129
Stack Moisture (%V)	6.81
Percent Isokinetic	111
Date	9/26/90

STAGE	Dp50 (microns)	NET WEIGHT (grams)	MASS FRACTION	MASS FRACTION LESS THAN	INTERVAL GEOMETRIC MIDPOINT (microns)	dM/dlog Dp (gr/dscf)	CONCENTRATION gr/dscf
Prelim & 1	13.7	0.07749	0.2050	0.795*	26.2	0.4654	0.2618
2	8.97	0.03221	0.0852	0.710	11.1	0.5932	0.1088
3	5.86	0.03592	0.0950	0.615	7.25	0.6547	0.1213
4	4.14	0.03533	0.0935	0.521	4.92	0.7908	0.1194
5	2.45	0.03725	0.0985	0.423	3.19	0.5540	0.1258
6	1.40	0.03849	0.1018	0.321	1.85	0.5329	0.1300
7	0.865	0.03986	0.1055	0.215	1.10	0.6458	0.1347
8	0.559	0.03836	0.1015	0.114	0.696	0.6841	0.1296
Back-up		0.04310	0.1140	0.000*	0.053	0.0711	0.1456
Total		0.37799	1.0000				

* These values assume top end and bottom end dp50s of 50 and .005 um.

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Table 2-41 reports the results for PSD Run 5 (Condition 3). Again, approximately 70 percent of the particulate was less than 9 um. Grainloading (concentration-grains/dry standard cubic foot) was much lower during this condition than it was during Condition 2 (0.04 gr/dscf total PM for Condition 3 versus 0.7 and 0.1 gr/dscf for total PM for Condition 2).

Table 2-42 reports the results from PSD Run 6 (Condition 1). Again, approximately 70 percent of the particulate is less than 9 um. Grainloading is comparable to that observed during Condition 3.

Figures 2-1 through 2-4 show the log-normal plots of PSD Runs 3 through 6, respectively. The log of Particle cut size (Dp50) at each impactor stage is plotted against mass fraction of particulate less than that Dp50, on a probability (normal) scale. Linear regressions analyses were conducted and the correlation coefficients (R^2) are shown on each figure.

2.11 CDD/CDF EMISSION VALUES INCORPORATING THE TOLUIENE RECOVERY RESULTS

In accordance with EPA Method 23, a final toluene rinse was completed on the CDD/CDF sampling train after the methylene chloride ($MeCl_2$) rinse procedure. This was done to determine how well the $MeCl_2$ was collecting all of the CDD/CDF material. As prescribed in the method, these values were to be used only as a QA indicator and are not to be incorporated into the emission values. Therefore, a full presentation of the data is given in Section 6. However, to gain perspective into how these values effect the gas phase CDD/CDF concentrations, stack gas CDD/CDF concentrations incorporating the toluene recovery amounts are given in Tables 2-43 through 2-45. Concentrations are given corrected to 7 percent O_2 as well as in 2378 TCDD Toxic Equivalents. Results for each test run as well as the overall condition averages are given. These values can be directly compared to the non-toluene CDD/CDF gas concentrations shown in Tables 2-9, 2-10, and 2-11.

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TABLE 2-41. PSD RUN 5 RESULTS (TEST NO 9);
CENTRAL CAROLINA HOSPITAL (1990)

FLUE GAS AND SAMPLING PARAMETERS	
Total Sampling Time (min.)	45
Average Stack Temperature (°F)	789
Average Sampling Rate (dscfm)	0.299
Standard Metered Volume, Vm(std) (dscf)	13.5
Standard Metered Volume, Vm(std) (dscm)	0.382
Stack Moisture (%V)	6.78
Percent Isokinetic	85.6
Date	9/28/90

STAGE	Dp50 (microns)	NET WEIGHT (grams)	MASS FRACTION	MASS FRACTION LESS THAN	INTERVAL GEOMETRIC MIDPOINT (microns)	dM/dlog DP (gr/dscf)	CONCENTRATION (gr/dscf)
Prelim & 1	13.8	0.05878	0.1821	0.8179*	26.3	0.1207	0.0673
2	9.07	0.03241	0.1004	0.7175	11.2	0.2024	0.0371
3	5.92	0.03293	0.1020	0.6155	7.33	0.2035	0.0377
4	4.18	0.03372	0.1045	0.5111	4.98	0.2559	0.0386
5	2.48	0.03763	0.1165	0.3945	3.22	0.1898	0.0431
6	1.41	0.01637	0.0507	0.3438	1.87	0.0769	0.0188
7	0.875	0.03404	0.1054	0.2384	1.11	0.1871	0.0390
8	0.566	0.03203	0.0992	0.1392	0.704	0.1939	0.0367
Back-up		0.04493	0.1392	0.0000*	0.053	0.0251	0.0515
Total		0.32283	1.0000				

* These values assume top end and bottom end dp50s of 50 and .005 um.

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TABLE 2-42. PSD RUN 6 RESULTS (TEST NO 10);
CENTRAL CAROLINA HOSPITAL (1990)

FLUE GAS AND SAMPLING PARAMETERS	
Total Sampling Time (min.)	60
Average Stack Temperature (°F)	723
Average Sampling Rate (dacfm)	0.293
Standard Metered Volume, Vm(std) (dscf)	17.6
Standard Metered Volume, Vm(std) (dscm)	0.498
Stack Moisture (%V)	7.88
Percent Isokinetic	88.8
Date	10/02/90

STAGE	Dp50 (microns)	Net Weight (grams)	MASS FRACTION	MASS FRACTION LESS THAN	INTERVAL GEOMETRIC MIDPOINT (microns)	dM/dlog DP (gr/dscf)	CONCENTRATION (gr/dscf)
Prelim & 1	13.7870	0.05572	0.1796	0.8204	26.2555	8.406E-02	0.047031
2	9.0369	0.02918	0.0941	0.7263	11.1620	1.343E-01	0.024632
3	5.8974	0.02817	0.0908	0.6356	7.3002	1.283E-01	0.023775
4	4.1655	0.03175	0.1023	0.5332	4.9564	1.775E-01	0.026797
5	2.4684	0.02752	0.0887	0.4445	3.2066	1.022E-01	0.023226
6	1.4060	0.03336	0.1075	0.3370	1.8629	1.152E-01	0.028160
7	0.8677	0.02659	0.0857	0.2513	1.1045	1.071E-01	0.022445
8	0.5579	0.02842	0.0916	0.1597	0.6958	1.250E-01	0.023986
Back-up		0.04955	0.1597	0.0000	0.0528	2.043E-02	0.041822
Total		0.31023	1.0000				

* These values assume top end and bottom end dp50s of 50 and .005 um.

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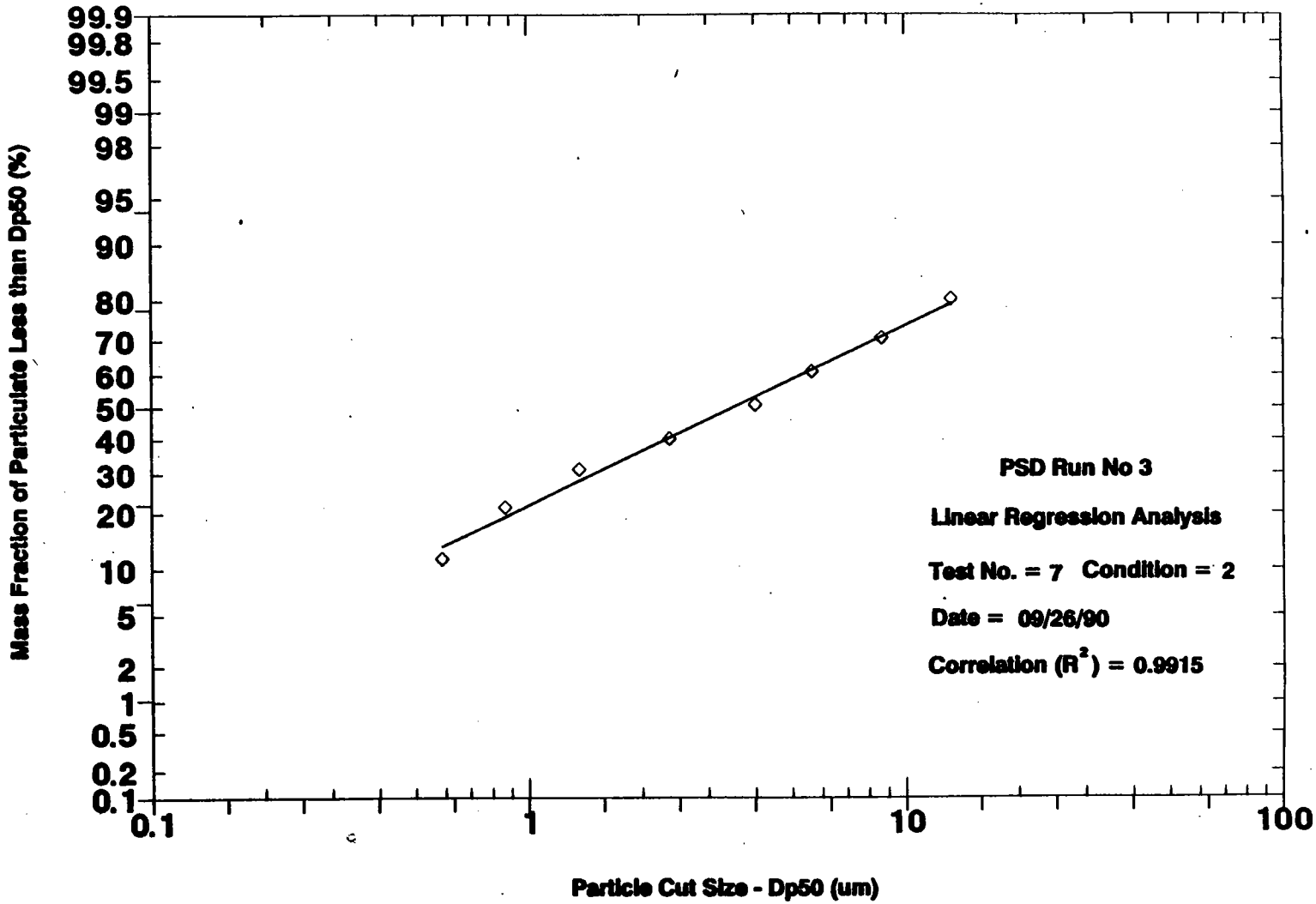

FIGURE 2-1. Run 3 (Test No 7) PSD Results - Log Particle Size vs Mass Fraction Less Than Particle Size. Central Carolina Hospital (1990)

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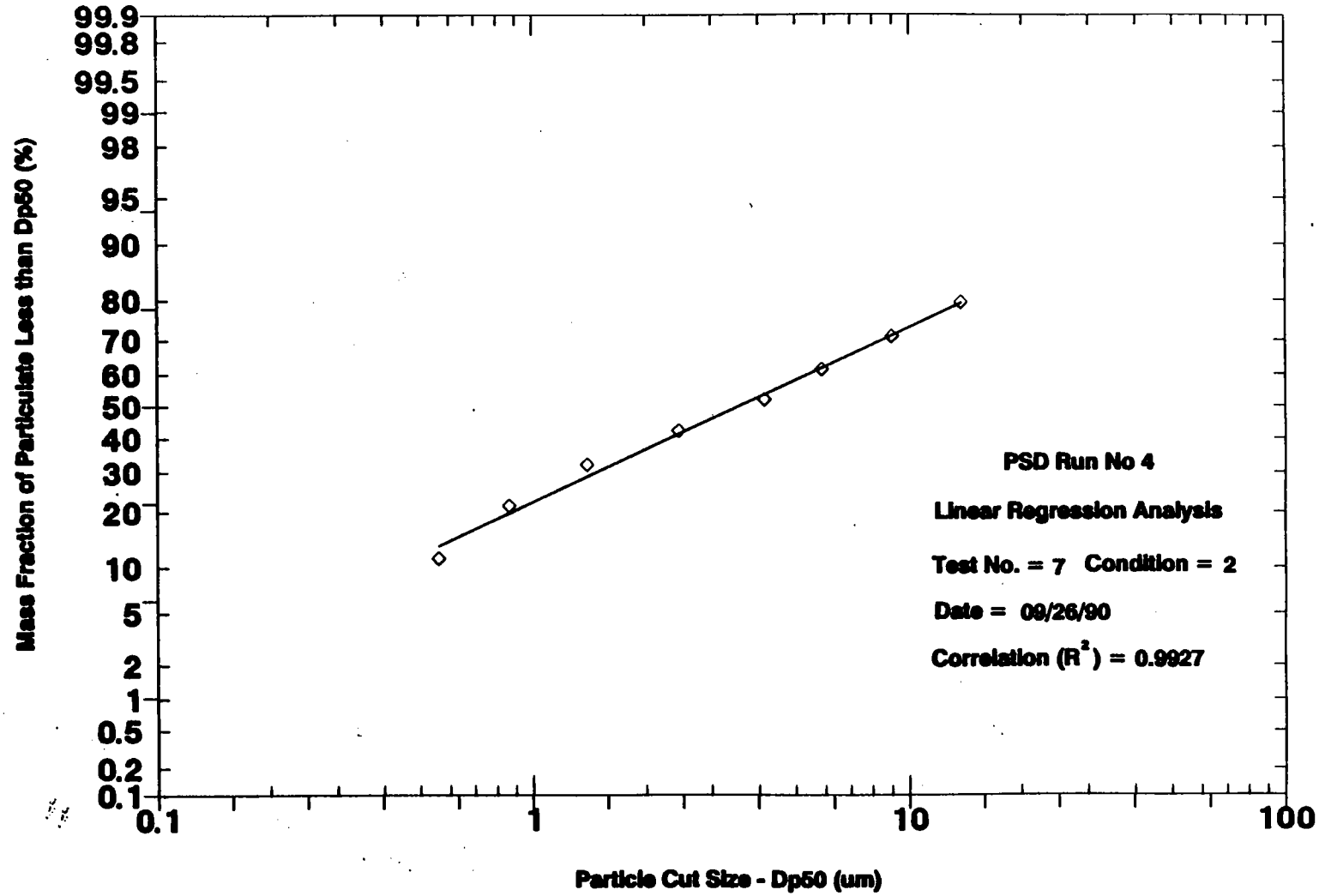

FIGURE 2-2. Run 4 (Test No 7) PSD Results - Log Particle Size vs Mass Fraction Less Than Particle Size. Central Carolina Hospital (1990)

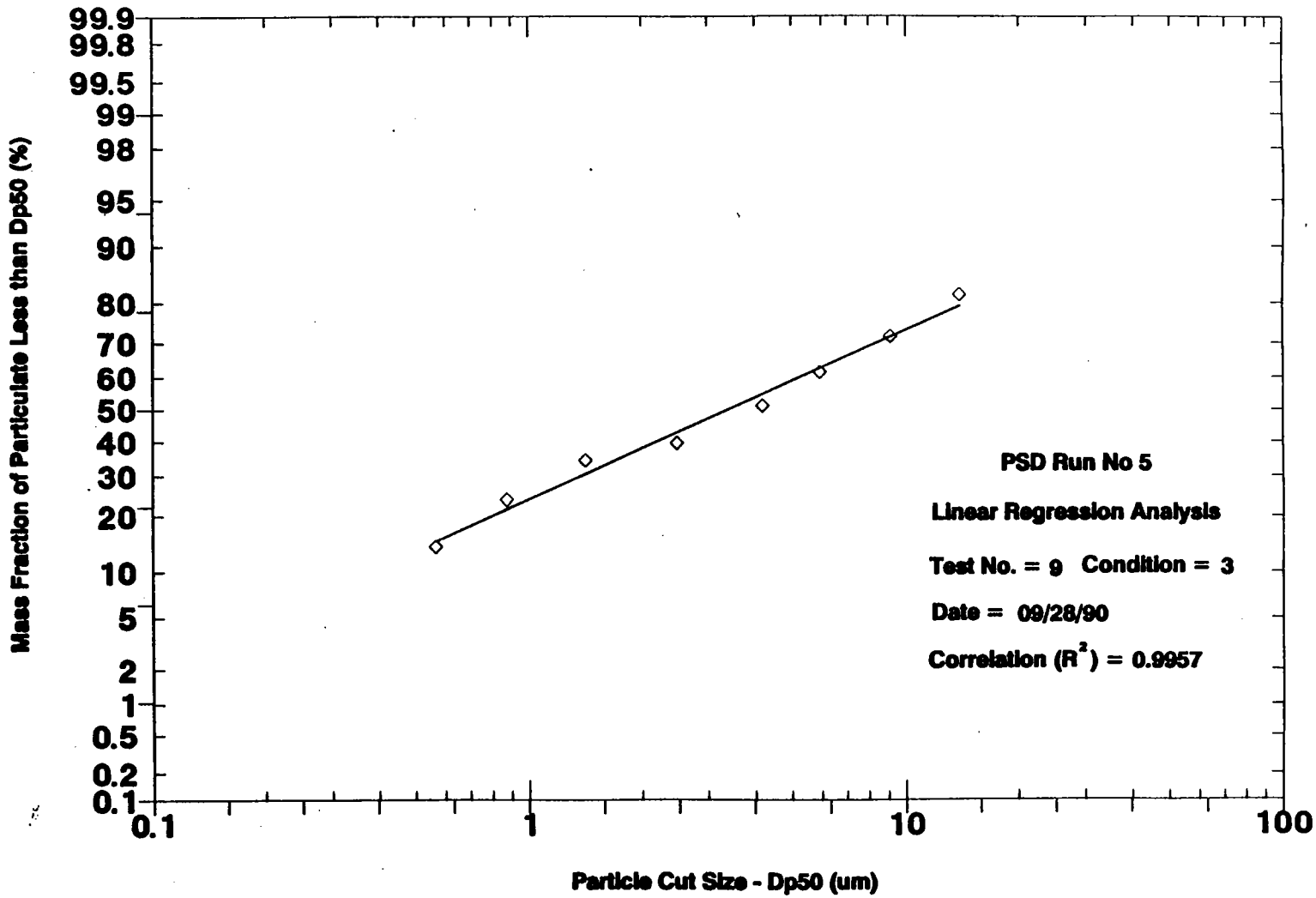

FIGURE 2-3. Run 5 (Test No 9) PSD Results - Log Particle Size vs Mass Fraction Less Than Particle Size. Central Carolina Hospital (1990)

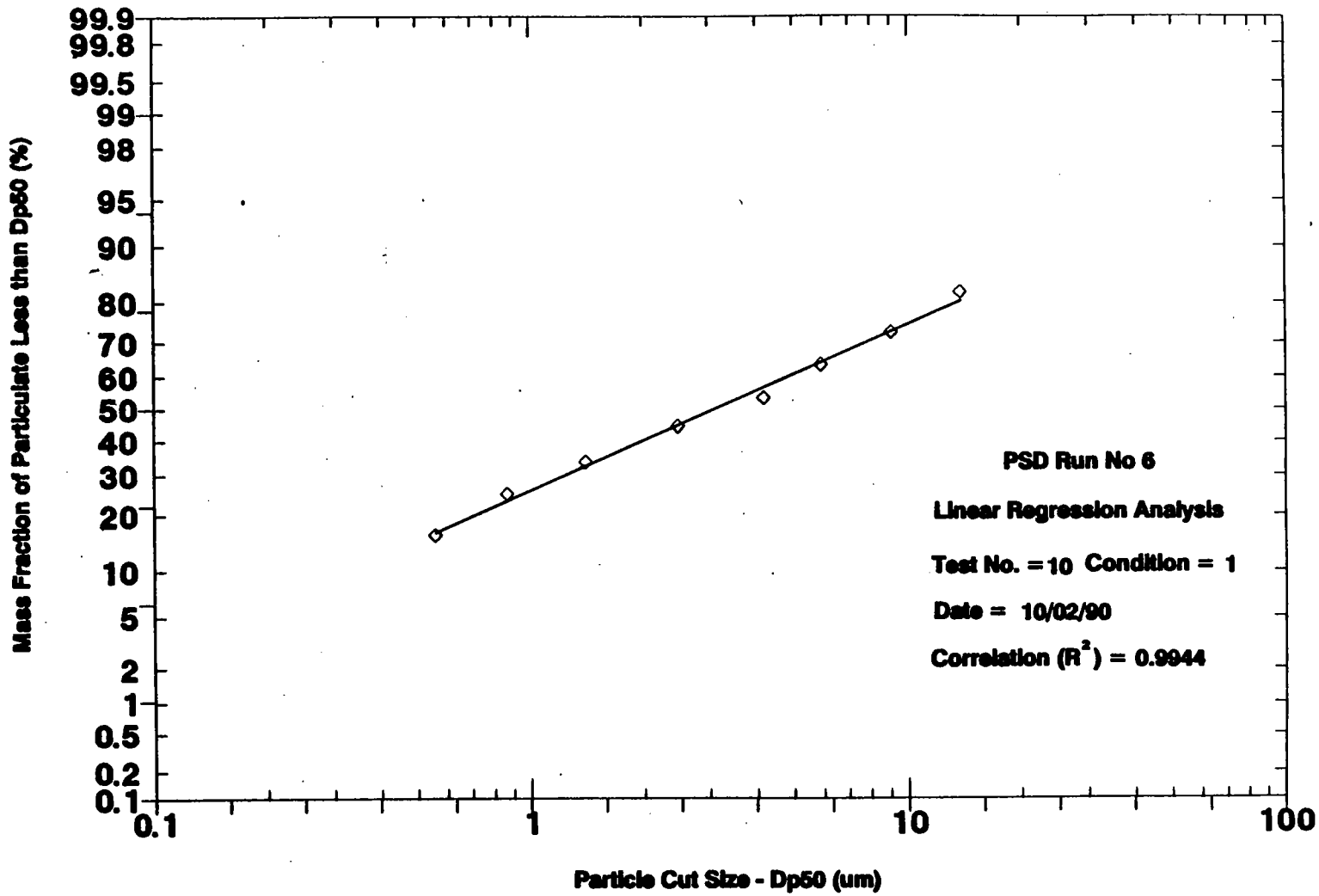

FIGURE 2-4. Run 6 (Test No 10) PSD Results - Log Particle Size vs Mass Fraction Less Than Particle Size. Central Carolina Hospital (1990)

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TABLE 2-43. CDD/CDF STACK GAS CONCENTRATIONS AND 2378 TOXIC EQUIVALENT STACK GAS CONCENTRATIONS ADJUSTED TO 7 PERCENT O2 FOR CONDITION 1 INCORPORATING THE TOLUENE RECOVERY RESULTS; CENTRAL CAROLINA HOSPITAL (1990)

CONGENER	CONCENTRATION a (ng/dscm, adjusted to 7 percent O2)				2378-TCDD b TOXIC EQUIV. FACTOR	2378 TOXIC EQUIVALENCIES (ng/dscm, adjusted to 7 percent O2)			
	RUN 1	RUN 3	RUN 10	AVERAGE		RUN 1	RUN 3	RUN 10	AVERAGE
DIOXINS									
2378 TCDD	0.59	(1.221)	(0.349)	0.72	1.00000	0.588	(1.221)	(0.349)	0.719
Other TCDD	16.68	159.08	18.25	64.67	0.00000	0.000	0.000	0.000	0.000
12378 PCDD	1.40	4.69	1.14	2.41	0.50000	0.700	2.347	0.568	1.205
Other PCDD	14.76	130.98	18.47	54.73	0.00000	0.000	0.000	0.000	0.000
123478 HxCDD	0.91	4.59	1.37	2.29	0.10000	0.091	0.459	0.137	0.229
123678 HxCDD	1.41	7.45	2.72	3.86	0.10000	0.141	0.745	0.272	0.386
123789 HxCDD	2.99	14.28	4.05	7.11	0.10000	0.299	1.428	0.405	0.711
Other HxCDD	13.83	103.21	25.43	47.49	0.00000	0.000	0.000	0.000	0.000
1234678-HpCDD	8.02	42.62	20.06	23.56	0.01000	0.080	0.426	0.201	0.236
Other HpCDD	9.60	52.43	22.47	28.17	0.00000	0.000	0.000	0.000	0.000
Octa-CDD	9.62	54.75	25.57	29.98	0.00100	0.010	0.055	0.026	0.030
Total CDD	79.8	575	140	265		1.909	6.681	1.957	3.516
FURANS									
2378 TCDF	1.97	8.21	2.47	4.22	0.10000	0.197	0.821	0.247	0.422
Other TCDF	66.75	482.41	83.37	210.84	0.00000	0.000	0.000	0.000	0.000
12378 PCDF	2.99	11.53	3.74	6.09	0.05000	0.149	0.577	0.187	0.304
23478 PCDF	5.70	30.31	9.02	15.01	0.50000	2.852	15.156	4.511	7.506
Other PCDF	63.59	365.18	74.40	167.73	0.00000	0.000	0.000	0.000	0.000
123478 HxCDF	7.01	53.07	12.46	24.18	0.10000	0.701	5.307	1.246	2.418
123678 HxCDF	3.64	22.05	6.36	10.68	0.10000	0.364	2.205	0.636	1.068
234678 HxCDF	4.48	45.72	12.82	21.01	0.10000	0.448	4.572	1.282	2.101
123789 HxCDF	0.17	1.35	0.60	0.71	0.10000	0.017	0.135	0.060	0.071
Other HxCDF	21.60	150.10	41.92	71.21	0.00000	0.000	0.000	0.000	0.000
1234678-HpCDF	8.99	83.02	23.44	38.48	0.01000	0.090	0.830	0.234	0.385
1234789-HpCDF	1.12	12.85	5.17	6.38	0.01000	0.011	0.129	0.052	0.064
Other HpCDF	6.46	72.60	23.32	34.13	0.00000	0.000	0.000	0.000	0.000
Octa-CDF	5.41	84.72	36.81	42.31	0.00100	0.005	0.085	0.037	0.042
Total CDF	200	1,420	336	653		4.84	29.8	8.49	14.4
Total CDD+CDF	280	2,000	476	918		6.74	36.5	10.4	17.9

a ng/dscm = nanogram per dry standard cubic meter. Standard conditions are defined as 1 atm and 68° F.

b North Atlantic Treaty Organization, Committee on the Challenges of Modern Society. Pilot Study on International Information Exchange on Dioxins and Related Compounds: International Toxicity Equivalency Factor (I-TEF) Methods of Risk Assessment for Complex Mixtures of Dioxins and Related Compounds. Report No. 176, August 1988.

[ ] = minimum detection limit. ( ) = estimated maximum possible concentration.

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TABLE 2-44. CDD/CDF STACK GAS CONCENTRATIONS AND 2378 TOXIC EQUIVALENT STACK GAS CONCENTRATIONS ADJUSTED TO 7 PERCENT O2 FOR CONDITION 2 INCORPORATING THE TOLUENE RECOVERY RESULTS; CENTRAL CAROLINA HOSPITAL (1990)

CONGENER	CONCENTRATION a (ng/dscm, adjusted to 7 percent O2)				2378-TCDD b TOXIC EQUIV. FACTOR	2378 TOXIC EQUIVALENCIES (ng/dscm, adjusted to 7 percent O2)			
	RUN 2	RUN 4	RUN 8	AVERAGE		RUN 2	RUN 4	RUN 8	AVERAGE
DIOXINS									
2378 TCDD	19.38	46.44	22.24	29.35	1.00000	19.385	46.442	22.237	29.355
Other TCDD	455.05	824.60	560.19	613.28	0.00000	0.000	0.000	0.000	0.000
12378 PCDD	60.21	181.92	112.93	118.35	0.50000	30.106	90.962	56.463	59.177
Other PCDD	398.94	1217.39	728.62	781.65	0.00000	0.000	0.000	0.000	0.000
123478 HxCDD	57.25	156.57	131.43	115.08	0.10000	5.725	15.657	13.143	11.508
123678 HxCDD	67.67	199.42	136.73	134.61	0.10000	6.767	19.942	13.673	13.461
123789 HxCDD	120.43	378.72	245.24	248.13	0.10000	12.043	37.872	24.524	24.813
Other HxCDD	557.79	1486.85	1056.77	1033.80	0.00000	0.000	0.000	0.000	0.000
1234678-HpCDD	321.62	811.76	760.44	631.27	0.01000	3.216	8.118	7.604	6.313
Other HpCDD	336.68	885.18	827.45	683.10	0.00000	0.000	0.000	0.000	0.000
Octa-CDD	417.74	614.12	952.82	661.56	0.00100	0.418	0.614	0.953	0.662
Total CDD	2,810	6,800	5,530	5,050		77.7	220	139	145
FURANS									
2378 TCDF	59.03	171.50	10.49	80.34	0.10000	5.903	17.150	1.049	8.034
Other TCDF	1757.26	4822.55	394.11	2324.64	0.00000	0.000	0.000	0.000	0.000
12378 PCDF	169.40	697.96	251.50	372.95	0.05000	8.470	34.898	12.575	18.648
23478 PCDF	235.72	826.53	321.24	461.16	0.50000	117.862	413.265	160.620	230.582
Other PCDF	2706.91	11130.98	3882.92	5906.94	0.00000	0.000	0.000	0.000	0.000
123478 HxCDF	505.16	2011.66	1049.81	1188.88	0.10000	50.516	201.166	104.981	118.888
123678 HxCDF	303.09	1268.23	636.07	735.80	0.10000	30.309	126.823	63.607	73.580
234678 HxCDF	296.98	900.89	558.40	585.42	0.10000	29.698	90.089	55.840	58.542
123789 HxCDF	21.02	78.82	38.56	46.13	0.10000	2.102	7.882	3.856	4.613
Other HxCDF	1730.97	6804.35	3601.04	4045.45	0.00000	0.000	0.000	0.000	0.000
1234678-HpCDF	803.30	2562.79	1782.03	1716.04	0.01000	8.033	25.628	17.820	17.160
1234789-HpCDF	121.46	309.63	227.63	219.57	0.01000	1.215	3.096	2.276	2.196
Other HpCDF	647.03	1798.33	1342.50	1262.62	0.00000	0.000	0.000	0.000	0.000
Octa-CDF	560.44	785.47	838.12	728.01	0.00100	0.560	0.785	0.838	0.728
Total CDF	9,920	34,200	14,900	19,700		255	921	423	533
Total CDD+CDF	12,700	41,000	20,500	24,700		332	1,140	562	678

a ng/dscm = nanogram per dry standard cubic meter. Standard conditions are defined as 1 atm and 68° F.

b North Atlantic Treaty Organization, Committee on the Challenges of Modern Society. Pilot Study on International Information Exchange on Dioxins and Related Compounds: International Toxicity Equivalency Factor (I-TEF) Methods of Risk Assessment for Complex Mixtures of Dioxins and Related Compounds. Report No. 176, August 1988.

[ ] = minimum detection limit. ( ) = estimated maximum possible concentration.

TABLE 2-45. CDD/CDF STACK GAS CONCENTRATIONS AND 2378 TOXIC EQUIVALENT STACK GAS CONCENTRATIONS ADJUSTED TO 7 PERCENT O2 FOR CONDITION 3 INCORPORATING THE TOLUENE RECOVERY RESULTS; CENTRAL CAROLINA HOSPITAL (1990)

CONGENER	CONCENTRATION a (ng/dscm, adjusted to 7 percent O2)				2378-TCDD b TOXIC EQUIV. FACTOR	2378 TOXIC EQUIVALENCIES (ng/dscm, adjusted to 7 percent O2)			
	RUN 5	RUN 6	RUN 9	AVERAGE		RUN 5	RUN 6	RUN 9	AVERAGE
DIOXINS									
2378 TCDD	0.66	(0.198)	2.05	0.97	1.00000	0.657	(0.198)	2.048	0.968
Other TCDD	51.72	10.08	119.00	60.27	0.00000	0.000	0.000	0.000	0.000
12378 PCDD	1.73	0.62	4.75	2.37	0.50000	0.867	0.310	2.375	1.184
Other PCDD	32.51	10.38	95.08	45.99	0.00000	0.000	0.000	0.000	0.000
123478 HxCDD	1.10	0.51	2.79	1.47	0.10000	0.110	0.051	0.279	0.147
123678 HxCDD	1.64	0.86	4.26	2.26	0.10000	0.164	0.086	0.426	0.226
123789 HxCDD	3.38	1.62	7.05	4.02	0.10000	0.338	0.162	0.705	0.402
Other HxCDD	21.63	10.50	50.28	27.47	0.00000	0.000	0.000	0.000	0.000
1234678-HpCDD	11.32	5.69	19.30	12.10	0.01000	0.113	0.057	0.193	0.121
Other HpCDD	12.23	6.66	23.28	14.06	0.00000	0.000	0.000	0.000	0.000
Octa-CDD	15.70	7.15	25.06	15.97	0.00100	0.016	0.007	0.025	0.016
Total CDD	154	54.3	353	187		2.264	0.872	6.051	3.062
FURANS									
2378 TCDF	3.12	0.78	9.41	4.44	0.10000	0.312	0.078	0.941	0.444
Other TCDF	117.35	26.13	363.91	169.13	0.00000	0.000	0.000	0.000	0.000
12378 PCDF	3.74	1.44	10.25	5.14	0.05000	0.187	0.072	0.513	0.257
23478 PCDF	6.39	2.52	15.99	8.30	0.50000	3.194	1.260	7.995	4.150
Other PCDF	57.97	22.23	208.09	96.10	0.00000	0.000	0.000	0.000	0.000
123478 HxCDF	8.30	4.32	19.85	10.83	0.10000	0.830	0.432	1.985	1.083
123678 HxCDF	4.29	2.16	10.42	5.62	0.10000	0.429	0.216	1.042	0.562
234678 HxCDF	5.93	3.42	13.78	7.71	0.10000	0.593	0.342	1.378	0.771
123789 HxCDF	0.30	0.16	0.67	0.38	0.10000	0.030	0.016	0.067	0.038
Other HxCDF	24.36	12.35	65.93	34.21	0.00000	0.000	0.000	0.000	0.000
1234678-HpCDF	16.27	7.66	27.48	17.14	0.01000	0.163	0.077	0.275	0.171
1234789-HpCDF	2.10	1.53	3.61	2.41	0.01000	0.021	0.015	0.036	0.024
Other HpCDF	12.14	6.21	21.08	13.14	0.00000	0.000	0.000	0.000	0.000
Octa-CDF	10.95	12.09	21.74	14.93	0.00100	0.011	0.012	0.022	0.015
Total CDF	273	103	792	389		5.77	2.52	14.3	7.51
Total CDD+CDF	427	157	1,150	576		8.03	3.39	20.3	10.6

a ng/dscm = nanogram per dry standard cubic meter. Standard conditions are defined as 1 atm and 68° F.

b North Atlantic Treaty Organization, Committee on the Challenges of Modern Society. Pilot Study on International Information Exchange on Dioxins and Related Compounds: International Toxicity Equivalency Factor (I-TEF) Methods of Risk Assessment for Complex Mixtures of Dioxins and Related Compounds. Report No. 176, August 1988.

[ ] = minimum detection limit. ( ) = estimated maximum possible concentration.

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3.0 PROCESS DESCRIPTION AND OPERATION

3.1 FACILITY DESCRIPTION

Central Carolina Hospital is a 137-bed hospital located in Sanford, North Carolina. The medical waste incinerator (MWI) at this facility is a Consumat C-75-P with a design capacity of 176 pounds per hour (lb/hr) of Type IV (pathological) waste. The unit is also designed to burn general medical (nonpathological) waste at a rate of about 250 lb/hr. Two natural-gas-fired auxiliary burners in the primary chamber are used to maintain a pre-set minimum combustion temperature. Primary chamber temperatures normally range between 1200 and 1600°F. The hospital burns red bag waste, sharps containers, and a small amount of waste from nearby doctors' offices. Cafeteria waste, cardboard boxes, and general waste is compacted and landfilled.

The MWI is charged manually by opening a large refractory-lined charging door that opens at the front of the primary chamber. As a safety feature, the primary burners and blowers switch off automatically when the charging door is opened. The MWI is designed for 8 to 12 hours of operation each day, with ashes removed manually after cooldown.

The secondary chamber on this unit is sized for a design gas retention time of about 0.3 to 0.4 second. A gas-fired auxiliary burner in the secondary chamber is activated automatically when the temperature falls below a preset level, normally about 1600°F. Setpoint and actual temperatures in each chamber are displayed on a dial in the control panel.

Combustion air is supplied to the unit by two combustion air blowers, one for the primary chamber and one for the secondary chamber. The primary chamber blower supplies air to a plenum to which three separate air ducts are attached. One of these ducts supplies air to the combustion air ports inside the primary chamber. The 20 primary chamber air ports are equally spaced around the wall of the chamber, about 8 inches off the floor. The other two ducts supply air to the primary chamber burners. All three of these air ducts have manually adjustable dampers that are set at about

45 degrees (half way between totally open and totally closed) and were not moved during the test program.

The secondary chamber combustion air blower supplies air to the secondary burner and to the secondary chamber flameport area. The distribution of the airflow is controlled by a manual damper that was set at about 45 degrees and not adjusted during testing. The secondary chamber blower is on during operation of the MWI; there is no modulation of the airflow.

The Consumat "P"-designated MWI's are dual-mode units that are designed to burn either wet (pathological) or dry (general medical) waste. This is accomplished through the use of a "wet waste"-"dry waste" switch on the control panel door. The switch controls the operation of the primary chamber burners and the combustion air blowers. Teting was conducted with the unit operating in the "wet waste" mode for both types of waste. Burndown was set at 4 hours. The unit operates in the following manner while on the "dry waste" setting. During the initial warmup period, the primary chamber burners and blower are controlled by a timer that was set at 1.5 hours (adjustable up to 3 hours) and the temperature setpoint. If the temperature setpoint is reached before the timer has cut off, burners and blower shut off until the temperature falls to about 50°F below the setpoint, where both cut on again. Once the preset warmup time has elapsed, the burners shut off, but the blower operation is controlled by the temperature setpoint. If after 4 hours of operation, for example, the temperature falls 50°F below the setpoint, the blower (but not the burners) comes on until the setpoint is reached. The unit operates in this manner until burndown is completed. The secondary chamber blower runs continuously while the unit is in operation, and the burner cycles off and on based on the secondary chamber temperature setpoint.

The warmup timer is not operative in the "wet waste" mode. In this mode the primary chamber burners and blower always operate simultaneously. When started cold, the burners and blower run until the temperature setpoint is reached, then both cutoff. When the primary chamber temperature falls to 50°F below the setpoint, the burners and blower come back on. The unit operates in this manner until burndown is completed. The time for burndown is set by the burndown timer and is the same for both wet and

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dry settings. The secondary chamber blower is always on and the burner cycles off and on based on the secondary chamber temperature setpoint.

There is no add-on air pollution control device on this MWI. Because of the inadequate length of the original stack, a stack extension with sampling ports was added for the test.

The general medical waste burned during the test program was red bag waste generated by the hospital. Because the hospital does not generate sufficient pathological waste to charge at the target test condition, pathological waste was obtained from two research labs located in Research Triangle Park, North Carolina. This pathological waste, comprised of animal carcasses, was transported to the site in double plastic bags inside cardboard boxes.

3.2 PRETEST ACTIVITIES

The proposed test program at this MWI included operating the unit under three different operating conditions. Condition I was a reduced rate of pathological waste (about 100 lb/hr, 15 minute charges, 1900°F secondary chamber setpoint). Condition II was the design rate for general medical waste (about 250 lb/hr, 15 minute charges, 1600°F secondary chamber setpoint). Condition III was the design rate for pathological waste (about 160 to 170 lb/hr, 15 minute charges, 1600°F secondary chamber setpoint). A pretest trial burn was conducted for the two design conditions (Conditions II and III) to determine the operational readiness of the incinerator and the ability of the incinerator to operate successfully at the desired operating conditions. Because Condition I was defined as a "reduced" rate, it was decided that a pretest at this condition was not necessary if Condition III could be achieved.

3.2.1 Pretests--General Medical Waste

September 11, 1990

The purpose of this pretest was to investigate the operating procedures of the MWI and to verify that it could be successfully operated for a period of at least 4 to 5 hours at the waste charging rate specified for the test period. During this pretest, general medical waste was to be charged at a rate of about 240 to 250 lb/hr (60 lb/charge, 15 minute charging frequency). The secondary burner setpoint was 1600°F.

When Radian and MRI personnel arrived at the hospital at 9:00 am, the MWI was not operating and, when opened, it was obvious that the unit was cold and had not been operated for several days. Most of the loose ashes had been removed, exposing a 6- to 10-inch thick layer of solid, clinker-like material (slag) that had accumulated on the hearth.

Hospital personnel explained that, although Consumat representatives indicated that combustion capability of the unit would be improved if the air ports were routinely cleaned, the hospital employees were not familiar with the proper cleaning procedures. Loose ash was routinely cleaned out after each burn but the air ports were not cleaned.

At the request of EPA, removal of the slag was undertaken. By around 2 p.m. the slag had been removed from the hearth and 19 of the 20 air ports had been located and drilled out with a masonry drill bit. This was considered sufficient to allow the pretest activities to continue.

Soon after completing the cleaning activities, an attempt was made to fire up the unit to begin the preheat period. When the unit was switched on, the secondary burner and primary chamber blower came on, but the primary burners did not ignite. After some investigation, an engineering services employee from the hospital manually adjusted the reset timer, and one of the primary burners came on. Hospital personnel indicated earlier in the day that the second burner had not been functioning recently. This burner would not ignite despite repeated attempts. Further efforts to identify the problem with the second burner indicated that the relay that opens the main gas valve might be malfunctioning.

At about 3:30, the decision was made to proceed with the burning of some waste with only one burner on because the primary burners are not generally needed after the initial few charges have brought the temperature up in the primary. Sixty-pound charges were fed to the MWI every 15 minutes for the next 1.5 hours. At about 4:25, the incinerator operator had to leave, and a decision was made to load only 1 or 2 more charges and stop rather than locate another operator. The last charge was loaded at 4:52, and the last temperature was recorded at 5:07.

While a complete pretest was not performed during this visit, several important observations were made. It was agreed that a service technician (from Consumat, if possible) needed to be brought in to correct the problems with the inoperative primary burner and the reset timer and to calibrate the thermocouples. The accuracy of the thermocouples was questioned because the highest recorded secondary temperature was only about 1400°F. This is essentially the lowest that the gauge will read when the setpoint is 1600°F. The temperature gauge was, therefore, pegged at the bottom of the scale during the burn period. The primary chamber temperature went up to about 1500°F once during the burn. Based on previous experience and the fact that the MWI was burning exclusively high-plastic, red bag waste, this indicated that the recorded secondary chamber temperature seemed too low.

The unit operated reasonably well during the 1.5-hour burn. On the second charge, dense black smoke was emitted from the door seals, burner port assemblies, thermocouple wire conduits, and stack for a period of about 90 seconds. The smoke then gradually ceased. Subsequent charges did not cause a repeat of this heavy smoke, although while the charging door was open, there was a significant amount of smoke emitted from the door. When the door was closed, the unit operated without visible emissions.

The following actions were planned as a result of this pretest: (1) the hospital would attempt to arrange for a service technician to visit the site as soon as possible, (2) a tentative schedule of test-related activities for the next 2 weeks would be prepared for the hospital so that they could schedule the operators and the storage and burning of their waste, and (3) if possible, a complete pretest on medical waste would be conducted on Friday, September 14.

September 14, 1990

On Friday, September 14, 1990, a followup pretest was conducted at the hospital. The purpose of this pretest was to observe the repairs made to the MWI as a result of the problems that arose during the September 11, 1990, pretest visit. Southern Electronic Controls, Inc., had been contracted by Consumat to service and repair the unit.

The inspection and servicing of the MWI began by removing and checking the secondary chamber burner assembly. This unit was basically in good condition. A minor adjustment was made to the burner igniter so that a better spark would be produced. The burner assembly was then returned to the secondary chamber burner housing.

Each of the primary burners was then removed, inspected, and returned, with only minor adjustments to the igniters being required. The "flame rods," which detect the presence of a flame from the burner and keep the gas valve open, were also removed and cleaned.

The unit was then switched on and, as occurred on September 11, 1990, the secondary burner ignited, but the primary burners did not. A check of the switches and relays that control the operation of the burners followed. It was discovered that two of the lead wires in the control box were cross-wired. This error prevented the correct operation of the primary chamber burner timer. After the wiring problem was corrected, one primary burner ignited, but the other did not. The relay boxes for each burner were then inspected and a faulty relay was found that prevented the gas valve from opening on the inoperative burner. The relay was removed and cleaned, the contact points were realigned, and the unit was replaced. Upon restarting the unit, all burners ignited.

Although the equipment necessary to check the accuracy of the thermocouples was not available, the upper and lower thermocouple assemblies were removed and inspected. It was found that the upper unit was wired backwards and that some of the insulation had chipped off. The result of these problems was that the secondary chamber thermocouple did not work at all. After the unit was rewired, the indicated temperature fluctuated drastically because of the damage to the insulation. Therefore, a new thermocouple was installed. The lower unit appeared to operate properly.

After these repairs had been completed, the unit was restarted and appeared to operate as designed. Red bag waste was charged to the MWI at a rate of 200 to 240 lb/hr (50 to 60 lb/charge, with a 15-minute charging frequency) for about 4 hours. All of the MWI systems (burners, thermocouples, timers, and temperature displays) seemed to be operating properly; however, an accumlation of material in the primary chamber indicated that the charging rate might be too high.

The extent of the repairs that were required for this MWI were unexpected. The problems at this unit appear to have been compounded by a lack of routine maintenance, recent changes in hospital personnel, and the fact that the operation of the unit and the maintenance of the unit are under two different departments in the hospital administration. It became apparent during the September 11, 1990, pretest that certain basic repairs to the unit would be necessary prior to operating the unit in a manner that would be considered "typical" of 6- to 10-year-old units.

The current Director of Engineering at the facility was aware that the MWI was not in good working condition and was anxious for the unit to be repaired. Other hospital personnel appeared to be interested in learning about the proper operation and maintenance of the unit. It appears that the operating condition of this unit was poor, but that most of the problems were easily corrected and that proper attention by hospital staff is needed.

September 18, 1990

The target charge rate was revised based on observations made during the September 14, 1990, pretest. The purpose of this pretest was to confirm that the MWI could be operated at this revised target test condition (200 lb/hr; 50 lb every 15 minutes; secondary chamber setpoint of 1600°F) for at least 5 hours. Red bag medical waste generated at the hospital was charged to the unit during this pretest.

The MWI was cleaned out and allowed to preheat for about 15 minutes prior to loading the first charge. At 11:15 am, the first charge of the day was placed in the incinerator. Temperature readings were taken immediately after the loading door was closed and at 5-minute intervals thereafter. Between 11:15 am and 4:15 pm, 19 charges ranging from 45.3 to 56.7 lb were loaded into the MWI at 15-minute intervals.

The following observations were made during the pretest burn:

1. The temperature in the primary chamber climbed to about 1300°F (the setpoint) in about 30 minutes, and after about 1 hour it had reached 1500°F. The temperature stayed between 1400° and 1500°F for the remainder of the burn period.

2. The secondary chamber temperature was very erratic and was influenced greatly by the charging cycle and the condition of the primary burners/blowers. When the

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primary burners are on, the secondary chamber temperature peaks are much higher than if the primary burners are off. The secondary chamber temperature peaks about 5 minutes after each charge, and the peaks tended to get higher after the unit had been operating for several hours. Very high peaks also occurred during the first hour while the primary burners were operating.

3. Near the end of the burn period, the ash bed in the unit had become so high that it was causing some difficulty in loading additional waste. Flames and dense black smoke came out when the charging door was opened, and large bags were difficult to load because the ash bed restricted access to the interior of the unit.

4. The unit appeared to operate well during the pretest; there was very little smoke from the stack, the temperatures were fairly stable within the expected range, and the burners/blowers cycled off and on as expected. The most obvious problem observed during the pretest was the continuing accumulation of material in the primary chamber. It was apparent that the unit was not capable of burning the waste completely at the charge rate being used. By the end of the burn period, the primary chamber was so full that it was difficult to charge.

When the incinerator was opened the following morning a large accumulation of hot, smoldering material was found in the primary chamber. Burnout was poor in terms of quality and quantity. The material flamed up immediately when efforts to remove it began. As was the case with other MWI's tested, this unit appears to be significantly overrated in terms of the quantity of red bag waste that can be burned per hour. Therefore, the charge rate for actual testing was further reduced to 160 lb/hr.

3.2.2 Pretests--Pathological Waste

September 19, 1990

The purpose of this pretest was to determine if the MWI could be operated at the target test condition (160 lb/hr; 40 lb every 15 minutes; 1600°F secondary chamber setpoint) for at least 4 hours. Pathological waste was charged to the unit during this pretest.

After the ash had been removed, the unit was allowed to preheat for about 40 minutes before charging began. The first charge was loaded into the unit at 1:20 pm.

The first few boxes ranged from 43 to 57 lb in weight. It was decided that 20-minute charging cycles would be used because the boxes were somewhat heavier than expected and no one believed that the boxes should be opened. The target feed rate was changed to about 55 lb every 20 minutes.

Because of the size of the large boxes, it was very difficult to load two in the same charge. The first box ignited and flamed out the door before the second could be pushed through the charging door. (The boxes are 16 in. x 16 in. x 30 in., generally weigh 25 to 50 lb, and must be placed through a waist-high opening about 24 in. x 24 in.) After the first charge, the loads consisted of one large box and two to six smaller boxes to total near the target weight. The smaller boxes could be tossed far enough into the unit to allow charging of the one large box.

After about an hour, the temperatures leveled out around the setpoints. Deviations occurred with each charge but were generally small and brief. After about 3 hours, the primary burners cycled off and on occasionally but the temperature stayed between 1475° and 1525°F. Each time the primary burners cut off, the secondary temperature fell sharply to the 1400° to 1450°F range. Within a few minutes, the primary burners came back on, and the increased airflow caused the secondary chamber temperature to return to the 1600° to 1625°F range.

The unit operated in this pattern until charging was completed at 5:20 (out of waste). There do not appear to be any temperature limitations that would affect the duration of the burn period. The waste bed inside the unit appeared to have good burnout; only a moderate amount of buildup from the 608 lb of waste charged remained. The other possible limitation is the size/weight of the boxes. The amount of variation in the weight of the boxes may cause the individual charges to vary, but attempts were made to maintain the target rate on a per hour basis.

During the period from 1:20 to 5:20 pm, 608 lb of waste were burned (three charges per hour for 4 hours) at an average rate of about 152 lb/hr. During the actual test period, the maximum target rate will be slightly higher. The "reduced rate" test will be conducted with a target rate of about 100 lb/hr. Neither of the pathological waste conditions are believed to present an operational problem.

3.3 PROCESS CONDITIONS DURING TESTING

The primary purpose of this source test was to characterize the uncontrolled emissions from a pathological MWI when both pathological waste and general medical waste are burned. Therefore, all testing was conducted with the unit operating in the "wet-waste" (pathological) mode. Also, this facility is typical of the size and design of many existing units in which pathological wastes are burned.

The incinerator appeared to operate properly throughout all the test runs for all three test conditions. The burnout, however, was visibly good only for the 100 lb/hr pathological waste condition and was very poor for the 160 lb/hr pathological waste condition and the 160 lb/hr medical waste condition.

The incinerator operating parameters monitored during each test run were the charge weight, charge frequency, type of waste, primary and secondary chamber temperatures, actual times the burners and blowers were on, and ash weights. A data logger was used to record all the above parameters except for the charge weight, type of waste, and ash weight, which were manually recorded. Averages for the recorded operating parameters are presented in Table 3-1, and the data sheets documenting the recorded parameters are presented in Appendix B. Figures 3-1 through 3-10 show the temperature profiles for each run. A summary of each test run is given below.

3.3.1 Condition I, Run 1 (Test Run 1)

For this condition, the target operating parameters were a charge of 100 lb/hr of pathological waste in 25-lb charges every 15 minutes and a secondary chamber temperature setpoint of 1900°F. The controller setpoints for the three runs at this condition were: primary chamber burner on/off temperature, 1500°F; primary chamber blower on/off temperature, 1500°F; secondary chamber burner on/off temperature, 1900°F; burndown time, 3 hours.

Thursday, September 20, 1990: The hearth was cleaned and the air ports cleared in preparation for the test. Preheat began at 1:40 p.m., and testing began when the first charge was introduced at 2:00, in keeping with the typical warmup time of this facility. This was also the recommended minimum warmup time by Consumat.

TABLE 3-1. PROCESS DATA SUMMARY FOR EMISSIONS TESTING AT AMI CENTRAL CAROLINA HOSPITAL

Test Run No.	Test Date	Target Test Conditions				Daily Operation (a)						Actual Test Conditions (b)							
		Charge Rate		Charge Type (c)	Charge Freq (min)	Secondary Chamber Setpoint Temp (F)	Preheat time (min)	Charge Time before test (min)	Hours of Charging (hr/d)	Total Waste Charged (lb/d)	Ash (% of Waste Charged)	Charge Rate		Charge Freq (min)	Avg Primary Chamber Temp (F)	Avg Sec. Chamber Temp (F)	Stack Gas Conditions		Avg gas Res. time in Sec Chamb (d) (sec)
		(lb/hr)	(lb/chrg)									(lb/hr)	(lb/chrg)				Flow Rate (acfm)	Avg Temp (F)	
1	9/20/90	100	25	P	15	1900	20	0	4.3	503	4.2	106	36	20	1418	1485	2425	752	0.12
2	9/21/90	160	40	H	15	1600	20	0	6	1016	13.7 (e)	163	41	15	1397	1734	2270	809	0.11
3	9/22/90	100	25	P	15	1900	20	0	4.5	588	3.8	118	45	23	1499	1499	2201	759	0.13
4	9/23/90	160	40	H	15	1600	20	0	6.1	905	19.1 (e)	153	39	15	1555	1576	2383	779	0.11
5	9/24/90	160	40	P	15	1600	20	0	4.1	675	6.7 (e)	169	48	17	1444	1481	2423	746	0.12
6	9/25/90	160	40	P	15	1600	20	0	4.1	697	5.9	144	46	19	1421	1462	2233	725	0.12
7	9/26/90	160	40	H	15	1600	20	0	4.5	769	19.1 (e)	163	41	15	1297	1669	(f)	(f)	(f)
8	9/27/90	160	40	H	15	1600	20	0	4.3	727	18.9 (e)	161	40	15	1458	1691	2383	766	0.11
9	9/28/90	160	40	P	15	1600	20	0	4.8	867	8.9	168	42	15	1445	1523	2556	771	0.11
10	10/2/90	100	25	P	15	1900	20	0	4.3	454	3.8	100	28	17	1445	1474	2272	749	0.12

(a) From start-up until burndown is initiated.
(b) Includes port changes and times for all trains; not just the method 5 trains.
(c) P = Pathological waste and H = Hospital waste.
(d) Residence time is based on the secondary chamber volume of 0.21 m3 (7.5 ft3) and is calculated as follows for Run 1:

$$\text{Res. time, sec} = \frac{(7.5\ ft3)(60s/min)(752+460F)}{(2425\ acfm)(1485+460F)}$$

(e) Ash was wet due to quenching.
(f) Not reported because Run 7 was invalidated.

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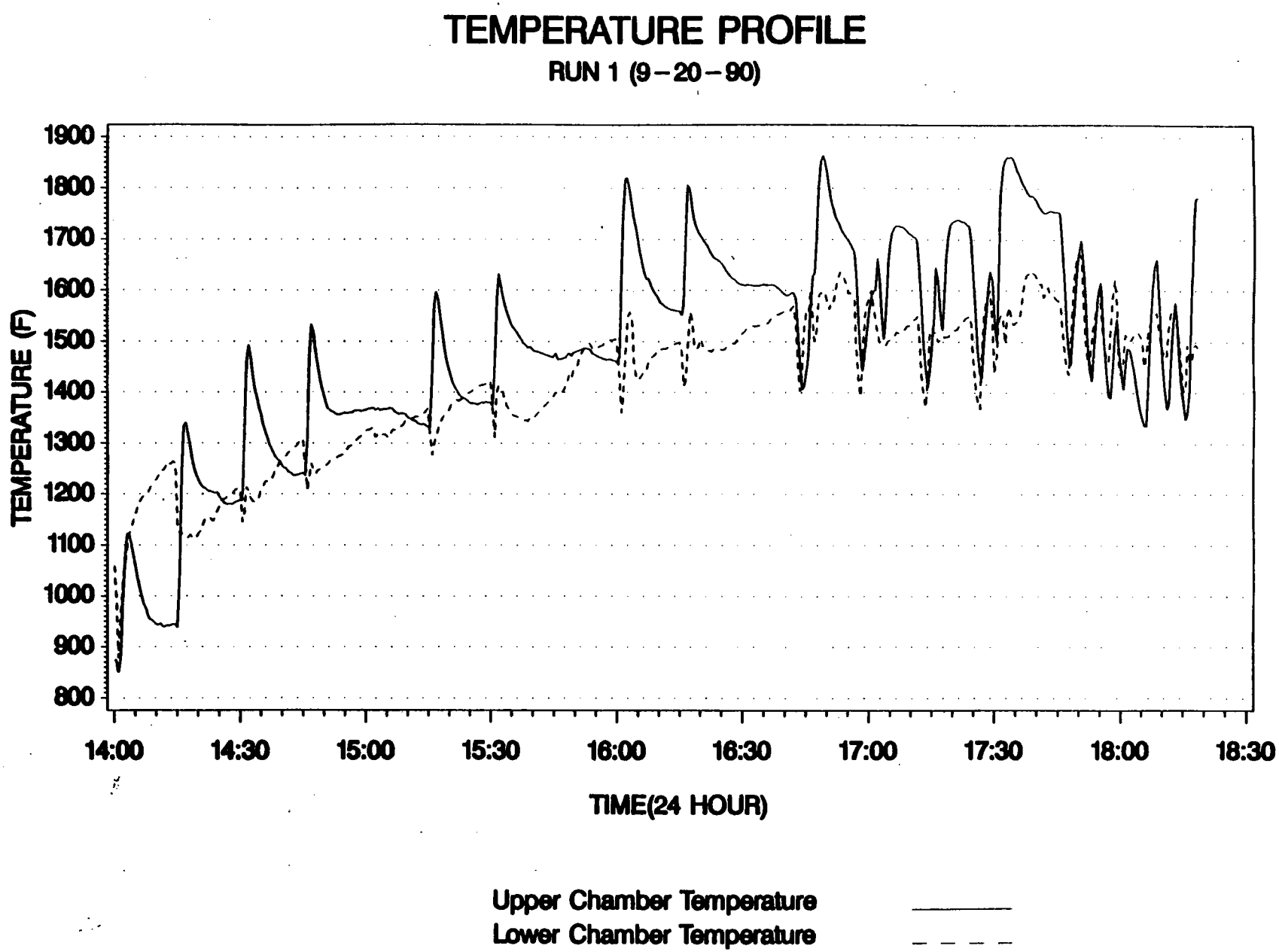

Figure 3-1. Temperature Profile for Run 1

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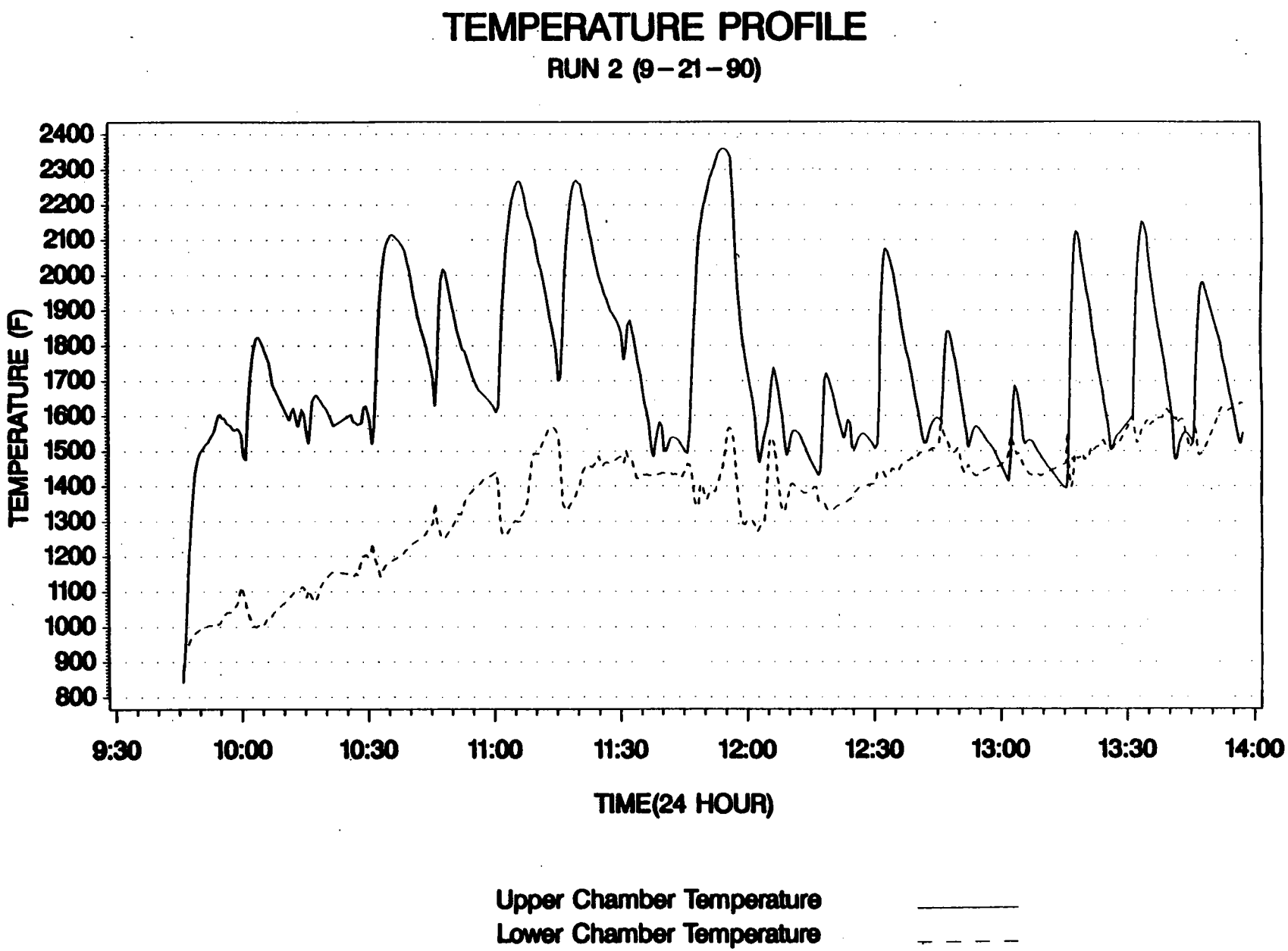

Figure 3-2. Temperature Profile for Run 2

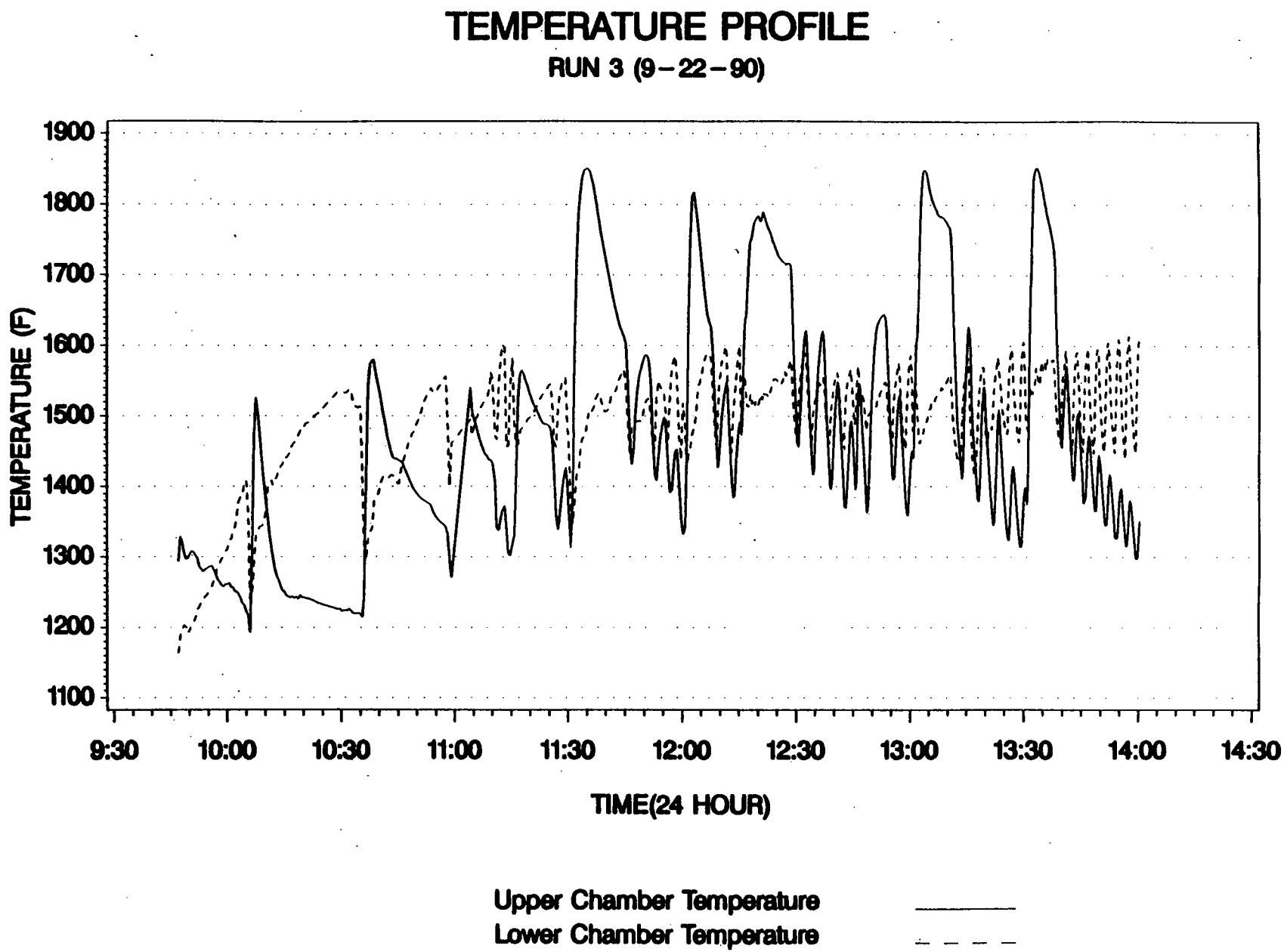

Figure 3-3. Temperature Profile for Run 3

118

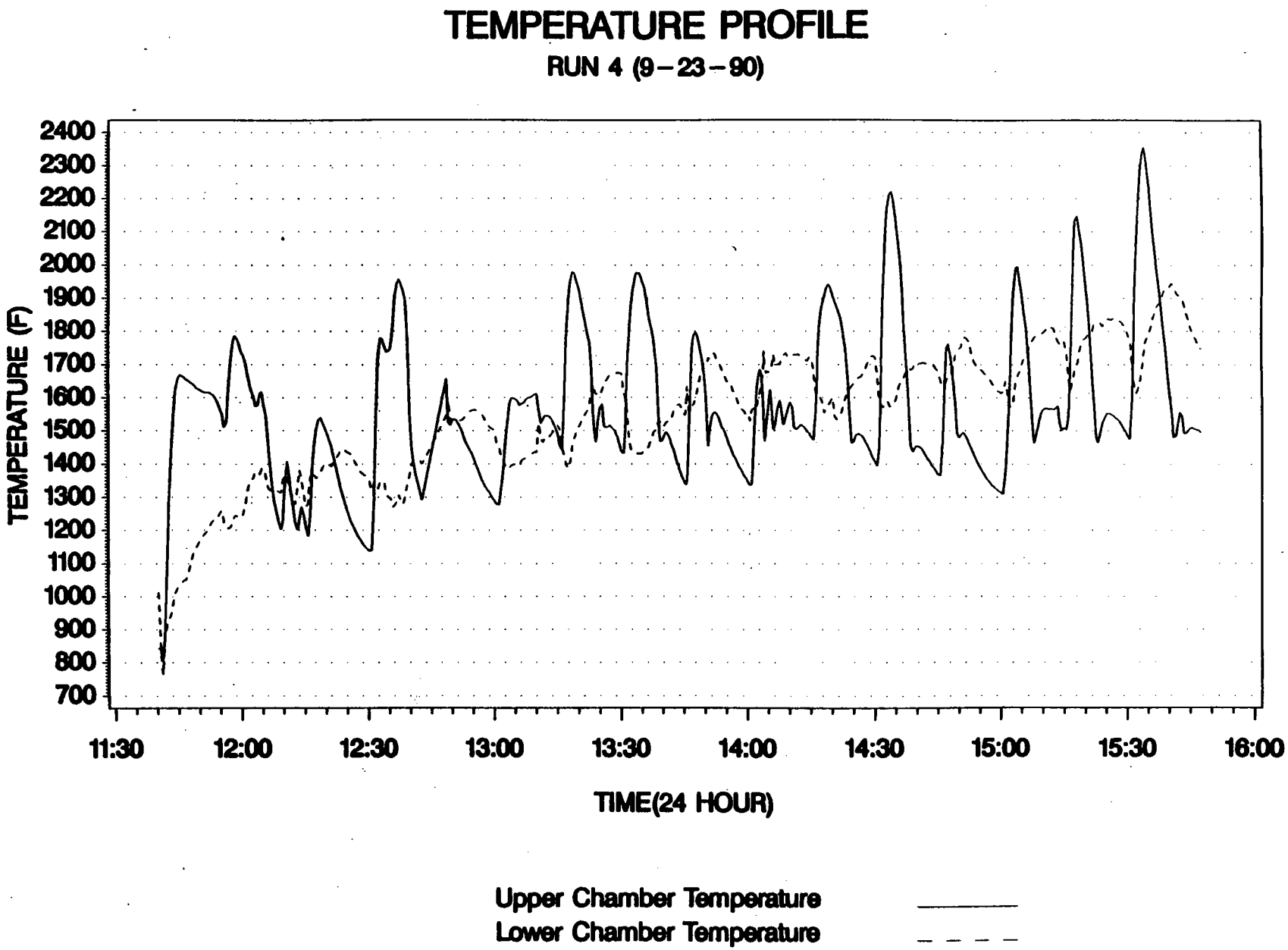

Figure 3-4. Temperature Profile for Run 4

119

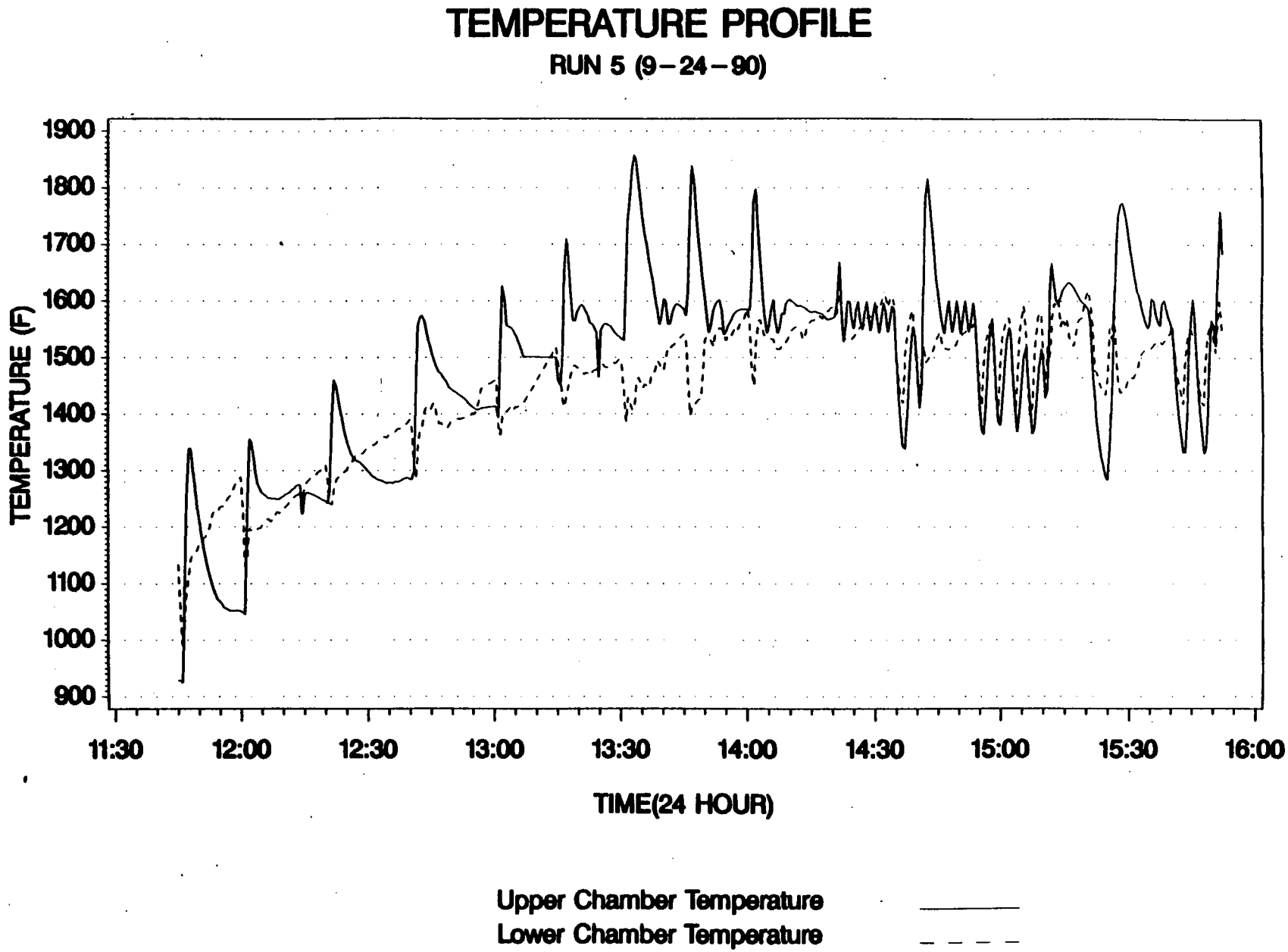

Figure 3-5. Temperature Profile for Run 5

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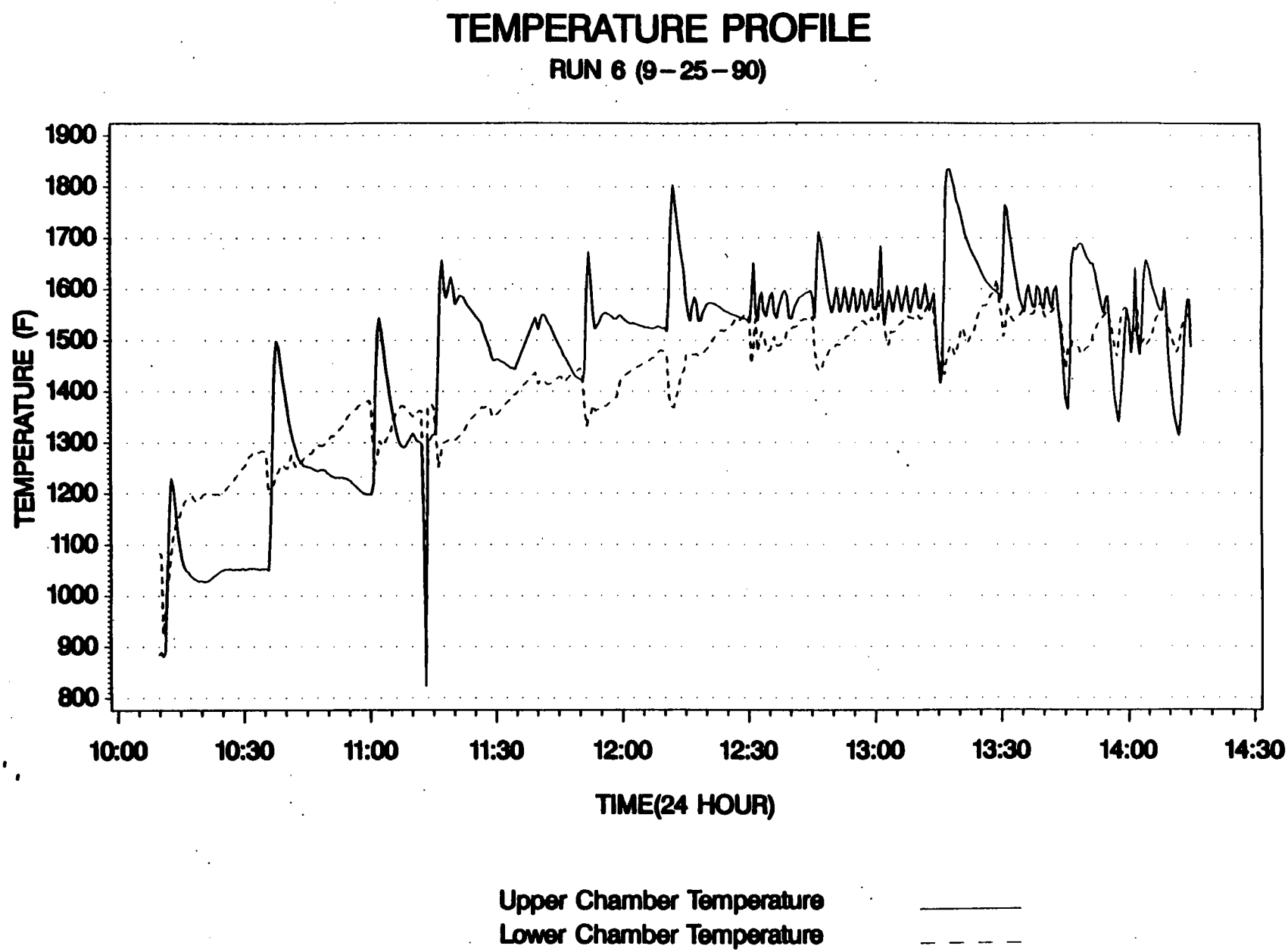

Figure 3-6. Temperature Profile for Run 6

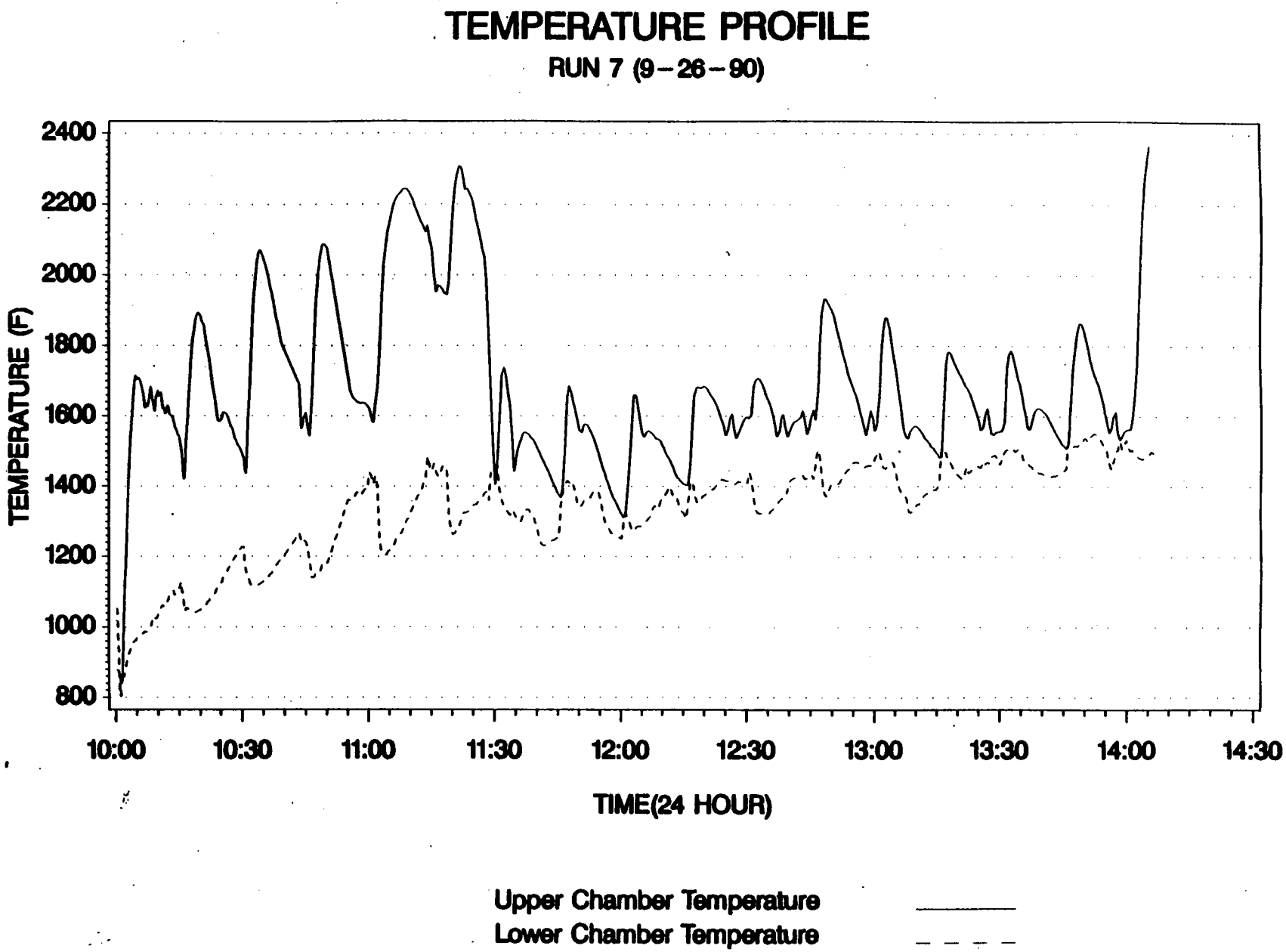

Figure 3-7. Temperature Profile for Run 7

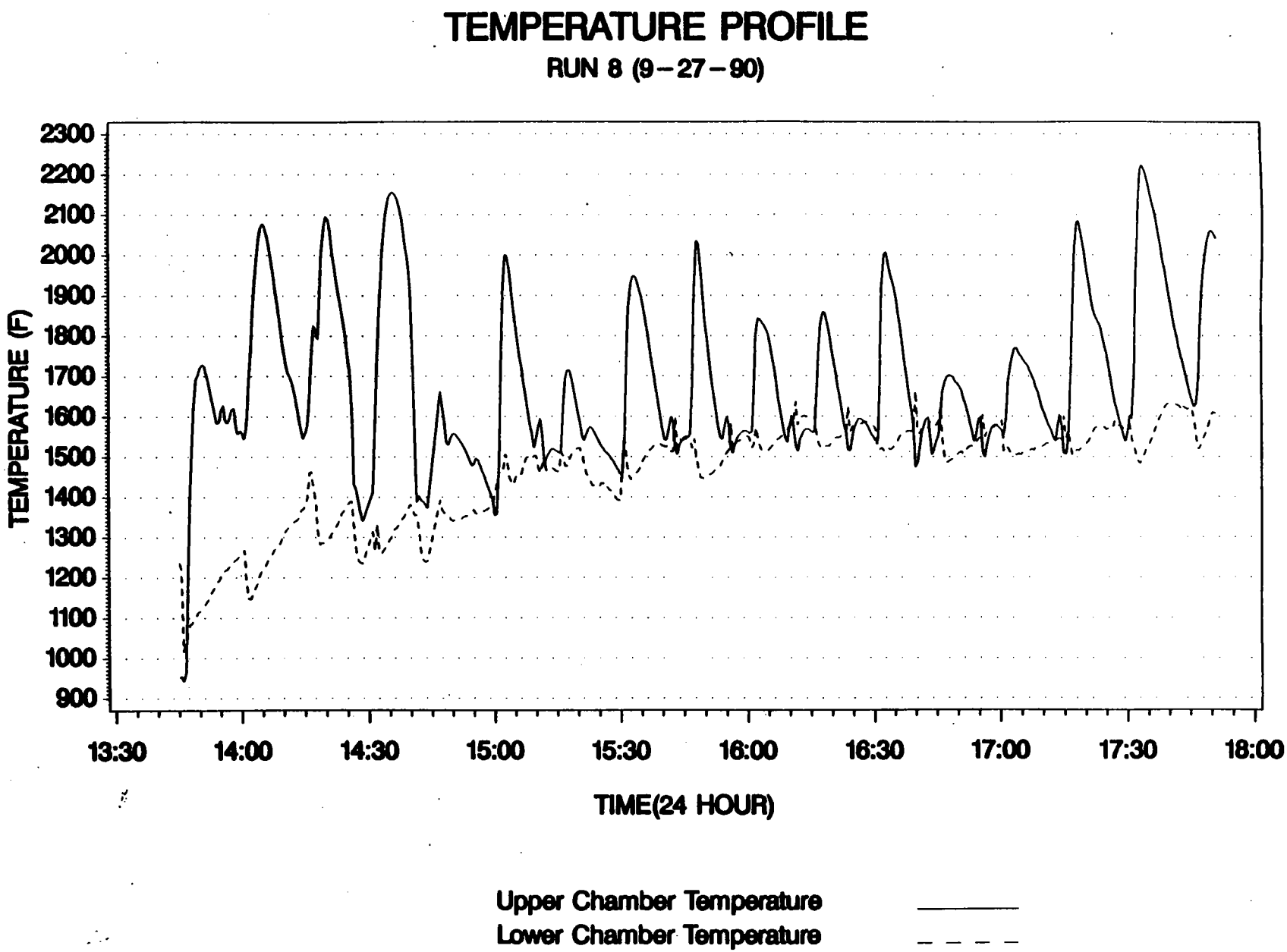

Figure 3-8. Temperature Profile for Run 8

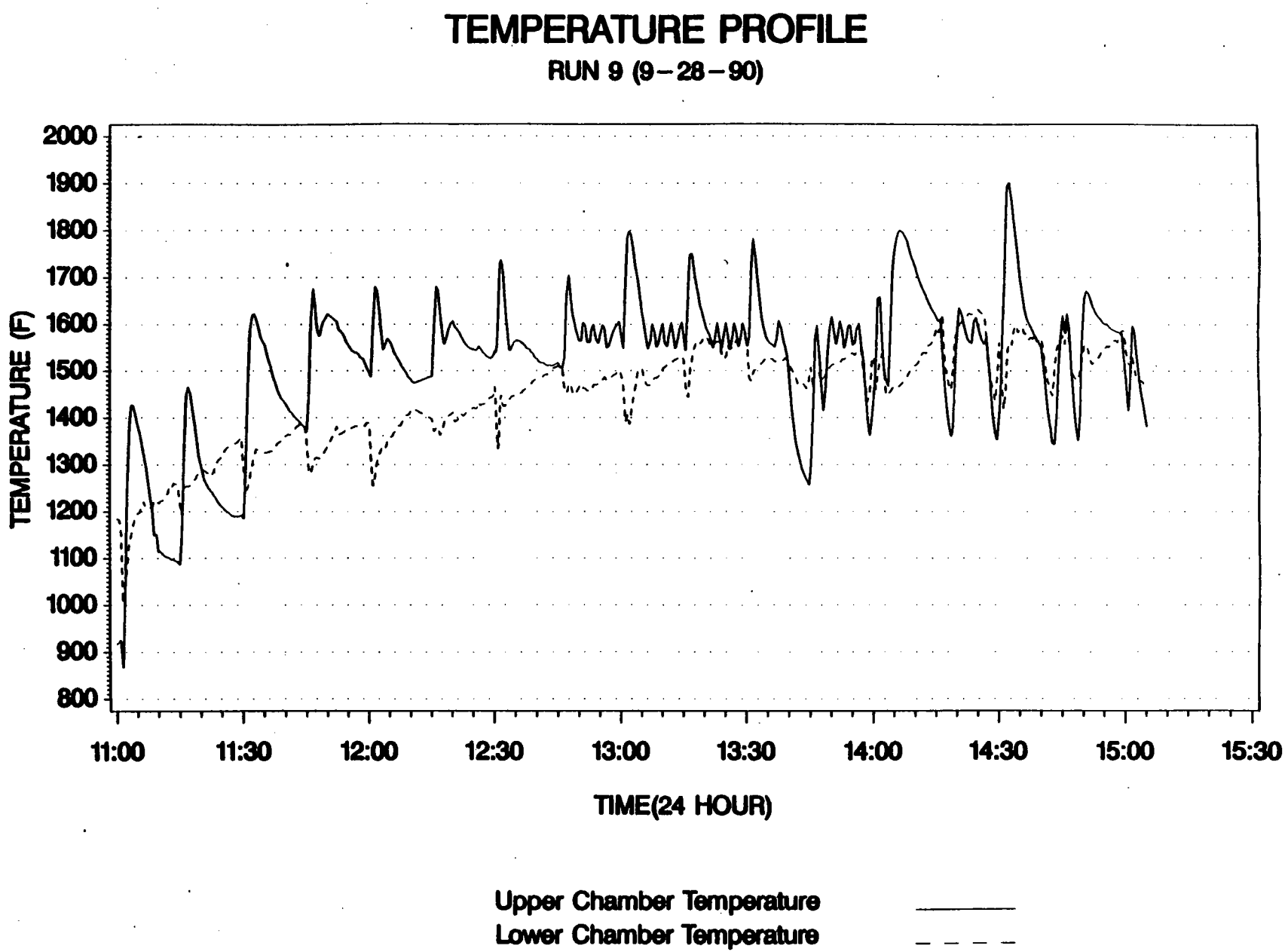

Figure 3-9. Temperature Profile for Run 9

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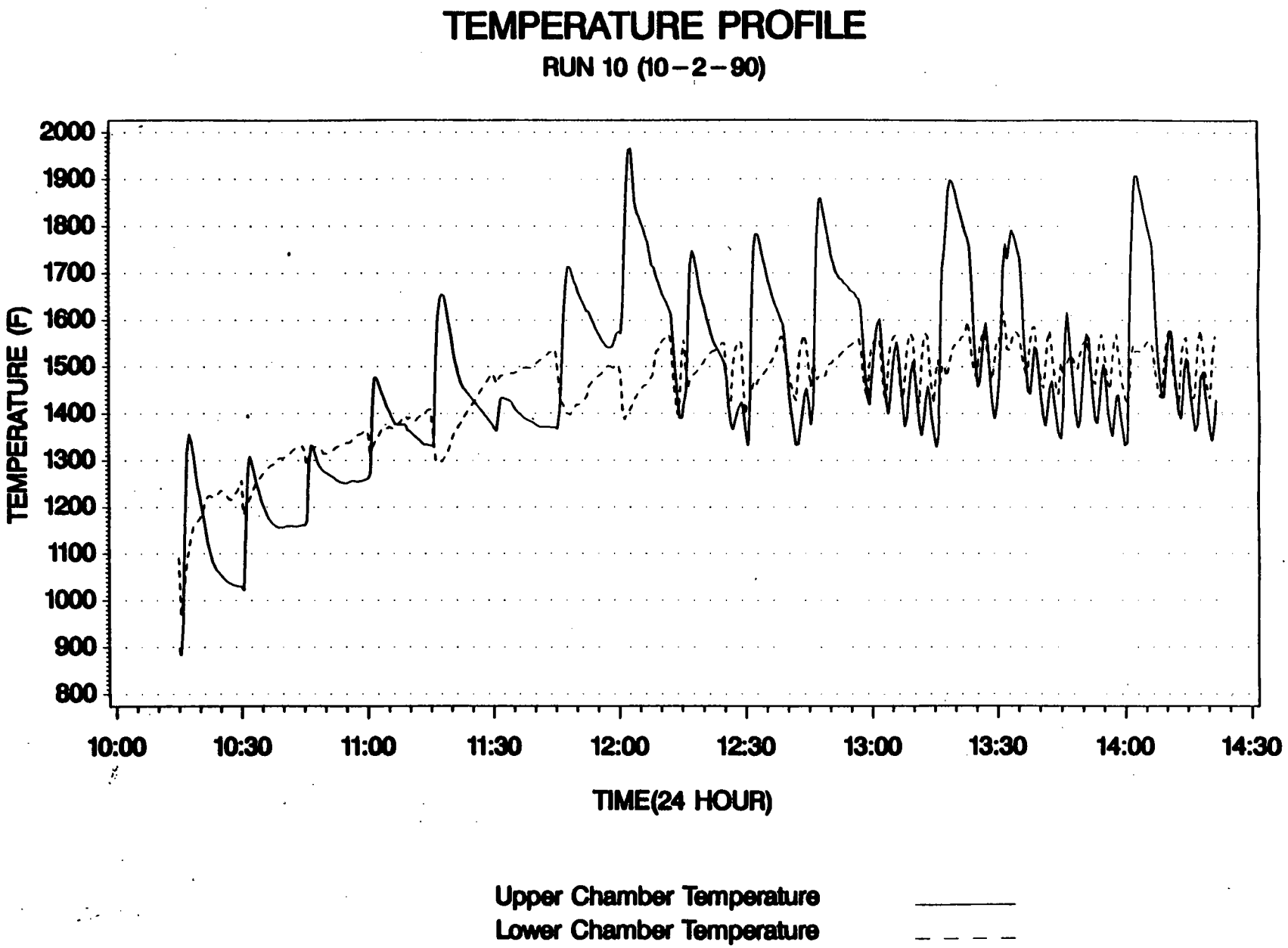

Figure 3-10. Temperature Profile for Run 10

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The incinerator ran smoothly with no problems. Because of the weight of the large boxes of pathological waste, the charging frequency had to be varied in order to maintain a charge rate of approximately 100 lb/hr. The primary chamber temperature leveled out at approximately 1500°F at 4:15. After approximately 1 hour of operation, the secondary chamber had reached a temperature of 1500°F and then cycled between a temperature of 1500°F and 1800°F for the remainder of the test. The incinerator secondary chamber temperature approached the setpoint temperature of 1900°F only once, at 5:33, when the temperature reached 1898°F.

The secondary chamber burner appears to be too small to consistently maintain a temperature greater than the primary chamber temperature while burning a low-Btu, high-moisture waste.

The last charge was introduced at 6:15, and testing was completed at 6:20.

The incinerator was opened the following morning (September 21, 1990) at 7:15, with ash cleanout beginning at 8:08 and being completed at 9:05. There was fairly good burnout of the waste, with only a few clumps of smoldering, unburned material. All of the ash was removed.

The total waste charged was 503.4 lb, and the total ash weight was 21.2 lb. The actual feed rate was 106 lb/hr, and the percent burndown was 95.8.

3.3.2 Condition II, Run 1 (Test Run 2)

For this condition, the target operating parameters were a charge of 160 lb/hr of general medical waste (red bag) in 40-lb charges every 15 minutes, with a secondary chamber temperature setpoint of 1600°F. The controller setpoints for these three runs at this condition were: primary chamber burner on/off temperature, 1500°F; primary chamber blower on/off temperature, 1500°F; secondary chamber burner on/off temperature, 1600°F; burndown time, 3 hours.

Friday, September 21, 1990: The hearth was cleaned and the air ports cleared before testing began. Preheat began at 9:25, and testing began with the first charge at 9:45. The incinerator ran smoothly with no major problems. At 11:25, the primary chamber temperature setpoint was changed from 1500°F to 1400°F in order to limit the temperature increase in the secondary chamber just after the charging cycle. With the

primary chamber burners and blower still on just after the charging cycle, the secondary chamber temperature was climbing above 2300°F. At 11:56, the primary chamber temperature setpoint was changed again to 1300°F. After this change, the primary chamber burner remained off for the remainder of the test, and the secondary chamber temperature remained between 1300°F and 2100°F.

Testing was completed at 2:37 pm, and the last charge was introduced at 3:45.

The incinerator was opened the following morning (September 22, 1990) at 6:45, with ash being removed starting at 7:33. There was a large amount of unburned, smoldering material remaining in the incinerator; this material burst into flame upon agitation. The ash bed had to be quenched with water in order to complete the ash removal. Ash removal was completed at 9:12.

The total waste charged was 1,015.8 lb, and the total wet ash weight was 139 lb. The actual feedrate was 162.5 lb/hr.

3.3.3 Condition I, Run 2 (Test Run 3)

The target operating parameters were a charge rate of 100 lb/hr pathological waste in 25-lb charges every 15 minutes and a secondary chamber temperature setpoint of 1900°F.

Saturday, September 22, 1990: The hearth was cleaned and the air ports cleared before testing began. The incinerator was started at 9:25 am and charging as well as testing began at 9:45. The charging periods varied from 15 to 30 minutes because of the weight of the large boxes of pathological waste.

The incinerator ran smoothly with no problems. The primary chamber temperature leveled out at 1500°F, and the secondary chamber temperature remained fairly low, only climbing above 1900°F twice at 2:05 and 2:35 pm. The last charge was introduced at 2:30 and testing was completed at 2:40.

The incinerator was opened the following morning (Sunday, September 23, 1990) at 9:20, and there was a small amount of unburned material in the ash bed. Ash removal started at 10:01 and was completed at 11:07. All of the ash was removed.

The total waste charged was 588.3 lb, and the total ash weight was 22.4 lb. The actual feed rate was 112.1 lb/hr, with a 96.2 percent burndown.

3.3.4 Condition II, Run 2 (Test Run 4)

The target operating parameters were a charge rate of 160 lb/hr of general medical waste (red bag) in 40-lb charges every 15 minutes, with a secondary chamber temperature setpoint of 1600°F.

Sunday, September 23, 1990: The ash removal door handle was broken during the ash removal. It had broken during ash removal several times in the past, according to the operator, and another handle latch pin had been welded on. The maintenance crew was not working that day, so the ash door was closed and a wedge was driven into the latching mechanism to hold the door closed tightly. The incinerator was started at 11:20 am, and charging as well as testing began at 11:40. The incinerator appeared to operate smoothly throughout the test, with the exception of the smoking from the stack. There was a constant stream of brown smoke, occasionally changing to dense, black smoke, coming from the stack throughout the test. Because there appeared to be much more smoke than in the previous medical waste test, the incinerator was inspected to determine if everything was operating properly. Everything appeared normal, and the wedge on the ash door was driven in tighter, but the smoking continued. The temperature in the primary chamber during this test run climbed to over 1900°F before the test was completed. During the other medical waste test runs, the primary chamber only reached a temperature of between 1500°F and 1600°F. The testing was completed at 3:54 pm, and the last charge was introduced at 5:45. It was decided to continue burning red bag waste after the testing had been completed in order to dispose of some of the red bag waste in the storage room. The process conditions were maintained during this time.

The incinerator was opened the following morning (September 24, 1990) at 8:28, and there were flaming and smoldering patches of unburned waste in the ash bed. Ash removal started at 8:58 and was completed at 9:31. The waste bed had to be quenched with water in order to complete the ash cleanout.

The total waste charged was 905.3 lb, and the total wet ash weight was 172.7 lb. The actual charge rate was 142.9 lb/hr.

3.3.5 Condition III, Run 1 (Test Run 5)

The target operating parameters were a charge feed rate of 160 lb/hr of pathological waste in 40-lb charges every 15 minutes, with a secondary chamber temperature setpoint of 1600°F. The controller setpoints for the three runs at this condition were: primary chamber burner on/off temperature, 1500°F; primary chamber burner on/off temperature, 1500°F; secondary chamber burner on/off temperature, 1600°F; burndown time, 3 hours.

Monday, September 24, 1990: After the hearth was cleaned and the air ports cleared, the maintenance personnel attempted to fix the ash door handle. They were not able to fix the door handle until a latch pin could be obtained, so a large C-clamp was used to clamp the door closed tightly. This method, which was more effective at sealing the ash door than the original handle, was used for the remainder of the tests.

The incinerator was started at 11:25, and charging as well as testing was started at 11:45. The incinerator ran smoothly with no problems throughout the test. The primary chamber temperature leveled out at around 1500°F, and the secondary chamber temperature alternated between 1400°F and 1700°F. The secondary chamber reached a temperature greater than 1800°F only twice during the test, at 1:47 and at 2:02. Testing was completed at 3:45, and the last charge was introduced at 3:50.

The incinerator was opened the following morning (September 25, 1990) at 8:38, and a large mound of smoldering, unburned waste remained. Cleanout was started at 8:18 and completed at 9:41. There were recognizable remnants of the pathological waste in the center of the waste bed. Burnout, which was fairly good on the 100 lb/hr pathological waste condition, appeared to be very poor on the 160 lb/hr pathological waste condition. Upon agitation, some of the waste burst into flame and had to be quenched with water.

The total waste charged was 674.6 lb, and the total wet ash weight was 45.1 lb. The actual charge rate was 150 lb/hr.

3.3.6 Condition III, Run 2 (Test Run 6)

The target operating parameters were a charge rate of 160 lb/hr of pathological waste in 40-lb charges every 15 minutes, with a secondary chamber temperature setpoint of 1600°F.

Tuesday, September 25, 1990: After the hearth was cleaned and the air ports cleared, the incinerator was started at 9:50 am. Charging as well as testing began at 10:10. The incinerator operated properly with no problems throughout the test. Testing was completed at 2:15, and the last charge was introduced at that time.

The incinerator was opened the following morning (September 26, 1990) and a large amount of smoldering, unburned waste remained. Cleanout was started at 8:54 and completed at 9:27. There were, again, recognizable remnants of the pathological waste in the center of the waste bed. Burnout was very poor.

The total waste charged was 697.2 lb, and the total ash weight was 41.4 lb. The actual charge rate was 156.7 lb/hr, with a 94.1 percent burndown.

3.3.7 Condition II, Run 3 (Test Run 7)

The target operating parameters were a charge rate of 160 lb/hr of hospital waste in 40-lb charges every 15 minutes and a secondary chamber temperature setpoint of 1600°F.

Wednesday, September 26, 1990: The hearth was cleaned and the air ports cleared before testing began. The incinerator was started at 9:40 am, and charging as well as testing began at 10:00. The incinerator operated smoothly throughout the test with no apparent problems. There was occasionally some smoke from the stack, while Run 2 at this condition smoked almost constantly. There was, however, during this run a 7-minute period when heavy smoke emerged from the stack after a large bag of plastic sharps containers had been charged.

A thermocouple sealed inside a pipe was placed in the suspected cold spot of the incinerator to give a continuous readout of the temperature inside the waste bed. The temperature within the pipe climbed from 119°F to 1245°F in approximately 1.5 hours and then started to decline. Within 1 hour, the temperature had dropped to 424°F and within another hour stabilized around 220°F. The temperature in the primary chamber at this time was approximately 1400°F.

Testing was completed at 2:06, and the last charge was introduced at 2:30. At the end of the test, it was discovered that the dioxin sampling probe had broken.

The incinerator was opened the following morning (September 27, 1990) and a large amount of burning waste remained. Ash cleanout started at 9:56 and was completed at 11:45. The waste bed had to be quenched with water in order to complete the cleanout.

The total waste charged was 769.4 lb, and the total wet ash weight was 146.7 lb. The actual charge rate was 162 lb/hr.

3.3.8 Condition II, Run 4 (Test Run 8)

The target operating parameters were a charge rate of 160 lb/hr of hospital waste in 40-lb charges every 15 minutes and a secondary chamber temperature setpoint of 1600°F.

Thursday, September 27, 1990: The hearth was cleaned and the air ports cleared before testing began. The incinerator was started at 11:20, but the secondary chamber burner was flaming out every few seconds. The igniter and the pilot were taken out and cleaned, and the unit was started again at 1:25. Everything appeared to be working properly, so charging as well as testing began at 1:45. The pipe with the thermocouple was placed in the center of the hearth in the line of fire of the primary burners. The pipe heated to 1500°F very quickly and then started to cool as the height of the waste bed was slowly increasing. At the end of the test, the pipe temperature was approximately 440°F, and the primary chamber temperature was approximately 1500°F. The incinerator ran properly throughout the test with no problems. Testing was completed at 5:56, and the last charge was introduced at 6:00.

The incinerator was opened the following morning (September 28, 1990) at 9:03, and a large smoldering and burning mound of ashes and unburned waste remained. Ash removal started at 9:30 and was completed at 10:30. The waste bed had to be quenched with water in order to complete the cleanout.

The total waste charged was 727.3 lb, and the total wet ash weight was 137.3 lb. The actual charge rate was 161.6 lb/hr.

3.3.9 Condition III, Run 3 (Test Run 9)

The target operating parameters were a charge rate of 160 lb/hr of pathological waste in 40-lb charges every 15 minutes and a secondary chamber temperature setpoint of 1600°F.

Friday, September 28, 1990: The hearth was cleaned and the air ports cleared before testing began. The incinerator was started at 10:40, and charging as well as testing began at 11:00. The incinerator operated smoothly with no apparent problems throughout the test. The pipe thermocouple temperature climbed rapidly to 1400°F and then dropped slowly throughout the test as the waste bed depth increased. At the end of the test, the pipe temperature was 685°F, while the primary chamber temperature was 1500°F. Testing was completed at 3:05, and the last charge was introduced at 3:55.

The incinerator was opened the following morning (September 29, 1990) at 9:20, and there was a large mound of black, smoldering, unburned waste. Cleanout began at 9:45 and was completed at 10:56. Once again, many recognizable unburned items were found.

The total waste charged was 867 lb, and the total ash weight was 77 lb. The actual charge rate was 165.1 lb/hr, with a 91.1 percent burndown.

3.3.10 Condition I, Run 3 (Test Run 10)

The target operating parameters were a charge rate of 100 lb/hr of pathological waste in 25-lb charges every 15 minutes and a secondary chamber temperature setpoint of 1900°F.

Tuesday, October 2, 1990: The hearth was cleaned and the air ports cleared before testing began. The incinerator was started at 9:55, and then it was discovered that the temperature indicator pipe had not been placed in the incinerator. The incinerator was shut down at 10:01, the pipe was placed on the hearth, and the incinerator was restarted at 10:03. The first charge was introduced at 10:15, and testing began. The indicator pipe temperature climbed rapidly to 1600°F and then fell slowly to approximately 800°F at the end of the test. The primary chamber temperature was approximately 1500°F at the end of the test. The incinerator ran smoothly with no apparent problems throughout the test. Testing was completed at 2:21, and the last charge was introduced at 2:30.

The incinerator was opened the following morning (October 3, 1990) at 9:25, and there was one small smoldering mass of unburned material in the ash bed. Burnout appeared to be very good.

The total waste charged was 453.3 lb, and the total ash weight was 17.2 lb. The actual charge rate was 100.8 lb/hr, with a 96.2 percent burndown.

4. SAMPLE LOCATIONS

The sampling locations used during the emission testing program at the AMI Central Carolina Hospital MWI are described in this section. Flue gas samples are collected at the exhaust stack using three sets of ports.

The exhaust stack at this facility has a 22-inch steel shell with refractory lining. The inside diameter of the refractory lining is about 18 inches. The existing stack is approximately 8 feet in height above the secondary chamber.

An unlined steel stack extension was fabricated for temporary installation at the top of the existing stack. The extension was 18 inches in diameter and 16 feet high. Three sets of test ports were provided as shown in Figure 4-1. The lower set of ports were used for the CEM, HCl/CEM, and manual HCl tests. The center set of ports were used for CDD/CDF and PM/Metals testing. The upper ports were used for microorganism sampling. The two upper sets of ports were aligned with each other in the vertical plane, while the lowest set was offset by 45° to prevent flow disturbances. The test ports were located in an ideal location according to EPA Method 1. There are at least two stack diameters of undisturbed flow downstream of the ports, and greater than eight diameters of undisturbed flow upstream of the ports. (NOTE: CDD/CDF and metals sampling probes are not treated as upstream disturbances for the upper set of ports.)

The number of traverse points required for CDD/CDF, PM/metals, and Microbial sampling is eight. Four points on each of two diameters were used as shown in Figure 4-2.

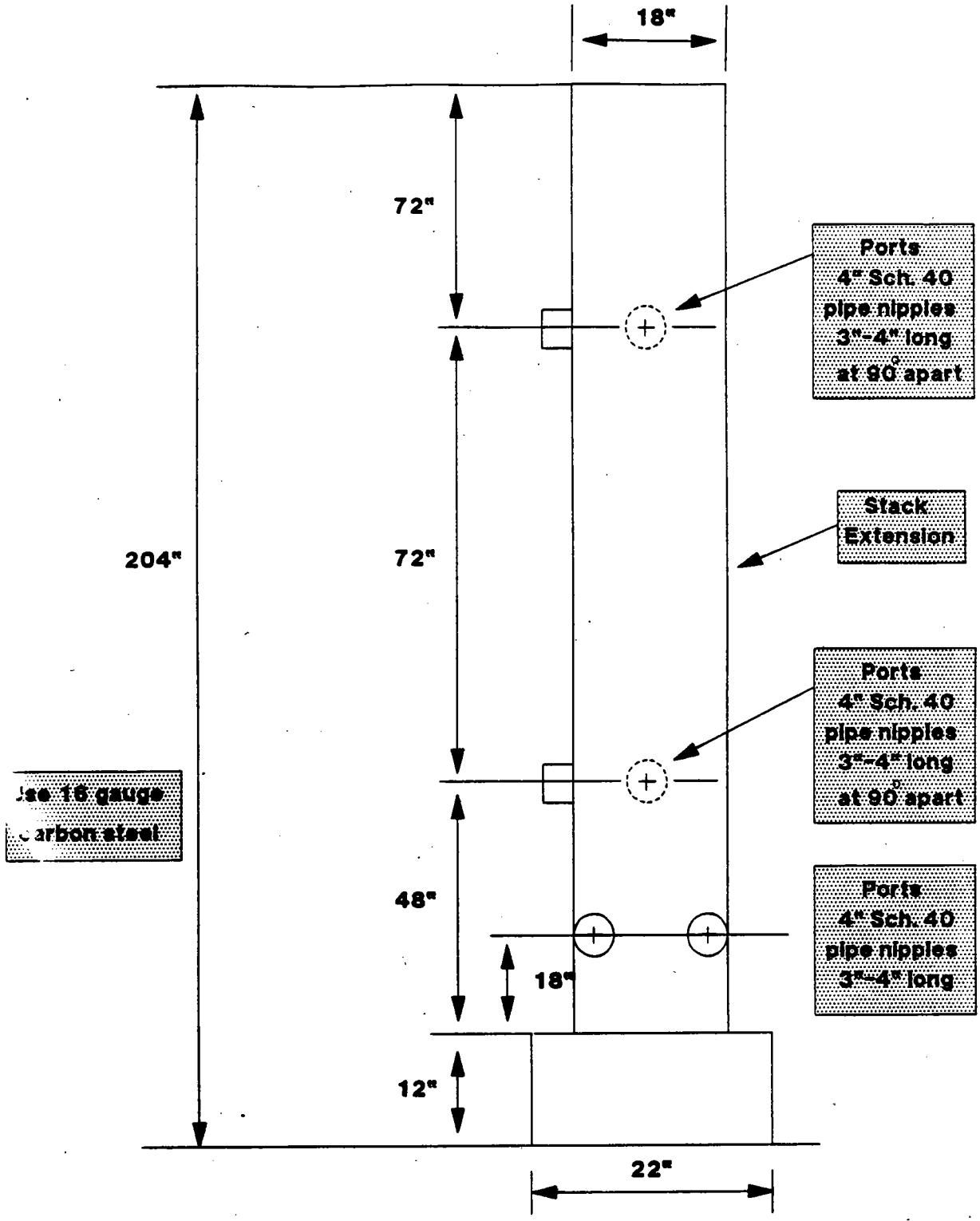

Figure 4-1. AMI Central Carolina Hospital Stack Extension Specifications

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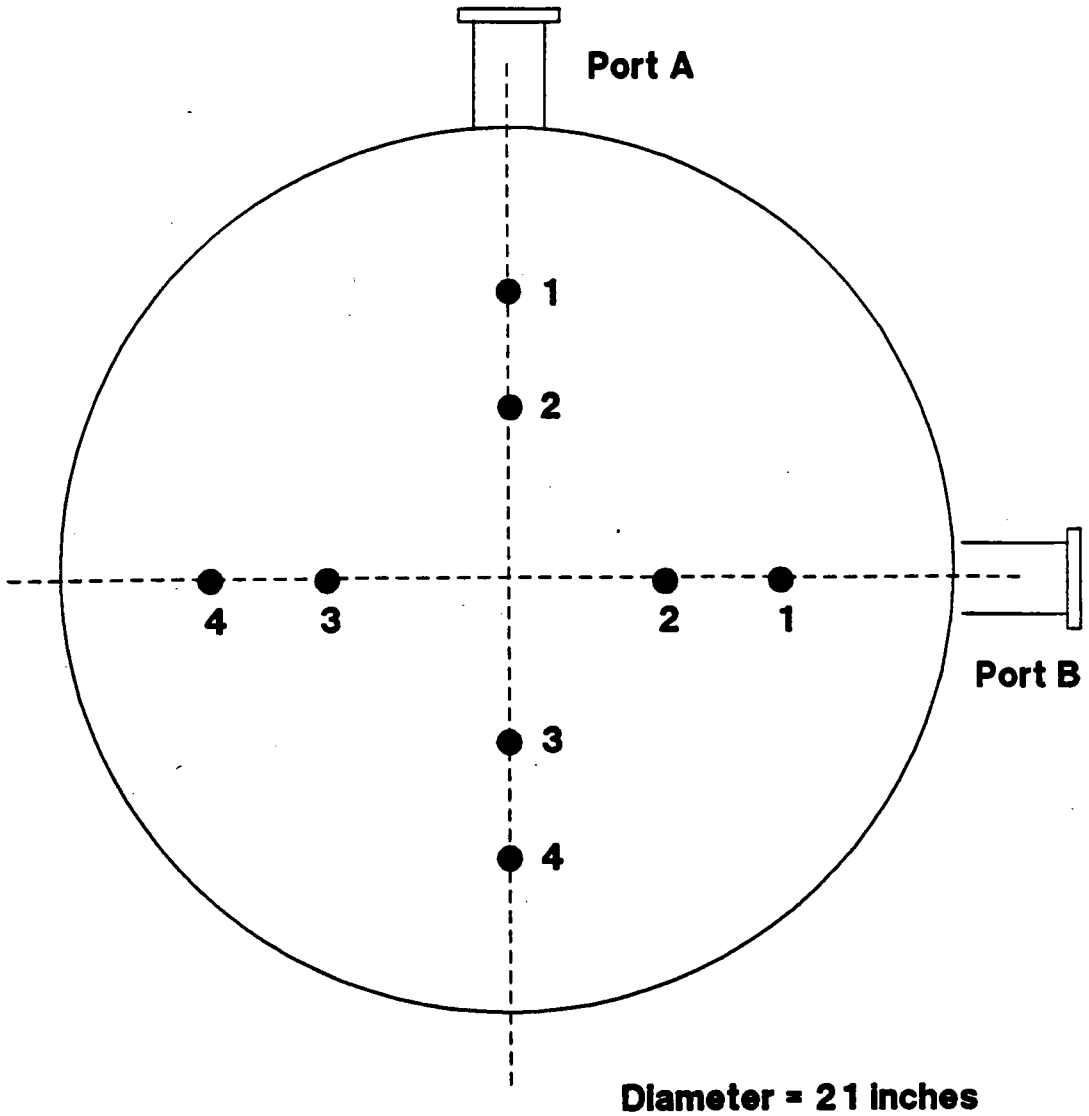

Point	Percent of Diameter	Inches from Inside Wall
1	6.7	1.2
2	25.0	4.5
3	75.0	13.5
4	93.3	16.8

Figure 4-2. Traverse Point Layout at the Exhaust Stack

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5. SAMPLING AND ANALYTICAL PROCEDURES BY ANALYTE

The sampling and analytical procedures used for the Central Carolina Hospital MWI test program are the most recent revisions of the published EPA methods. Where published methods are not available, state-of-the-art sampling and analytical methods are used. In this section, descriptions of each sampling and analytical method by analyte are provided.

A summary of the sampling methods that are used is included in Table 5-1. Sampling times, minimum sampling volumes, and detection limits are summarized for the manual sampling methods in Table 5-2.

5.1 CDD/CDF EMISSIONS TESTING METHOD

The sampling and analytical method for determining flue gas emissions of CDD/CDF is EPA Proposed Method 23. This methodology is a combination of the American Society of Mechanical Engineers (ASME) 1984 draft protocol and the EPA Method 8290. The analytical method is designated as Method 8290X by Triangle Laboratories, Inc., Research Triangle Park, North Carolina, who performed the analyses. (Because of proprietary reasons, Triangle Laboratories has requested that a copy of their standard operating procedures not be included in this test plan.)

5.1.1 CDD/CDF Sampling Equipment

The CDD/CDF sampling method uses the sampling train shown in Figure 5-1. Basically, the sampling system is similar to a Method 5 train with the exception of the following:

- Uses all components (quartz probe/nozzle liner, all other glassware, filters) which are pre-cleaned using solvent rinses and extraction techniques; and
- Uses a condensing coil and XAD-II® resin absorption module located between the filter and impinger train.

All sampling equipment specifications are detailed in the reference method shown in Appendix A.1 of the test plan.

TABLE 5-1. PROPOSED TEST METHODS AMI CENTRAL CAROLINA HOSPITAL MWI

Analyte	Method
CDD/CDF	EPA Proposed Method 23 with GC/MS Method 8290
Particulates Lead Mercury Arsenic Nickel Cadmium Chromium Beryllium Antimony Barium Silver Thallium	EPA/EMSL Multimetals Train
SO_2	EPA Instrument Methods 6C
O_2/CO_2	3A
CO	10
NO_x	7E
THC	25A/18
HCl	NDIR CEM Analyzer
HCl	EPA Draft Method 26
HBr	EPA Draft Method 26
HF	EPA Draft Method 26
Microorganisms in Emissions	EPA Draft Method "Microbial Survivability Tests for MWI Emissions"
Microorganisms in Pipe Test and Direct Ash Test	EPA Draft Method "Microbial Survivability Tests for MWI Ash"
Opacity	EPA Method 9
Loss On Ignition	Standard Methods of Water & Wastes 209G
Carbon	ASTM D 3178-84

TABLE 5-2. PROPOSED SAMPLING TIMES, MINIMUM SAMPLING VOLUMES AND DETECTION LIMITS FOR THE AMI CENTRAL CAROLINA HOSPITAL MWI TESTS

Sampling Train	Sampling Time (hours)	Minimum Sample Volume (dscf)	Analyte	Detection Limit	
				Flue Gas	Analytical
CDD/CDF	4[a]	120	CDD/CDF	0.3 ng/dscm	0.01 ng
PM/Metals	4[a]	120	PM	0.006 gr/dscf	50-100 mg[e]
			As	0.3 μg/dscm	0.002 μg/ml
			Cd	0.6 μg/dscm	0.006 μg/ml
			Cr	1.6 μg/dscm	0.015 μg/ml
			Pb	0.2 μg/dscm	0.002 μg/ml
			Hg	25 μg/dscm	0.25 μg/ml
			Ni	1.6 μg/dscm	0.015 μg/ml
			Be	0.3 μg/dscm	0.0003 μg/ml
			Ba	0.2 μg/dscm	0.002 μg/ml
			Sb	3.3 μg/dscm	0.032 μg/ml
			Ag	0.71 μg/dscm	0.007 μg/ml
			Tl	4.2 μg/dscm	0.040 μg/ml
HCl/HBr/HF	1.0	120 liters[b]	Cl^-	28 μg/dscm	0.11 μg/ml
			Br^-	32 μg/dscm	0.127 μg/ml
			F^-	100 μg/dscm	0.40[c] μg/ml
Microorganisms	3.2	30	Indicator spores[d]	30 viable spores[c] / dscm	1 viable spores / aliquot

[a] An average sampling rate of 0.5 ft^3/min was used to calculate sampling time.
[b] An average sampling rate of 2 liters/min was used to calculate the sample volume.
[c] Detection limit based on 100 ml aliquot. Method is still under development. Actual limit may vary.
[d] The indicator spore will be Bacillus stearothermophilus. (only 1 l)
[e] Based on average detection limits for tetra-octa CDD/CDF congeners.

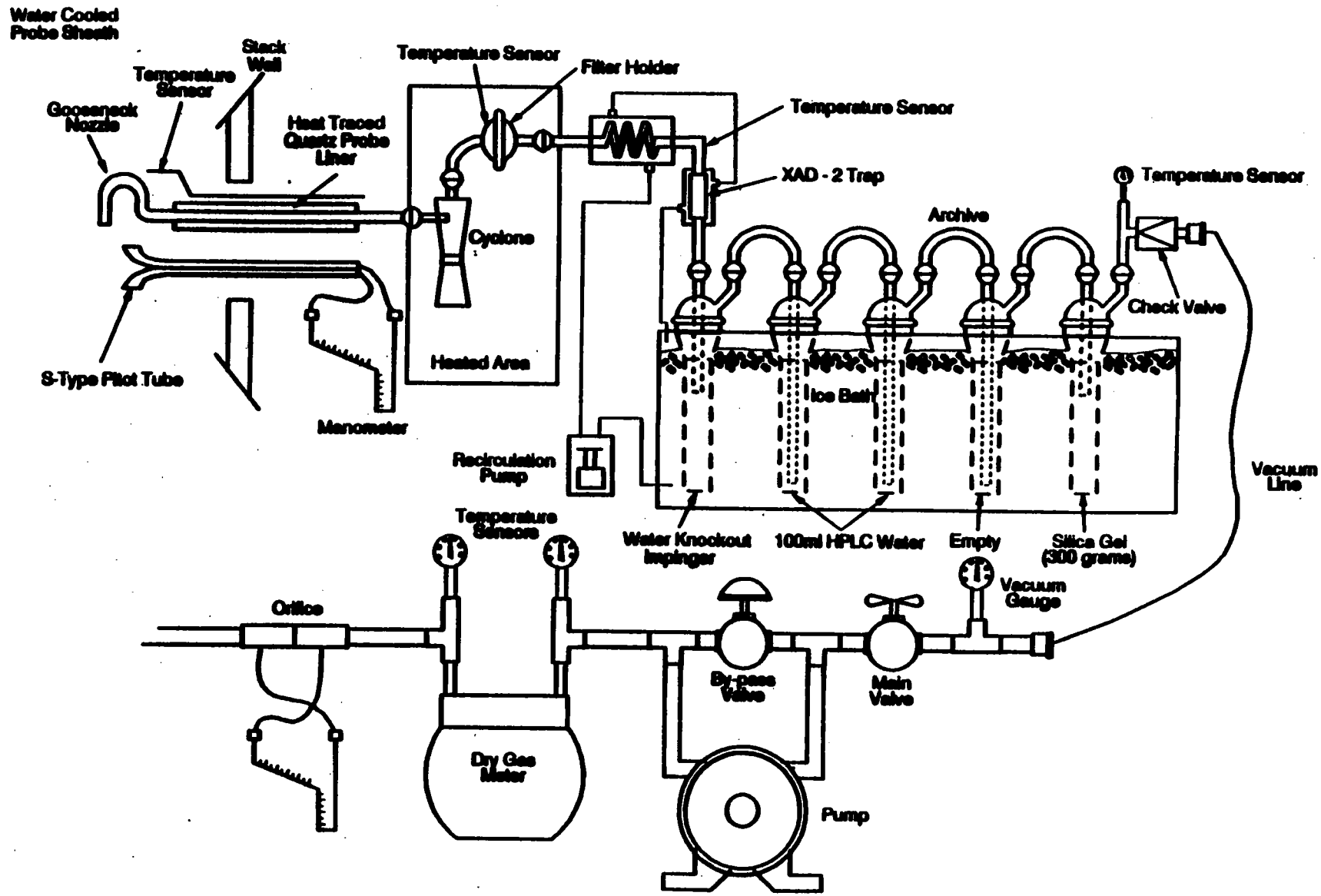

Figure 5-1. CDD/CDF Sampling Train Configuration

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5.1.2 CDD/CDF Equipment Preparation

In addition to the standard EPA Method 5 requirements, the CDD/CDF sampling method includes several unique preparation steps which ensure that the sampling train components are not contaminated with organics that may interfere with analysis. The glassware, glass fiber filters, and absorbing resin are cleaned and the filters and resin are checked for residuals before they are packed.

5.1.2.1 Glassware Preparation. Glassware is cleaned as shown in Table 5-3. Glassware is washed in soapy water, rinsed with distilled water, baked, and then rinsed with acetone followed by methylene chloride. Clean glassware is allowed to dry under a hood loosely covered with foil to prevent laboratory contamination. Once the glassware is dry, the air-exposed ends are sealed with methylene chloride-rinsed aluminum foil. All the glass components of the sampling train (including the glass nozzles) plus any sample bottles, flasks, petri dishes, graduated cylinders, and pipets that are used during sampling and recovery will be cleaned according to this procedure. Non-glass components (such as the Teflon®-coated filter screens and seals, tweezers, Teflon® squeeze bottles, nylon probe brushes, and nylon nozzle brushes) are cleaned following the same procedure except that no baking is performed.

This cleaning procedure deviates from the EPA proposed method; however, past experience has shown that the use of chromic acid solution may cause analytical interferences with the compounds of interest.

5.1.2.2 XAD-II® Resin and Filters Preparation. The XAD-II® absorbing resin and glass fiber filters are pre-cleaned by separate procedures according to the specified method. Only pesticide-grade solvents and HPLC-grade water are used to prepare for organic sampling and to recover these samples. The lot number, manufacturer, and grade of each reagent used is recorded in the laboratory notebook.

To prepare the filters, a batch of 50 is placed in a soxhlet pre-cleaned by extraction with toluene. The soxhlet is charged with fresh toluene and refluxed for 16 hours. After the extraction, the toluene is analyzed as described in Sections 5.2 and 5.3 of the reference method for the presence of Tetrachloro Dibenzo-p-Dioxins (TCDD) or Tetrachloro Dibenzofurans (TCDF). If these analytes are found, the filters are re-extracted until no TCDD or TCDF is detected. The filters are then dried completely

TABLE 5-3. CDD/CDF GLASSWARE CLEANING PROCEDURE
(Train Components, Sample Containers and Laboratory Glassware)

NOTE: USE VITON® GLOVES AND ADEQUATE VENTILATION WHEN RINSING WITH SOLVENTS

1. Soak all glassware in hot soapy water (Alconox®).
2. Tap water rinse to remove soap.
3. Distilled/deionized H_2O rinse (X3).[a]
4. Bake at 450°F for 2 hours.[b]
5. Acetone rinse (X3), (pesticide grade).
6. Methylene chloride (X3), (pesticide grade)
7. Cap glassware with clean glass plugs or methylene chloride rinsed aluminum foil.
8. Mark cleaned glassware with color-coded identification sticker.
9. Glassware is rinsed immediately before using with acetone and methylene chloride (laboratory proof).

[a] (X3) = three times.
[b] Step (4) has been added to the cleanup procedure to replace the dichromate soak specified in the reference method. Radian has demonstrated in the past that it sufficiently removes organic artifacts. It is not used for probe liners and non-glass components of the train that cannot withstand 450°F (i.e., teflon-coated filter screen and seals, tweezers, teflon squeeze bottles, nylon probe and nozzle brushes).

under a clean nitrogen (N_2) stream. Each filter is individually checked for holes, tears, creases, or discoloration, and if found, is discarded. Acceptable filters are stored in a pre-cleaned petri dish, labeled by date of inspection, and sealed with Teflon® tape.

To prepare the absorbing resin, the XAD-II® resin is cleaned in the following sequential order:

- Rinse with HPLC-grade water, discard water;
- Soak in HPLC-grade water overnight, discard water;
- Extract in soxhlet with HPLC-grade water for 8 hours, discard water;
- Extract with methanol for 22 hours, discard solvent;
- Extract with methylene chloride for 22 hours, discard solvent;
- Extract with methylene chloride for 22 hours, retain an aliquot of solvent for gas chromatography analysis of TCDDs and TCDFs; and
- Dry resin under a clean N_2 stream.

Once the resin is completely dry, it is checked for the presence of methylene chloride, TCDDs, and TCDFs as described in Section 3.1.2.3.1 of the reference method. If TCDDs or TCDFs are found, the resin is re-extracted. If methylene chloride is found, the resin is dried until the excess solvent is removed. The absorbent is to be used within four weeks of cleaning.

The cleaned XAD-II® resin is spiked with five CDD/CDF internal standards. Due to the special handling considerations required for the CDD/CDF internal standards, the spiking is performed by Triangle Laboratories. For convenience and to minimize contamination, Triangle Laboratories also performs the resin and filter cleanup procedures and loads the resin into the glass traps.

5.1.2.3 <u>CDD/CDF Method 5 Equipment Preparation</u>. The remaining preparation includes calibration and leak checking of all sampling train equipment. This includes: meterboxes, thermocouples, nozzles, pitot tubes, and umbilicals. Referenced calibration procedures are followed when available. The results are properly documented in a laboratory notebook or project file and retained. If a referenced calibration technique for a particular piece of apparatus is not available, then a

state-of-the-art technique is used. A discussion of the techniques used to calibrate this equipment is presented in Section 7.2.7.

5.1.3 CDD/CDF Sampling Operations

5.1.3.1 Preliminary Measurements. Prior to sampling, preliminary measurements are required to ensure isokinetic sampling. These include determining the traverse point locations, performing a preliminary velocity traverse, cyclonic flow check, and moisture determination. These measurements are used to calculate a "K factor." The K factor is used to determine an isokinetic sampling rate from stack gas flow readings taken during sampling.

Measurements are then made of the duct inside diameter, port nozzle length, and the distances to the nearest upstream and downstream flow disturbances. These measurements are then used to determine sampling point locations by following EPA Reference Method 1 guidelines. The distances are then marked on the sampling probe using an indelible marker.

5.1.3.2 Assembling the Train. Assembling the CDD/CDF sampling train components is completed in the recovery trailer and final train assembly is performed at the stack location. First, the empty, clean impingers are assembled and laid out in the proper order in the recovery trailer. Each ground glass joint is carefully inspected for hairline cracks. The first impinger is a knockout impinger which has a short tip. The purpose of this impinger is to collect condensate which forms in the coil and XAD-II® resin trap. The next two impingers are modified tip impingers which each contain 100 ml of HPLC-grade water. The fourth impinger is empty, and the fifth impinger contains 200 to 300 grams of blue indicating silica gel. After the impingers are loaded, each impinger is weighed, and the initial weight and contents of each impinger are recorded on a recovery data sheet. The impingers are connected together using clean glass U-tube connectors and arranged in the impinger bucket as shown in Figure 5-2. The height of all the impingers is approximately the same to obtain a leak free seal. The open ends of the train are sealed with methylene chloride-rinsed aluminum foil or clean ground glass caps.

The second step is to load the filter into the filter holder in the recovery trailer. The filter holder is then capped off and placed with the resin trap and condenser coil

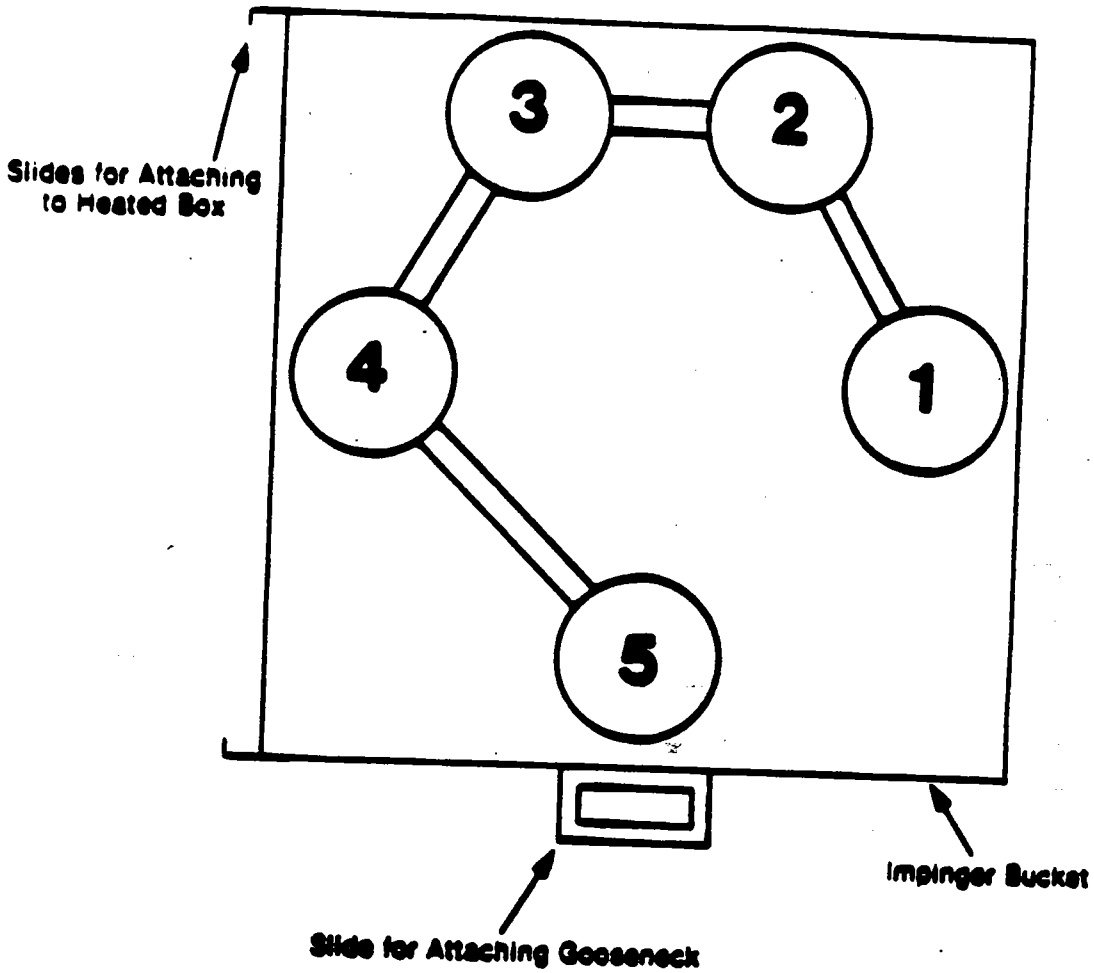

Figure 5-2. Impinger Configuration for CDD/CDF Sampling

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(capped) into the impinger bucket. A supply of pre-cleaned foil and socket joints is also placed in the bucket in a clean plastic bag for the convenience of the samplers. To avoid contamination of the sample, sealing greases are not used. The train components are transferred to the sampling location and assembled as previously shown in Figure 5-1.

5.1.3.3 Sampling Procedures. After the train is assembled, the heaters are turned on for the probe liner and heated filter box and the sorbent module/condensor coil recirculating pump is turned on. When the system reaches the appropriate temperatures, the sampling train is ready for pre-test leakchecking. The temperature of the sorbent module resin must not exceed 50°C (120°F) at any time and during testing it must not exceed 20°C (68°F). The filter skin temperature is maintained at 120 ±14°F (248 ±25°F). The probe temperature is maintained above 100°C (212°F).

The sampling trains are leak checked at the start and finish of sampling. (Method 5/23 protocol only requires post-test leakchecks and recommends pre-test leakchecks.) Radián protocol also incorporates leak checks before and after every port change. An acceptable pre-test leak rate is less than 0.02 acfm (ft^3/min) at approximately 15 inches of mercury (in. Hg). If during testing, a piece of glassware needs to be emptied or replaced, a leak check is performed before the glassware piece is removed, and after the train is re-assembled.

To leak check the assembled train, the nozzle end is capped off and a vacuum of 15 in. Hg is pulled in the system. When the system is evacuated, the volume of gas flowing through the system is timed for 60 seconds. After the leak rate is determined, the cap is slowly removed from the nozzle end until the vacuum drops off, and then the pump is turned off. If the leak rate requirement is not met, the train is systematically checked by first capping the train at the filter, at the first impinger, etc., until the leak is located and corrected.

After a successful pre-test leak check has been conducted, all train components are at their specified temperatures, initial data is recorded [dry gas meter (DGM) reading], the test can be initiated. Sampling train data are recorded periodically on standard data forms. A checklist for CDD/CDF sampling is included in Table 5-4. A sampling operation that is unique to CDD/CDF sampling is that the gas temperature

TABLE 5-4. CDD/CDF SAMPLING CHECKLIST

Before test starts:

1. Check impinger set to verify the correct order, orientation and number of impingers. Verify probe markings, and remark if necessary.

2. Check that you have all the correct pieces of glassware. Have a spare probe liner, probe sheath, meter box and filter ready to go at location.

3. Check for data sheets and barometric pressure.

4. Bag sampling equipment for CO_2/O_2 needs to be ready except when using CEMs for CO_2/O_2 determinations.

5. Examine meter box - level it, zero the manometers and comfirm that the pump is operational.

6. Verify the filter is loaded correctly and as tight as possible; place filter in line with the train and leak check at 15 inches Hg.

7. Add probe to train.

8. Check thermocouples - make sure they are reading correctly.

9. Conduct pitot leak check, recheck manometer zero.

10. Do final leak check; record leak rate and vacuum on sampling log.

11. Turn on variacs and check to see that the heat is increasing.

12. Check that cooling water is flowing and on. Add ice to impinger buckets.

13. Check isokinetic K-factor - make sure it is correct. (Refer to previous results to confirm assumptions). (Two people should calculate this independently to double check it.)

During Test:

1. Notify crew chief of any sampling problems ASAP. Train operator should fill in sampling log and document any abnormalities.

2. Perform simultaneous/concurrent testing with other locations (if applicable). Maintain filter temperature between 248°F ±25°F. Keep temperature as steady as possible. Maintain the resin trap and impinger temperatures below 68°F. Maintain probe temperature above 212°F.

TABLE 5-4. CDD/CDF SAMPLING CHECKLIST, continued

3. Leak check between ports and record on data sheet. Leak check if the test is stopped to change silica gel, to decant condensate, or to change filters.

4. Record sampling times, rate, and location for the fixed gas bag sampling (CO, CO_2, O_2), if applicable.

5. Blow back pitot tubes periodically is expected mositure entrapment.

6. Change filter if vacuum suddenly increases or exceeds 15 inches Hg.

7. Check impinger solutions every 1/2 hour; if the knockout impinger is approaching full, stop test and empty it into a pre-weighed bottle and replace it in the train.

8. Check impinger silica gel every 1/2 hour; if indicator color begins to fade, request a prefilled, preweighed impinger from the recovery trailer.

9. Check the ice in the impinger bucket frequently. If the stack gas temperatures are high, the ice will melt at the bottom rapidly. Maintain condensor coil and silica gel impinger gas temperatures below 68°F.

After test is completed:

1. Record final meter reading.

2. Do final leak check of sampling train at maximum vacuum during test.

3. Do final pitot leak check.

4. Check completeness of data sheet. Verify the impinger bucket identification is recorded on the data sheets. Note any abnormal conditions.

5. Leak check function (level, zero, etc.) of pitot tubes and inpsect for tip damage.

6. Disassemble train, cap sections, and take each section and all data sheets down to recovery trailer.

7. Probe recovery (use 950 ml bottles)
   a) Bring probes into recovery trailer (or other enclosed area).
   b) Wipe the exterior of the probe to remove any loose material that could contaminate the sample.

TABLE 5-4. CDD/CDF SAMPLING CHECKLIST, continued

c) Carefully remove the nozzle/probe liner and cap it off with prerinsed aluminum foil.
d) For acetone rinses (all trains)
   - Attach precleaned cyclone flask to probe to catch rinses
   - Wet all sides of probe interior with acetone
   - While holding the probe in an inclined position, put precleaned probe brush down into probe and brush it in and out
   - Rinse the brush, while in the probe, with acetone
   - Do this at least 3 times until all the particulate has been recovered.
   - Recover acetone into a preweighed, prelabeled sample container
e) Follow the procedure outlined in (d) using methylene chloride. Recover the solvent into the same acetone recovery bottle.
f) Follow the procedure outlined in (d) using toluene. Recover this solvent into a separate preweighed prelabelled sample container.

7. Cap both ends of nozzle/probe liner for the next day, and store in dry safe place.

8. Make sure data sheets are completely filled out, legible, and give them to the Crew Chief.

entering the resin trap must be below 20°C (68°F). The gas is cooled by a water jacket condenser through which ice water is circulated.

The leak rates and sampling start and stop times are recorded on the sampling task log. Also, any other events that occur during sampling are recorded on the task log, such as sorbent module heat excursions, pitot cleaning, thermocouple malfunctions, heater malfunctions, or any other unusual occurrences.

If the probe liner breaks while the DGM is not running (i.e., during port changes or after the run is completed), the probe liner is replaced, the run is completed, and sample recovery done on both the broken sections of the glass liner and the replacement liner. If the break occurs while the DGM is running and the exact time of the break is noted, the test is stopped so that the probe liner can be replaced. The run is then completed and sample recovery done on all liner sections. If the recovered sample appears unusual, the sample is discarded and an additional run is performed later. If the recovered sample appears normal, the run is tentatively acceptable.

At the conclusion of the test run, the sample pump (or flow) is turned off, the probe is removed from the duct, a final DGM reading is taken, and a post-test leak check is completed. The procedure is identical to the pre-test procedure; however, the vacuum should be at least one inch Hg higher than the highest vacuum attained during sampling. An acceptable leak rate is less than 4 percent of the average sample rate or 0.02 acfm (whichever is lower). If a final leak rate does not meet the acceptable criterion, the test run may still be accepted upon approval of the test administrator. If so, the measured leak rate is reduced by subtracting the allowable leak rate from it and then multiplied for the period of time in which the leak occurred. This "leaked volume" is then subtracted from the measured gas volume in order to determine the final gas sample volume.

5.1.4 CDD/CDF Sample Recovery

To facilitate transfer from the sampling location to the recovery trailer, the sampling train is disassembled into the following sections: the probe liner, filter holder, filter to condenser glassware, condenser sorbent module, and the impingers in their bucket. Each of these sections is capped with methylene chloride-rinsed aluminum foil or ground glass caps before removal to the recovery trailer. Once in the trailer, field

recovery follows the scheme shown in Figure 5-3. The samples are recovered and stored in cleaned amber glass bottles to prevent light degradation.

The solvents used for train recovery are all pesticide grade. The use of the highest grade reagents for train recovery is essential to prevent the introduction of chemical impurities which interfere with the quantitative analytical determinations.

Field recovery results in the sample components listed in Table 5-5. The sorbent module is stored in a cooler on ice at all times. The samples are shipped to the analytical laboratory by truck accompanied by written information designating target analyses.

5.1.5 CDD/CDF Analytical Procedures

The analytical procedure used to obtain CDD/CDF concentrations from a single flue gas sample is by HRGC and HRMS (resolution from 8000-10000 m/e). The target CDD/CDF congeners are listed in Table 5-6. The analyses are performed by Triangle Laboratories, Inc., by Method 8290X.

The flue gas samples are analyzed in two fractions according to the scheme in Figure 5-4. One fraction is the total train methylene chloride and acetone rinses, filter(s), and sorbent module; the other fraction is comprised of the toluene rinse of applicable portions of the sampling train. For the CDD/CDF analysis, isotopically-labeled surrogate compounds and internal standards are added to the samples before the extraction process is initiated. The internal standards and surrogates that are used are described in detail in EPA Method 23.

Data from the mass spectrometer are recorded and stored on a computer file as well as printed on paper. Results such as amount detected, detection limit, retention time, and internal standard and surrogate standard recoveries are calculated by computer. The chromatograms are retained by the analytical laboratory and also included in the analytical report delivered to Radian Corporation.

5.1.5.1 Preparation of Samples for Extraction. Upon receiving the sample shipment, the samples are checked against the Chain-of-Custody forms and then assigned an analytical laboratory sample number. Each sample component is reweighed to determine if leakage occurred during travel. Color, appearance, and other particulars of the samples are noted. Samples are extracted within 21 days of collection.

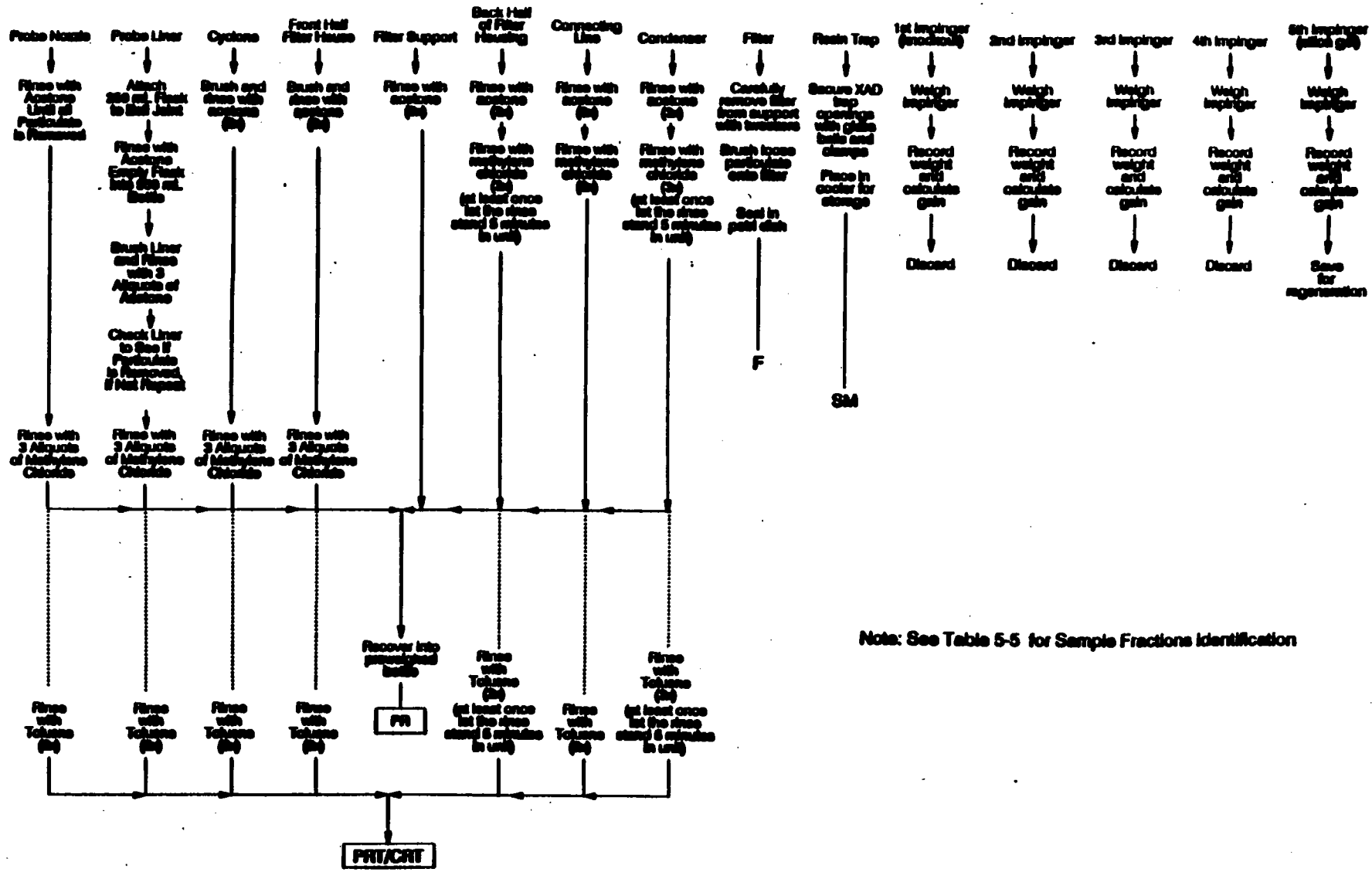

Figure 5-3. PCB/CDD/CDF/TCO Field Recovery Scheme

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TABLE 5-5. CDD/CDF SAMPLE FRACTIONS SHIPPED TO ANALYTICAL LABORATORY

Container/ Component	Code	Fraction
1	F	Filter(s)
2	PR[a]	Acetone and methylene chloride rinses of nozzle/probe, cyclone, front half/back half filter holder, filter support, connecting glassware, condensor
3	PRT[b] CRT[b]	Toluene rinse of nozzle/probe, cyclone, front half/back half filter holder, filter support, connecting line and condensor
4	SM	XAD-II® resin trap (sorbent module)

[a] Rinses include acetone and methylene chloride recovered into the same sample bottle.
[b] Rinses of toluene recovered into separate sample bottle (sometimes toluene probe rinse (PRT) and coil rinse (CRT) are recovered separately).

TABLE 5-6. CDD/CDF CONGENERS TO BE ANALYZED

DIOXINS:

2,3,7,8 tetrachlorodibenzo-p-dioxin (2,3,7,8 TCDD)
Total tetrachlorinated dibenzo-p-dioxins (TCDD)
1,2,3,7,8 pentachlorodibenzo-p-dioxin (1,2,3,7,8 PeCDD)
Total pentachlorinated dibenzo-p-dioxins (PeCDD)
1,2,3,4,7,8 hexachlorodibenzo-p-dioxin (1,2,3,4,7,8 HxCDD)
1,2,3,6,7,8 hexachlorodibenzo-p-dioxin (1,2,3,6,7,8 HxCDD)
1,2,3,7,8,9 hexachlorodibenzo-p-dioxin (1,2,3,7,8,9 HxCDD)
Total hexachlorinated dibenzo-p-dioxins (HxCDD)
1,2,3,4,6,7,8 heptachlorodibenzo-p-dioxin (1,2,3,4,6,7,8 HpCDD)
Total heptachlorinated dibenzo-p-dioxins (HpCDD)
Total octachlorinated dibenzo-p-dioxins (OCDD)

FURANS:

2,3,7,8 tetrachlorodibenzofurans (2,3,7,8 TCDF)
Total tetrachlorinated dibenzofurans (TCDF)
1,2,3,7,8 pentachlorodibenzofuran (1,2,3,7,8 PeCDF)
2,3,4,7,8 pentachlorodibenzofuran (2,3,4,7,8 PeCDF)
Total pentachlorinated dibenzofurans (PeCDF)
1,2,3,4,7,8 hexachlorodibenzofuran (1,2,3,4,7,8 HxCDF)
1,2,3,6,7,8 hexachlorodibenzofuran (1,2,3,6,7,8 HxCDF)
2,3,4,6,7,8 hexachlorodibenzofuran (2,3,4,6,7,8 HxCDF)
1,2,3,7,8,9 hexachlorodibenzofuran (1,2,3,7,8,9 HxCDF)
Total hexachlorinated dibenzofurans (HxCDF)
1,2,3,4,6,7,8 heptachlorodibenzofuran (1,2,3,4,6,7,8 HpCDF)
1',2,3,4,7,8,9 heptachlorodibenzofuran (1',2,3,4,7,8,9 HpCDF)
Total heptachlorinated dibenzofurans (HpCDF)
Total octachlorinated dibenzofurans (OCDF)

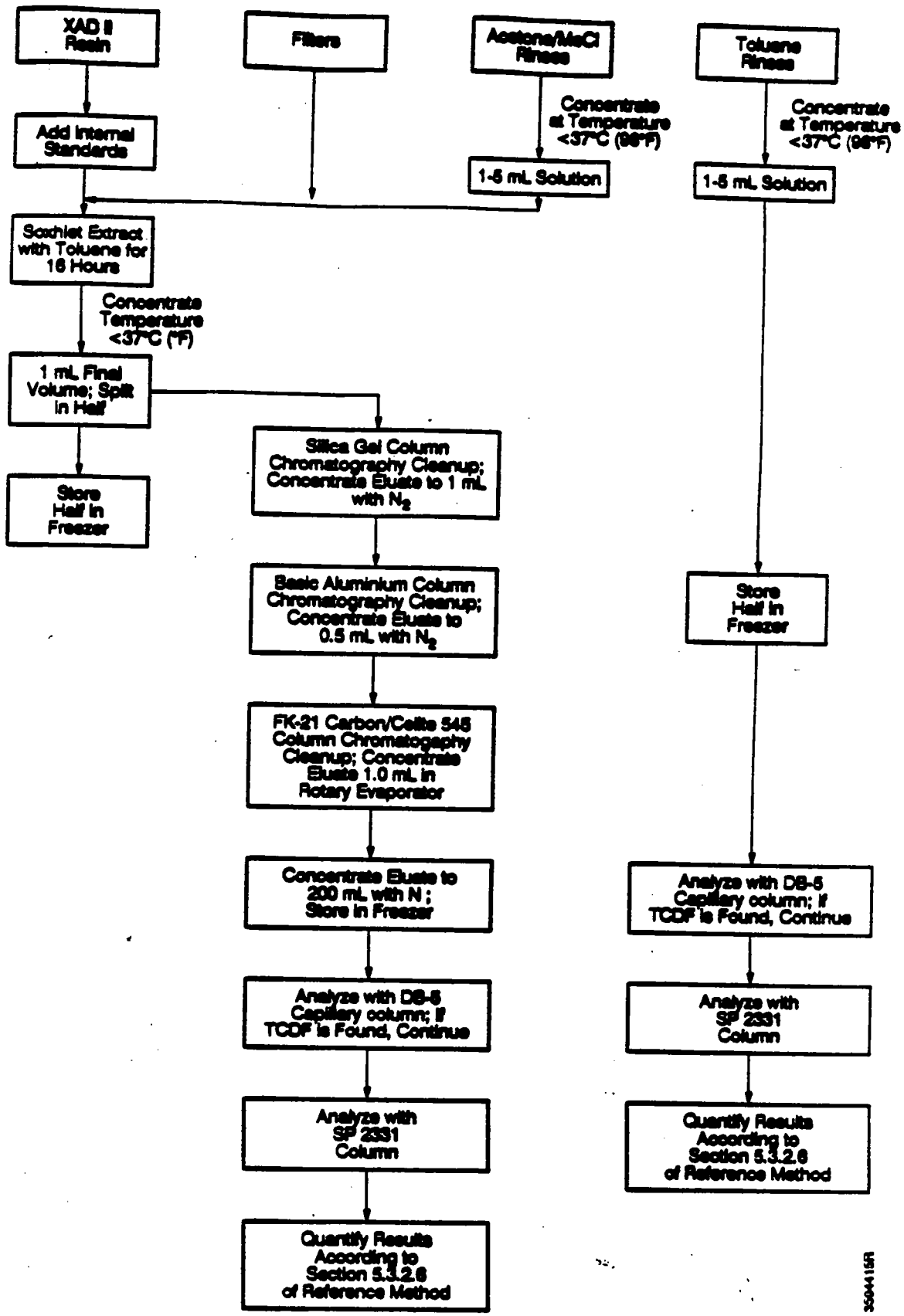

Figure 5-4. Extraction and Analysis Schematic for CDD/CDF Samples

5.1.5.2 Calibration of GC/MS System. A five-point calibration of the GC/MS system is performed to demonstrate instrument linearity over the concentration range of interest. Relative response factors are calculated for each congener or compound of interest. The response factors are verified on a daily basis using a continuing calibration standard consisting of a mid-level mixed isomer standard. The instrument performance is acceptable only if the measured response factors for the labeled and unlabeled compounds and the ion-abundance ratios are within the allowable limits specified in the method (52200, 52201 FR 891220).

5.1.6 CDD/CDF Analytical Quality Control

All quality control procedures specified in the test method are followed. Blanks are used to determine analytical contamination, calibration standards are used for instrument calibration and linearity checks, internal standards are used to determine isomer recoveries and adjust response factors for matrix effects, surrogate standards are used to measure the collection efficiency of the sampling methodology, and an alternate standard is used as a column efficiency check.

5.1.6.1 CDD/CDF Quality Control Blanks. Three different types of sample blanks are collected for CDD/CDF analysis. The type of blanks that are required are shown in Table 5-7.

Reagent blanks of 1000 ml of each reagent used at the test site are saved for potential analysis. Each reagent blank is of the same lot as was used during the sampling program. Each lot number and reagent grade is recorded on the field blank label and in the laboratory notebook.

A glassware blank (proof blank) is recovered from each set of sample train glassware that is used to collect the organic samples. The precleaned glassware, which consists of a probe liner, filter holder, condensor coil, and impinger set, is loaded as if for sampling and then quantitatively recovered exactly as the samples are. Analysis of the generated fractions is used to check the effectiveness of the glassware cleaning procedure only if sample analysis indicates a potential contamination problem.

A field blank is collected from a set of CDD/CDF glassware that has been used to collect at least one sample and has been recovered. The train is re-loaded and left at a sampling location during a test run. The train is then recovered. The purpose of the

TABLE 5-7. CDD/CDF BLANKS COLLECTED

Blank	Collection	Analysis
Field Blanks	One run collected and analyzed for each sampling location.	Analyze with flue gas samples.
Glassware Proof Blank	Each train to be used (2) will be loaded and quantitatively recovered prior to sampling	Archive for potential analysis
Method Blank	At least one for each analytical batch	Analyze with each analytical batch of flue gas samples
Reagent Blanks	One 1000 ml sample for each reagent and lot.	Archive for potential analysis.

field blank is to measure the level of contamination that occurs from handling, loading, recovering, and transporting the sampling train. The field blanks are analyzed with the flue gas samples. If they are unsatisfactory in terms of contamination, reagent blanks may be analyzed to determine the specific source of contamination.

To verify the flue gas sample was quantitatively recovered, toluene rinses are also analyzed separately from the other fractions. These results are not incorporated into the final emission values; however, they are used as QA/QC indicators.

In addition to the three types of blanks that are required for the sampling program, the analytical laboratory analyzes a method blank with each set of flue gas samples. This consists of prepping and analyzing reagent water by the exact procedure used for the samples analysis. The purpose of this is to verify that there is no laboratory contamination of the field samples.

5.1.6.2 Quality Control Standards and Duplicates. Recoveries of the internal standards must be between 40 to 130 percent for the tetra- through hexachlorinated compounds and between 25 to 130 percent for the hepta- and octachlorinated homologues. If these requirements are not met, the data is acceptable if the signal to noise ratio is greater than or equal to ten. If these requirements are met, the results for the native (sampled) species are adjusted according to the internal standard recoveries.

Surrogate standard recoveries must be between 70 to 130 percent. If the recoveries of all standards are less than 70 percent, the project director is notified immediately to determine if the surrogate results can be used to adjust the results of the native species.

Duplicate analysis is performed for every ten samples. The purpose of this is to evaluate the precision of the combined sample preparation and analytical methodology.

A summary of the acceptance, criteria, control limits, and corrective action for the procedures described in this section is shown in Table 7-1.

5.2 PARTICULATE MATTER AND METALS EMISSIONS TESTING METHOD

Sampling for PM and metals is performed according to an EPA Emission Measurement Branch (EMB) draft protocol entitled "Methodology for the Determination of Metals Emissions in Exhaust Gases from Incineration Processes." The protocol is presented in Appendix A. This method is applicable for the determination of

particulates and Pb, Ni, zinc (Zn), phosphorus (P), Cr, copper (Cu), manganese (Mn), selenium (Se), Be, Tl, Ag, Sb, Ba, Cd, As, and Hg emissions from various types of incinerators. Analyses of the Central Carolina Hospital MWI test samples will be performed for As, Cd, Cr, Hg, Ni, Pb, Sb, Ag, Ba, Be, and Tl.

The PM emissions are also determined from this sampling train. Particulate concentrations are based on the weight gain of the filter and the front half acetone rinses (probe, nozzle, and filter holder). After the gravimetric analyses have been completed, the sample fractions are then analyzed for the target metals as discussed in Section 5.2.5.

5.2.1 PM/Metals Sampling Equipment

The methodology uses the sampling train shown in Figure 5-5. The 5-impinger train consists of a quartz nozzle/probe liner followed by a heated filter assembly with a Teflon® filter support, a series of impingers, and the usual EPA Method 5 meterbox and vacuum pump. The sample is not exposed to any metal surfaces in this train. The contents of the sequential impingers are: two impingers with a 5 percent HNO_3/10 percent H_2O_2 solution, two impingers with a 4 percent $KMnO_4$/10 percent sulfuric acid (H_2SO_4) solution, and an impinger containing silica gel. An optional empty knockout impinger may be added if the moisture content of the flue gas is high. The second impinger containing HNO_3/H_2O_2 shall be of the Greenburg-Smith design; the other impingers shall have straight tubes. The impingers are connected together with clean glass U-tube connectors and are arranged in an impinger bucket as shown in Figure 5-6. Sampling train components are recovered and analyzed in separate front and back half fractions according to the described method.

5.2.2 PM/Metals Sampling Equipment Preparation

5.2.2.1 Glassware Preparation. Glassware is washed in hot soapy water, rinsed with tap water (3X), and then rinsed with deionized distilled water (3X). The glassware is then subjected to the following series of soaks and rinses:

- Soak in a 10 percent HNO_3 solution for a minimum of 4 hours;
- Rinse with deionized distilled water rinse (3X); and
- Rinse with acetone rinse.

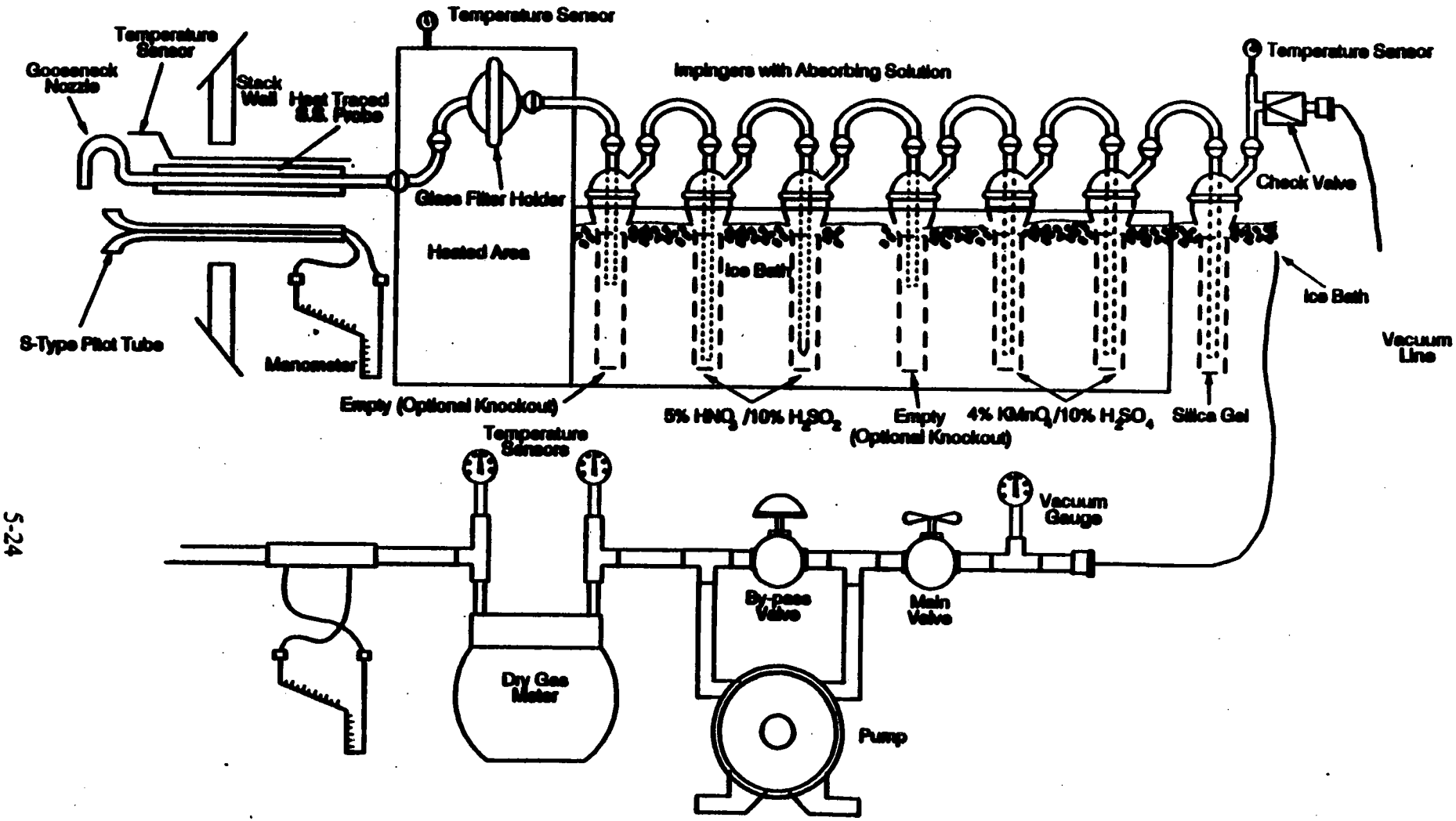

Figure 5-5. Schematic of Multiple Metals Sampling Train

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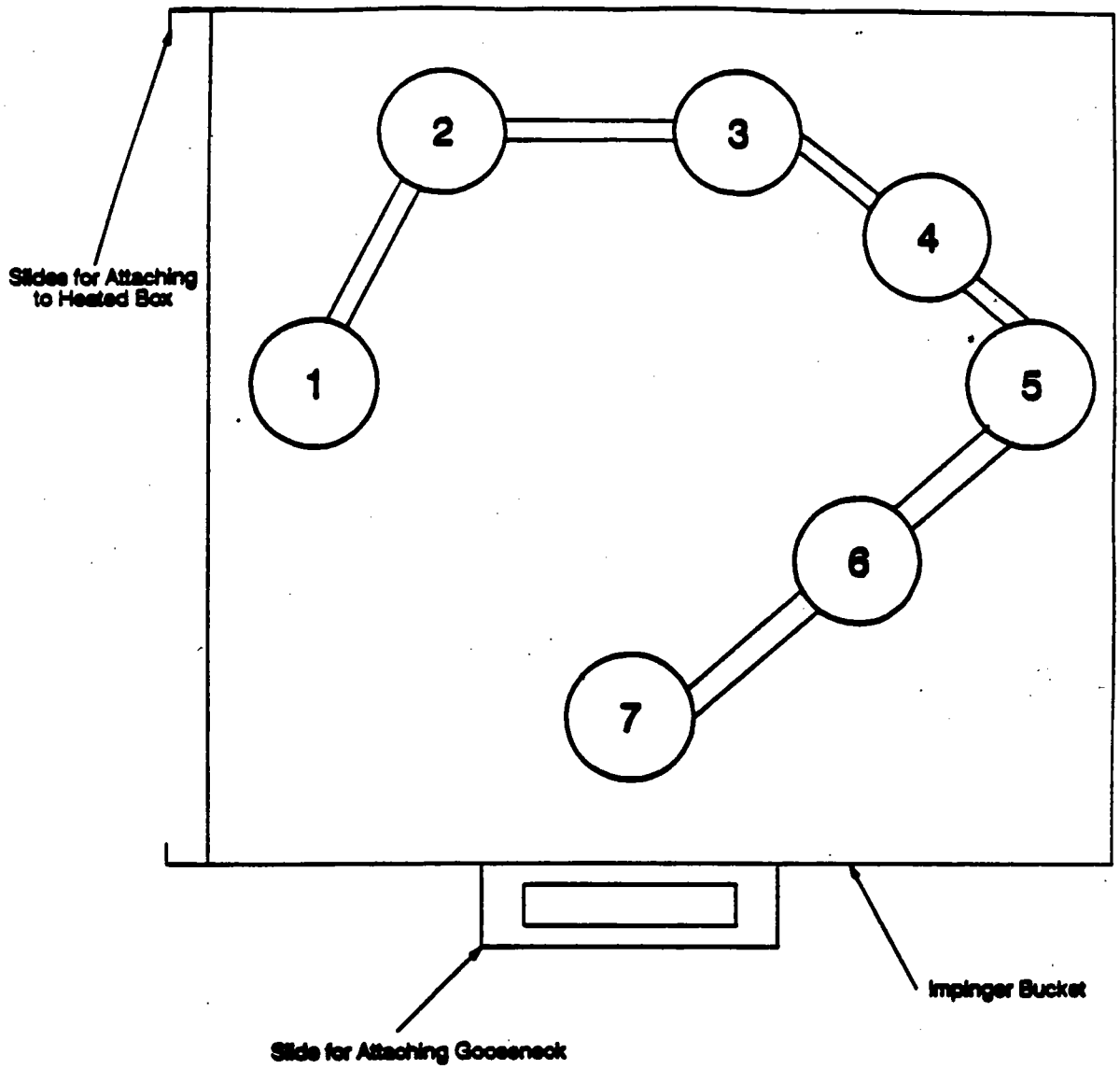

Figure 5-6. Impinger Configuration for PM/Metals Sampling
(optional knock out impinger not shown)

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The cleaned glassware is allowed to air dry in a contamination-free environment. The ends are then covered with parafilm. All glass components of the sampling train plus any sample bottles, pipets, Erlenmeyer flasks, petri dishes, graduated cylinders, and other laboratory glassware used during sample preparation, recovery, and analysis are cleaned according to this procedure.

5.2.2.2 Reagent Preparation. The sample train filters are Pallflex Tissuequartz 2500QAS filters. The acids and H_2O_2 peroxide are Baker "Instra-analyzed" grade or equivalent. The peroxide is purchased specifically for this test site and is kept cold until it is opened.

The reagent water is Baker "Analyzed HPLC" grade or equivalent. The lot number, manufacturer, and grade of each reagent that is used is recorded in the laboratory notebook.

The HNO_3/H_2O_2 absorbing solution and the acidic $KMnO_4$ absorbing solution is prepared fresh daily according to Sections 4.2.1 and 4.2.2 of the reference method. The analyst wears both safety glasses and protective gloves when the reagents are mixed and handled. Each reagent has its own designated transfer and dilution glassware. This glassware is marked for identification with a felt tip glass marking pen and used only for the reagent for which it is designated.

The analyst may save time preparing the acidic $KMnO_4$ solution each day by observing the following procedure, beginning at least one day before the reagent is needed.

- Quantitatively remove 400 ml from a 4 liter bottle of Baker "Analyzed HPLC" water. Label this bottle 4.4 percent $KMnO_4$ in water.

- Quantitatively add 160 g of potassium permanganate crystals to the bottle; stir with a Teflon® stirring bar and stirring plate as thoroughly as possible. This reagent will be stored on the counter in a plastic tub at all times.

- Each morning the acidic reagent is needed, decant 900 ml of $KMnO_4$ solution into a 1000 ml volumetric flask. Carefully add 100 ml of concentrated H_2SO_4 and mix. This reagent is volatile and must be mixed cautiously. Hold the flask cap on the flask, mix once, vent quickly. Complete the mixing slowly until the mixture is homogenous. Allow the solution to cool and bring the final volume to 1000 ml with H_2O.

- Carefully filter this reagent through Wattman 541 filter paper into another volumetric flask or 2 liter amber bottle. Label this bottle 4 percent acidic $KMnO_4$ absorbing solution. Vent the top and store the reagent in a plastic tub at all times.

5.2.2.3 Equipment Preparation. The remaining preparation includes calibration and leak checking of all train equipment as specified in EPA Method 5. This equipment includes the probe nozzles, pitot tubes, metering system, probe heater, temperature gauges, leakcheck metering system, and barometer. A laboratory field notebook is maintained to record these calibration values.

5.2.3 PM/Metals Sampling Operations

The sampling operations used for PM/Metals testing are virtually the same as those for the CDD/CDF tests as discussed in Section 5.1.2. The only differences are that there is no condensor coil so coil temperatures are not recorded and glass caps, Teflon® tape, or parafilm is used to seal off the sample train components rather than foil. Detailed instructions for assembling the metals sampling train are found beginning on page 14 of the reference method.

5.2.4 PM/Metals Sample Recovery

Begin recovery procedures as soon as the probe is removed from the stack and the post-test leakcheck is completed.

To facilitate transfer from the sampling location to the recovery trailer, the sampling train is disassembled into three sections: the nozzle/probe liner, filter holder, and impingers in their bucket. Each of these sections is capped with Teflon® tape or parafilm before removal to the recovery trailer.

Once in the trailers, the sampling train is recovered as separate front and back half fractions. A diagram illustrating front half and back half sample recovery procedures is shown in Figure 5-7. No equipment with exposed metal surfaces is used in the sample recovery procedures. The weight gain in each of the impingers is recorded to determine the moisture content in the flue gas. Following weighing of the impingers, the front half of the train is recovered, which includes the filter and all sample-exposed surfaces forward of the filter. The probe liner is rinsed with acetone by tilting and rotating the probe while squirting acetone into its upper end so that all inside surfaces are wetted. The acetone will be quantitatively collected into the appropriate bottle.

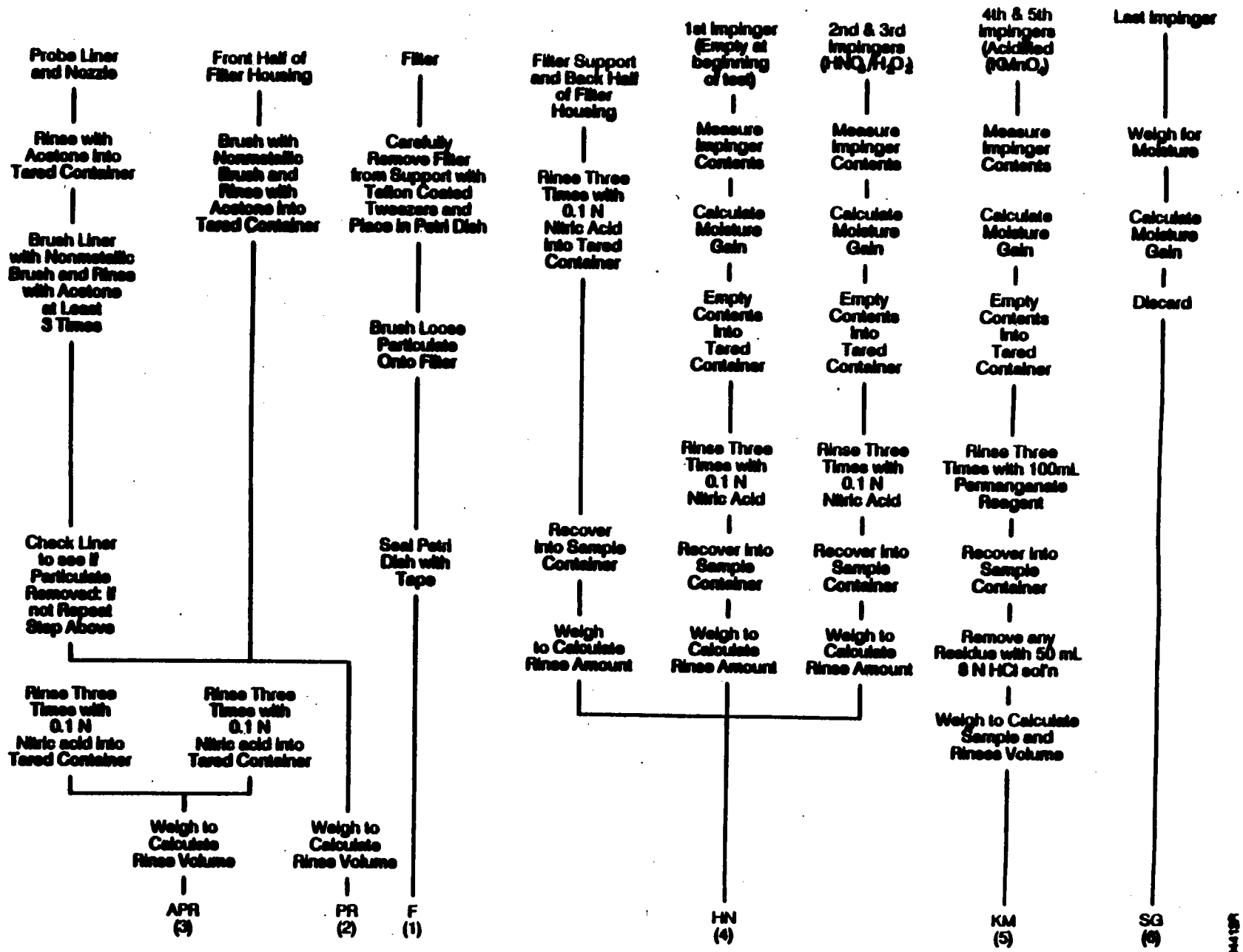


Figure 5-7. Metals Sample Recovery Scheme

This rinse is followed by additional brush/rinse procedures using a non-metallic brush; the probe is held in an inclined position and acetone is squirted into the upper end as the brush is pushed through with a twisting action. All of the acetone and particulate is caught in the sample container. This procedure is repeated until no visible particulate remains and finished with a final acetone rinse of the probe and brush. The front half of the filter is also rinsed with acetone until all visible particulate is removed. After all front half acetone washes are collected, the cap is tightened, the liquid level marked, and the bottle weighed to determine the acetone rinse volume. The method specifies a total of 100 ml of acetone may be used for rinsing these components. However, Radian feels that a thorough rinse requires more reagent. An acetone reagent blank of approximately the same volume as the acetone rinses is analyzed with the samples.

The nozzle/probe liner, and front half of the filter holder is rinsed three times with 0.1N HNO_3 and placed into a separate amber bottle. The bottle is capped tightly, the weight of the combined rinse recorded, and the liquid level marked. The filter is placed in a clean, well-marked glass petri dish and sealed with Teflon® tape.

Prior to recovering the back half impingers, the contents are weighed for moisture control determinations. Any unusual appearance of the filter or impinger contents are noted. Pictures may be taken to further document any abnormality.

The contents in the knockout impinger (if used) is recovered into a preweighed, prelabeled bottle with the contents from the HNO_3/H_2O_2 impingers. These impingers and connecting glassware are rinsed thoroughly with 0.1N HNO_3, the rinse is captured in the impinger contents bottle, and a final weight is taken. Again, the method specifies a total of 100 ml of 0.1N HNO_3 be used to rinse these components. A HNO_3 reagent blank of approximately the same volume as the rinse volume is analyzed with the samples.

The impingers that contain the acidified $KMnO_4$ solution are poured together into a preweighed, prelabeled bottle. The impingers and connecting glassware are rinsed with at least 100 ml of the acidified $KMnO_4$ solution (from the same batch used for sampling) a minimum of three times. Rinses are added to the sample recovery bottle. A final 50 ml 8N hydrochloric acid (HCl) rinse is conducted and placed into the sample recovery

bottle. A final weight is recorded and the liquid level is marked on the bottle. The bottle cap is loosely tightened to allow venting.

After final weighing, the silica gel from the train is saved in a bag for regeneration after the job has been completed. The ground glass fittings on the silica gel impinger are wiped off after sample recovery to assure a leak tight fit for the next test.

A reagent blank is recovered in the field for each of the following reagents:

- Acetone blank - 100 ml sample size;
- 0.1N HNO_3 blank - 1000 ml sample size;
- 5 percent HNO_3/10 percent H_2O_2 blank - 200 ml sample size;
- Acidified $KMnO_4$ blank - 1000 ml sample size; this blank should have a vented cap;
- 8N HCl blank - 50 ml sample size;
- Dilution water; and
- Filter blank - one each.

Each reagent blank is of the same lot as was used during the sampling program. Each lot number and reagent grade is recorded on the field blank label.

The liquid level of each sample container is marked on the bottle in order to determine if any sample loss occurred during shipment. If sample loss has occurred, the sample may be voided or a method may be used to incorporate a correction factor to scale the final results depending on the volume of the loss.

Approximate detection limits for the various metals of interest are summarized in Table 5-8.

5.2.5 Particulate Analysis

The same general gravimetric procedure described in Method 5, Section 4.3 is followed. Both filters and precleaned beakers are weighed to a constant weight before use in the field. The same balance used for taring is used for weighing the samples.

TABLE 5.8 APPROXIMATE DETECTION LIMITS FOR METALS OF INTEREST USING EMB DRAFT METHOD

Metal	Method[a]	Analytical Detection Limits ($\mu g/ml$)	Instack Method Detection Limits[b] Front Half (300 ml sample size) ($\mu g/m^3$)	Instack Method Detection Limits[b] Back Half (150 ml sample size) ($\mu g/m^3$)
Chromium	ICAP	0.007	1.7	0.8
Cadmium	ICAP	0.004	1.0	0.5
Arsenic[d]	GFAAS	0.001	0.3	0.1
Lead[d]	GFAAS	0.001	0.2	0.1
Mercury	CVAAS	0.0002	0.05	0.03[c]
Nickel	ICAP	0.015	3.6	1.8
Barium	ICAP	0.002	0.5	0.3
Beryllium	ICAP	0.0003	0.07	0.04
Silver	ICAP	0.007	1.7	0.9
Antimony	ICAP	0.032	7.7	3.8
Thallium	ICAP	0.040	9.6	4.8

[a] ICAP = Inductively Coupled Argon Plasma
GFAAS = Graphite Furnace Atomic Absorption Spectroscopy
CVAAS = Cold Vapor Atomic Absorption Spectroscopy

[b] These detection limits are based on a stack gas sample volume of 1.25 m^3. If 5 m^3 are collected, the instack method detection limits are 1/4 of the values indicated.

[c] The detection limit for mercury is the same in the HNO_3/H_2O_2 fraction as it is in the $KMnO_4$ fraction.

[d] If Fe and Al are present, samples will be diluted which may raise analytical detection limits.

The acetone rinses are evaporated under a clear hood at 20°C (68°F) in a tared beaker temperature silica gel. The filter is also desiccated under the same conditions to a constant weight. Weight gain is reported to the nearest 0.1 mg. Each replicate weighing must agree to within 0.5 mg or 1 percent of total weight less tare weight, whichever is greater, between two consecutive weighings, and must be at least 6 hours apart.

5.2.6 Metals Analytical Procedures

A diagram illustrating the sample preparation and analytical procedure for the target metals is shown in Figure 5-8.

The front half fractions basically are digested with concentrated HNO_3 and hydrofluoric (HF) acid in either a microwave pressure vessel or a Parr® bomb. The microwave digestion takes place over a period of approximately 10 to 12 minutes in intervals of 1 to 2 minutes at 600 watts; the Parr® bomb digestion is for 6 hours at 140°C (285°F). Both the digested filter and the digested probe rinses are combined to yield the front half sample fraction. The fraction is diluted to a specified volume with water and divided for analysis by applicable instrumentation.

The absorbing solutions from the HNO_3/H_2O_2 impingers are combined. An aliquot is removed for the analysis of mercury by CVAAS and the remainder is acidified and reduced to near dryness. The sample is then digested in either a microwave or by conventional digestion, with 50 percent HNO_3 and 3 percent H_2O_2. After the fraction has cooled, it is filtered and diluted to a specified volume with water.

Each sample fraction is analyzed by ICAPS using EPA Method 200.7. All target metals except mercury, iron, and aluminum, are quantified. If iron and aluminum are present, the samples are diluted to reduce their interferences on arsenic and lead. If arsenic or lead levels are less than 2 ppm, GFAAS is used to analyze for these elements by EPA Methods 7060 and 7421. Matrix modifiers such as specific buffering agents may be added to these aliquots to react with and tie up interfering agents. The total volume of the absorbing solutions and rinses for the various fractions are measured and recorded in the field notebook.

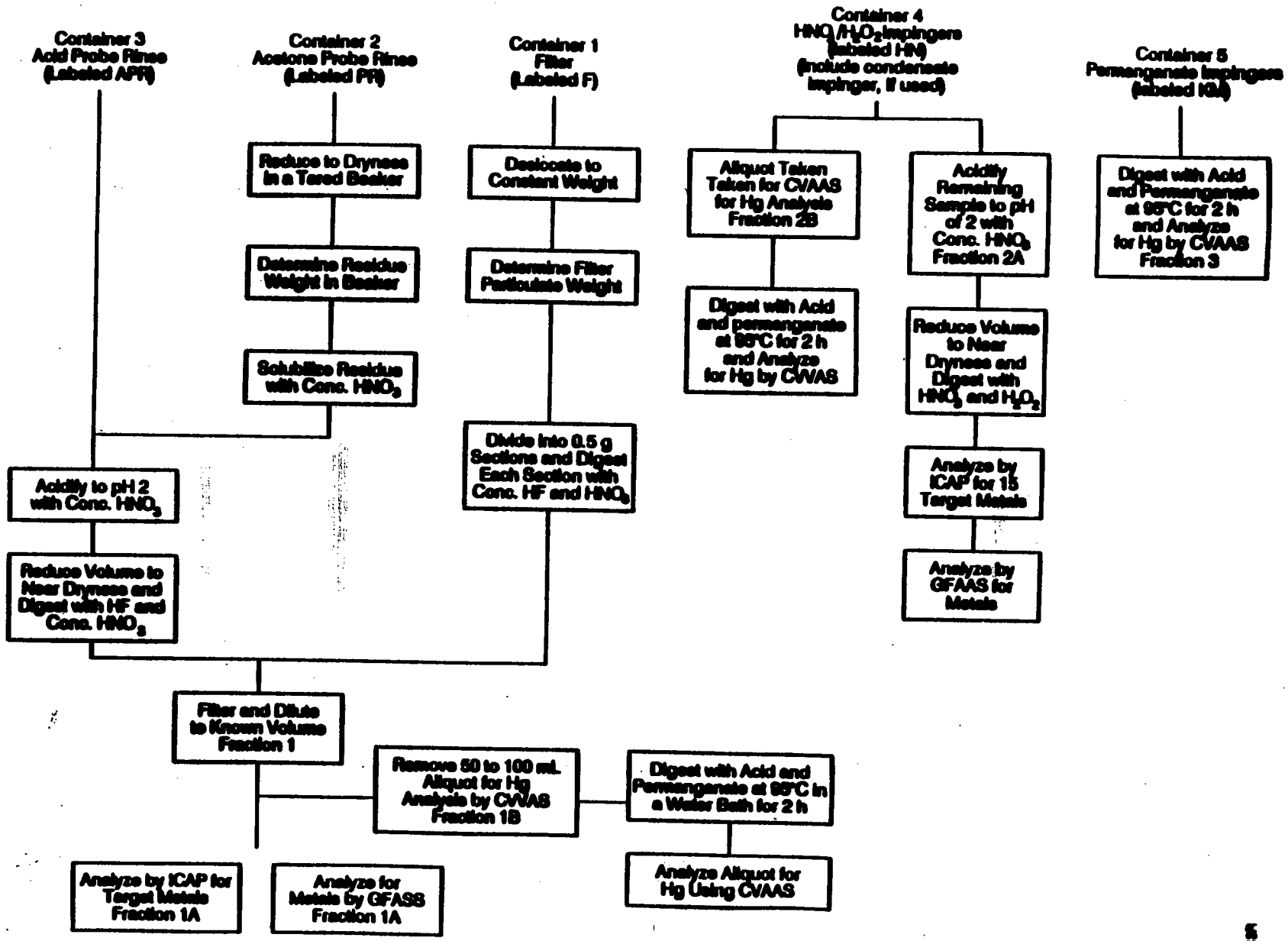


Figure 5-8. Metals Sample Preparation and Analysis Scheme

To prepare for mercury analysis by CVAAS, an aliquot from the $KMnO_4$ impingers, HNO_3/H_2O_2 impingers, filter digestion, and front half rinses are digested with acidic reagents at 95°C in capped BOD bottles for approximately 3 hours. Hydroxylamine hydrochloride solution and stannous chloride is added immediately before analysis. Cold vapor AAS analysis for mercury follows the procedure outlined in EPA Method 7470 or in Standard Methods for Water and Wastewater Analysis, Method 303F.

5.2.7 Quality Control for Metals Analytical Procedures

All quality control procedures specified in the test method are followed. All field reagent blanks are processed, digested, and analyzed as specified in the test method. To ensure optimum sensitivity in measurements, the concentrations of target metals in the solutions are at least 10 times the analytical detection limits.

5.2.7.1 ICAP Standards and Quality Control Samples. The quality control procedures include running two standards for instrument checks (or frequency of 10 percent), two calibration blank runs (or frequency of 10 percent), one interference check sample at the beginning of the analysis (must be within 10 percent or analyze by standard addition), one quality control sample to check the accuracy of the calibration standards (must be within 10 percent of calibration), one duplicate analysis and one standard addition for every 10 samples (must be within 5 percent of average or repeat all analysis).

Standards less than 1 μg/ml of a metal are prepared daily; those with concentrations greater than this are made weekly or bi-monthly.

5.2.7.2 Graphite Furnace Standards and Quality Control Samples. Standards used for GFAAS analysis must be matrix matched with the samples analyzed and the matrix modifiers that were added. Standards less than 1 μg/ml of a metal are prepared daily; those with concentrations greater than this are made weekly or bi-monthly. A minimum of five standards make the standard curve. Quality control samples are

prepared from a separate 10 μg/ml standard by diluting it into the range of the samples.

All samples are analyzed in duplicate. A matrix spike on one front half sample and one back half sample for each 10 field samples is analyzed. If recoveries of less than 75 percent or greater than 120 percent are obtained for the matrix spike, each sample is analyzed by the method of additions. One quality control sample is analyzed to check the accuracy of the calibration standards. The results must be within 10 percent or the calibration repeated.

5.2.7.3 Mercury Standards and Quality Control. An intermediate mercury standard is prepared weekly; working standards are prepared daily. The calibration curve is made with at least six points. Quality Control samples are prepared from a separate 10 μg/ml standard by diluting it into the range of the samples.

A quality control sample must agree within 10 percent of the calibration, or the calibration repeated. A matrix spike on one of every 10 samples from the HNO_3/H_2O_2 back half sample fraction must be within 20 percent or the samples are analyzed by the method of standard addition.

5.3 MICROBIAL SURVIVABILITY TESTING

The Central Carolina Hospital MWI was loaded with waste containing indicator spores which measure the ability of microbes to survive the incineration process. This directly reflects microbial destruction efficiency for that incinerator. The first test method is aimed at determining microbial survivability in the combustion gases and the ash. This method involves inoculating a known quantity of spores in solution onto materials normally found in the medical waste stream (i.e., petri dishes, gauze, etc.). Direct ash sampling and flue gas testing are conducted in order to determine the destruction efficiency. Test procedures follow guidelines set forth by the EPA draft methods located in Appendix A.3 and A.4 of the test plan.

The second test method utilizes spiked spore samples encased in insulated metal containers charged to the incinerator with the waste stream. These tests are aimed at comparing this method with the direct ash sampling method and should provide a general assessment of microbial survivability and destruction efficiency. Three sets of samples (two different diameters) are periodically charged into the incinerator through out the test day. Following the test, the viability of the indicator spores in each sample

is checked to assess the destruction efficiency of spores that remain in the ash. Testing procedures used here follow an EPA draft method entitled "Microbial Survivability Test for Medical Waste Incinerator Ash." The following sections detail both spiking procedures (emissions/ash and pipe) as well as the spore flue gas sampling and analytical techniques.

5.3.1 Spiking Procedure for Emissions and Ash Microbial Loading

In addition to the pipe samples, a second series of waste materials inoculated with indicator spores are charged into the incinerator. A known quantity of B. stearothermophilus wet spores are inoculated onto or in materials normally found in the medical waste stream such as petri dishes, test tubes, gauze, etc. The waste is loaded into the incinerator to coincide with the emission tests conducted at the incinerator outlet. Direct ash samples are collected after the ash has cooled sufficiently.

5.3.1.1 Equipment. A "wet spore" culture solution is prepared by the University of Alabama. The culture inoculum is divided between the nine sampling runs as shown in Figure 5-9. The spore solution is prepared as a frozen slurry in 1-liter amounts. Inoculation quantities are approximately 600 to 700 mls. The culture inoculum is added to various materials using sterile syringes or other implements as required.

5.3.1.2 Spiking Preparation and Procedure. The spiked waste sample is prepared so that about 1×10^{11} to 1×10^{12} spores are charged into the incinerator per sample run (the exact quantity is recorded). The total charge is separated into four culture batches. Each bag of spiked waste is loaded into the ram feeder at equal time intervals over the course of the emissions test run. For the proposed 4-hour test, spiked bags are loaded at sampling times of 0, 1, 2, and 3 hours from the start of testing.

5.3.2 Indicator Spore Flue Gas Sampling

Flue gas is extracted from the incinerator stack during the burn cycle to determine spore emissions. The testing procedure follows the previously mentioned, draft EPA method. Flue gas samples are collected isokinetically in a buffered solution in impingers (no filter). The recovered samples are divided into different volume aliquots. These samples are cultured and colonies are identified using gram stains to establish cellular morphology, and possibly other biochemical tests as needed.

	Fermentation Batch 1			Fermentation Batch 2			Fermentation Batch 3		
	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9
Fraction a	a	a	a	a	a	a	a	a	a
Fraction b	b	b	b	b	b	b	b	b	b
Fraction c	c	c	c	c	c	c	c	c	c
Fraction d	d	d	d	d	d	d	d	d	d
Fraction e	e	e	e	-- if required to get 1×10^{12} spores --			e	e	e

Notes: Each fraction will be loaded into the incinerator at equally spaced intervals over the duration of the test run during normal charge periods.

At least twelve fractions or doses per test condition. Additional fractions will be added from Batch 4 (fraction e) if necessary to achieve 1×10^{12} spores per run.

Figure 5-9. Indicator Spore Spiking Scheme for Combustion Gas Destruction Efficiency Testing

The colonies are then enumerated. The following sections describe the flue gas sampling techniques to be used.

5.3.2.1 Equipment. A schematic of the spore sampling train is shown in Figure 5-10. Flue gas samples are extracted isokinetically through a quartz nozzle/probe system housed in a water-cooled sheath. A smaller tube is located inside the sampling probe to deliver a buffered solution at the nozzle end of the probe. This allows the gas sample stream to be immediately buffered, preventing acid condensate from killing viable spores. From the probe, the sample stream is delivered to a series of chilled impingers. The first two contain 200 ml and 100 ml, respectively, of phosphate-buffered solution to collect indicator spores. The third impinger serves as a knock-out (empty) and the fourth contains silica gel. In between the third and fourth impinger, a small amount of quartz wool was placed to collect PM. This material was rinsed into the impinger catch during recovery operations. The remainder of the sampling train is identical to a Method 5 system. (Meter box containing pump, meter, velocity and sampling pressure manometers, etc.)

A Peristaltic pump is used to deliver the buffer solution to the probe tip. The pump is capable of accurately metering a 10 to 20 ml/minute flow rate.

5.3.2.2 Sampling Preparation. All equipment used for sampling and sample recovery, which come into contact with the sample, is H_2O_2/alcohol disinfected and washed before each run. The nozzle/probe liner, impingers, impinger connections, and the nozzle/probe brush are first washed using the same procedure as discussed in Section 5.3.4.2. Following washing, all components are disinfected with H_2O_2/alcohol. After completing this procedure, all components are sealed with Parafilm® to prevent contamination. Additional sample containers, recovery items, and analytical equipment are sterilized by autoclaving or another equivalent method. Some of the items which need to be sterilized are wash bottles, two liter glass sample storage bottles, incubation tubes, petri dishes, filter units, reagent water (sterile deionized), and buffering reagent.

The train is assembled by first antiseptically adding the buffer solution to the first two impingers. Silica gel is added to the fourth impinger and the impinger train is connected to the meter box via an umbilical line. A pre-test leakcheck on the impinger

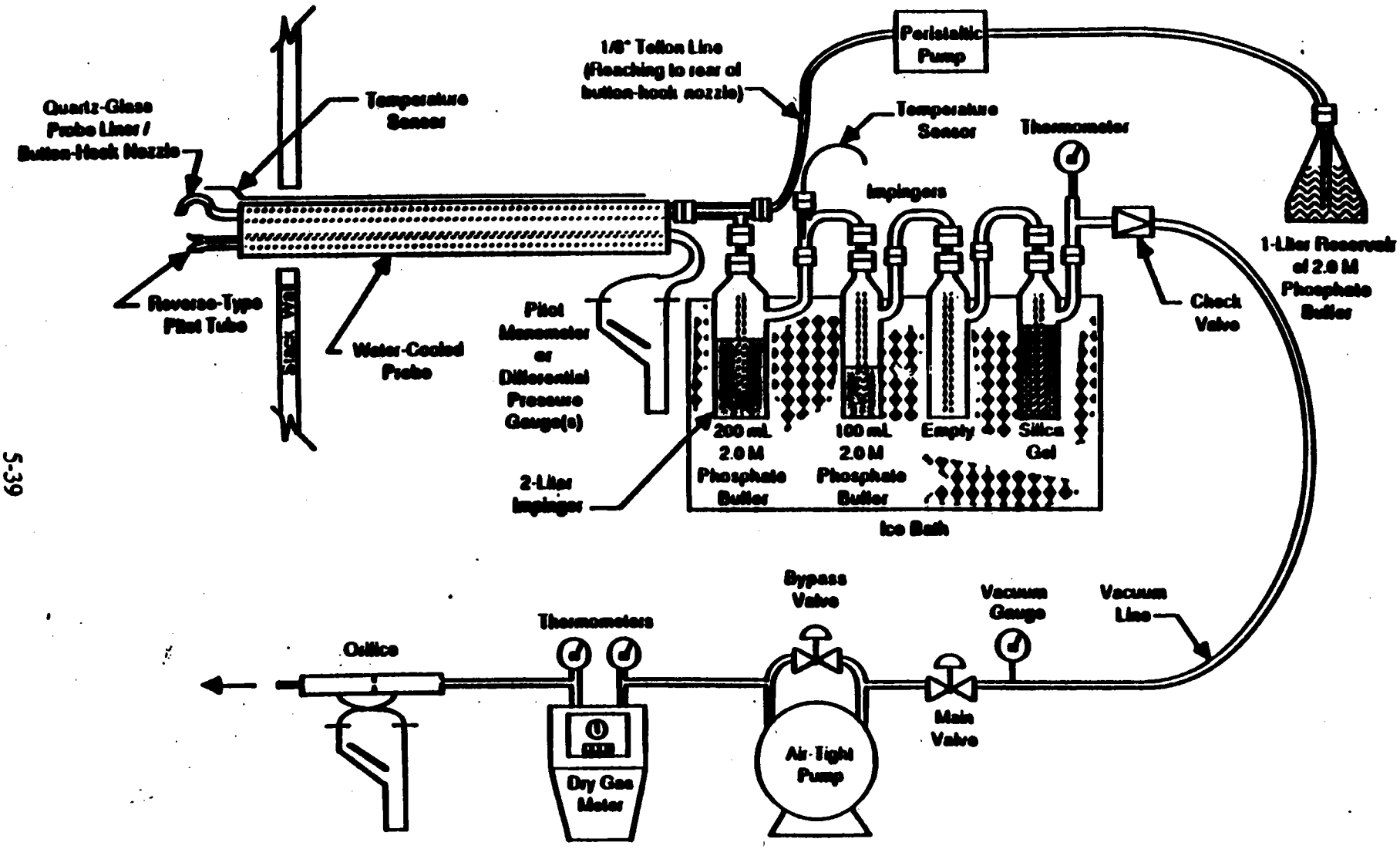


Figure 5-10. Sampling Train for Determination of Indicator Spore Emissions

train is completed at approximately 15 in. Hg. Leakage rates in excess of 4 percent of the average sampling rate or 0.02 cfm, whichever is less, are unacceptable.

5.3.2.3 Flue Gas Sampling. Before inserting the probe into the stack, the nozzle cap is removed and alignment of the nozzle and pitot tube are checked. The probe cooling water flow is started and adjusted. The buffering system pump is then started making sure that the probe is slightly inclined so that the buffer solution drains into the first impinger. The probe is inserted into the duct and located at the first sampling traverse point. Isokinetic sampling commences in accordance with Method 5 guidelines. All sampling parameters (ΔP, gas meter readings, stack temperature, meter temperatures, meter ΔH, meter vacuum, first impinger temperature, and silica gel impinger temperature) are periodically monitored, adjusted, and recorded throughout the test run.

Two different trains are used. When the first traverse is completed, the second traverse is immediately started with the second train.

After completion of the test run, the probe is removed from the stack and the flow of buffering solution turned off. The final meter reading is recorded and the sample train is leak checked. Post-test leakchecks are completed at a vacuum equal to or greater than the maximum vacuum reached during the sampling run. Acceptable post-test leakcheck criterion is the same as was previously mentioned for the pre-test leakchecks.

5.3.2.4 Sample Recovery. Sample recovery procedures are summarized in Figure 5-11. After the probe has cooled, the probe cooling water is turned off. The nozzle tip is inspected for port scrapings or any external matter near the tip and removed if found. The probe is disconnected from the impinger train and along with the probe buffer delivery tube, are rinsed and brushed with sterile buffer solution. All rinses are collected in a sterile sample bottle.

The impingers are weighed and the contents are antiseptically transferred to the sample bottle containing the nozzle/probe rinsings. The pH of the sample is adjusted if necessary to 6.0 to 7.5 with 1.0 N NaOH. The level of liquid in the sample bottle is marked to determine later if leakage occurred during transport. The bottle is then packed in ice so that sample temperatures are maintained at or below 4°C (39°F), for shipment to the laboratory.

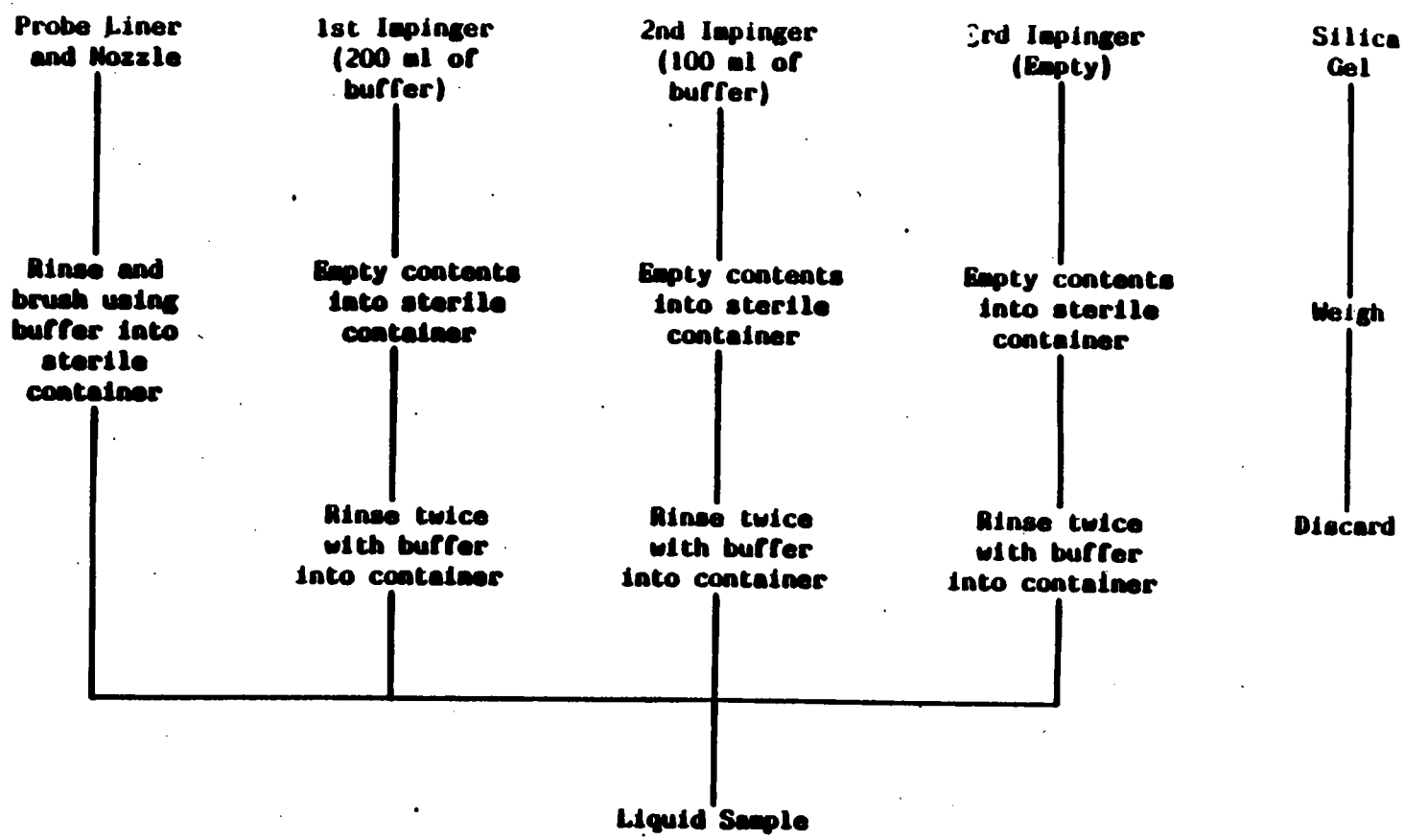


Figure 5-11. Sample Recovery Scheme for Microbial Viability Testing

5.3.3 Direct Ash Sampling for Indicator Spores

Direct ash sampling provides an indication of the ability of the indicator organism to survive the incinerator process under various conditions. An outline of the proposed ash sampling protocol can be found in Appendix A of the test plan. Ash samples are recovered from the ash when it has cooled sufficiently. Ash samples are taken using a sampling thief. During each sampling run, three samples are taken. Two are transported to the laboratory to culture and identify and the third sample is used to determine the pH of the material. Laboratory samples are tested in accordance with proposed Draft Method found in Appendix A of the test plan.

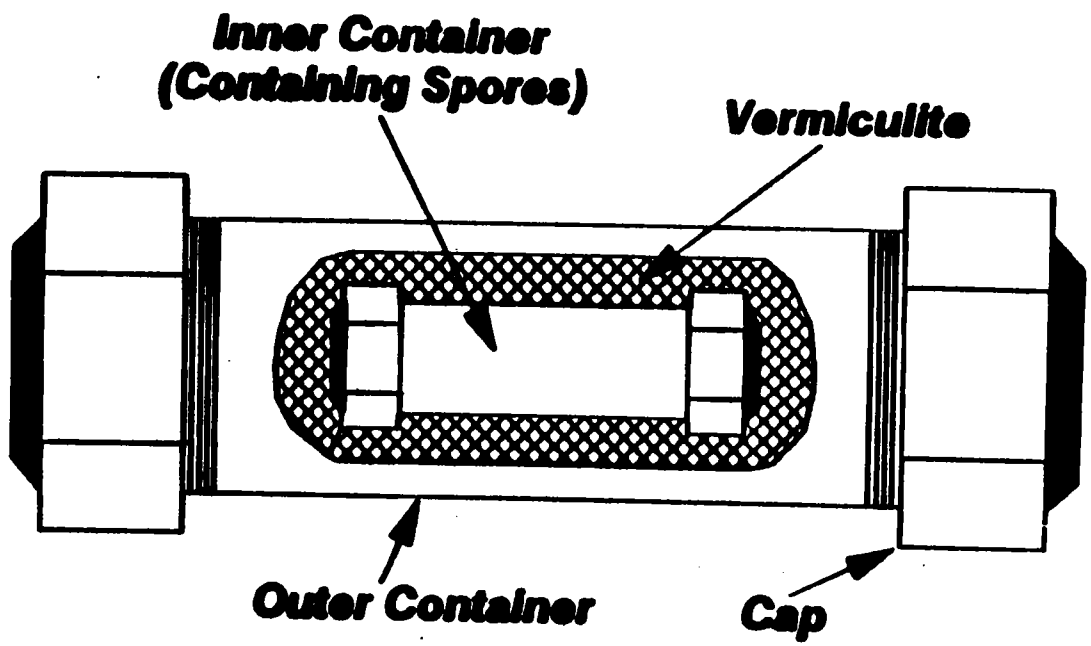
5.3.3.1 Equipment. Ash samples are taken using a precleaned plastic scoop and placed in sample containers for transport to the laboratory. These samples are stored on ice. The pH of the ash is determined by adding a known amount of deionized water to a weighed aliquot of ash and measuring the pH by specific ion electrode.

5.3.4 Pipe Spiking Procedures

The waste is charged into the incinerator with known quantities of Bacillus stearothermophilus (B. stearothermophilus) contained in insulated pipes. Samples are cultured according to the Draft Method found in Appendix A.4 of the test plan. Colonies of B. stearothermophilus are then gram stained to ensure correct cellular morphology and further identified using biochemical tests as needed. Enumeration of B. stearothermophilus is then completed.

5.3.4.1 Spiking Equipment. A diagram of the pipe sample assembly used for the pipe test is shown in Figure 5-12. The indicator organisms are freeze-dried spores (lyophilized) that were prepared by American Type Culture Collection in Rockville, Maryland. A small amount of lyophilized material equalling approximately 10^6 spores is prepared and placed in a small glass vial. Each pipe sample uses the contents of 1 spore vial.

The sample is placed in a short piece (2-4 inch) of 3/8 stainless steel tubing capped on both ends with Swagelock™ caps. This "inner container" is then placed in an "outer container" which is a 1¼ inch or 2 inch diameter steel pipe nipple about 4 to 6 inches long. Each outer container is identified with a unique identification number for tracking of feed time and location. Enough vermiculite or other thermal insulation



Two sizes will be used:
2" diameter x 6" long and 1 1/2" diameter x long

Figure 5-12. Ash Quality Pipe Assemblies

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surrounds the inner container to maintain its position in the center of the outer container and to protect it from thermal shock. Both ends of the outer container are capped.

5.3.4.2 Spiking Preparation. The inner container and caps are cleaned and disinfected before use. This procedure consists of soaking the containers for at least one hour in 1.0 N HNO_3, washing with laboratory detergent, rinsing 3 times with tap water, 3 times with sterilized deionized water, and finally, rinsing with 90 percent alcohol.

The spiked sample is prepared by placing a known amount of spores (targeted at 10^6) inside the inner container and then sealed using the end caps. The inner container is placed in the outer container with enough vermiculite to position it in the center. Additional vermiculite is added and tapped down gently. Finally, the outer container is sealed by securing the other end cap.

5.3.4.3 Spiking Procedure. The incinerator spike varies according to the loading procedure. The Central Carolina Hospital MWI is a ram-loading, continuous-burning incinerator, which operates from approximately 7:00 a.m. to 3:00 p.m. each day. A single pipe spike is charged to the incinerator at the beginning, middle, and end of each day's operation. The first pipe is fed in the first load of the day at about 7:00 a.m. The second pipe is added to a load approximately at noon. The last pipe is added with the last load of the day (about 3:00 p.m.). The exact times for charging the spikes are coordinated with hospital personnel.

The pipe sample is placed in the charging hopper at random locations that correspond to where the MWI bags are placed in the hopper.

5.3.4.4 Sample Recovery. The pipes are recovered from the incinerator following a cool down period the morning following the test run. The ash cleanout door is opened at about 7:00 a.m. During this period, the location of the samples on the grate is recorded to the extent possible. The samples are recovered and the hot ashes removed from the ignition chamber. Excess debris is removed from the outer container and each pipe is placed in a plastic bag. The pipe samples are maintained at or below 4°C (39°F) in an ice cooler with care to protect them from contamination from melting ice.

5.3.5 Microbial Analysis

The quantity of viable spores are determined from the pipe samples, flue gas samples, and the direct ash samples. Sample preparation for the three sample types is discussed below.

5.3.5.1 Pipe Sample and Ash Analytical Preparation Procedure. The sample preparation and analysis scheme for the pipe and ash samples are presented in Figures 5-13 and 5-14. The analysis is performed within 96 hours after sample recovery. The contents of the inner container of the pipe and the direct ash samples are transferred to separate sterile incubation tubes. The inside of the sample containers are rinsed with sterile phosphate buffer solution into the respective incubation tube. Any glassware used for this transfer procedure is rinsed with sterile deionized water into the respective incubation tubes. The direct ash samples are mixed and aseptically added to 100 mls of sterile deionized water before further processing.

5.3.5.2 Flue Gas Sample Analytical Preparation Procedure. The sample preparation and analysis scheme is presented in Figures 5-15. The level of each sample is checked to determine if leakage during shipment occurred. Each sample contains approximately 1.5 to 2.0 liters of sample. The sample is then aliquoted and prepared as shown in Figure 5-15. Three 10 ml aliquots, three 100 ml aliquots, and three equal volume of the remaining solution is prepared. The aliquots are placed in sterile incubation tubes, one set is processed without heat-treatment, the other with heat-treatment. Each aliquot is then filtered and placed onto agar plates as discussed in the following sections.

5.3.5.3 Colonial Enumeration and Identification Procedure. Agar plates are prepared by pouring the molten trypticase soy agar into a sufficient number of petri dishes for both sample and field blanks. The media is then allowed to harden. Each sample is then filtered through a separate vacuum filter unit employing a sterile cellulose nitrate filter (0.2 μm). The incubation tube is rinsed with sterile deionized water and poured through the filter as well. Each filter is removed from the filtering unit using sterile forceps and placed face up on an agar plate. The plates are incubated in an air convection incubator at 65°C (49°F) for 18 to 24 hours prior to colonial examination.

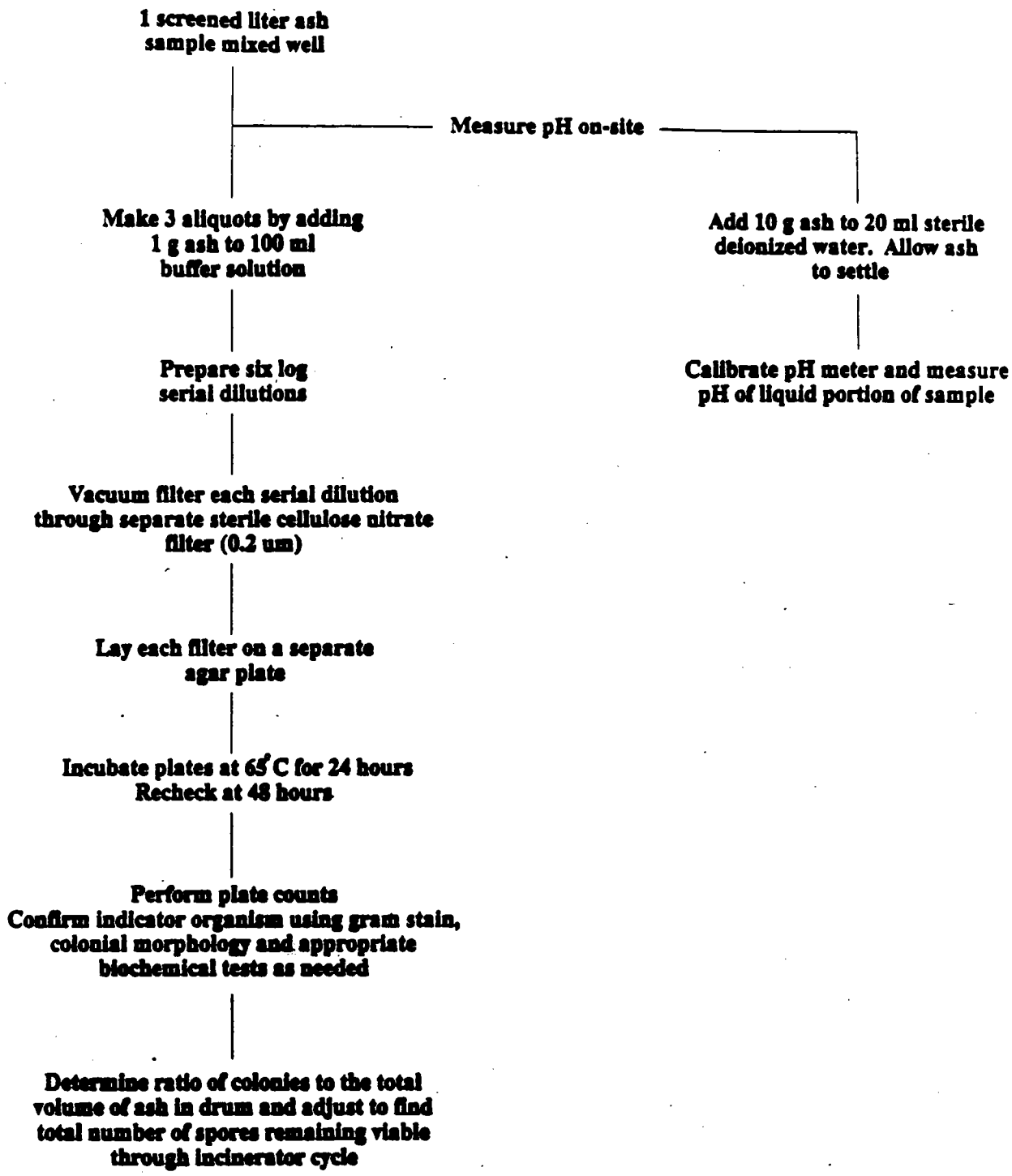

Figure 5-13. Sample and Analysis Scheme for Microbial Testing of Ash Samples

Recovered inner container

Transfer contents to a incubator tube

Rinse inner tube with sterile phosphate Buffer into the Incubator tube

Vacuum filter through seprate sterile Naigene® cellulose nitrate 0.2um filter unit

Lay each filter on a separate agar plate

Incubator plates at 65°C for 24 hours Recheck at 48 hours

Enumeratic colonies of B. stearothermophilus on filters

Figure 5-14. Analysis Scheme for Pipe Sample Microbial Viability Tests

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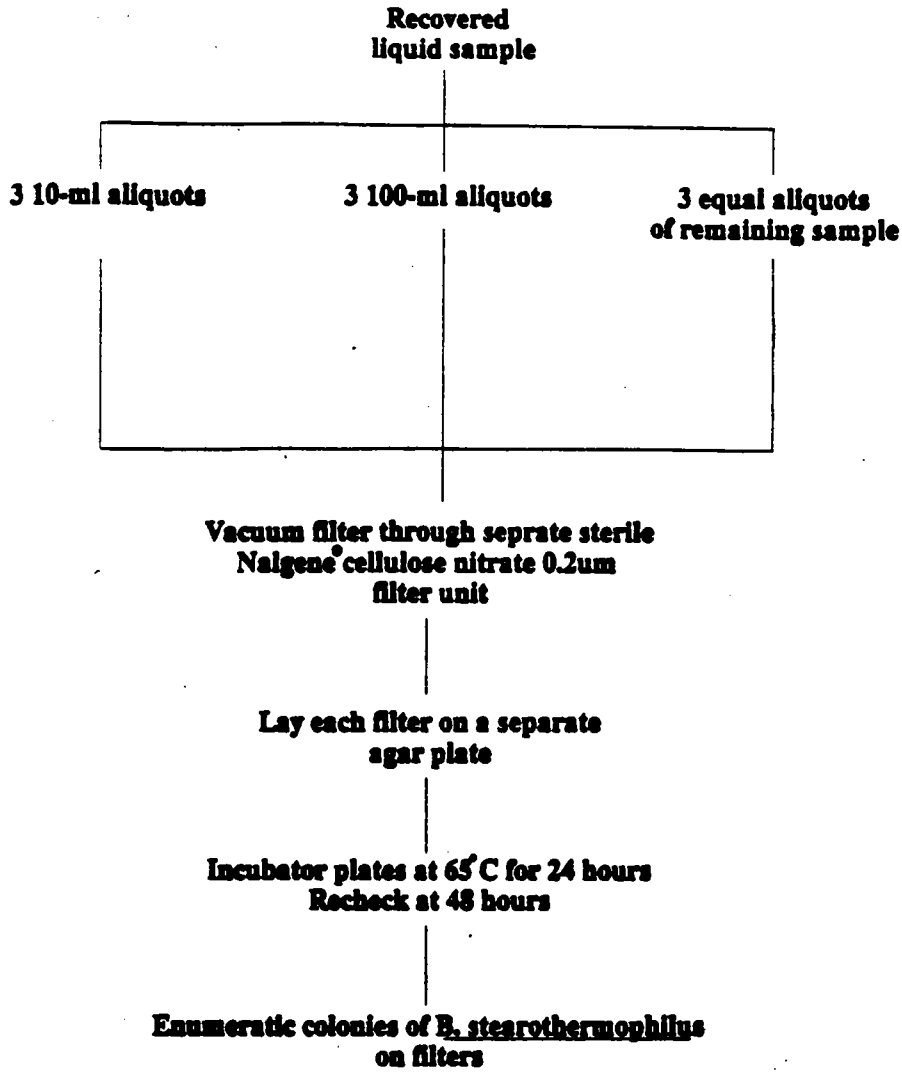

Figure 5-15. Sample Preparation and Analysis Scheme for Microbial Testing

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The plates are removed from the incubator and colonies of B. stearothermophilus are quantified. A variety of tests including a gram stain and biochemicals may be used to confirm that the colonies are B. stearothermophilus.

5.3.5.4 Indicator Spore Analytical Quality Control. The QA/QC procedures followed during spore enumeration and verification procedures (analysis) are documented in Table 5-9. An aliquot from one batch of the wet spore spiking slurry is sent to RTI to verify the manufacturer's count.

Field blanks from a flue gas (impinger) sample as well as a non-charged pipe sample, are analyzed to check for contamination during preparation or recovery procedures. Duplicates are analyzed for impinger samples from two test runs.

A blank ash sample is collected prior to the test program to check for the presence of indicator spores prior to any spiking.

5.4 HYDROGEN CHLORIDE/HYDROGEN BROMIDE/HYDROGEN FLUORIDE EMISSIONS TESTING BY EPA METHOD 26

Hydrogen chloride HBr, and HF sampling is accomplished using a single sampling train. The procedure follows the EPA Method 26 draft protocol entitled "The Determination of HCl Emissions from Municipal and Hazardous Waste Incinerators." In this method, an integrated gas sample is extracted from the stack and passed through acidified water. In acidified water, HCl solubilizes and forms Cl^- ions. Ion chromatography is used to detect the Cl^- ions present in the sample. For this test program, the presence of Br^- and F^- ions are also be detected by IC. The method is included in Appendix A.

5.4.1 HCl/HBr/HF Sampling Equipment

A diagram of the HCl/HBr/HF sampling train is shown in Figure 5-16. The sampling train consists of a quartz probe with a pallflex Teflon/glass filter to remove PM, and a series of chilled midget impingers and a DGM system. A small amount of quartz glass wool was placed in the front half of the filter holder to help remove excessive PM found in this gas stream. Because the high temperatures of the stack and the shortness of the sampling probe keep sample gas in the probe above the acid dewpoint, the probe is not heated. The train consists of an optional knockout impinger followed by two impingers containing 0.1 N sulfuric acid (H_2SO_4) to collect HCl, HBr,

TABLE 5-9. INDICATOR SPORE TESTING QA/QC CHECKS

Sample Type	Number	QA/QC Check
Wet Spores	1	Verify manufacturer's wet spore count by sending an aliquot from one slurry to RTI for count.
Field Blank - Impinger Sample	1	Prepare train through leakcheck, run buffer solution for 2 hours, collect 1 field blank sample
Field Blank - Pipe Sample	2	Fully prepare pipe sample without placing spore charge inside to check for handling contamination
Duplicates - Impinger Sample	2	Complete duplicate analyses on 2 impinger samples from 2 test runs
Field Duplicates - Pipe Samples	3	Load duplicate pipe samples on 3 separate occasions into incinerator and analyze
Pre-Test Ash Blank	1	Collect ash samples using the test procedures prior to any spiking of indicator spores

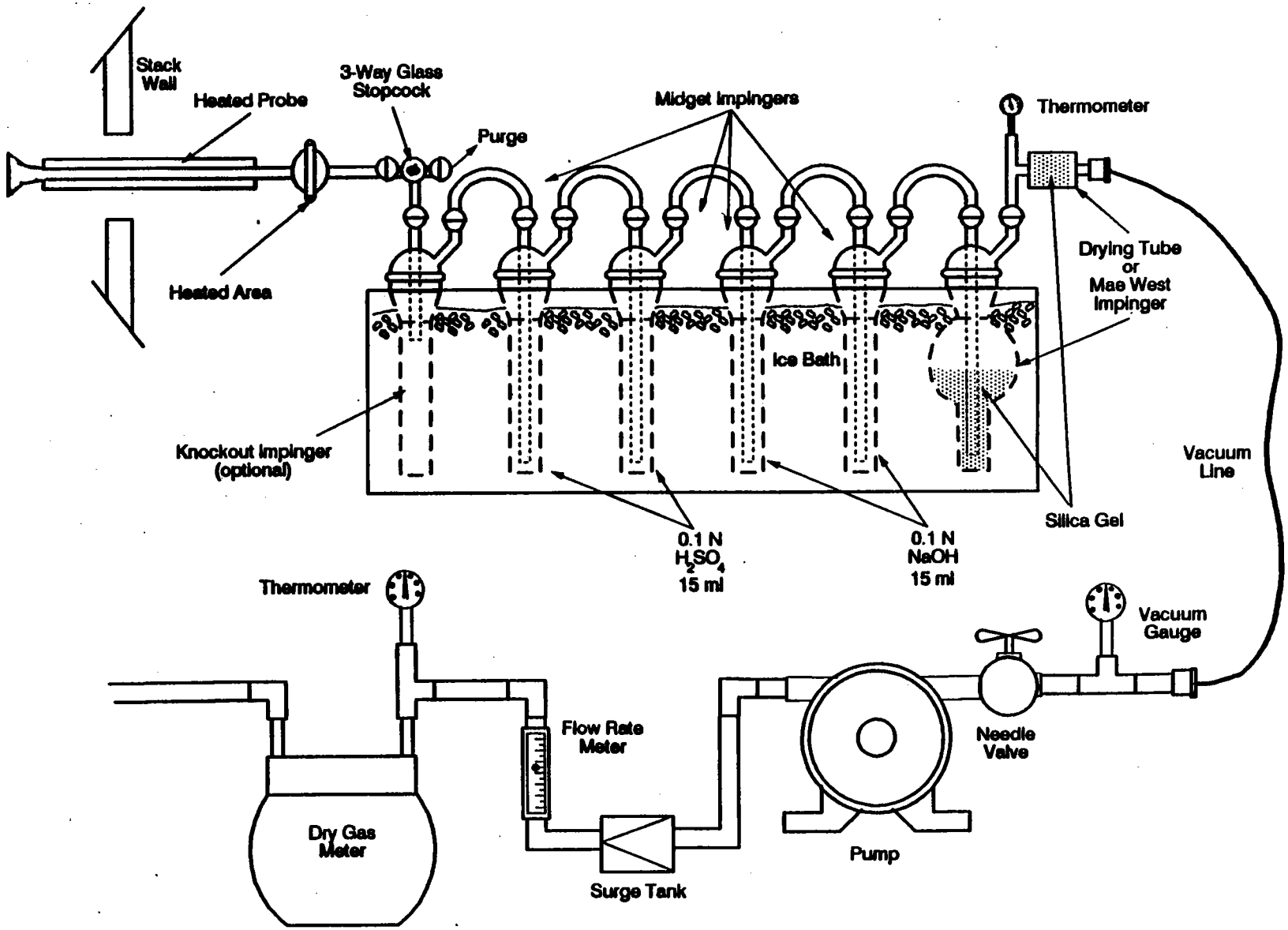

Figure 5-16. HCl Sample Train Configuration

and HF; two impingers containing 0.1 N NaOH to capture any pollutants present in the flue gas that might cause DGM damage; and finally one silica gel impinger.

5.4.2 HCl/HBr/HF Sampling Preparation

5.4.2.1 Equipment Preparation. Sampling preparation includes calibration and leak checking of all train equipment. This includes meterboxes, thermocouples, and umbilicals. Referenced calibration procedures are followed when available, and the results properly documented and retained. If a referenced calibration technique for a particular piece of apparatus is not available, then a state-of-the-art technique is used.

5.4.2.2 Assembling the Train. Assembly of the sampling train is done both in the recovery trailer and at the stack location. First, the empty clean impingers are assembled and laid out in the proper order. The optimal knockout impinger was not used for testing at this facility. The first two impingers contained 15 to 20 ml 0.1 N H_2SO_4 each, followed by two impingers filled with 15 to 20 ml each of 0.1 N NaOH, and finally an impinger containing 20 to 30 grams of silica gel. When the impingers are loaded, they may be wrapped with Teflon® tape to secure the two sections of the impinger. The impingers are connected together using U-tube connectors and arranged in the impinger bucket. The height of all the impingers should be approximately the same to easily obtain a leak-free seal. The open ends of the train are sealed with aluminum foil.

5.4.3 HCl/HBr/HF Sampling Operations

Prior to sampling, the HCl/HBr/HF train is leakchecked as required by Method 26 protocol. The leak checking procedure is the same as that discussed in Section 5.1. The leak rate, sampling start and stop times, and any other events are be recorded on the sampling task log. Upon completion of a sampling run, repeat the leakcheck procedure. Sampling train data are recorded every five minutes, and include readings of the DGM, DGM temperature, flow rate meter, and vacuum gauge.

5.4.4 HCl/HBr/HF Sample Recovery

The impingers are disconnected from the probe and filter and moved to the recovery trailer. Once in the trailer, the contents of the two acidified impingers are quantitatively recovered with deionized distilled water and placed into a clean sample bottle. The sample bottle should be sealed, mixed and labeled, and the fluid level marked. The contents of the second set of impingers (containing the 0.1 N NaOH) are discarded for every triplicate series except for one. These will be archived for possible future analyses. The sample recovery scheme is shown in Figure 5-17.

5.4.5 HCl/HBr/HF Analytical Procedures

Before analysis, the samples are checked against the chain-of-custody forms and then given an analytical laboratory sample number. Then, each sample is examined to determine if any leakage occurred and any color or other particulars of the samples are noted.

The IC conditions are described by the type of analytical column and whether suppressed or nonsuppressed IC is used. Prior to sample analysis, a stable baseline is established and water samples are injected until no Cl^-, Br^-, or F^- appears in the chromatogram. Then, the IC is calibrated using standards spanning the appropriate concentration range, starting with the lowest concentration standard. Next, a QC check sample is injected in duplicate, followed by a water blank and the field samples. The calibration standards are re-injected at the end of the analysis to allow compensation for any drift in the instrument response during analysis of the field samples. The Cl^-, Br^-, and F^- sample concentrations are calculated from either the respective ion peak area or peak height and the calibration curve.

5.4.6 HCl/HBr/HF Analytical Quality Control

The IC is calibrated with a minimum of three concentrations, not including zero. A correlation coefficient of greater than or equal to 0.995 must be achieved to have an acceptable calibration. At least 10 percent of the total number of samples are analyzed in duplicate. Ion concentrations in the duplicates must agree to within ±20 percent.

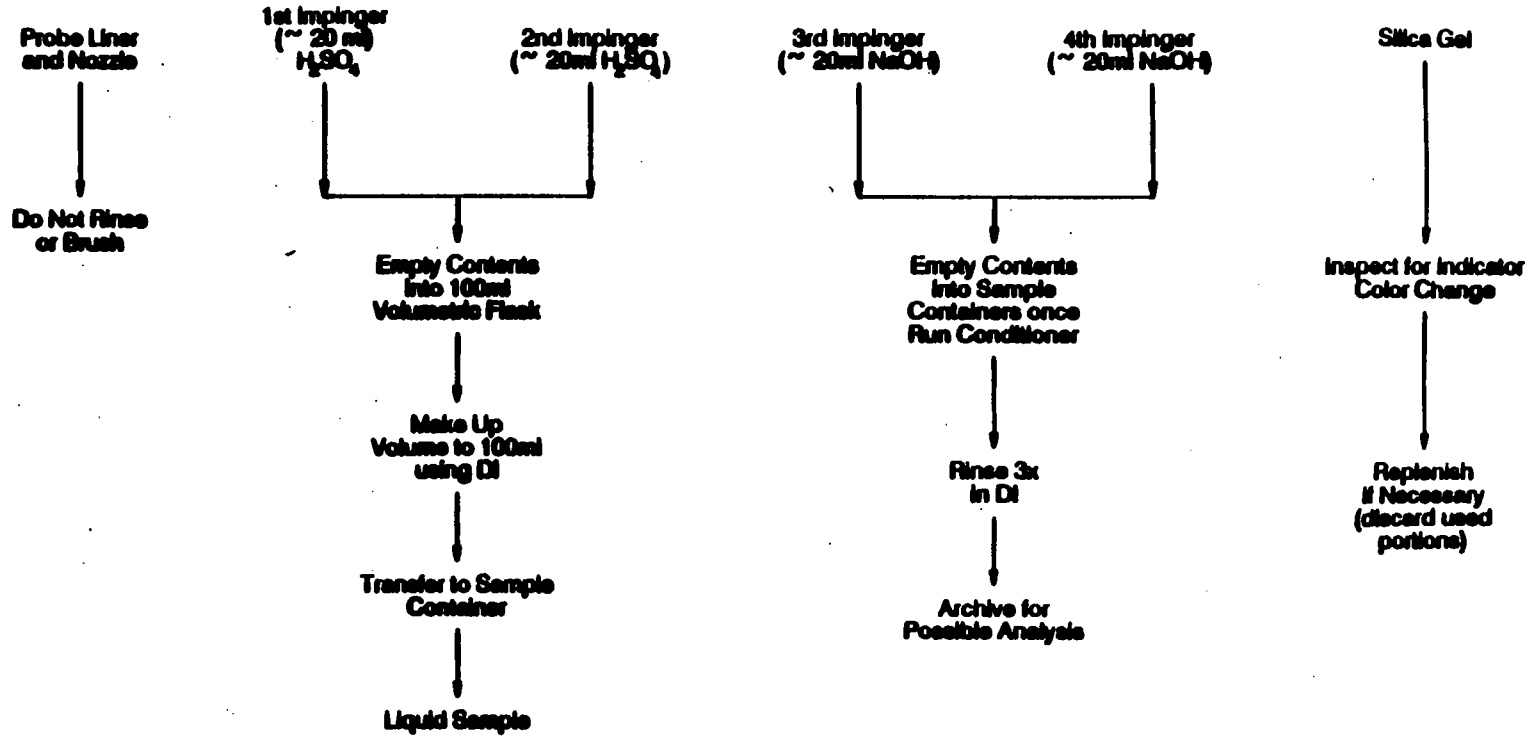

Figure 5-17. HCl/HBr/HF Sample Recovery Scheme

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5.5 EPA METHODS 1-4

5.5.1 Traverse Point Location By EPA Method 1

The number and location of sampling traverse points necessary for isokinetic and flow sampling will be dictated by EPA Method 1 protocol. These parameters are based upon how much duct distance separates the sampling ports from the closest downstream and upstream flow disturbances. The minimum number of traverse points for a circular duct less than 24 inches is 4 (8 total sample points). Several sets of perpendicular sampling ports are established in the incinerator outlet. Traverse point locations are determined for each port depending on the distances to duct disturbances (see Section 4).

5.5.2 Volumetric Flow Rate Determination by EPA Method 2

Volumetric flow rate is measured according to EPA Method 2. A Type K thermocouple and S-type pitot tube are used to measure flue gas temperature and velocity, respectively. All of the isokinetically sampled methods that are used incorporate Method 2 (CDD/CDF, PM/Metals, Microorganisms).

5.5.2.1 Sampling and Equipment Preparation. For EPA Method 2, the pitot tubes are calibrated before use following the directions in the method. Also, the pitots are leak checked before and after each run.

5.5.2.2 Sampling Operations. The parameters that are measured include the pressure drop across the pitots, stack temperature, and stack static and ambient pressure. These parameters are measured at each traverse point, as applicable. A computer program is used to calculate the average velocity during the sampling period.

5.5.3 O_2 and CO_2 Concentrations by EPA Method 3A

The O_2 and CO_2 concentrations are determined by CEMs following EPA Method 3A. Flue gas is extracted from the duct and delivered to the CEM system through heated Teflon® tubing. The sample stream is then conditioned (particulate and moisture removed) and is directed to the analyzers. The O_2 and CO_2 concentrations are, therefore, determined on a dry basis. Average concentrations are calculated to coincide with each respective time period of interest. More information on the CEM system will be given in Section 5.6.

5.5.4 Average Moisture Determination by EPA Method 4

The average flue gas moisture content is determined according to EPA Method 4. Before sampling, the initial weight of the impingers is recorded. When sampling is completed, the final weights of the impingers are recorded, and the weight gain is calculated. The weight gain and the volume of gas sampled are used to calculate the average moisture content (percent) of the flue gas. The calculations are performed by computer. Method 4 is incorporated in the techniques used for all of the manual sampling methods that are used during the test.

5.6 CONTINUOUS EMISSIONS MONITORING (CEM) METHODS

EPA Methods 3A, 7E, 6C, and 10 are continuous monitoring methods for measuring CO_2, O_2, NO_x, SO_2, and CO concentrations. Total hydrocarbons are analyzed by EPA Method 25A. Flue gas HCl concentrations are also monitored using CEM procedures using state-of-the-art equipment and procedures. A diagram of the CEM system is shown in Figure 5-18.

Two extractive systems are used to obtain flue gas samples for the CEM systems. One system is for HCl monitoring and the other system is for all other CEMs. For the main CEM extraction system, samples are withdrawn continuously at a single point from the incinerator outlet duct and transferred to the CEM trailer through heat-traced Teflon® line. The flue gas is conditioned (temperature lowered and moisture removed) before the flue gas stream is split using a manifold to the various analyzers. Hydrocarbon measurements are made on a wet basis; therefore, its sample stream bypasses the gas conditioner.

5.6.1 CEM Sampling Equipment

5.6.1.1 Sample Probes. The main CEM probe consists of a black iron pipe mounted to a Swagelok® reducing union which is attached directly to the heat trace tubing. The probe is placed approximately at a point of average velocity in the stack determined by a prior velocity traverse.

5.6.1.2 Heated Lines. Heated sample lines are used to transfer the flue gas samples to the instrument trailer for O_2, CO_2, NO_x, SO_2, CO, and THC analyses. These lines are heated in order to prevent condensation. Condensate could clog sample lines or provide a medium for the flue gas sample to react and change composition.

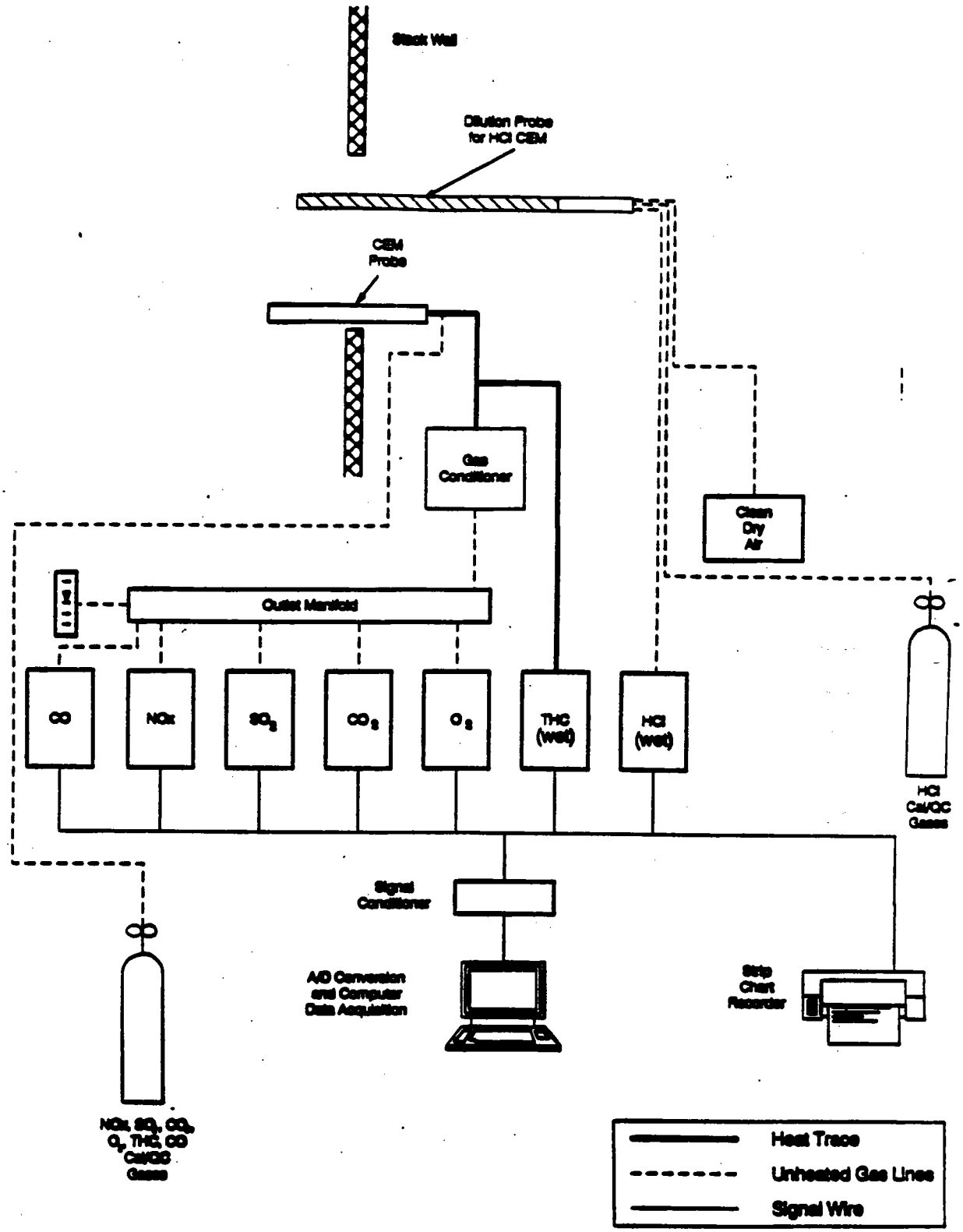

Figure 5-18. Scematic of CEM System

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All heat trace lines contain three 3/8 inch Teflon® tubes. One tube carries the sample, one tube is used for calibration and QC gases, and the other is available as a backup. These gases can then be directed up to the sampling probe and through the entire sampling/conditioning system.

5.6.1.3 Gas Conditioning. Exemplar PEL 3 and PEL 4-Special gas conditioners are used to reduce the moisture content of the flue gas. The Exemplar systems use thermoelectric cooling plates to lower the temperature of the gas and condense any moisture in the sample. Condensate is immediately removed from the sample path by a dried sample slipstream that blows across the plates, greatly reducing the potential for sample bias. Additionally, the systems operate under positive pressure eliminating the possibility of a leak. The gas conditioner may be located in the CEM trailer or at the sampling location depending on site conditions.

5.6.1.4 HCl CEM Sample System. The HCl flue gas concentrations are monitored using a CEM analyzer as well as by manual test runs. The HCl CEM sampling system uses a GMD Model 797 dilution probe. This probe cannot be used at the expected flue gas temperature ranges (approximately 1600-1900°F). Therefore, a slip-stream of flue gas is extracted from the stack and allowed to cool to approximately 400 to 500°F as it passes through a length of smaller pipe (i.e., 1 inch ID). The dilution probe is placed in a sampling well in the slipstream pipe for HCl CEM gas extraction. A thermocouple is located adjacent to the probe to monitor gas temperatures (see Figure 5-16). A nominal dilution ratio of 200:1 is used.

5.6.2 CEM Principles of Operation

5.6.2.1 SO_2 Analysis. The Western 721A SO_2 analyzer is essentially a continuous spectrophotometer in the ultraviolet (UV) range. The SO_2 selectively absorbs UV light at a wavelength of 202.5 nm. To take advantage of this property of SO_2, the analyzer emits UV light at 202.5 nm and measures the absorbance (A) of the radiation through the sample cell by the decrease in intensity. Beer's law, $A = abc$, is used to convert the absorbance into SO_2 concentration (A = absorbance, a = absorbitivity, b = path length, c = concentration). The SO_2 measurements are performed using EPA Method 6C.

5.6.2.2 NO_x Analysis. The principle of operation of this instrument is a chemiluminescent reaction in which ozone (O_3) reacts with nitric oxide (NO) to form

oxygen (O_2) and nitrogen dioxide (NO_2). During this reaction, a photon is emitted which is detected by a photomultiplier tube. The instrument is capable of analyzing total oxides of nitrogen ($NO + NO_2$) by thermally converting NO_2 to NO in a separate reaction chamber prior to the photomultiplier tube, if desired. The NO_x measurements are performed using EPA Method 7E.

5.6.2.3 O_2 Analysis. Oxygen analysis is completed using one of the instruments discussed below.

The Thermox WDG III measures O_2 using an electrochemical cell. Porous platinum electrodes are attached to the inside and outside of the cell which provide the instrument voltage response. Zirconium oxide contained in the cell conducts electrons when it is hot due to the mobility of O_2 ions in its crystal structure. A difference in O_2 concentration between the sample side of the cell and the reference (outside) side of the cell produces a voltage. This response voltage is proportional to the logarithm of the O_2 concentration ratio. A linearizer circuit board is used to make the response linear. Reference gas is ambient air at 20.9 percent O_2 by volume.

The Beckman 755 O_2 analyzer uses electron paramagnetic resonance to detect O_2 molecules. Unlike most substances, O_2 has a triplet electron ground state which leaves one electron unpaired, making it a paramagnetic molecule. This electron may have one of two spin quantum states ($m_s = \pm 1/2$). By applying an alternating electromagnetic field of the proper frequency, the Beckman 755 O_2 analyzer induces resonance between the two spin quantum states. In effect, the O_2 analyzer measures the electromagnetic energy absorbed by O_2 molecules at the resonant frequency. Oxygen measurements are performed using EPA Method 3A.

5.6.2.4 CO_2 Analysis. Non-dispersive infrared (NDIR) CO_2 analyzers emit a specific wavelength of infrared (IR) radiation through the sample cell which is selectively absorbed by CO_2 molecules. The intensity of radiation which reaches the end of the sample cell is compared to the intensity of radiation through a CO_2-free reference cell. A reference cell is used to determine background absorbance which is subtracted from the sample absorbance. The detector uses two chambers filled with CO_2 which are connected by a deflective metallic diaphragm. One side receives radiation from the sample cell and the other side receives radiation from the reference cell. Since more

radiation is absorbed in the sample cell than in the reference cell, less radiation reaches the sample side of the detector. This causes a deflection of the diaphragm due to increased heat from radiation absorption on the reference side. Deflection of the diaphragm creates an electrical potential which is proportional to absorbance. Absorbance is directly proportional to CO_2 concentration in the gas. Carbon dioxide measurements are performed using EPA Method 3A.

5.6.2.5 CO Analysis. Either a TECO Model 48 or a Model 48H analyzer will be used to monitor CO emissions. Both TECO analyzers measure CO using the same principle of operation as CO_2 analysis. The instruments are identical except that a different wavelength of infrared radiation is used; 5 nm is selective for CO. Carbon monoxide measurements are performed using EPA Method 10.

5.6.2.6 Total Hydrocarbon Analysis. Either a Beckman Model 400, 402 or 404 will be used to monitor Total Hydrocarbon (THC) emissions. By allowing the THC sample stream to bypass the gas conditioners, concentrations will be determined on a wet basis. All analyses employ Flame Ionization Detectors (FID). As the flue gas enters the detector the hydrocarbons are combusted in a hydrogen flame. The ions and electrons formed in the flame enter an electrode gap, decrease the gas resistance, and permit a current flow in an external circuit. The resulting current is proportional to the instantaneous concentration of the total hydrocarbons. This method is not selective between species. EPA Method 25A applies to the continuous measurement of total gaseous organic concentrations of primarily alkanes, alkenes, and/or arenes (aromatic hydrocarbons). The results are reported on a methane basis and methane is used as the calibration gas.

5.6.2.7 HCl CEM Analysis. HCl flue gas concentrations are continuously monitored using an NDIR/GFC instrument manufactured by Thermo Electron Corporation (TECO). Detection of HCl is achieved by alternately passing an infrared (IR) beam between reference HCl gas and reference HCl free gas contained in the filter wheel. The "chopped" beam passes through the sample cell to the detector. The difference in IR beam strength caused by the absorption of the IR beam is proportional to the HCl concentration.

5.6.3 CEM Calibration

All the CEM instruments are calibrated once during the test program (and linearized, if necessary) using a minimum of three certified calibration gases (zero and two upscale points). Radian performs the multipoint calibrations with four general categories of certified gases: zero gas (generally N_2), a low scale gas concentration, a midrange concentration, and a high scale concentration (span gas). The criterion for acceptable linearity is a correlation coefficient (R^2) of greater than or equal to 0.998, where the independent variable is cylinder gas concentration and the dependent variable is instrument response. If an instrument does not meet these requirements, it is linearized by adjusting potentiometers on the linerarity card within the instrument or by other adjustments, if necessary.

The CEM analyzers are calibrated before and after each test run (test day) on a two point basis: zero gas (generally N_2), and a high-range span gas. These calibrations are used to calculate response factors used for sample gas concentration determinations. Instrument drift as a percent of span is also determined using these calibrating for each test run.

After each initial calibration, midrange gases for all instruments are analyzed, with no adjustment permitted, as a quality control (QC) check. If the QC midrange gas concentration observed is within ±2 percent of full scale, the calibration is accepted and the operator may begin sampling. If the QC check does not fulfill this requirement, another calibration is performed and linearization may be performed if deemed necessary. Calibration procedures are further detailed in the daily operating procedure (Section 5.6.5).

Table 5-10 lists the concentration of all calibration and QC gases to be used on this test program.

5.6.4 Data Acquisition

The data acquisition system used for AMI Central Carolina Hospital MWI test program consists of an Omega signal conditioner, a Tecmar A/D converter and a COMPAQ 286 computer. All instrument outputs are connected in parallel to stripchart recorders and the Omega signal conditioner. The stripchart recorders are a back-up system to the computer data acquisition system data. The signal conditioner adjusts the

TABLE 5-10. CEM OPERATING RANGES AND CALIBRATION GASES

Analyte	Gas Concentration
CO_2	
Instrument	Beckman 865
Range	0-20%
Span Gas Value	18%
Zero Gas	N_2
Midrange QC Gas Value	10%
Low Range QC Gas Value	5%
CO - dry	
Instrument	TECO 48H
Range	0-50,000 ppm
Span Gas Value	1000, 9000 or 19,000 ppm[a]
Zero Gas	N_2
Midrange QC Gas Value	1000 or 9000 ppm
Low Range QC Gas Value	2100 ppm
CO - wet	
Instrument	TECO 48
Range	0-100, 0-200, 0-5000 ppm
Span Gas Value	1000, 180 or 90 ppm[a]
Zero Gas	N_2
Midrange QC Gas Value	180 ppm
Low Range QC Gas Value	90 ppm
O_2	
Instrument	Thermox WDG III
Range	0-25%
Span Gas Value	20%
Zero Gas	0.2% O_2
Midrange QC Gas Value	10%
Low Range QC Gas Value	5%
SO_2	
Instrument	Western 721A
Range	0-500 or 0-5000 ppm
Span Gas Value	200 or 50 ppm
Zero Gas	N_2
Midrange QC Gas	100 ppm
Low Range QC Gas	30 ppm

TABLE 5-10. CEM OPERATING RANGES AND CALIBRATION GASES, continued

Analyte	Gas Concentration
NO_x	
Instrument	TECO 10AR
Range	0-250 ppm
Span Gas Value	200 ppm
Zero Gas	N_2
Midrange QC Gas Value	100 ppm
Low Range QC Gas Value	50 ppm
THC	
Instrument	Beckman 402
Range	0-10, 0-50, 0-100 ppm
Span Gas Value	100 ppm as methane
Zero Gas	N_2
Midrange QC Gas Value	45 ppm as methane
Low Range QC Gas Value	25 ppm as methane
HCl	
Instrument	TECO Model 15
Range	0-2000 ppm
Span Gas Value	1800 ppm
Zero Gas	N_2
Midrange QC Gas Value	900 ppm
Low Range QC Gas Value	100 ppm

[a] Several sets of calibration/QC gases were acquired in order to closely approximate stack gas concentrations.

voltage response range from the output range of the instrument (typically 0-100 mV or 0-10 mV) to 0-5 volts. The A/D converter then digitizes the analog inputs for use by the computer. A Radian computer program translates the digitized voltages into relevant concentrations in engineering units (ppmV, %V, etc.). The computer program has several modes of operation: calibration, data acquisition, data reduction, data view, data edit, and data import. The import function is used to combine other data files for comparison and correlation. On-line color graphics and data manipulation are included in the data acquisition portion of the program so that the operator and on-site engineers may monitor trends in the process.

5.6.5 Daily Operating Procedure

The following is a detailed standard operating procedure for calibrating and operating the CEMS:

1. Turn on COMPAQ computer and EPSON printer, put printer on-line, and load the CEM.EXE program. Be sure that the CEM instruments have been on for at least 20 hours.

2. Synchronize watch with sample location leaders.

3. Turn on strip chart recorders (SCR) and make appropriate notes on charts and in logbook (write down all procedures and observations in logbook and on SCRs as the day progresses).

4. Turn on the gas conditioners and blow back compressor. Blow back the system.

5. Open all calibration gas cylinders so that they may be introduced to the instruments via control panel valves.

6. Perform daily pre-test leak check on CEMs by introducing ultra high purity nitrogen to the system. Zero all instruments except the Thermox O_2 analyzers. Make adjustments to the zero potentiometers as required to zero the instruments. Be sure to check and maintain all flows throughout calibration and operation.

7. Record the zero values in the computer calibration routine.

8. Introduce 0.2 percent O_2 to set the low scale response for the Thermox O_2 analyzers and repeat Step 7 for these instruments.

9. Introduce the mixed span gases for O_2, CO_2, and CO. Make adjustments as required to these instruments.

10. Enter these values in the computer calibration routine.

11. Introduce the NO_x span gas.

12. Make adjustments to the NO_x instruments as required and enter the value into the computer calibration routine.

13. Introduce the SO_2 span gas for the SO_2 analyzer, repeat Step 12 for the SO_2 analyzer. (Note that all calibration gases are passed through the entire sampling system.)

14. Switch the Western SO_2 analyzer range to 0-500 ppm introduce the span gas for this range and repeat Step 12 for this instrument.

15. Introduce the HCl span gas to the HCl dilution probe/CEM analyzer. Repeat Step 12 for this system.

16. Check the calibration table on the computer, and make a hardcopy. Put the computer in the standby mode.

17. Introduce QC gases to instruments in the same sequence as the calibration gases. Record three minutes of data for each, once the responses have stabilized. If the QC gas response is not within ±2 percent of the instrument range the operator should recalibrate the instrument, or perform other corrective actions.

18. Begin sampling routine, with the computer on stand by.

19. Start the data acquisition system when signaled by radio that system is in stack.

20. Carefully check all flows and pressures during the operation of the instruments and watch for apparent problems in any of the instruments, such as unusual readings or unreasonable fluctuations. Check the gas conditioning system periodically and drain the traps.

21. Stop the data acquisition system at the end of the test when signaled.

22. Perform final leakcheck of system.

23. Perform the final calibration (Repeat steps 6-17) except make no adjustments to the system.

24. Check for drift on each channel.

5.7 VISIBLE EMISSIONS

The opacity of emissions are determined visually by a qualified observer following EPA Method 9. The observer is certified within 6 months before the test, as required by the method. Opacity observations are recorded to the nearest 5 percent at 15-second intervals. Twenty-four observations are recorded and averaged per each data set. Observation will continue throughout the 4-hour test run each day.

5.8 PROCESS SAMPLING PROCEDURE

Incinerator ash is composited each test day into a cleaned, 55 gallon plastic drum after initial cooling in 30 gallon cans that are used by the facility. After testing is completed for that day, approximately 1 gallon of ash is taken from the composited sample using a sample thief. This composite is then quartered. The quarters are sent to respective laboratories for analyses of LOI/carbon, metals, and CDD/CDF. The fourth quarter is archived or used as needed.

5.9 PARTICLE SIZE DISTRIBUTION SAMPLING METHODS

Results from the PSD tests characterized particulate mass into ranges separated by the PSD sampler's 50 percent effective cut points (Dp50) for each stage. The Dp50 represents the aerodynamic diameter of a particle that has been collected by that respective PSD stage with 50 percent collection efficiency.

Particle size distribution measurements were obtained with Anderson Mark III in-stack cascade impactor employing a pre-separator. A schematic of the sampling train is shown in Figure 5-19. The impactor consists of eight stages plus a final filter. Each stage has a number of concentric round jets offset on each succeeding stage such that the one plate serves both as jet and impaction surface. The Anderson MK III is operated in the range from 0.3 to 0.7 acfm and the flue gas is sampled isokinetically (100 $\pm$ 20 percent) with a recommended weight gain of 50 mg.

The impactor was prepared by loading the substrates into the impactor and recording the identification number and tare weight. The stage order was checked for correctness as the stages were assembled. The impinger train was prepared according to EPA Method 5. Then, the impactor and preseparator/nozzle were attached to the probe and the probe attached to the impinger train. Once assembled, the sampling train was leak checked at 15 in. Hg. The leakrate had to be below 0.02 cfm.

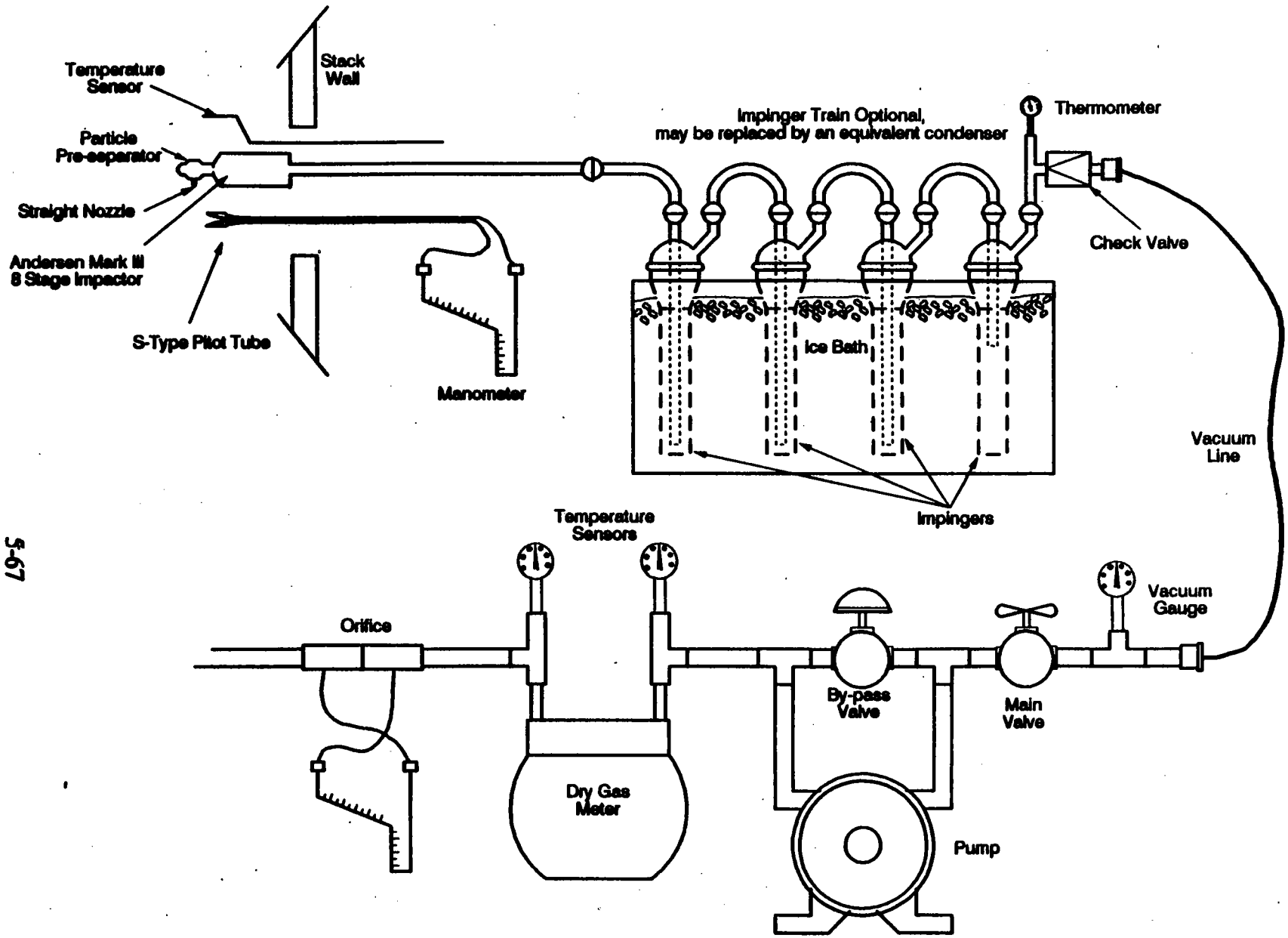

Figure 5-19. Anderson MK III In-Stack Impactor with Particle Pre-Separator Sampling Train

Prior to sampling, a preliminary velocity tranverse was conducted to determine a point of average velocity. The nozzle was then selected to ensure both isokinetic sampling as well as to give the desired particle separation. The impactor was preheated to approximately stack temperature prior to placing it inside the duct. Sampling was then conducted at a single point of average velocity at a fixed sampling rate. The sampling rate was not adjusted during the run.

After sampling was completed, the impactor was cooled and each stage was carefully recovered. Particles from the nozzle, pre-separator, and rinse were added to the first stage catch. Each substrate was examined for particle bounce, overloading, and re-entrainment. The substrates were weighted to a constant weight as detailed in Section 5.2.

6. QUALITY ASSURANCE/QUALITY CONTROL

Specific Quality Assurance/Quality Control (QA/QC) procedures were strictly adhered to during this test program to ensure the production of useful and valid data throughout the course of the project. A detailed presentation of QC procedures for all manual flue gas sampling, process sample collection, and CEM operations can be found in the Central Carolina Test Plan. This section will report the test program QA parameters so that the degree of data quality may be ascertained.

In summary, a high degree of data quality was maintained throughout the project. All sampling train leak checks met the QC criteria. Isokinetic sampling rates were kept within 10 percent of 100 percent for all the PM/Metals, CDD/CDF, and Microbial emission test runs. Metals analytical QA results revealed good spike recovery data. However, substantial field blank contamination of arsenic and nickel were present. Dioxins analytical procedures for Runs 2, 4, and 8 were modified because of unexpected heavy sample loading. This is further discussed in Section 6.4.1. The CEM data incorporated a variety of QC checks and QA procedures such as QC gas responses, daily drift, and others. The HCl CEM data agreed fairly well with manual HCl data. CEM quality assurance is presented in Section 6.5. Microbial indicator spore analyses were completed using a high number of enumerations per sample. Microbial Survivability Quality Assurance is further discussed in Sections 6.2.3, 6.3, and 6.4.4. Six Particle Size Distributions (PSD) tests were conducted and the following on-site recovery assessment, results from four test runs were reported.

Section 6.1 presents the QA/QC definitions and data quality objectives. Section 6.2 presents manual flue gas sampling and recovery QA parameters. Section 6.3 discusses the QC procedures for ash and pipe sampling and Section 6.4 presents method-specific analytical QA parameters. Section 6.5 discusses the CEM QA parameters. Section 6.6 presents a QA discussion on the PSD tests. Section 6.7 presents a discussion on data variability.

6.1 QA/QC DEFINITIONS AND OBJECTIVES

The overall QA/QC objective is to ensure precision, accuracy, completeness, comparability, and representativeness for each major measurement parameter called for

in this test program. For this test program, quality control and quality assurance can be defined as follows:

- Quality Control: The overall system of activities whose purpose is to provide a quality product or service. QC procedures are routinely followed to ensure high data quality.

- Quality Assurance: A system of activities whose purpose is to provide assurance that the overall quality control is being done effectively. Assessments can be made from QA parameters on what degree of data quality was achieved.

- Data Quality: The characteristics of a product (measurement data) that bear on its ability to satisfy a given purpose. These characteristics are defined as follows:

  - Precision - A measure of mutual agreement among individual measurements of the same property, usually under prescribed similar conditions. Precision is best expressed in terms of the standard deviation and in this report will be expressed as the relative standard deviation or coefficient of variation.

  - Accuracy - The degree of agreement of a measurement (or an average of measurements of the same thing), X, with an accepted reference or true value, T, can be expressed as the difference between two values, X-T, the ratio X/T, or the difference as a percentage of the reference or true value, 100 (X-T)/T.

  - Completeness - A measure of the amount of valid data obtained from a measurement system compared with the amount that was expected to be obtained under prescribed test conditions.

  - Comparability - A measure of the confidence with which one data set can be compared with another.

  - Representativeness - The degree to which data accurately and precisely represent a characteristic of a population, variations of a parameter at a sampling point, or an environmental condition.

A summary of the estimated precision, accuracy, and completeness objectives is presented in Table 6-1.

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TABLE 6-1. SUMMARY OF PRECISION, ACCURACY, AND COMPLETENESS OBJECTIVES[a]

Parameter	Precision (RSD)	Accuracy[b] (%)	Completeness[c] (%)
Dioxins/Furans Emissions	±40[d]	±50	100
Metals Emissions	±15[d]	±30	100
Particulate Matter Emissions	±12	±10	100
HCl/HBr/HF Concentrations	±10[d]	±15	95
Indicator Spore Emissions	ND	ND	100
CEM Concentrations	±20	±15	95
Velocity/Volumetric Flow Rate	±6	±10	95
Fixed Gases/Molecular Weight	±0.3%V	±0.5%V	100
Flue Gas Moisture	±20	±10	95
Flue Gas Temperature	±2°F	±5°F	100

RSD = Relative Standard Deviation. Uses worst case assumption that variation amongst run results is not due to process variation.
ND = Not Determined at this time.

[a] Precision and accuracy estimated based on results of EPA collaborative tests. All values stated represent worst case values. All values are absolute percentages unless otherwise indicated.
[b] Relative error (%) derived from audit analyses, where:

$$\text{Percent Relative Error} = \frac{\text{Measured Value - Actual Value}}{\text{Actual Value}} \times 100$$

[c] Minimum valid data as a percentage of total tests conducted.
[d] Analytical phase only. Percent difference for duplicate analyses, where:

$$\text{Percent Relative Error} = \frac{\text{First Value - Second Value}}{0.5\ (\text{First + Second Values})} \times 100$$

[e] Minimum requirements of EPA Method 6C, based on percent of full scale.
[f] No measureable bias has been detected in the available literature.

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6.2 MANUAL FLUE GAS SAMPLING AND RECOVERY PARAMETERS

The following section will report method-specific sampling QA parameters so that insight can be gained at the quality of emissions test data produced from manual tests during the test program.

6.2.1 CDD/CDF Sampling Quality Assurance

Table 6-2 lists both the pre-test and post-test leak checks completed on the CDD/CDF sampling trains. The acceptance criterion is that all post-test leak checks must be less than 0.02 cfm or 4 percent of the average sampling rate (whichever is less). All CDD/CDF post-test leak checks met the acceptance criterion.

Table 6-3 presents the isokinetic sampling rates for CDD/CDF, PM/Metals, and Microbial Survivability sampling trains. The acceptance criterion is that the average sampling rate must be within 10 percent of 100 percent isokinetic. All CDD/CDF test runs deviated by no more than 6 percent of 100 percent, thereby meeting the isokinetic criterion.

All dry gas meters are fully calibrated every six months against an EPA approved intermediate standard. The full calibration factor or meter Y is used to correct actual metered sample to true sample volume. To verify the full calibration, a post-test calibration is performed. The full and post-test calibration coefficients must be within 5 percent to meet Radian's internal QA/QC acceptance criterion. As can be seen from Table 6-4, the post-test calibration factor for the meter box used for CDD/CDF was well within the 5 percent criterion of the full calibration factor at -0.08 percent.

Field blanks are collected to verify the absence of any sample contamination. The CDD/CDF sampling train was fully prepared, leakchecked, and then recovered. Table 6-5 compares the CDD/CDF analytical results for the MM5 field blank versus average MM5 catches for the test runs (toluene field blank results are presented in the following section). No 2378 TCDD was detected in the MM5 field blank. The confirmation analysis reported a much lower 2378 TCDF value than the full screen at 0.070 ng versus 0.35 ng. Other CDD/CDF congeners were detected in the MM5 field blank but at much lower amounts than in any of the test runs. Because the amount of contamination was so low and the consistency of contamination throughout the test

TABLE 6-2. LEAK CHECK RESULTS FOR CDD/CDF EMISSIONS TESTS; CENTRAL CAROLINA HOSPITAL (1990)

DATE	RUN NUMBER	PRE-TEST LEAK RATE (acfm)	MAXIMUM VACUUM DURING TEST	AVG. SAMPLE RATE (dscfm)	4% SAMPLE RATE (dscfm) a	ACCEPTABLE LEAK LEVEL (acfm)	MEASUREMENTS POST-TEST LEAK RATE	INCHES FOR SECOND CHECK
09/20/90	1	0.011	6	0.43	0.017	0.017	0.012 b	10 b
09/21/90	2	0.005	6	0.38	0.015	0.015	0.012	10
09/22/90	3	0.009	6	0.42	0.017	0.017	0.004	8
09/23/90	4	0.012	15	0.41	0.016	0.016	0.015	18
09/24/90	5	0.010	4	0.42	0.017	0.017	0.018	9
09/25/90	6	0.012	6	0.44	0.018	0.018	0.008	10
09/26/90	7	0.014	5	0.42	0.017	0.017	0.005	10
09/27/90	8	0.010	8	0.43	0.017	0.017	0.008	12
09/28/90	9	0.012	6	0.44	0.018	0.018	0.008	10
10/02/90	10	0.008	6	0.42	0.017	0.017	0.008	9

a This value is in dry standard cubic feet per minute (dscfm) and may be slightly different than actual cfm (acfm).

b This value represents pre-port change leak change. Final value not recorded.

TABLE 6-3. ISOKINETIC SAMPLING RATES FOR CDD/CDF, METALS, AND MICROORGANISMS TEST RUNS; CENTRAL CAROLINA HOSPITAL (1990)

DATE	RUN NUMBER	CDD/CDF ISOKINETIC SAMPLE RATE (%)	TOXIC METALS ISOKINETIC SAMPLE RATE (%)	MICROORGANISMS ISOKINETIC SAMPLE RATE (%)
09/20/90	1A	101	97	95.2
	1B			96.9
09/21/90	2A	96.3	99.1	93.1
	2B			93.6
09/22/90	3A	95.7	98.9	95.1
	3B			96.1
09/23/90	4A	94.3	97.3	94.8
	4B			92.2
09/24/90	5A	95.4	99.1	95
	5B			92.2
09/25/90	6A	96.9	97.9	95
	6B			92.6
09/27/90	8A	97.6	96.3	94.8
	8B			95.2
09/28/90	9A	99.9	97.8	93.8
	9B			95.9
10/02/90	10A	97.2	100	97.9
	10B			100

TABLE 6-4. DRY GAS METER POST-TEST CALIBRATION RESULTS; CENTRAL CAROLINA HOSPITAL (1990)

SAMPLING TRAIN	METER BOX NUMBER	FULL CALIBRATION FACTOR	POST-TEST CALIBRATION FACTOR	POST-TEST DEVIATION (%) a
CDD/CDF	N-30	0.989	0.9882	-0.08
PM/Metal	N-31	0.9992	0.9900	-0.92
Microorganisms (Runs A)	N-32	1.0002	0.9971	-0.31
Microorganisms (Runs B)	9	1.007	NC	NC
Halogens	V5	1.0104	NC	NC

a $\frac{\text{(Post-Test)} - \text{(Full)}}{\text{(Full)}} \times 100$

NC = Not Conducted

TABLE 6-5. CDD/CDF FIELD BLANK RESULTS COMPARED TO AVERAGE RUN RESULTS; CENTRAL CAROLINA HOSPITAL (1990)

FULL SCREEN ANALYSES	MM5 FIELD BLANK (total ng)	MM5 CONDITION 1 AVERAGE (total ng)	MM5 CONDITION 2 AVERAGE (total ng)	MM5 CONDITION 3 AVERAGE (total ng)
DIOXINS				
2378 TCDD	[0.060]	0.2	32.4	1.1
TOTAL TCDD	(0.070)	64.6	707.0	72.2
12378 PCDD	[0.080]	2.4	131.7	2.8
TOTAL PCDD	0.29	57.0	1001.3	57.2
123478 HxCDD	[0.100]	2.3	128.0	1.7
123678 HxCDD	[0.100]	3.9	149.8	2.7
123789 HxCDD	(0.180)	7.1	276.3	4.7
TOTAL HxCDD	0.85	60.9	1702.3	41.3
1234678-HpCDD	0.58	23.6	701.7	14.1
TOTAL HpCDD	0.58	51.9	1461.7	30.5
Octa-CDD	(0.950)	29.8	730.3	18.4
FURANS				
2378 TCDF	0.35	48.1	715.7	35.1
TOTAL TCDF	0.63	241.0	4716.7	237.3
12378 PCDF	0.14	6.1	416.3	6.1
23478 PCDF	0.23	15.1	513.3	9.8
TOTAL PCDF	1.9	189.2	7523.3	129.9
123478 HxCDF	(0.680)	24.1	1328.3	12.7
123678 HxCDF	0.38	10.7	822.7	6.6
234678 HxCDF	(0.460)	21.0	651.3	9.0
123789 HxCDF	[0.100]	0.7	51.5	0.4
TOTAL HxCDF	0.72	127.9	7373.3	69.1
1234678-HpCDF	1.60	38.3	1912.3	19.9
1234789-HpCDF	[0.200]	6.4	243.7	2.8
TOTAL HpCDF	3.00	79.0	3560.0	38.0
Octa-CDF	0.91	41.8	799.0	17.3
CONFIRMATION ANALYSES:				
2378-TCDD	[0.040]	3.4	64.7	4.2
2378-TCDF	(0.070)	4.1	111.5	5.2
TOTAL TCDD	0.05	74.7	769.7	80.4
TOTAL TCDF	0.84	214.9	3286.7	206.0

[ ] = minimum detection limit

( ) = estimated maximum possible concentration

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program could not be determined, no field blank corrections were made on the emissions results. Analytical blank results are further discussed in Section 6.4.1.

6.2.1.1 CDD/CDF Toluene Recovery Results. As a newly developed step in EPA CDD/CDF sample recovery protocol, a final toluene rinse was completed on the sample train glassware. Following the test, the nozzle/probe, filter housing, and condenser coil were recovered using methylene chloride. This sample fraction was analyzed along with the filter and XAD trap to determine total CDD/CDF collected in the sample. A final toluene rinse of all the above components was completed and analyzed separately as a part of EPA Method 23 QA protocol. The following discussion and tables present those results.

Tables 6-6, 6-7, and 6-8 compares the toluene recovery amounts of CDD/CDF congeners to the respective MM5 amounts from full screen analyses for each run in Conditions 1, 2, and 3, respectively (all units in picograms). The ratio of the toluene catch to the MM5 expressed as a percentage (T/M x 100), is also given. The results reveal a relatively small amount of CDD/CDF isomers present in the toluene samples. For Condition 1 (Runs 1, 3, and 10), T/M ratios range from 0 to 6.63 percent (Octa-CDF - Run 10). Condition 2 values range from 0 to 0.111 percent. The Condition 2 toluene amounts are similar to Condition 1; however, the MM5 catches for Condition 2 are much higher resulting in overall lower T/M ratios. Condition 3 T/M ratios ranged from 0 to 4.55 percent (Octa-CDD - Run 6).

The confirmation toluene analytical results are compared to the confirmation MM5 values in Table 6-9. The T/M ratios presented here are also very low. T/M values ranged from 0 to 1.03 percent (Run 10).

The toluene field blank analytical results are compared to the toluene test run analytical results in Table 6-10. The field blank appears to have higher concentrations of all congeners than the average run catches. The laboratory method blank results listed in Section 6.4 did not show any contamination. Therefore, the toluene test results may have been even lower than shown in the previous tables if this sample prep/recovery contamination as revealed by the field blank was consistent throughout the test program.

TABLE 6-6. CDD/CDF TOLUENE RINSE FULL SCREEN ANALYTICAL RESULTS COMPARED TO MM5 ANALYTICAL RESULTS FOR CONDITION 1 (total pg); CENTRAL CAROLINA HOSPITAL (1990)

	RUN 1			RUN 3			RUN 10			AVERAGE		
CONGENER	MM5 (pg)	TOLUENE (pg)	TOL/MM5 (%)	MM5 (pg)	TOLUENE (pg)	TOL/MM5 (%)	MM5 (pg)	TOLUENE (pg)	TOL/MM5 (%)	MM5 (pg)	TOLUENE (pg)	TOL/MM5 (%)
DIOXINS												
2378 TCDD	630	[10.90]	0.000	(1200.)	[7.900]	0.000	(370.0)	[24.30]	0.000	733	[14.367]	0.000
Other TCDD	17,870	[10.90]	0.000	156,000	235.0	0.151	19,200	97.1	0.506	64,357	166.1	0.258
12378 PCDD	1,500	[11.10]	0.000	4,600	(9.700)	0.211	1,200	[48.30]	0.000	2,433	9.7	0.399
Other PCDD	15,800	11.3	0.072	128,400	247.0	0.192	19,400	123.0	0.634	54,533	127.1	0.233
123478 HxCDD	980	[13.30]	0.000	4,500	(9.400)	0.209	1,400	(45.40)	3.243	2,293	27.4	1.195
123678 HxCDD	1,500	7.80	0.520	7,300	(19.70)	0.270	2,800	(79.00)	2.821	3,867	35.5	0.918
123789 HxCDD	3,200	[14.70]	0.000	14,000	25.0	0.179	4,200	(85.40)	2.033	7,133	55.2	0.774
Other HxCDD	14,820	0.40	0.003	101,200	193.0	0.191	26,800	295.0	1.101	47,607	162.8	0.342
1234678-HpCDD	8,500	87.2	1.026	41,700	155.0	0.372	20,700	506.0	2.444	23,633	249.4	1.055
Other HpCDD	10,200	88.8	0.871	51,300	189.0	0.368	23,300	453.0	1.944	28,267	243.6	0.862
Octa-CDD	10,000	304.0	3.040	53,400	376.0	0.704	25,900	(1130.)	4.363	29,767	603.3	2.027
Total CDD	85,000	500	0.588	563,600	1,459	0.259	145,270	2,814	1.937	264,623	1591	0.601
FURANS												
2378 TCDF	18,500	14.5	0.078	104,000	267.0	0.257	21,700	209.0	0.963	48,067	163.5	0.340
Other TCDF	89,500	11.7	0.013	388,000	594.0	0.153	101,300	540.0	0.533	192,933	381.9	0.198
12378 PCDF	3,200	[9.800]	0.000	11,300	28.0	0.248	3,900	51.1	1.310	6,133	39.6	0.645
23478 PCDF	6,100	9.50	0.156	29,700	71.0	0.239	9,400	138.0	1.468	15,067	72.8	0.483
Other PCDF	68,100	24.5	0.036	358,000	659.0	0.184	77,800	860.9	1.107	167,967	514.8	0.306
123478 HxCDF	7,500	13.3	0.177	52,000	122.0	0.235	12,900	271.0	2.101	24,133	135.4	0.561
123678 HxCDF	3,900	[9.300]	0.000	21,600	(55.50)	0.257	6,600	128.0	1.939	10,700	91.8	0.857
234678 HxCDF	4,800	[12.80]	0.000	44,800	104.0	0.232	13,300	252.0	1.895	20,967	178.0	0.849
123789 HxCDF	180	[16.30]	0.000	1,300	(25.10)	1.931	560	[76.40]	0.000	680	25.1	3.690
Other HxCDF	23,120	17.5	0.076	147,300	204.0	0.138	43,740	659.0	1.507	71,387	293.5	0.411
1234678-HpCDF	9,600	27.2	0.283	81,300	241.0	0.296	24,100	(685.0)	2.842	38,333	317.7	0.829
1234789-HpCDF	1,200	[25.50]	0.000	12,600	24.7	0.196	5,300	(169.0)	3.189	6,367	96.9	1.521
Other HpCDF	6,900	23.1	0.335	71,100	207.3	0.292	25,000	510.0	2.040	34,333	246.8	0.719
Octa-CDF	5,800	[71.10]	0.000	83,000	203.0	0.245	36,500	2420.0	6.630	41,767	1311.5	3.140
Total CDF	248,400	141	0.057	1,406,000	2806	0.200	382,100	6,969	1.824	678,833	3,305	0.487
Total CDD+CDF	333,400	641	0.192	1,969,600	4264	0.217	527,370	9,783	1.855	943,457	4,896	0.519

[ ] = minimum detection limit (not used in the averages or summations)

( ) = estimated maximum possible concentration (included in averages and summations)

TABLE 6-7. CDD/CDF TOLUENE RINSE FULL SCREEN ANALYTICAL RESULTS COMPARED TO MM5 ANALYTICAL RESULTS FOR CONDITION 2 (total pg); CENTRAL CAROLINA HOSPITAL (1990)

CONGENER	RUN 2			RUN 4			RUN 8			AVERAGE		
	MM5 (pg)	TOLUENE (pg)	TOL/MM5 (%)	MM5 (pg)	TOLUENE (pg)	TOL/MM5 (%)	MM5 (pg)	TOLUENE (pg)	TOL/MM5 (%)	MM5 (pg)	TOLUENE (pg)	TOL/MM5 (%)
DIOXINS												
2378 TCDD	19,000	[9.100]	0.000	53,100	4.6	0.009	25,200	18.6	0.074	32,433	11.6	0.036
Other TCDD	446,000	19.9	0.004	996,000	0.0	0.000	660,000	497.4	0.075	700,667	258.7	0.037
12378 PCDD	59,000	16.4	0.028	208,000	(22.30)	0.011	128,000	67.8	0.053	131,667	35.5	0.027
Other PCDD	391,000	20.1	0.005	1,392,000	52.6	0.004	826,000	312.2	0.038	869,667	128.3	0.015
123478 HxCDD	56,100	16.4	0.029	179,000	25.5	0.014	149,000	54.9	0.037	128,033	32.3	0.025
123678 HxCDD	66,300	24.8	0.037	228,000	26.4	0.012	155,000	68.0	0.044	149,767	39.7	0.027
123789 HxCDD	118,000	40.6	0.034	433,000	49.4	0.011	278,000	125.0	0.045	276,333	71.7	0.026
Other HxCDD	546,600	122.2	0.022	1,700,000	149.7	0.009	1,198,000	457.1	0.038	1,148,200	243.0	0.021
1234678-HpCDD	315,000	(233.0)	0.074	928,000	210.0	0.023	862,000	398.0	0.046	701,667	280.3	0.040
Other HpCDD	330,000	195.0	0.059	1,012,000	162.0	0.016	938,000	391.0	0.042	760,000	249.3	0.033
Octa-CDD	409,000	454.0	0.111	702,000	216.0	0.031	1,080,000	574.0	0.053	730,333	414.7	0.057
Total CDD	2,756,000	1142	0.041	7,778,000	919	0.012	6,274,000	2964	0.047	5,602,667	1675.0	0.030
FURANS												
2378 TCDF	409,000	57.7	0.014	1,130,000	107.0	0.009	608,000	491.0	0.081	715,667	218.6	0.031
Other TCDF	2,171,000	185.3	0.009	6,810,000	386.0	0.006	3,022,000	2349.0	0.078	4,001,000	973.4	0.024
12378 PCDF	166,000	36.5	0.022	798,000	90.7	0.011	285,000	222.0	0.078	416,333	116.4	0.028
23478 PCDF	231,000	45.3	0.020	945,000	101.0	0.011	364,000	310.0	0.085	513,333	152.1	0.030
Other PCDF	2,653,000	188.2	0.007	12,727,000	808.3	0.006	4,401,000	2528.0	0.057	6,593,667	1174.8	0.018
123478 HxCDF	495,000	134.0	0.027	2,300,000	251.0	0.011	1,190,000	571.0	0.048	1,328,333	318.7	0.024
123678 HxCDF	297,000	76.3	0.026	1,450,000	164.0	0.011	721,000	352.0	0.049	822,667	197.4	0.024
234678 HxCDF	291,000	82.5	0.028	1,030,000	130.0	0.013	633,000	267.0	0.042	651,333	159.8	0.025
123789 HxCDF	20,600	[13.40]	0.000	90,100	(24.00)	0.027	43,700	25.0	0.057	51,467	24.5	0.048
Other HxCDF	1,696,400	219.2	0.013	7,779,900	615.0	0.008	4,082,300	1555.0	0.038	4,519,533	796.4	0.018
1234678-HpCDF	787,000	360.0	0.046	2,930,000	442.0	0.015	2,020,000	962.0	0.048	1,912,333	588.0	0.031
1234789-HpCDF	119,000	48.7	0.041	354,000	50.4	0.014	258,000	146.0	0.057	243,667	81.7	0.034
Other HpCDF	634,000	186.3	0.029	2,056,000	308.6	0.015	1,522,000	502.0	0.033	1,404,000	332.3	0.024
Octa-CDF	549,000	315.0	0.057	898,000	155.0	0.017	950,000	489.0	0.051	799,000	319.7	0.040
Total CDF	10,519,000	1,935	0.018	41,298,000	3,633	0.009	20,100,000	10,769	0.054	23,972,333	5,446	0.023
Total CDD+CDF	13,275,000	3,077	0.023	49,076,000	4,552	0.009	26,374,000	13,733	0.052	29,575,000	7,121	0.024

[ ] = minimum detection limit (not used in the averages or summations)

( ) = estimated maximum possible concentration (included in averages and summations)

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TABLE 6-8. CDD/CDF TOLUENE RINSE FULL SCREEN ANALYTICAL RESULTS COMPARED TO MM5 ANALYTICAL RESULTS FOR CONDITION 3 (total pg); CENTRAL CAROLINA HOSPITAL (1990)

	RUN 5			RUN 6			RUN 9			AVERAGE		
CONGENER	MM5 (pg)	TOLUENE (pg)	TOL/MM5 (%)	MM5 (pg)	TOLUENE (pg)	TOL/MM5 (%)	MM5 (pg)	TOLUENE (pg)	TOL/MM5 (%)	MM5 (pg)	TOLUENE (pg)	TOL/MM5 (%)
DIOXINS												
2378 TCDD	720	[24.30]	0.000	(220.0)	[5.900]	0.000	2,500	(3.800)	0.152	1,147	3.80	0.331
Other TCDD	56,680	[24.30]	0.000	11,200	[5.900]	0.000	148,000	[21.6]	0.000	71,960	[17.3]	0.000
12378 PCDD	1,900	[23.70]	0.000	690	[7.200]	0.000	5,800	8.5	0.147	2,797	8.50	0.304
Other PCDD	35,600	(28.70)	0.081	11,510	(22.70)	0.197	116,200	47.3	0.041	54,437	32.9	0.060
123478 HxCDD	1,200	[20.80]	0.000	570	[6.100]	0.000	3,400	(8.200)	0.241	1,723	8.20	0.476
123678 HxCDD	1,800	[20.30]	0.000	960	[6.000]	0.000	5,200	10.2	0.196	2,653	10.2	0.384
123789 HxCDD	3,700	[23.10]	0.000	1,800	[6.800]	0.000	8,600	19.7	0.229	4,700	19.7	0.419
Other HxCDD	23,700	[21.30]	0.000	11,670	[6.300]	0.000	61,400	77.1	0.126	32,257	77.1	0.239
1234678-HpCDD	12,400	[75.60]	0.000	6,300	29.0	0.460	23,600	[70.30]	0.000	14,100	29.0	0.206
Other HpCDD	13,400	[75.60]	0.000	7,400	0.0	0.000	28,400	68.5	0.241	16,400	68.5	0.418
Octa-CDD	17,200	[280.0]	0.000	7,600	346.0	4.553	30,500	143.0	0.469	18,433	245	1.326
Total CDD	168,300	28.7	0.017	59,920	398	0.664	431,100	386	0.900	219,773	271	0.123
FURANS												
2378 TCDF	28,000	20.9	0.075	8,000	(7.300)	0.091	69,200	106.0	0.153	35,067	44.7	0.128
Other TCDF	162,000	0.0	0.000	35,800	(7.300)	0.020	408,800	337.0	0.082	202,200	172.2	0.085
12378 PCDF	4,100	[21.20]	0.000	1,600	[6.500]	0.000	12,500	(34.30)	0.274	6,067	34.3	0.565
23478 PCDF	7,000	[22.00]	0.000	2,800	[6.700]	0.000	19,500	51.2	0.263	9,767	51.2	0.524
Other PCDF	63,500	(25.10)	0.040	24,700	9.8	0.040	254,000	457.8	0.180	114,067	164.2	0.144
123478 HxCDF	9,100	[12.70]	0.000	4,800	6.7	0.140	24,200	66.3	0.274	12,700	36.5	0.287
123678 HxCDF	4,700	[12.20]	0.000	2,400	[4.000]	0.000	12,700	40.3	0.317	6,600	40.3	0.611
234678 HxCDF	6,500	[16.80]	0.000	3,800	[5.500]	0.000	16,800	42.9	0.255	9,033	42.9	0.475
123789 HxCDF	330	[21.50]	0.000	180	[7.000]	0.000	820	[4.000]	0.000	443	[10.833]	0.000
Other HxCDF	26,670	(27.20)	0.102	13,720	1.3	0.009	80,480	130.5	0.162	40,290	53.0	0.132
1234678-HpCDF	17,800	32.9	0.185	8,500	15.4	0.181	33,500	95.3	0.284	19,933	47.9	0.240
1234789-HpCDF	2,300	[31.50]	0.000	1,700	[9.500]	0.000	4,400	13.7	0.311	2,800	13.7	0.489
Other HpCDF	13,300	8.2	0.062	6,900	3.8	0.055	25,700	71.0	0.276	15,300	27.7	0.181
Octa-CDF	12,000	[237.0]	0.000	13,400	(39.20)	0.293	26,500	75.3	0.284	17,300	57.3	0.331
Total CDF	357,300	114	0.032	128,300	90.8	0.071	989,100	1522	0.154	491,567	576	0.117
Total CDD+CDF	525,600	143	0.027	188,220	489	0.260	1,420,200	1908	0.134	711,340	846	0.119

[ ] = minimum detection limit (not used in the averages or summations)

( ) = estimated maximum possible concentration (included in averages and summations)

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TABLE 6-9. CDD/CDF TOLUENE RINSE CONFIRMATION ANALYTICAL RESULTS COMPARED TO MM5 ANALYTICAL RESULTS FOR ALL CONDITIONS; CENTRAL CAROLINA HOSPITAL (1990)

CONGENER	RUN 1			RUN 3			RUN 10			AVERAGE		
	MM5 (pg)	TOLUENE (pg)	TOL/MM5 (%)	MM5 (pg)	TOLUENE (pg)	TOL/MM5 (%)	MM5 (pg)	TOLUENE (pg)	TOL/MM5 (%)	MM5 (pg)	TOLUENE (pg)	TOL/MM5 (%)
DIOXINS												
2378 TCDD	1,600	[24.40]	0.000	7,500	9.0	0.120	1,100	[6.300]	0.000	3,400	9.0	0.265
Other TCDD	18,600	[24.40]	0.000	176,500	211.0	0.120	18,800	97.1	0.516	71,300	154.1	0.216
FURANS												
2378 TCDF	2,100	[9.100]	0.000	7,800	(16.40)	0.210	2,400	24.8	1.033	4,100	20.6	0.502
Other TCDF	71,500	14.5	0.020	473,200	904.0	0.191	87,600	819.2	0.935	210,767	579.2	0.275

CONGENER	RUN 2			RUN 4			RUN 8			AVERAGE		
	MM5 (pg)	TOLUENE (pg)	TOL/MM5 (%)	MM5 (pg)	TOLUENE (pg)	TOL/MM5 (%)	MM5 (pg)	TOLUENE (pg)	TOL/MM5 (%)	MM5 (pg)	TOLUENE (pg)	TOL/MM5 (%)
DIOXINS												
2378 TCDD	32,700	[20.80]	0.000	105,000	15.0	0.014	56,300	(47.10)	0.084	64,667	31.1	0.048
Other TCDD	449,300	(97.70)	0.022	1,005,000	13.4	0.001	660,700	294.0	0.044	705,000	135.0	0.019
FURANS												
2378 TCDF	57,800	13.4	0.023	196,000	(23.10)	0.012	80,800	(90.30)	0.112	111,533	42.3	0.038
Other TCDF	1,722,200	233.6	0.014	5,514,000	393.0	0.007	2,289,200	2750.0	0.120	3,175,133	1125.5	0.035

CONGENER	RUN 5			RUN 6			RUN 9			AVERAGE		
	MM5 (pg)	TOLUENE (pg)	TOL/MM5 (%)	MM5 (pg)	TOLUENE (pg)	TOL/MM5 (%)	MM5 (pg)	TOLUENE (pg)	TOL/MM5 (%)	MM5 (pg)	TOLUENE (pg)	TOL/MM5 (%)
DIOXINS												
2378 TCDD	2,900	28.8	0.993	720	[9.700]	0	9,100	[21.60]	0	4,240	28.8	0.679
Other TCDD	56,300	0	0.000	11,280	[9.700]	0	160,900	[21.60]	0	76,160	[15.7]	0.000
FURANS												
2378 TCDF	3,400	17.9	0.526	860	[5.300]	0	11,400	(20.20)	0.177	5,220	19.1	0.365
Other TCDF	128,600	0	0.000	29,040	[5.300]	0	444,600	340	0.076	200,747	340	0.169

[ ] = minimum detection limit. (not used in the averages or summations)

( ) = estimated maximum possible concentration (included in averages and summations)

TABLE 6-10. CDD/CDF TOLUENE FIELD BLANK RESULTS; CENTRAL CAROLINA HOSPITAL (1990)

FULL SCREEN ANALYSES	TOLUENE FIELD BLANK (total pg)	TOLUENE COND 1 AVG (total pg)	TOLUENE COND 2 AVG (total pg)	TOLUENE COND 3 AVG (total pg)
DIOXINS				
2378 TCDD	10.0	0.0	7.7	1.3
TOTAL TCDD	245.0	102.2	180.2	5.7
12378 PCDD	53.0	3.2	35.5	2.8
TOTAL PCDD	360.0	127.1	156.4	35.7
123478 HxCDD	60.0	18.3	32.3	2.7
123678 HxCDD	82.2	35.5	39.7	3.4
123789 HxCDD	175.0	36.8	71.7	6.6
TOTAL HxCDD	895.0	173.7	386.7	35.7
1234678-HpCDD	618.0	249.4	280.3	9.7
TOTAL HpCDD	1140.0	493.0	452.0	32.5
Octa-CDD	887.0	603.3	414.7	163.0
FURANS				
2378 TCDF	337.0	163.5	218.6	44.7
TOTAL TCDF	1430.0	545.4	1192.0	157.1
12378 PCDF	149.0	26.4	116.4	11.4
23478 PCDF	289.0	72.8	152.1	17.1
TOTAL PCDF	2550.0	614.0	1443.3	172.9
123478 HxCDF	544.0	135.4	318.7	24.3
123678 HxCDF	317.0	61.2	197.4	13.4
234678 HxCDF	366.0	118.7	159.8	14.3
123789 HxCDF	27.2	33.8	16.3	0.0
TOTAL HxCDF	2450.0	590.3	1480.7	105.1
1234678-HpCDF	1210.0	317.7	588.0	47.9
1234789-HpCDF	(219.0)	64.6	81.7	4.6
TOTAL HpCDF	2160.0	344.4	1002.0	80.1
Octa-CDF	1380.0	874.3	319.7	38.2
CONFIRMATION ANALYSES:				
2378-TCDD	(24.10)	4.5	20.7	0.0
2378-TCDF	46.20	8.2	42.3	10.1
TOTAL TCDD	165.00	110.0	140.0	0.0
TOTAL TCDF	1080.00	459.3	1130.0	170.0

[ ] = minimum detection limit

( ) = estimated maximum possible concentration

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6.2.2 PM/Metals Sampling Quality Assurance

Table 6-11 presents the leak check results for the PM/Metals. All post-test leak checks met the "0.02 cfm or 4 percent of the sample rate" acceptance criterion.

The isokinetic sampling rates for the PM/Metals trains are listed in Table 6-3. All isokinetic values were within 4 percent of 100 percent, thereby meeting the ± 10 percent criterion.

The post-test dry gas meter calibration check for box number N-31 used for PM/Metals sampling is shown in Table 6-4. The results of -0.92 percent deviation from the full calibration value is well within the 5 percent acceptance criterion.

Table 6-12 presents the results from the metals field blank analysis compared to the average values from the test runs. No metals were detected in the back half fractions (impingers 1,2 and impingers 3,4) except for chromium. Front half field blank results show detections of arsenic, barium, cadmium, chromium, lead, and nickel. Only nickel, chromium, and arsenic field blank amounts are greater than ~4 percent of any of the average run amounts. Arsenic field blank results show the highest relative contamination at 11.4 μg which ranges from 21 to 50 percent of the front half run catches. No arsenic was detected in the field blank back half fraction.

6.2.3 Microbial Survivability in Emissions Quality Assurance

Table 6-13 presents the leak check results for the Microbial Survivability in emissions test runs. All leak checks met the "0.02 cfm or 4 percent of sample rate" acceptance criterion.

Microbial emission testing isokinetic results are presented in Table 6-3. All 18 test runs met the isokinetic criterion of ± 10 percent of 100 percent.

The microbial emissions field blank results are shown in Table 38a. No spores were detected in the 18 enumeration repetitions.

The post-test dry gas meter calibration check for the microbial emissions dry gas meter is shown in Table 6-4. Post-test calibration factors for the "A" runs were within the 5 percent acceptance criterion at -0.31 percent. No post-test calibration was performed on meter box 9 which was used for the "B" runs.

TABLE 6-11. LEAK CHECK RESULTS FOR TOXIC METALS; CENTRAL CAROLINA HOSPITAL (1990)

DATE	RUN NUMBER	PRELIMINARY LEAK RATE (acfm)	MAXIMUM VACUUM DURING TEST	AVG. SAMPLE RATE (dscfm) a	4% SAMPLE RATE (acfm)	ACCEPTABLE LEAK LEVEL (acfm)	MEASUREMENT POST-TEST LEAK RATE	INCHES FOR SEC. CHK.
09/20/90	1	0.009	4	0.42	0.017	0.017	0.005	9
09/21/90	2	0.011	4	0.39	0.016	0.016	0.010	10
09/22/90	3	0.008	2	0.39	0.016	0.016	0.006	10
09/23/90	4	0.006	13	0.41	0.016	0.016	0.018	17
09/24/90	5	0.004	4	0.43	0.017	0.017	0.006	10
09/25/90	6	0.004	2	0.41	0.016	0.016	0.003	8
09/26/90	7	0.006	4	0.41	0.016	0.016	0.003	7
09/27/90	8	0.010	5	0.42	0.017	0.017	0.004	10
09/28/90	9	0.005	4	0.45	0.018	0.018	0.006	11
10/02/90	10	0.004	3	0.40	0.016	0.016	0.006	7

a This value is in dry standard cubic feet per minute (dscfm) and may be slightly different than actual cfm (acfm).

TABLE 6-12. METALS FIELD BLANK RESULTS COMPARED TO AVERAGE AMOUNTS COLLECTED DURING THE TEST RUNS; CENTRAL CAROLINA HOSPITAL (1990)

METAL	FIELD BLANK (ug)			CONDITION 1 (ug)			CONDITION 2 (ug)			CONDITION 3 (ug)		
	FRONT HALF	IMPINGERS 1,2	IMPINGERS 3,4 c	FRONT HALF	IMPINGERS 1,2	IMPINGERS 3,4 c	FRONT HALF	IMPINGERS 1,2	IMPINGERS 3,4 c	FRONT HALF	IMPINGERS 1,2	IMPINGERS 3,4 c
Antimony	(59.5) a	[7.3] b		1520.33	2254.67		1323.33	3160.00		1420.67	2287.33	
Arsenic	11.7	[0.46]		29.17	4.78		55.93	15.04		23.37	11.83	
Barium	22.5	[0.23]		695.67	33.57		1643.33	69.27		581.33	31.23	
Beryllium	[0.50]	[0.23]		0.00	0.00		0.00	0.00		0.92	0.00	
Cadmium	17.0	[0.57]		833.67	0.00		1082.67	0.00		1196.67	0.00	
Chromium	16.0 c	(1.25)		92.27	5.79		87.67	7.22		50.27	5.93	
Lead	32.0	[3.4]		13946.67	1.26		17833.33	1.53		10670.00	0.63	
Mercury	[2.4]	[6.1]	[0.67]	19.40	507.00	1.47	62.13	1214.00	5.59	369.33	4469.00	695.65
Nickel	44.0	[2.3]		41.43	1.03		21.43	0.00		18.43	0.78	
Silver	[8.2]	[3.8]		0.00	23.64		0.00	48.00		0.00	21.70	
Thallium	[14]	[6.2]		338.33	0.00		339.00	5.33		779.33	0.00	

a Values enclosed in parenthesis represent estimates as they are less than five times the detection limit.

b Values enclosed in brackets represent minimum detection limits for elements not detected in the samples.

c Impingers 3 and 4 only sample fractions analyzed for mercury content.

TABLE 6-13. LEAK CHECK RESULTS FOR MICROBIAL SURVIVABILITY IN EMISSIONS SAMPLING RUNS; CENTRAL CAROLINA HOSPITAL (1990)

DATE	RUN NUMBER	PRE-TEST LEAK RATE (acfm)	MAXIMUM VACUUM DURING TEST	AVG. SAMPLE RATE (dscfm)	4% SAMPLE RATE (dscfm) a	ACCEPTABLE LEAK LEVEL (acfm)	MEASUREMENT POST-TEST LEAK RATE	INCHES FOR SEC. CHK.
09/20/90	1A	0.002	2.7	0.59	0.024	0.02	0.003	5
	1B	0.008	3	0.60	0.024	0.02	0.003	6
09/21/90	2A	0.004	19	0.59	0.024	0.02	0.008	28
	2B	0.006	6	0.54	0.022	0.02	0.006	10
09/22/90	3A	0.004	4.5	0.59	0.024	0.02	0.001	6
	3B	0.005	2	0.60	0.024	0.02	0.003	6
09/23/90	4A	0.004	9	0.55	0.022	0.02	0.005	8
	4B	0.006	5	0.57	0.023	0.02	NR	7
09/24/90	5A	0.006	4.5	0.58	0.023	0.02	0.005	9
	5B	0.006	3	0.50	0.02	0.02	0.005	9
09/25/90	6A	0.003	5	0.65	0.026	0.02	0.003	8
	6B	0.004	3	0.62	0.025	0.02	0.008	9
09/27/90	8A	0.001	11.5	0.56	0.022	0.02	0.006	15
	8B	0.008	14	0.56	0.022	0.02	0.01	18
09/28/90	9A	0.003	4	0.61	0.024	0.02	0.006	9
	9B	0.008	1	0.59	0.024	0.02	0.008	5
10/02/90	10A	0.012	4.5	0.61	0.024	0.02	0.014	7
	10B	0.004	1	0.59	0.024	0.02	0.008	3

a This value is in dry standard cubic feet per minute (dscfm) and may be slightly different than actual cfm (acfm).
NR = Data Not Recorded

6.2.4 Halogen Flue Gas Sampling Quality Assurance

Halogen flue gas concentration tests did not use an isokinetic sampling method. A constant flow of flue gas was extracted from the stack through a heated 3 foot quartz probe. The sample stream was bubbled through a series of impinger collection solutions and sent to the laboratory for analysis of Cl^-, F^-, and Br^-. A slight modification to the method (EPA Method 26) was incorporated into the test scheme by placing a small amount of quartz wool into the upstream side of the HCl filter housing.

Leak checks were completed before and after each halogen test run. They were conducted by establishing approximately 10 inches of vacuum on the train, plugging the end of the probe, turning off the flow, and checking for any detectable vacuum loss over a 30-second period. If a leak was observed in the system, the run was invalidated. (There was no quantitation of leak rate.) All halogen test results had sample trains which met the post-test leak check criterion.

Halogen field blank results are shown in Table 6-14. A small amount of HCl was detected in the field blanks (0.245 and 0.25 mg for FB-A and FB-B). These amounts only represent a maximum of 3 percent of the lowest run average amount.

6.3 QC PROCEDURES FOR ASH AND PIPE SAMPLING

As stated in Section 5.3, the incinerator waste charges were spiked with B. stearothermophilus in both wet and dry forms. Solutions of B. stearothermophilus (wet spores) were spiked to the incinerator to coincide with simultaneous emissions testing and daily ash sampling. Assessments of B. stearothermophilus survivability could then be made. A pre-aliquoted stock solution of wet spores of approximately 500 ml was deposited onto paper waste material and placed in a new, clean plastic garbage bags for each spike. This package was then added to the normal waste loads at precise spiking times. Freeze-dried quantities of B. steareothermophilus (dry spores) were placed in sealed pipes (See Figure 5-12) to determine the viability of "thermally shaded" microbial matter. Two pipes (one large and one small) were placed into the charging bin three times daily.

For both wet and dry spore spiking procedures, only pre-cleaned/disinfected materials were used for handling, application, and transport. The wet spore aliquots were divided and sealed at the manufacturer. This prevented any losses of material

TABLE 6-14. HALOGEN FIELD BLANK RESULTS COMPARED TO RUN RESULTS; CENTRAL CAROLINA HOSPITAL (1990)

ANALYTE	FIELD BLANK A (total mg)	FIELD BLANK B (total mg)	CONDITION 1 AVERAGE (total mg)	CONDITION 2 AVERAGE (total mg)	CONDITION 3 AVERAGE (total mg)
HCl	0.245	0.250	7.31	105	7.85
HF	[0.042]	[0.042]	0.19	0.88	0.13
HBr	(0.0637)	[0.013]	0.08	0.21	0.07

a Values enclosed in brackes represent minimum detection limits for compounds not detected in the samples.

( ) Denotes estimate as value is less than 5 times detection limit.

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during shipment or upon application. (The empty solution container was also placed in the spiked waste charge.) The spiked charge was tied closed and deposited upright into the incinerator. Personnel handling the spiking material used disposable plastic gloves to prevent any cross-contamination.

The inner containers for the pipe samples were acid washed and alcohol disinfected. These were then placed in clean baggies awaiting the dry spore charge. The dry spore was loaded into the pipe container on the same day as it was spiked. The dry spore material was received from the manufacturer in seal, glass vials. This allowed for easy and complete transfer of all the spore material to the inner container.

In conjunction with the wet spore/microbial survivability tests, incinerator ash was collected before each test day (from the previous test run). The ash was also analyzed for metals, CDD/CDF, carbon, loss on ignition, moisture content, as well as indicator spores. All of the ash was completely removed from the incinerator bed every morning, passed through a 1-inch mesh stainless steel (SS) sieve and placed in a large 55-gallon drum. Using a sample "thief", four approximately 500 gram samples were taken and placed in pre-cleaned, amber glass bottles. All material used for sampling, sample compositing, and sample aliquoting was cleaned to prevent any sample contamination.

During the ash removal process, the pipe samples were also recovered. The outer containers were allowed to cool and then opened. The inner container was removed and placed in a clean, dry Ziplock baggie, labeled and kept in a clean environment prior to shipment to the laboratory. Further Microbial QA information is presented in Section 6.4.4.

6.4 ANALYTICAL QUALITY ASSURANCE

The following section reports QA parameters for the CDD/CDF, Metals, Halogen, and Microbial Survivability analytical results.

6.4.1 CDD/CDF Analytical Quality Assurance

6.4.1.1 Flue Gas (MM5) Analytical Procedure. There were two samples generated for each flue gas (MM5) test run. One sample consisted of the pooled MM5 sample which received both the full screen and confirmation analyses. The second sample was the post-recovery, toluene rinse, which also received a full screen and confirmation analysis. The full screen analyses were conducted using a DB-5 GC column

which allows for the separation of each class of chlorination (i.e., tetras, petra, etc.) and fully resolves 2378 TCDD from the other TCDD isomers. The confirmation analysis, performed on a DB-225 GC column, is needed to fully resolve the 2378 TCDF from the other TCDF isomers. The 2378 TCDD and total TCDD isomers are also reported on the confirmation analysis. The final results for 2378 TCDF and other TCDF emission parameters were taken from the confirmation analysis. All other CDD/CDF results were taken from the full screen analysis. (Toluene Runs 9 and 10,2378 TCDD, Total TCDD were taken from confirmation analyses - see Section 6.4.1.2.)

A component of the CDD/CDF analytical laboratory's QA/QC program is adding isotopically labeled standards to each sample during various stages of analysis to determine recovery efficiencies and to aid in the quantitation of "native" CDD/CDF species. Four different type standards are added. Surrogate standards are usually spiked on the XAD absorbent trap prior to the sampling session. (Toluene surrogates are added to the sample prior to extraction.) Recovery of these compounds allows for the evaluation of overall sample collection efficiency and analytical matrix effects. Internal standards are spiked after the sampling session but prior to extraction. Alternate standards are also spiked at this stage. Recovery percentage of internal standards are used in quantifying the flue gas native CDD/CDF isomers. Recovery of alternate standards allows for extraction/fractionation efficiencies to be determined. Finally, recovery standards are added after fractionation, just prior to the HRGC/HRMS analysis. Internal standards recovery are determined relative to recovery standards recovery. Recovery standards recovery efficiencies are not typically reported with the analytical results.

Poor recovery percentage of the various standards can reveal poor data quality. In some cases, if an analysis with a poor recovery is also accompanied by a suitable QA/QC "flag", the sample result can be validated. A full discussion of the analytical QA/QC program can not be presented in this summary report, but can be found in Triangle's CDD/CDF Data User Manual.

6.4.1.2 <u>CDD/CDF MM5 Analytical Protocol Changes</u>. Based on previous Hospital MWI test programs, high levels of organics were expected to be found in the

CDD/CDF MM5 samples. Therefore a different analytical protocol was developed for the analysis. One percent of the MM5 extract was used for Runs 2, 4, and 8 (Condition 2) instead of the typical 50 percent. This resulted in a diluted fraction which did not saturate the MS detector. However, surrogate (pre-sample) spike recoveries could not be determined. Additional standards were added at higher than normal amounts to allow full quantitation of the CDD/CDF congeners for Runs 2, 4 and 8.

A slight modification to the CDD/CDF data reduction protocol was also incorporated into the toluene flue gas samples. Values for Runs 9 and 10,2378 TCDD and Total TCDD (Other) were taken from the confirmation analysis as designated by Triangle Laboratories. This is further explained in the TLI Project No. 16653T Case Narrative shown in Appendix E3.

6.4.1.3 CDD/CDF MM5 Blank Results. Both method blanks and field blanks were analyzed for CDD/CDF isomers. Modified Method 5 samples as well as the toluene rinses were submitted. Table 6-15 presents these results. The MM5 method blanks had no CDD/CDF isomers except for a small amount of O_{ctu}-TCDF (0.18 ng). The toluene Field Blank had relatively high quantities of all isomers when compared to the run results (picograms). The toluene method blanks were clean.

6.4.1.4 CDD/CDF Standard Recoveries. Tables 6-16 and 6-17, and Tables 6-18 and 6-19 present the standard recovery values for the MM5 flue gas and toluene flue gas samples, respectively. Both full screen (FS) and confirmation (C) values are presented. The analytical acceptance criterion for internal standard recoveries is 40 percent to 130 percent for tetra- through hexa-chlorinated compounds, while the range is 25 percent to 130 percent for hepta- and octa-chlorinated compounds. Recoveries outside of these limits may still be acceptable if other identification criteria are met.

As stated before, surrogate recoveries for MM5 Samples 2, 4, and 8 could not be determined because of the modified analytical routine. All other MM5 surrogate recoveries were within ±30 percent.

Internal standard recoveries for MM5 Runs 1-10 FS and C all met the acceptable criteria. All toluene internal standards recoveries were within the acceptance criteria except for Run 1 13C12-HxCDD 678 and several Run 5 isomers. The Run 5 toluene sample had no native hexa-substituted isomers present in hence high standards recoveries

TABLE 6-15. METHOD BLANK AND FIELD BLANK RESULTS FOR THE MM5 AND TOLUENE FLUE GAS SAMPLES; CENTRAL CAROLINA HOSPITAL HOSPTIAL (1990)

FULL-SCREEN ANALYSIS	MM5 TLI-METHOD BLANK (total ng)	MM5 TLI-METHOD BLANK (1/2 OM-50%) (total ng)	MM5 FIELD BLANK (total ng)	TOL TLI-METHOD BLANK (total pg)	TOL FIELD BLANK (total pg)
DIOXINS					
2378 TCDD	[6.500]	[0.050]	[0.060]	[25.50]	10.0
TOTAL TCDD	[6.500]	[0.050]	(0.070)	[25.50]	245.0
12378 PCDD	[8.600]	[0.060]	[0.080]	[31.20]	53.0
TOTAL PCDD	[8.600]	[0.060]	0.29	(34.40)	360.0
123478 HxCDD	[8.500]	[0.050]	[0.100]	[44.40]	60.0
123678 HxCDD	[8.300]	[0.050]	[0.100]	[43.40]	82.2
123789 HxCDD	[9.500]	[0.050]	(0.180)	[49.30]	175.0
TOTAL HxCDD	[8.700]	[0.050]	0.85	[45.60]	895.0
1234678-HpCDD	[14.50]	[0.080]	0.58	[160.0]	618.0
TOTAL HpCDD	[14.50]	[0.080]	0.58	[160.0]	1140.0
Octa-CDD	[26.50]	0.18	(0.950)	[453.0]	887.0
FURANS					
2378 TCDF	[4.500]	[0.040]	0.35	[19.20]	337.0
TOTAL TCDF	[4.500]	[0.040]	0.63	[19.20]	1430.0
12378 PCDF	[6.300]	[0.050]	0.14	[25.50]	149.0
23478 PCDF	[6.600]	[0.050]	0.23	[26.60]	289.0
TOTAL PCDF	[6.400]	[0.050]	1.9	[26.00]	2550.0
123478 HxCDF	[5.000]	[0.030]	(0.680)	[27.30]	544.0
123678 HxCDF	[4.800]	[0.030]	0.38	[26.20]	317.0
234678 HxCDF	[6.600]	[0.040]	(0.460)	[36.20]	366.0
123789 HxCDF	[8.400]	[0.050]	[0.100]	[46.20]	27.2
TOTAL HxCDF	[5.900]	[0.030]	0.72	[32.30]	2450.0
1234678-HpCDF	[6.000]	[0.030]	1.60	[48.50]	1210.0
1234789-HpCDF	[10.10]	[0.060]	[0.200]	[80.70]	(219.0)
TOTAL HpCDF	[7.500]	[0.040]	3.00	[60.60]	2160.0
Octa-CDF	[22.40]	[0.100]	0.91	[383.0]	1380.0

[ ] = minimum detection limit

( ) = estimated maximum possible concentration

TABLE 6-16. STANDARDS RECOVERY RESULTS FOR CDD/CDF ANALYSES, TEST RUN SAMPLES; CENTRAL CAROLINA HOSPITAL (1990)

SAMPLE ID	MM5-RUN 1	MM5-RUN 2	MM5-RUN 3	MM5-RUN 4	MM5-RUN 5	MM5-RUN 6	MM5-RUN 8	MM5-RUN 9	MM5-RUN 10
FULL SCREEN ANALYSES									
SURROGATE STANDARDS RECOVERY (%)									
37Cl-TCDD	86.7		94.9		91.7	91.0		90.2	89.9
13C12-PeCDF 234	107.0		99.7		97.1	100.0		88.0	97.4
13C12-HxCDF 478	90.5		98.5		94.1	94.3		95.0	93.0
13C12-HxCDD 478	86.3		86.1		86.4	71.6		90.6	86.8
13C12-HpCDF 789	78.1		81.7		82.5	87.7		76.2	75.9
ALTERNATE STANDARDS RECOVERY									
13C12-HxCDF 789	81.8	84.7	81.1	91.0	86.2	86.5	82.3	89.6	85.2
13C12-HxCDF 234	102.0	104.0	101.0	105.0	101.0	97.4	107.0	108.0	109.0
INTERNAL STANDARDS RECOVERY									
13C12-2378-TCDF	63.0	78.3	79.7	81.7	75.5	78.6	82.7	87.2	67.4
13C12-2378-TCDD	74.6	84.3	81.7	89.1	81.9	85.1	79.6	82.6	71.4
13C12-PeCDF 123	76.7	96.1	89.1	97.9	82.3	92.2	106.0	99.8	79.1
13C12-PeCDD 123	81.4	120.0	91.5	128.0	77.7	124.0	115.0	98.9	87.6
13C12-HxCDF 678	115.0	105.0	109.0	103.0	115.0	97.5	99.4	113.0	119.0
13C12-HxCDD 678	122.0	106.0	113.0	102.0	119.0	129.0	103.0	119.0	125.0
13C12-HpCDF 678	83.2	84.1	80.3	90.9	81.9	77.5	81.7	81.6	93.7
13C12-HpCDD 678	77.0	75.3	74.9	78.1	77.8	78.3	70.9	74.1	86.1
13C12-OCDD	52.1	55.4	54.0	62.2	55.3	58.4	53.4	54.4	70.8
CONFIRMATION DATA									
SURROGATE STANDARD RECOVERY %									
37Cl-TCDD	98.2		96.5		100.0	101.0		97.2	96.9
INTERNAL STANDARDS RECOVERY %									
13C12-2378-TCDF	76.2	91.3	87.6	98.7	90.9	90.8	93.9	87.5	85.0
13C12-2378-TCDD	78.6	91.6	91.1	98.0	94.7	93.8	95.4	96.2	82.6

TABLE 6-17. STANDARDS RECOVERY RESULTS FOR CDD/CDF ANALYSES
BLANK SAMPLES;
CENTRAL CAROLINA HOSPITAL (1990)

SAMPLE ID	MM5-FIELD BLANK	MM5-TLI BLANK
FULL SCREEN ANALYSES	(1/2 10 OM)	
SURROGATE STANDARDS RECOVERY (%)		
37Cl-TCDD	90.4	
13C12-PeCDF 234	78.1	
13C12-HxCDF 478	91.6	
13C12-HxCDD 478	86.1	
13C12-HpCDF 789	65.8	
ALTERNATE STANDARDS RECOVERY		
13C12-HxCDF 789	65.1	76.3
13C12-HxCDF 234	87.0	98.8
INTERNAL STANDARDS RECOVERY		
13C12-2378-TCDF	66.2	69.1
13C12-2378-TCDD	73.8	72.0
13C12-PeCDF 123	102.0	83.4
13C12-PeCDD 123	98.4	101.0
13C12-HxCDF 678	104.0	80.1
13C12-HxCDD 678	116.0	83.2
13C12-HpCDF 678	59.9	68.8
13C12-HpCDD 678	49.7	65.9
13C12-OCDD	32.8	53.6
CONFIRMATION DATA		
SURROGATE STANDARD RECOVERY %		
37Cl-TCDD	100.0	
INTERNAL STANDARDS RECOVERY %		
13C12-2378-TCDF	79.8	
13C12-2378-TCDD	75.8	

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TABLE 6-18. STANDARDS RECOVERY RESULTS FOR CDD/CDF TOLUENE ANALYSES, TEST RUN SAMPLES
CENTRAL CAROLINA HOSPITAL (1990)

SAMPLE ID	TOL-RUN 1	TOL-RUN 2	TOL-RUN 3	TOL-RUN 4	TOL-RUN 5	TOL-RUN 6	TOL-RUN 8	TOL-RUN 9	TOL-RUN 10
FULL SCREEN ANALYSIS									
SURROGATE STANDARDS RECOVERY (%)									
37Cl-TCDD	47.8	53.3	31.6	49.1	31.9	51.8	54.7	69.0	50.9
13C12-PeCDF 234	63.4	75.6	52.4	75.6	48.3	61.8	69.4	79.6	52.8
13C12-HxCDF 478	88.8	76.4	86.0	63.1	170.0	71.1	80.2	77.2	88.7
13C12-HxCDD 478	105.0	93.8	111.0	81.2	171.0	95.0	100.0	110.0	101.0
13C12-HpCDF 789	43.0	44.6	41.2	45.7	71.0	45.8	55.1	56.4	32.4
ALTERNATE STANDARDS RECOVERY									
13C12-HxCDF 789	54.6	54.3	47.6	55.1	78.1	56.4	67.9	68.5	53.9
13C12-HxCDF 234	85.3	82.8	83.9	79.7	128.0	70.2	76.5	87.6	77.8
INTERNAL STANDARDS RECOVERY									
13C12-2378-TCDF	44.9	49.8	30.2	44.8	33.8	53.0	51.9	70.4	50.4
13C12-2378-TCDD	52.8	58.7	35.3	56.3	33.5	56.7	59.2	72.6	61.3
13C12-PeCDF 123	65.9	74.6	53.9	74.3	43.2	58.3	65.5	74.4	59.7
13C12-PeCDD 123	96.5	103.0	74.3	110.0	63.6	86.0	106.0	106.0	57.1
13C12-HxCDF 678	103.0	81.0	95.7	73.7	180.0	77.2	77.6	77.8	89.6
13C12-HxCDD 678	149.0	118.0	142.0	110.0	218.0	104.0	103.0	111.0	105.0
13C12-HpCDF 678	67.5	61.0	64.3	59.1	126.0	58.5	63.7	63.2	52.0
13C12-HpCDD 678	60.9	58.9	52.5	63.4	72.2	62.2	70.1	71.0	47.7
13C12-OCDD	42.1	47.4	34.4	57.7	28.9	43.8	49.4	51.3	33.1
CONFIRMATION DATA									
SURROGATE STANDARD RECOVERY (%)									
37Cl-TCDD	50.4	59.1	40.3	54.2	43.0	59.5	56.2	67.1	61.5
INTERNAL STANDARDS RECOVERY (%)									
13C12-2378-TCDF	60.9	69.1	33.9	48.6	39.4	49.8	53.7	59.3	54.4
13C12-2378-TCDD	48.8	56.4	40.3	56.4	49.1	58.8	60.2	72.5	68.0

TABLE 6-19. STANDARDS RECOVERY RESULTS FOR CDD/CDF TOLUENE ANALYSES, BLANK SAMPLES; CENTRAL CAROLINA HOSPITAL (1990)

SAMPLE ID	TOL-TLI BLANK	TOL-FIELD BLANK
FULL SCREEN ANALYSIS		
SURROGATE STANDARDS RECOVERY (%)		
37Cl-TCDD	31.3	58.1
13C12-PeCDF 234	37.0	73.5
13C12-HxCDF 478	73.1	84.9
13C12-HxCDD 478	83.7	103.0
13C12-HpCDF 789	24.7	53.2
ALTERNATE STANDARDS RECOVERY		
13C12-HxCDF 789	35.6	71.9
13C12-HxCDF 234	61.8	80.8
INTERNAL STANDARDS RECOVERY		
13C12-2378-TCDF	30.0	54.6
13C12-2378-TCDD	34.4	59.8
13C12-PeCDF 123	38.6	67.4
13C12-PeCDD 123	52.2	90.5
13C12-HxCDF 678	78.2	86.3
13C12-HxCDD 678	95.5	112.0
13C12-HpCDF 678	45.8	63.4
13C12-HpCDD 678	31.9	64.0
13C12-OCDD	16.7	30.6
CONFIRMATION DATA		
SURROGATE STANDARD RECOVERY (%)		
37Cl-TCDD		63.7
INTERNAL STANDARDS RECOVERY (%)		
13C12-2378-TCDF		58.8
13C12-2378-TCDD		62.9

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these compounds do not present a problem. All CDD/CDF data was inspected and released as valid by the Triangle Laboratory QA officer.

Table 6-20 present the recovery standards for the ash samples. All recoveries were within acceptable limits. Further information on standards recoveries can be found in Appendix E.1.

6.4.2 Metals Analytical Quality Assurance

The analytical methods used for the flue gas samples, the ash samples, and the metals samples are fully discussed in Section 5. The following paragraph will briefly report to metals analytical QA parameters.

Table 6-21 present the method blank metals results for both the ash and flue gas samples. Only barium was detected in the ash blank. Barium was also detected in the flue gas method blank. Relatively high amounts of arsenic, chromium, and nickel were found in the field blank. This was more fully discussed in Section 6.2.2.

Table 6-22 presents the method spike results for the metals analyses. All spiked recoveries were within the QA allowance of ±20 percent of 100 percent except for the back half fraction of mercury. This does not appear to be significant enough to affect the overall quality of the final results. At this point, no front half method spike duplicate values have been determined.

6.4.3 Halogen Analytical Quality Assessment

The analysis for Cl^-, F^-, and Br^- incorporate stringent QA/QC guidelines. Table 6-23 presents the method blank results for the IC analysis. None of the target halogen ions were detected in any of the method blanks, laboratory proof blanks, or the reagent blank. The field blank revealed very low amounts of HCl but only represented 3 percent of the average run amounts.

The matrix spike recoveries are also shown in Table 6-23. Results for all 3 ions were within the 20 percent criteria.

6.4.4 Microbial Survivability Quality Assurance

The stock wet spore solution, that were used for spiking the incinerator was analyzed. These results are listed in Table 6-24. Two pre-aliquoted wet spore bags were

TABLE 6-20. STANDARDS RECOVERY RESULTS FOR CDD/CDF ASH ANALYSES; CENTRAL CAROLINA HOSPITAL (1990)

SAMPLE ID	ASH CONDITION 1	ASH CONDITION 2	ASH CONDITION 3	ASH-TLI BLANK
FULL SCREEN ANALYSIS				
SURROGATE STANDARDS RECOVERY (%)				
37Cl-TCDD	73.3	77.3	68.0	37.0
13C12-PeCDF 234	88.8	94.1	88.5	55.6
13C12-HxCDF 478	121.0	108.0	93.2	58.8
13C12-HxCDD 478	119.0	114.0	107.0	80.9
13C12-HpCDF 789	74.4	68.4	59.0	52.1
ALTERNATE STANDARDS RECOVERY				
13C12-HxCDF 789	81.3	86.2	67.4	55.3
13C12-HxCDF 234	112.0	109.0	92.7	78.2
INTERNAL STANDARDS RECOVERY				
13C12-2378-TCDF	98.0	99.5	95.2	33.7
13C12-2378-TCDD	74.0	77.8	69.3	41.6
13C12-PeCDF 123	83.9	84.7	77.7	46.9
13C12-PeCDD 123	73.6	72.1	66.7	77.7
13C12-HxCDF 678	98.1	90.5	79.5	64.3
13C12-HxCDD 678	92.1	94.2	85.7	94.1
13C12-HpCDF 678	89.6	81.4	71.8	58.0
13C12-HpCDD 678	73.0	75.8	63.3	61.6
13C12-OCDD	48.8	57.5	37.6	58.8
CONFIRMATION DATA				
SURROGATE STANDARD RECOVERY (%)				
37Cl-TCDD	77.3	88.0	71.8	
INTERNAL STANDARDS RECOVERY (%)				
13C12-2378-TCDF	67.2	79.0	61.5	
13C12-2378-TCDD	75.9	84.9	70.6	

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TABLE 6-21. METALS ASH AND FLUE GAS METHOD BLANK RESULTS; CENTRAL CAROLINA HOSPITAL (1990)

METAL	ASH METHOD BLANK (mg/kg)	FLUE GAS METHOD BLANK			FIELD BLANK		
		FRONT HALF (total ug)	IMPINGERS 1,2 (total ug)	IMPINGERS 3,4 a (total ug)	FRONT HALF (total ug)	IMPINGERS 1,2 (total ug)	IMPINGERS 3,4 a (total ug)
Antimony	[6.4]	[16]	[7.0]		(59.5)	[7.3]	
Arsenic	[4.0]	[1.0]	[0.44]		11.7	[0.46]	
Barium	2.30	6.75	[0.22]		22.5	[0.23]	
Beryllium	[0.20]	[0.50]	[0.22]		[0.50]	[0.23]	
Cadmium	[0.50]	[1.2]	(0.978)		17.0	[0.57]	
Chromium	[1.0]	[2.5]	[1.1]		16.0	(1.25)	
Lead	[3.0]	[0.75]	[3.3]		32.0	[3.4]	
Mercury	[0.039]	[2.4]	[4.0]	[0.37]	[2.4]	[6.1]	[0.67]
Nickel	[2.0]	[5.0]	[2.2]		44.0	[2.3]	
Silver	[3.3]	[8.2]	[3.6]		[8.2]	[3.8]	
Thallium	[5.4]	[14]	[5.9]		[14]	[6.2]	

a Impingers 3 and 4 sample fractions analyzed for mercury content only.

NOTE:

-- Values enclosed in brackets represent minimum detection limits for elements not detected in the samples.

-- Values enclosed in parenthesis represent estimates as they are less than five times the detection limit.

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TABLE 6-22. METALS METHOD BLANK SPIKE RESULTS; CENTRAL CAROLINA HOSPITAL (1990)

METAL	METHOD SPIKE			METHOD SPIKE DUPLICATE		
	FRONT HALF	IMPINGERS 1,2	IMPINGERS 3,4	FRONT HALF	IMPINGERS 1,2	IMPINGERS 3,4
Antimony	104	95.2		NC	81.0	
Arsenic	98.0	96.2		NC	94.4	
Barium	97.6	96.6		NC	96.0	
Beryllium	99.6	96.0		NC	94.4	
Cadmium	102	101		NC	101	
Chromium	104	99.6		NC	98.2	
Lead	100	95.2		NC	92.8	
Mercury	115	109	64.1	NC	101	80.1
Nickel	92.2	89.6		NC	90.0	
Silver	113	NC		NC	NC	
Thallium	83.4	89.2		NC	85.8	

NC = Analysis not completed

TABLE 6-23. HALOGEN METHOD BLANK, LAB PROOF BLANK, REAGENT BLANK AND MATRIX SPIKE RECOVERY; CENTRAL CAROLINA HOSPITAL (1990)

ANALYTE	METHOD BLANK 1 (total mg)	LAB PROOF BLANK SET 1 (total mg)	LAB PROOF BLANK SET 2 (total mg)	REAGENT BLANK H2SO4 (total mg)	FIELD BLANK A (total mg)	FIELD BLANK B (total mg)	ANALYTE	MATRIX SPIKE RECOVERY (%)	MATRIX SPIKE DUPLICATE RECOVERY (%)
HCl	[0.011]	[0.011]	[0.011]	[0.0099]	0.245	0.250	HCl	97.20	106
HF	[0.042]	[0.043]	[0.043]	[0.037]	[0.042]	[0.042]	HF	96.20	96.80
HBr	[0.013]	[0.013]	[0.013]	[0.011]	(0.064)	[0.013]	HBr	106.0	96.20

NOTE:

[ ] = Minimum Detection Limit

( ) = Denotes estimated value as number is less than 5 times detection limit.

TABLE 6-24. WET SPORE SPIKE SOLUTION CONIRMATION ANALYSIS; CENTRAL CAROLINA HOSPITAL (1990)

SAMPLE ID	MANUFACTURER'S COUNT (spore/ml)	CONFIRMATION AVERAGE (viable spores/ml)	CONFIRMATION COUNT STANDARD DEVIATION (viable spores/ml)
Spike Aliquot Spore Susp.-1	6.72E+08	3.0E+09	1.0E+09
Spike Aliquot Spore Susp.-2	7.88E+08	3.0E+09	2.0E+09

NOTE: All Values were taken from the average of the 10 ml - 48-hour counts
Spike Aliquot Spore Susp.-1 was labelled 3.68E+11 spores/bag at 500 ml/bag.
Spike Aliquot Spore Susp.-2 was labelled 3.94E+11 spores/bag at 500 ml/bag.

submitted for confirmation analysis. The confirmation counts of 3×10^9 and 3×10^9 spores/ml were higher than the manufacturer's respective count of 6.72×10^8 and 7.88×10^8 spores/ml. However, because the final analyses were also completed by the same laboratory conducting confirmation anlayses, the confirmation results were used to calculate Overall Microbial Survivability.

A dry spore sample was also sent in for QA analysis. These results are shown in Table 6-25. The sample was sent to the laboratory as it was received from the manufacturer (in a glass vial). The confirmation count exceeded the manufacturer count at 5.2×10^6 versus 3.45×10^5, respectively.

Two empty pipe samples (blanks) that were not charged to the incinerator were also submitted to the laboratory for analysis. These results are listed on Page 2 in Appendix E.3 (CCH-298, CCH-299). One large and one small pipe field blank were submitted. The results were 10 and >200 spores, respectively. Therefore, either the sample recovery procedures or the analytical methods appear to have contaminated both pipe field blanks.

Two pipes which were loaded with spores and not charged to the incinerator (ambient pipes) were also submitted for analysis (see Apppendix E.3-CCH-300, CCH-301). The results show that the large pipe sample has 10 spores detected and the small pipe sample had >200 spores found. The number of spores detected probably does not represent the total spores present. This is because all pipe samples were rinsed and filtered without any dilutions. Henceforth quantitation of higher numbers of spores (pipes were loaded with 5.2×10^6 spores) was not feasible without performing serial dilutions.

6.5 CEM QUALITY ASSURANCES

Flue gas was analyzed for carbon monoxide (CO), oxygen (O_2), carbon dioxide (CO_2), sulfur dioxide (SO_2), nitrogen oxides (NO_x), and total hydrocarbons (THC), using EPA Methods 10, 3A, 6C, 7E, and 25A, respectively. An additional CEM analyzer was also employed for real time HCl gas concentrations.

TABLE 6-25. DRY SPORE SPIKE SOLUTION CONFIRMATION ANALYSIS; CENTRAL CAROLINA HOSPITAL (1990)

SAMPLE ID	MANUFACTURER'S COUNT (spores/vial)	CONFIRMATION AVERAGE (viable spores/vial)	CONFIRMATION COUNT STANDARD DEVIATION (viable spores/vial)
Dry Spore Glass Vial	3.45E+05	5.2E+06 a	1.0E+06

NOTE: All Values were taken from the average of the 10 ml - 48-hour counts

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6.5.1 CEM Data Overview

CEM sampling system and instruments were operated performing daily QA/QC procedures. These included QC gas challenges, sample systems blow back, probe maintenance, filter replacement, conditioner inspection and maintenance, calibration drift checks and others. The aim was to ensure a quality data product. Details of the CEM QC procedures are fully outlined in this test program's test plan.

Table 6-26 presents the CEM internal QA/QC checks along with their respective acceptance criteria which were conducted at the Central Carolina tests.

6.5.2 Calibration Drift Checks

All CEM analyzers were calibrated daily with a zero gas (generally nitrogen), and a high-range span gas. Calibrations were performed prior to and at the completion of each test run. By comparing the post-test calibration to the pre-test calibration, the calibration drift was determined (zero drift and span drift). Post-test calibrations were not completed for 4 out of the 9 HCl CEM test runs. This was because HCl calibrations had to be completed at stack gas temperatures and the incinerator would go into a "burndown" mode (lower temperature) before the post-test calibration could be performed.

Daily drift requirements between calibrations for both zero and span was ±3 percent of full scale as required by EPA Methods 6C and 3A. Although Method 10 for CO allows ±10 percent of full scale drift, the CO drift requirements were ±3 percent for this test program, to ensure the quality of data produced.

Table 6-27 lists the zero and span calibration drift results for each CEM analyzer on each test day. All drifts met QC allowances except HCl-Runs 1 and 9, and THC-Runs 7 and 9. The HCl data for the above runs were drift corrected. The THC CEM data for Run 7 were not included in the final results. No drift corrections were made on the THC-Run 9 data.

6.5.3 Daily QC Gas Challenges

After initial calibration, mid-range QC gases for all instruments were analyzed with no adjustment, as a quality control check of daily calibrations and to provide day-to-day precision estimates for each instrument. The calibration was considered

TABLE 6-26. CEM INTERNAL QA/QC CHECKS

Check	Frequency	Criteria
Initial Leak Check	Once/Site	< 4% of Total flow while under vacuum
Daily Leak Checks	Before Each Test Run	< 0.5% O_2 with 0.2% O_2 gas
Calibration Drift	Daily	< ±3% Span zero and upscale gas (can use ±10 ppm limit for HCl if less restrictive)
Multipoint Linearity Check (Calibration Error)	Every 3rd Day 3 point for O_2, CO_2, NO_x, SO_2, HCl 4 point for CO, THC	r = 0.998
Sample System Bias	Every 3rd Day Zero and Span	< 5% Span
Response Time	Once/Site	85% of time for stable SO_2 measurements
NO_x Convertor	Once/Site	> 90% conversion efficiency
Stratification Test	Once/Site	Within 10% of average

TABLE 6-27. DAILY CALIBRATION DRIFTS; CENTRAL CAROLINA HOSPITAL (1990)

PARAMETER: O2
ZERO CALIBRATION GAS: 0.2% O2
FULL SCALE: 25

DATE	RUN	ZERO INSTRUMENT DRIFT (% of Span)	SPAN INSTRUMENT DRIFT (% of Span)
09/20/90	1	0.0100	-0.5900
09/21/90	2	0.0200	-0.1000
09/22/90	3	0.0100	-0.3300
09/23/90	4	0.0500	-0.3200
09/24/90	5	0.1600	-0.5000
09/25/90	6	0.0200	-0.3100
09/26/90	7	0.1900	-0.6100
09/28/90	9	0.0500	-0.6500
10/02/90	10	-0.0400	-0.4400

PARAMETER: CO
ZERO CALIBRATION GAS: N2
FULL SCALE: 5000

DATE	RUN	ZERO INSTRUMENT DRIFT (% of Span)	SPAN INSTRUMENT DRIFT (% of Span)
09/20/90	1	-0.0500	-0.2000
09/21/90	2	0.0000	-0.0400
09/22/90	3	0.0800	-0.2000
09/23/90	4	0.0000	-0.2000
09/24/90	5	-0.0200	-0.0400
09/25/90	6	-0.0100	-0.0900
09/26/90	7	0.0900	-0.1000
09/28/90	9	-0.0500	-0.0900
10/02/90	10	-0.0200	-0.1100

PARAMETER: CO2
ZERO CALIBRATION GAS: N2
FULL SCALE: 20

DATE	RUN	ZERO INSTRUMENT DRIFT (% of Span)	SPAN INSTRUMENT DRIFT (% of Span)
09/20/90	1	0.0600	-1.4700
09/21/90	2	0.0200	0.0700
09/22/90	3	0.0700	0.6200
09/23/90	4	-0.0200	0.0300
09/24/90	5	0.0300	0.0400
09/25/90	6	0.0500	0.0100
09/26/90	7	-0.0400	0.2000
09/28/90	9	-0.1700	-0.0400
10/02/90	10	-0.0200	0.0000

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TABLE 6-27. DAILY CALIBRATION DRIFTS; (continued)
CENTRAL CAROLINA HOSPITAL (1990)

PARAMETER: HCl
ZERO CALIBRATION GAS: N2
FULL SCALE: 2000

DATE	RUN	ZERO INSTRUMENT DRIFT (% of Span)	SPAN INSTRUMENT DRIFT (% of Span)
09/20/90	1	0.3700	-20.0100
09/21/90	2	0.6100	-0.1300
09/22/90	3	no final cal	no final cal
09/23/90	4	-0.1200	-0.5400
09/24/90	5	-0.2600	-0.6900
09/25/90	6	no final cal	no final cal
09/26/90	7	no final cal	no final cal
09/28/90	9	1.4500	9.5500
10/02/90	10	no final cal	no final cal

PARAMETER: SO2
ZERO CALIBRATION GAS: N2
FULL SCALE: 500

DATE	RUN	ZERO INSTRUMENT DRIFT (% of Span)	SPAN INSTRUMENT DRIFT (% of Span)
09/20/90	1	-0.0200	-0.1900
09/21/90	2	-0.0100	0.0000
09/22/90	3	0.0500	0.0800
09/23/90	4	-0.0300	-0.1400
09/24/90	5	0.0400	-0.0100
09/25/90	6	-0.0200	-0.1600
09/26/90	7	0.0000	-0.0500
09/28/90	9	-0.0300	-0.0800
10/02/90	10	-0.0200	-0.0700

PARAMETER: NOX
ZERO CALIBRATION GAS: N2
FULL SCALE: 250

DATE	RUN	ZERO INSTRUMENT DRIFT (% of Span)	SPAN INSTRUMENT DRIFT (% of Span)
09/20/90	1	0.0200	-2.0900
09/21/90	2	-0.1200	-1.0500
09/22/90	3	-0.3800	-2.0000
09/23/90	4	no final cal	no final cal
09/24/90	5	-0.0700	-1.9300
09/25/90	6	0.0900	0.5700
09/26/90	7	-0.2900	-0.8200
09/28/90	9	0.1000	0.0500
10/02/90	10	0.4500	1.3200

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TABLE 6-27. DAILY CALIBRATION DRIFTS; (continued)
CENTRAL CAROLINA HOSPITAL (1990)

PARAMETER: THC
ZERO CALIBRATION GAS: N2
FULL SCALE: 100

DATE	RUN	ZERO INSTRUMENT DRIFT (% of Span)	SPAN INSTRUMENT DRIFT (% of Span)
09/20/90	1	0.8900	-0.8800
09/21/90	2	3.9500	0.8700
09/22/90	3	-1.8700	0.9300
09/23/90	4	-1.7100	0.3700
09/24/90	5	-1.1600	-0.9700
09/25/90	6	-1.5100	-1.2500
09/26/90	7	-4.2700	-4.2400
09/28/90	9	-1.4200	-4.7800
10/02/90	10	-1.9600	-1.0600

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acceptable if the difference between the measured response and the certified concentration was within ±2 percent of full scale of the analyzer full range.

Table 6-28 presents the results of the daily QC gas challenges. Several QC gas responses exceeded the QC criterion. However, other QC challenges were made for these instruments with acceptable results.

6.5.4 Multipoint Linearity Check

During the test program, the multipoint linearity was determined for each CEM analyzer. This is important because flue gas concentrations are determined from a two point linear regression analysis (zero calibration and span calibration gas). Multipoint calibrations are performed with either three or four certified gases depending on the instrument: a zero gas, a low scale gas concentration, a mid-range concentration, and a high scale concentration (span gas). The QC criterion for acceptable linearity will be a correlation coefficient (r) of greater than or equal to .998, where the independent variable is the cylinder gas concentration and the dependent variable is the instrument response.

Table 6-29 presents the results of CEM linearity checks. All linearity checks met the acceptance criteria, except for one CO_2 and one SO_2 check. Other CO_2 and SO_2 linearity checks met the acceptance criteria.

6.5.4 Sample Bias

All calibrations and linearity checks were performed through the entire sampling system. Therefore, any system bias which may have existed was compensated for in the calibrations.

6.6 PSD QUALITY ASSURANCE

The most important QC procedure performed on a PSD test is inspecting the quality of particulate loadings on every impactor stage. Assesments can then be made on the validity of the test run. All PSD test runs were inspected during the Central Carolina Hospital MWI test program and observations were noted on the field data sheets (see Appendix A.6). Only those runs with discrete "particulate piles", showing no evidence of overloading, were accepted. The PSD Runs 1 and 2 were overloaded and underloaded, respectively, and were, therefore, not accepted as valid test runs. Runs 3

TABLE 6-28. QC GAS RESPONSES;
CENTRAL CAROLINA HOSPITAL (1990)

DATE	PARAMETER	TRUE CONCENTRATION	MEASURED CONCENTRATION	PERCENT DIFFERENCE a
09/20/90	O2 b	10.1	10.1	0.00%
		5.0	4.9	-0.40%
09/21/90		10.1	10.1	0.00%
09/22/90		10.1	10.1	0.00%
09/23/90		10.1	10.1	0.00%
09/24/90		10.1	12.3	8.80%
09/25/90		20.2	20.4	0.80%
		10.1	10.1	0.00%
		5.00	5.00	0.00%
09/26/90		10.1	10.1	0.00%
09/27/90		10.1	10.2	0.40%
09/28/90		10.1	11.0	3.60%
		5.0	5.0	0.00%
		20.0	20.0	0.00%
		20.2	20.2	0.00%
10/02/90		5.0	4.9	-0.40%
09/20/90	CO(dry) c	198.0	189.3	-0.17%
		50.0	41.8	-0.16%
09/21/90		198.0	186.7	-0.23%
09/22/90		198.0	182.5	-0.31%
09/23/90		198.0	188.9	-0.18%
09/24/90		198.0	188.4	-0.19%
09/25/90		198.0	188.4	-0.19%
		50.0	44.2	-0.12%
		198.0	192.3	-0.11%
09/27/90		198.0	187.0	-0.22%
09/28/90		198.0	221.0	0.46%
		50.0	48.8	-0.02%
		400.0	402.1	0.04%
10/02/90		50.0	48.6	-0.03%

NOTE:

a percent difference = 100 * (measured value - true value)/span

b in units of percent

c in units of ppm

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TABLE 6-28. QC GAS RESPONSES (continued);
CENTRAL CAROLINA HOSPITAL (1990)

DATE	PARAMETER	TRUE CONCENTRATION	MEASURED CONCENTRATION	PERCENT DIFFERENCE a
09/20/90	CO2 b	9.03	8.7	-1.65%
		5.03	4.9	-0.65%
09/21/90		9.03	9.0	-0.15%
09/22/90		9.03	9.0	-0.15%
09/23/90		9.03	9.0	-0.15%
09/24/90		9.03	7.9	-5.65%
09/25/90		17.97	18.0	0.15%
		9.03	9.2	0.85%
		5.03	5.1	0.35%
09/26/90		9.03	9.1	0.35%
09/27/90		9.03	9.0	-0.15%
09/28/90		9.03	7.7	-6.65%
		5.03	5.1	0.35%
		17.97	18.0	0.15%
		17.97	18.0	0.15%
10/02/90		5.03	5.1	0.35%
09/20/90	SO2 c	99.9	103.5	0.72%
		50.4	51.5	0.22%
09/21/90		99.9	99.1	-0.16%
09/22/90		99.9	100.1	0.04%
09/23/90		99.9	98.5	-0.28%
09/24/90		99.9	98.5	-0.28%
09/25/90		99.9	100.3	0.08%
		50.4	50.2	-0.04%
		25.2	26.3	0.22%
09/26/90		99.9	97.6	-0.46%
09/27/90		99.9	96.9	-0.60%
09/28/90		99.9	91.5	-1.68%
		50.4	52.8	0.48%
		25.2	25.7	0.10%
10/02/90		99.9	101.6	0.34%
		50.4	50.4	0.00%
		25.2	25.8	0.12%

NOTE:

a percent difference = 100 * (measured value - true value)/span

b in units of percent

c in units of ppm

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TABLE 6-28. QC GAS RESPONSES (continued);
CENTRAL CAROLINA HOSPITAL (1990)

DATE	PARAMETER	TRUE CONCENTRATION	MEASURED CONCENTRATION	PERCENT DIFFERENCE a
09/20/90	NOX c	102.0	101.7	-0.15%
		51.7	51.5	
09/21/90		51.7	51.5	-0.10%
09/22/90		102.0	102.4	0.20%
09/23/90		102.0	102.0	0.00%
09/24/90		102.0	103.7	0.85%
09/25/90		102.0	104.1	1.05%
		51.7	52.0	0.15%
		250.0	253.2	1.60%
09/26/90		102.0	103.5	0.75%
09/27/90		102.0	104.4	1.20%
09/28/90		102.0	102.8	0.40%
		51.7	52.3	0.30%
10/02/90		102.0	104.2	1.10%
		51.7	52.0	0.15%
09/20/90	THC (wet) c	91.6	91.0	-0.60%
		15.0	15.5	0.50%
09/22/90		91.6	83.7	-7.90%
09/23/90		91.6	88.2	-3.40%
09/24/90		91.6	91.9	0.30%
09/25/90		91.6	89.9	-1.70%
		15.0	14.5	-0.50%
09/26/90		91.6	89.5	-2.10%
09/27/90		91.6	95.2	3.60%
09/28/90		15.0	19.6	4.60%
		240.0	230.8	-9.20%
10/02/90		15.0	15.3	0.30%
09/20/90	HCL (wet) c	1826.8	1845.0	0.91%

NOTE:

a percent difference = 100 * (measured value - true value)/span

b in units of percent

c in units of ppm

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TABLE 6-29. LINEARITY RESULTS;
CENTRAL CAROLINA HOSPITAL (1990)

PARAMETER	DATE	TRUE CONCENTRATION	MEASURED CONCENTRATION	CORRELATION (R)
02 *	9/25/90	0.20	0.2	0.99980
		5.00	5.0	
		10.10	10.1	
		20.20	20.4	
02 *	9/28/90	0.20	0.2	0.99865
		5.00	5.0	
		10.10	11.0	
		20.20	20.2	
CO **	9/28/90	0.00	0.0	0.99815
		50.00	48.8	
		198.00	221.0	
		400.00	402.1	
CO2 *	9/25/90	0.00	0.0	0.99995
		5.03	5.1	
		9.03	9.2	
		17.97	18.0	
		450.00	475.8	
C02 *	9/28/90	0.00	0.0	0.99596
		5.03	5.1	
		9.03	7.7	
		17.97	18.0	
SO2 **	9/25/90	0.00	0.0	0.99991
		25.20	26.3	
		50.40	50.2	
		99.90	100.3	
SO2 **	9/28/90	0.00	0.00	0.99674
		25.20	25.70	
		50.40	52.80	
		99.90	91.50	
SO2 **	10/02/90	0.00	0.00	0.99994
		25.20	25.80	
		50.40	50.40	
		99.90	101.60	

* in units of percent
** in units of ppm
*** as methane in units of ppm

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TABLE 6-29. LINEARITY RESULTS; (continued)
CENTRAL CAROLINA HOSPITAL (1990)

PARAMETER	DATE	TRUE CONCENTRATION	MEASURED CONCENTRATION	CORRELATION (R)
NOx **	9/25/90	0.00	0.0	0.99999
		51.70	52.0	
		102.00	104.1	
		250.00	253.2	
HCl(wet) **	9/28/90	0.00	0.0	0.99982
		101.20	120.2	
		965.90	964.1	
THC ***	9/25/90	0.00	0.00	1.00000
		15.00	14.50	
THC ***	9/28/90	0	0	0.99978
		15	19.6	
		240	230.8	
		91.60	89.90	

* in units of percent
** in units of ppm
*** as methane in units of ppm

through 6 were validated by the recovery technician and the results are reported in Section 2.9.

All PSD sample trains were carefully configured and a pre-test leak check was completed on the system. In order to prevent sample particulate matter from being disturbed, post-test leak checks can not be completed on a PSD sample train. All pre-test PSD leak checks met the acceptable criterion of less than 0.02 cfm at 0 inches Hg vacuum.

6.7 DATA VARIABILITY

6.7.1 Overview

Coefficients of Variation (CV) were calculated for all the final stack gas pollutant concentrations. The CV or relative standard deviation (RSD) is calculated by dividing the standard deviation by the mean and expressed as a percentage. CVs from several distinct groups of data can be combined into a "Pooled CV". The pooled CV is calculated as follows:

$$CV = \frac{S}{M} \times 100$$

Where:

CV = Coefficient of variation

S = Standard deviation (calculated using LOTUS 123™ which uses n and not n-1 where n = number of data points.)

M = mean

$$CV_p = \sqrt{\frac{\Sigma (CV_i)^2 n_i}{\Sigma n_i}}$$

CV_p = pooled coefficient of Variation

CV_i = Coefficient of variation for a simple sample set i.

n_i = Number of data points in that sample set.

The CV values expressed in the following tables are not intended to represent sampling/analytical precision. They are more a reflection of the variability of the data as a whole, including process caused emission variability.

6.7.2 CDD/CDF Data Variation

Table 6-30 presents the CVs for the CDD/CDF flue gas concentrations. Values are listed for each congener for each triplicate run as well as a pooled CV for the entire nine runs. Pooled CVs are also compiled for all of the congeners and for the entire test program (overall). The overall pooled CV for the CDD/CDF flue gas concentrations was 64.4 percent.

Table 6-31 presents CVs for the metal flue gas concentrations. The overall pooled CV for the metals flue gas concentrations is 65.0 percent.

The Halogen gas test CVs are listed in Table 6-32. Values were calculated for each run as each run consisted of multiple "sub-runs" (1A, 1B, 1C, etc). The overall pooled CV for all three halogen flue gas concentrations is 29.8 percent.

Table 6-33 presents the CV values for the CEM 30 second averages. It should be noted in comparing these numbers to the manual test CVs, that the CEM data reflect real time, almost instantaneous changes in concentrations. The manual tests are all integrated tests which by sampling over an extended period of time, result in a "smoothed" average concentration for that time period. The overall pooled CV for the CEM data 159 percent. Results from the triplicate manual tests did not fluctuate nearly as much as the 30 second CEM readings, therefore had much lower CVs.

TABLE 6-30. COEFFICIENTS OF VARIATIONS FOR THE CDD/CDF FLUE GAS CONCENTRATIONS; CENTRAL CAROLINA HOSPITAL (1990)

CONGENER	CV:1,3,10 (%)	CV:2,4,8 (%)	CV:5,6,9 (%)	POOLED CV (%)
DIOXINS				
2378 TCDD	47.4	45.8	83.8	61.5
Other TCDD	100.7	29.7	76.8	75.1
12378 PCDD	63.3	46.0	76.3	63.1
Other PCDD	95.8	46.9	80.6	77.2
123478 HxCDD	68.5	39.5	68.7	60.5
123678 HxCDD	64.3	43.6	67.4	59.4
123789 HxCDD	68.4	46.2	59.3	58.7
Other HxCDD	80.2	40.4	64.0	63.7
1234678-HpCDD	58.1	37.2	49.3	48.9
Other HpCDD	60.7	38.3	52.2	51.2
Octa-CDD	60.3	33.1	49.6	48.9
FURANS				
2378 TCDF	64.0	87.6	84.5	79.4
Other TCDF	88.1	83.1	86.7	86.0
12378 PCDF	59.8	66.3	75.2	67.4
23478 PCDF	69.3	60.7	71.0	67.1
Other PCDF	80.1	67.1	86.3	78.2
123478 HxCDF	82.1	56.2	63.8	68.3
123678 HxCDF	72.8	58.2	65.2	65.7
234678 HxCDF	82.0	46.1	60.3	64.5
123789 HxCDF	68.4	56.4	60.0	61.8
Other HxCDF	76.1	55.6	70.1	67.8
1234678-HpCDF	80.7	45.4	50.3	60.8
1234789-HpCDF	74.0	38.7	39.7	53.4
Other HpCDF	78.6	40.9	49.5	58.6
Octa-CDF	75.9	18.7	35.9	49.6
Pooled CV	73.8	51.4	66.6	
Overall Pooled CV	64.4			

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TABLE 6-31. COEFFICIENTS OF VARIATION OF THE FLUE GAS METALS CONCENTRATIONS; CENTRAL CAROLINA HOSPITAL (1990)

FLOW RATE (dscmm)	CONDITION 1 CV (%)	CONDITION 2 CV (%)	CONDITION 3 CV (%)	POOLED CV
Antimony	69.7	21.9	8.62	42.4
Arsenic	121	36.6	123	102
Barium	77.1	14.6	16.1	46.3
Beryllium	ND	1.1	ND	1.1
Cadmium	93.4	16.0	25.4	50.2
Chromium	93.2	11.2	116	86.2
Lead	19.2	22.8	28.2	24.2
Mercury	92.9	30.5	ND	69.1
Nickel	ND	66.4	113.1	92.7
Silver	ND	28.8	ND	28.8
Thallium	ND	ND	ND	ND
Pooled CV	87.6	30.8	78.6	
Overall Pooled CV	65.0			

ND = Not Detected

TABLE 6-32. COEFFICIENTS OF VARIATION FOR HALOGEN FLUE GAS CONCENTRATIONS; CENTRAL CAROLINA HOSPITAL (1990)

TEST RUN NUMBER	HCl (%)	HF (%)	HBr (%)
CV-1	28.8	25.8	4.40
CV-3	2.33	29.5	5.89
CV-10	48.2	60.0	12.6
Pooled Condition 1	34.4	42.6	8.67
CV-2	8.71	46.3	46.6
CV-4	47.2	36.7	31.3
CV-8	34.3	30.5	8.61
Pooled Condition 2	36.0	37.3	30.6
CV-5	20.1	21.7	ND
CV-6	6.28	15.2	ND
CV-9	26.8	16.5	9.36
Pooled Condition 3	19.7	18.0	9.36
Pooled Analyte	30.6	33.8	21.4
Total Pooled Halogen		29.8	

TABLE 6-33. COEFFICIENTS OF VARIATION OF CEM GAS CONCENTRATIONS; CENTRAL CAROLINA HOSPITAL (1990)

RUN NUMBER	DATE	COEFFICIENTS OF VARIATION (percent)							POOLED CV BY DAY
		O2	CO2	CO	NOx	SO2	HCl	THC	
1	9/20/90	6.09	23.6	325	51.3	58.8	172	174	157
2	9/21/90	10.7	33.5	248	49.7	122	44.8	259	146
3	9/22/90	7.67	28.7	235	71.2	55.8	91.5	177	122
4	9/23/90	9.76	31.1	201	68.7	88.7	62.5	398	176
5	9/24/90	6.15	27.8	252	46.9	43.3	32.9	447	196
6	9/25/90	5.76	24.0	254	49.0	41.0	36.7	323	158
8	9/27/90	10.0	32.6	283	46.6	133	56.2	130	131
9	9/28/90	7.73	28.5	296	44.8	42.6	43.8	411	194
10	10/02/90	8.78	32.2	228	61.3	57.4	39.5	251	133
Pooled Compound		8.26	29.3	260	55.2	78.6	76.6	306	
Overall Pooled		159							

7.0 REFERENCES

1. North Atlantic Treaty Organization, Committee on the Challenges of Modern Society. Pilot Study on International Information Exchange on Dioxins and Related Compounds: International Toxicity Equivalency Factor (I-TEF) Methods of Risk Assessment for Complex Mixtures of Dioxins and Related Compounds. Report No. 176, August 1988.

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United States
Environmental Protection
Agency

Research Triangle Park, North Carolina 27711

Air

Medical Waste Incinerators
Emission Test Report

Bernard [illegible]
[illegible]

EPA

MEDICAL WASTE INCINERATION

EMISSION TEST REPORT

Borgess Medical Center
Kalamazoo, Michigan

Prepared for:

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1. INTRODUCTION

The United States Environmental Protection Agency (EPA) has determined that medical waste incinerator (MWI) emissions may reasonably be anticipated to contribute to the endangerment of public health and welfare. As a consequence, new source performance standards (NSPS) for new MWIs are being developed under Sections 111(b), 111(d), and 129 of the Clean Air Act, as amended November 1990.

The Office of Air Quality Planning and Standards (OAQPS), through its Industrial Studies Branch (ISB) and Emissions Measurement Branch (EMB), is responsible for reviewing the existing air emissions data base and gathering additional data where necessary. A series of MWI emission tests were conducted to support the regulatory development program. One testing program was conducted at the MWI facility at Borgess Medical Center in Kalamazoo, Michigan.

The pollutants being studied for standards development are the criteria pollutants: particulate matter (PM), sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), and total hydrocarbons (THC); as well as acid gases, such as hydrogen chloride (HCl); chlorinated organics, including dioxins and furans; and trace metals.

1.1 TEST OBJECTIVES

The purpose of the testing program at the Borgess Medical Center was to obtain uncontrolled and controlled emission data from a well designed controlled-air, continuous ram-fed MWI. These data will be used in the regulatory development program for MWIs.

The MWI located at Borgess Medical Center was selected for emissions testing for the following reasons:

- The MWI system is representative of well-designed, controlled-air MWIs currently in use;
- Of known MWI systems, this MWI possesses the proper combination of hardware and operations to facilitate testing of dry carbon injection directly into the flue gas duct as a means of mercury (Hg) and dioxin control. The MWI system employs a waste heat recovery boiler to cool flue gas upstream of the dry lime injection/fabric filter (DI/FF) air pollution control system (APCS); and

- This MWI system was tested last year in a joint test program between EPA and the State of Michigan. EPA and Midwest Research Institute (MRI) personnel are familiar with the facility. Test ports were already in place and a large body of test data (23 runs) is available with which to compare the test data from this test.

Another consideration in performing emissions testing at this facility was the cooperative attitude of the hospital personnel. All parties involved expressed an interest in and a willingness to cooperate in the source test program.

Eight tests were conducted; three without carbon injection, two with carbon injection at 1 lb/hr, and three with carbon injection at 2.5 lb/hr. Only two tests were conducted at 1 lb/hr of carbon injection due to time and budgetary restraints.

The specific objectives of the test program are to:

- Determine the levels of uncontrolled CO, PM, SO_2, NO_x, HCl (acid gases), metals, THC and polychlorinated dibenzo-p-dioxins (CDD) and polychlorinated dibenzofurans (CDF) emitted from the combustor when burning medical wastes (measured at the APCS inlet);

- Determine the levels of controlled PM, acid gases, metals including Hg, and CDD/CDF emissions associated with a dry lime injection fabric filter (DI/FF) control technology (measured at the APCS outlet);

- Determine the levels of PM and CDD/CDF at the waste heat boiler inlet upstream of the APCS inlet location;

- Calculate the control efficiencies for PM, acid gases, metals, and CDD/CDF and investigate Hg and CDD/CDF removal efficiency of in-duct carbon injection at two injection rates; and

- Determine the degree of combustion of the feed wastes based on percent carbon and loss on ignition (LOI) of the bottom ash and fly ash collected in the fabric filter.

Key process operating variables, including flue gas oxygen (O_2), carbon dioxide (CO_2), primary and secondary chamber temperatures, air flows, and the total amount of waste charged, were monitored and recorded to document the operating conditions during each test.

The test program included an internal quality control program. The goal of the quality assurance/quality control (QA/QC) activities was to ensure that the results are of known precision and accuracy, and that they are complete, representative and comparable.

1.2 SITE DESCRIPTION

Borgess Medical Center is located in Kalamazoo, Michigan. The MWI at this facility is a Cleaver Brooks Model 780-A/31 controlled (starved)-air incinerator that consists of a primary chamber, a thermal reactor (secondary chamber), and a retention chamber (tertiary chamber). The MWI is designed for intermittent duty, and the unit must be shut down and the primary chamber opened to remove the bottom ash from the chamber. The incinerator is rated at a heat input rate of 5.8×10^6 kJ/hr (5.5×10^6 Btu/hr).

A mechanical hopper/ram charging system feeds waste into the primary chamber of the incinerator. Ash is manually removed from the primary chamber of the incinerator on the morning after each burning day.

The waste heat boiler is a 200 horsepower (1960 kilowatt) Cleaver-Brooks unit with a maximum steam production rating of 6800 lb/hr (3090 kg/hr).

The air pollution control system (APCS) consists of dry lime injection for HCl gas control and a fabric filter baghouse for PM control. Hydrated lime is injected into the duct between the waste heat boiler and the fabric filter baghouse. The fabric filter baghouse is a MicroPul pulse-jet baghouse with continuous cleaning.

Both the incinerator/boiler system and the APCS are described in greater detail in Section 3 of this report.

1.3 PROCESS DATA ACQUISITION

During the emissions tests performed at the Borgess Medical Center MWI facility, process data were collected to document the operating conditions. Process data acquisition was the primary responsibility of the MRI Process Monitor.

Waste charges were weighed on a scale and recorded manually on log sheets by the MRI representative. Natural gas flow rates were read from the utility gas meter and recorded on log sheets. Primary and secondary temperatures, as indicated by the temperature controllers, were recorded manually by MRI. Other pertinent conditions

and equipment positions were observed at the control panel and manually recorded by the MRI process monitor.

Primary and secondary chamber temperature signals from the unit's process controller were wired to a data acquisition system. The data logger provided a hard copy record of the temperatures measured. A portable PC computer was connected to the data logger via a parallel port connection. Commercial software was used to collect the output from the data logger and record it on the PC's hard drive.

1.4 EMISSIONS MEASUREMENT PROGRAM

This section provides an overview of the emissions measurement program conducted at Borgess Medical Center. Included in this section are summaries of the test matrix, sampling locations, sampling methods, and laboratory analysis.

1.4.1 Test Matrix

The sampling and analytical matrix performed at the Borgess Medical Center is presented in Table 1-1. Both manual emissions tests and continuous emission monitors (CEMs) were employed for the MWI test program. In addition to flue gas sampling, incinerator bottom ash and fabric filter fly ash samples were taken.

1.4.2 Sampling Methods

Total PM emissions and emissions of 13 toxic metals [aluminum (Al), lead (Pb), chromium (Cr), cadmium (Cd), copper (Cu), mercury (Hg), nickel (Ni), arsenic (As), beryllium (Be), antimony (Sb), barium (Ba), silver (Ag), and thallium (Tl)] were determined using a single sample train. Particulate loading on the filter and front half (nozzle/probe, filter holder) rinses was determined gravimetrically. Metals analyses were then completed on the filter front half rinses and back half impinger catches using atomic absorption (AA) and inductively coupled argon plasma (ICAP) techniques. Flue gas samples for CDD/CDF were collected using EPA Method 23. Flue gas was extracted isokinetically, and CDD/CDF were collected on the filter, on a chilled adsorbent trap, and in the impingers. The analysis was completed using high resolution gas chromatography (HRCG) coupled with high resolution mass spectrometry (HRMS) detection.

TABLE 1-1. BORGESS MEDICAL CENTER MWI TEST MATRIX

Sample Location	Number of Runs	Sample Type	Sample Method	Sample Duration	Analysis Method	Laboratory
Boiler Inlet	8	CDD/CDF	EPA Method 23 with	4 hours	GCMS 8290 Mass Spectrometry and High Resolution MS for CDD/CDF	Triangle Labs, Inc.
Boiler Inlet	8	PM	EPA Method 5	4 hours	Gravimetric	Radian
Baghouse Inlet	8	Particulates/Metals (Pb, Cr, Cd, Be, Hg, Ni, As, Sb, Ag, Ba, Tl)	EPA Method 5/Combined Metals Train	4 hours	Gravimetric; Atomic Adsorption/ICAP, respectively	Radian
Baghouse Inlet	8	CDD/CDF	EPA Method 23	4 hours	GCMS 8290 Mass Spectrometry and High Resolution MS for CDD/CDF	Triangle Labs, Inc.
Baghouse Inlet	24	HCl/HBr/HF	EPA Method 26	1 hour	Ion Chromatography	Radian
Baghouse Inlet	8	SO_2 O_2/CO_2 NO_x CO THC HCl	EPA Method 6C EPA Method 3A EPA Method 7E EPA Method 10 EPA Method 25A HCl CEM using dilution probe	Continuous	UV Analyzer CEM Zirconium Oxide Cell/NDIR CEM Chemiluminescence CEM NDIR CEM FID CEM NDIR CEM	Radian

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TABLE 1-1. CONTINUED

Sample Location	Number of Runs	Sample Type	Sample Method	Sample Duration	Analysis Method	Laboratory
Stack	8	Particulates/Metals (Pb, Cr, Cd, Be, Hg, Ni, As, Sb, Ag, Ba, Tl)	EPA Method 5/Combined Metals Train	4 hours	Gravimetric; Atomic Adsorption/ICAP, respectively	Radian
Stack	8	CDD/CDF	EPA Method 23 and GC/MS Method 8290	4 hours	Mass Spectrometry and High Resolution MS for CDD/CDF	Triangle Labs, Inc.
Stack	8	HCl/HBr/HF	EPA Method 26	1 hour	Ion Chromatography	Radian
Stack	8	SO_2 O_2/CO_2 THC HCl	EPA Method 6C EPA Method 3A EPA Method 25A HCl CEM using dilution probe	Continuous	UV Analyzer CEM Zirconium Oxide Cell/NDIR CEM FID CEM NDIR CEM	Radian
Incinerator	8	Incinerator Bottom Ash	Representative Composite Sample	1/day	LOI, Carbon, Metals	Radian, McCoy Labs
Incinerator	8	Incinerator Bottom Ash	Representative Composite Sample	1/day	Dioxins/Furans	Triangle Labs, Inc.
Incinerator	8	Baghouse Flyash	Representative Composite Sample	1/day	LOI, Carbon, Metals	Radian, McCoy Labs
Incinerator	8	Baghouse Flyash	Representative Composite Sample	1/day	Dioxins/Furans	Triangle Labs, Inc.

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TABLE 1-1. CONTINUED

Sample Location	Number of Runs	Sample Type	Sample Method	Sample Duration	Analysis Method	Laboratory
Lime	8	Lime	Representative Composite Sample	1/day	Metals	Radian
Lime	8	Lime	Representative Composite Sample	1/day	Dioxins/Furans	Triangle Labs, Inc.

Hydrogen chloride, hydrogen bromide (HBr), and hydrogen fluoride (HF) concentrations in the stack gas were determined using EPA Method 26. Gas was extracted from the stack and passed through an acidified collection solution which stabilized the respective halogen ions (Cl^-, Br^-, F^-). The quantity of ions collected was then determined using ion chromatography (IC) analyses.

Gaseous emissions (NO_x, CO, SO_2, THC, and HCl) were measured using CEMs continuously during the day. Hydrogen chloride emissions were measured both manually and with CEMs. The concentration of diluent gases (O_2, CO_2) were measured using CEMs while all tests were being performed so that the emission results could be normalized to a reference O_2 or CO_2 basis. The O_2 and CO_2 results were also used in the calculation of flue gas molecular weight for stack gas flow rate calculations.

In addition to the flue gas samples, incinerator bottom ash and baghouse flyash were also sampled during the test program. Daily composites were directed to one laboratory for LOI/carbon content analyses and to another laboratory for metals and CDD/CDF analyses. Lime was also collected and analyzed for metals and CDD/CDF.

Additional descriptions of the sampling and analytical procedures are provided in Section 5.

1.4.3 Laboratory Analyses

All manual flue gas test samples were submitted for extensive laboratory analyses. Samples from CDD/CDF emission tests were analyzed for tetra-octa CDD/CDF isomers by Triangle Laboratories, Inc (Triangle). Ash samples were also analyzed by Triangle for these compounds. Analytical procedures followed EPA Method 23 protocols (Analytical Method 8290X). This technique incorporates HRGC/HRMS analytical procedures.

Samples from particulate matter/metals emission tests were analyzed by Radian's Perimeter Park (PPK) laboratory. Analytical procedures included inductively coupled argon plasma spectroscopy (ICAPS), graphite furnace atomic absorption spectroscopy (GFAAS), and cold vapor atomic absorption spectroscopy (CVAAS). Incinerator ash was also analyzed for metals content using these techniques. Particulate matter was analyzed using gravimetric techniques following EPA Method 5 guidelines. Samples from halogen emission tests were also analyzed at Radian's PPK laboratory. Quantities

of chloride, bromide, and fluoride ions in the impinger solutions were determined using IC techniques.

The incinerator ash was analyzed by McCoy Labs for volatile matter (LOI) by ASTM D3174 and for carbon content by ASTM Method D 3178.

1.5 QUALITY ASSURANCE/QUALITY CONTROL (QA/QC)

All flue gas testing procedures followed comprehensive QA/QC procedures as outlined in the Borgess Medical Center Test Plan and the EPA reference methods. A full description of the resulting QA parameters is given in Section 6 of this report. All post-test leak check criterion were met for all 10 trains. The allowable isokinetic QC range of ±10 percent was met in all test runs except for two runs with the PM/MM5 train at the boiler inlet. Since the deviation was minor, the runs were accepted. All post-test dry gas meter calibration checks were within 5 percent of the full calibration factor.

Field blank results showed CDD/CDF levels similar to the levels in the samples taken from the baghouse outlet during Conditions 2 and 3. This indicates that CDD/CDF emissions at the baghouse outlet during these conditions were near to or below the levels measurable by the testing procedures. The halogen field blank showed no contamination. No contamination was found in the mercury 101A field blank. The front halves of the metals field blanks contained high levels of Al, Cr, and Ni relative to the inlet samples, and high levels of all metals relative to the outlet samples. The back halves of the metals field blanks also showed similar contamination levels relative to the samples especially for Cu and As at the inlet, and for all metals at the outlet. This means that the reported emissions for these metals at the inlet and outlet are probably biased high. Furthermore, where measured levels of metals at only the outlet location were similar to the levels in the field blanks, reported removal efficiencies are lower than the actual removal efficiencies of the metals. This can explain the high degree of dissimilarity between the removal efficiencies of different metals in some runs.

1.6 DESCRIPTION OF REPORT CONTENTS

Section 2 gives a summary of the test results. Included in the contents of this section are the emissions test log, CDD/CDF results, toxic metals results, PM emissions results, halogen results, CEM results, and ash LOI and carbon results.

Section 3 details the process and operation of the Borgess incinerator and gives process results. Included in the process results are the waste feed amounts and incineration chamber temperatures.

Section 4 provides a detailed description and drawings of the sample locations.

Section 5 presents detailed descriptions of sampling and analytical procedures. The descriptions that are covered in this section are the CDD/CDF testing method, the PM and toxic metals testing method, the manual halogen emissions testing method, EPA Methods 1 through 4, CEM methods, and process sampling procedures.

Section 6 provides details of the QA/QC procedures used on this program and the QC results. Included in this section is a summary of QA/QC objectives, QC procedures for the manual flue gas sampling methods, QC procedures for the ash sampling, analytical QC procedures and QA parameters, and CEM QC procedure and QA parameters.

Appendices containing the actual field data sheets and computer data listings are contained in a separate volume.

2.0 DISCUSSION OF RESULTS

This section presents results of the test program conducted at the Borgess Medical Center from September 7 through 16, 1991. Included in this section are results of manual flue gas tests conducted for CDD/CDF, toxic metals, mercury, PM, and halogens. This section also contains the results of continuous emissions monitoring for O_2, CO_2, CO, NO_x, SO_2, THC, and HCl gases. Results from analyses of incinerator bottom ash and baghouse ash are also included.

Test conditions are defined by the rate of carbon injection into the duct at the baghouse inlet. The carbon injection point was just upstream of a venturi where lime was also injected. Carbon injection rates were 0 lb/hr for 3 tests, 1 lb/hr for the next 2 tests, and 2.5 lb/hr for the last 3 tests. A dry solids screw feeder was used to feed carbon into a funnel and pipe connected to the duct. The carbon was drawn into the duct by negative pressure and mixed with the flue gas in the venturi. The venturi was about 50 feet upstream of the baghouse, which allowed a residence time of approximately 1.4 seconds in the duct before entering the baghouse. Test conditions were as follows:

Condition	Carbon Injection Rate (lb/hr)	Runs
1	0	2 through 4
2	1	5 through 6
3	2.5	7 through 9

The ID fan was adjusted during Run 1 so that the volumetric flow rate of gas through the system was above the target range for the test. Results from Run 1 were, therefore, archived and are not included in this report.

2.1 EMISSIONS TEST LOG

Eight test runs were conducted over eight test days. Flue gas sample locations were at the waste heat boiler inlet, baghouse inlet, and baghouse outlet. One test run was conducted on each day with all sampling trains except the HCl train running simultaneously. Gas concentrations were monitored with the CEMS during the testing period. Table 2-1 presents the emissions test log. This table shows the test date, run number and condition, test type, run times, and port change times for all the flue gas testing conducted during this program.

2.2 CDD/CDF EMISSIONS

2.2.1 Overview

Simultaneous CDD/CDF test runs were conducted at the boiler inlet, baghouse inlet, and baghouse outlet of the Borgess MWI. One 4-hour run was conducted each day, with all trains sampling at the same time.

Daily ash samples from the incinerator and baghouse were also collected. Each ash sample was analyzed for tetra through octa CDD/CDF isomers.

Table 2-2 presents a summary of the CDD/CDF flue gas emissions and ash discharge rates. Flue gas emission rates were found to be higher at the baghouse inlet than at the boiler inlet, indicating that CDD/CDF were formed in the boiler. Baghouse outlet values were lower than baghouse inlet values, indicating a removal of CDD/CDF in the baghouse. Boiler inlet CDD/CDF averages ranged from 101.6 μg/hr to 231.6 μg/hr. Baghouse inlet values ranged from 325.0 μg/hr to 590.7 μg/hr. Baghouse outlet values ranged from 10.24 μg/hr to 201.4 μg/hr.

All CDD/CDF congeners were detected in both the baghouse and bottom ash samples. CDD/CDF baghouse ash discharge rates were higher for Conditions 2 and 3 than Condition 1 indicating that the carbon injection removed CDD/CDF from the flue gas.

Dioxins/furans average emission test results are reported in Section 2.2.2, results from each run in Section 2.2.3, sample parameters are shown in Section 2.2.4, and incinerator ash and baghouse ash CDD/CDF concentrations in Section 2.2.5. All field data and analytical data are shown in Appendices A and E, respectively.

TABLE 2-1. BORGESS MWI SAMPLING TEST LOG

SAMPLE LOCATION	SAMPLE TRAIN	RUN #	DATE	START	STOP	RESTART	END
Boiler Inlet	PM	2	09/07/91	1215	1415	1528	1728
	CDD/CDF	2	09/07/91	1215	1415	1528	1728
Baghouse Inlet	Mercury	2	09/07/91	1215	1415	1525	1725
	PM/Metals	2	09/07/91	1215	1415	1525	1725
	CDD/CDF	2	09/07/91	1215	1415	1525	1725
Baghouse Outlet	Mercury	2	09/07/91	1215	1415	1525	1725
	PM/Metals	2	09/07/91	1215	1415	1525	1725
	CDD/CDF	2	09/07/91	1215	1415	1525	1725
Boiler Inlet	PM	3	09/09/91	1130	1425	1540	1745
	CDD/CDF	3	09/09/91	1130	1425	1540	1745
Baghouse Inlet	Mercury	3	09/09/91	1132	1425	1542	1748
	PM/Metals	3	09/09/91	1132	1425	1542	1748
	CDD/CDF	3	09/09/91	1130	1423	1540	1747
Baghouse Outlet	Mercury	3	09/09/91	1130	1424	1540	1746
	PM/Metals	3	09/09/91	1130	1424	1540	1746
	CDD/CDF	3	09/09/91	1130	1424	1540	1746
Boiler Inlet	PM	4	09/10/91	1205	1405	1515	1715
	CDD/CDF	4	09/10/91	1205	1405	1515	1715
Baghouse Inlet	Mercury	4	09/10/91	1207	1407	1518	1718
	PM/Metals	4	09/10/91	1207	1407	1518	1718
	CDD/CDF	4	09/10/91	1205	1405	1516	1716
Baghouse Outlet	Mercury	4	09/10/91	1207	1407	1516	1716
	PM/Metals	4	09/10/91	1207	1407	1516	1716
	BHO-D4	4	09/10/91	1206	1406	1516	1716
Boiler Inlet	PM	5	09/11/91	1115	1315	1415	1615
	CDD/CDF	5	09/11/91	1115	1315	1415	1615
Baghouse Inlet	Mercury	5	09/11/91	1117	1317	1417	1617
	PM/Metals	5	09/11/91	1117	1317	1417	1617
	CDD/CDF	5	09/11/91	1115	1315	1415	1615
Baghouse Outlet	Mercury	5	09/11/91	1115	1315	1415	1615
	PM/Metals	5	09/11/91	1115	1315	1415	1615
	CDD/CDF	5	09/11/91	1115	1315	1415	1615
Boiler Inlet	PM	6	09/12/91	1230	1510	1620	1820
	CDD/CDF	6	09/12/91	1230	1510	1620	1820
Baghouse Inlet	Mercury	6	09/12/91	1230	1512	1512	1622
	PM/Metals	6	09/12/91	1230	1512	1512	1622
	CDD/CDF	6	09/12/91	1230	1510	1510	1620
Baghouse Outlet	Mercury	6	09/12/91	1230	1512	1620	1820
	PM/Metals	6	09/12/91	1230	1512	1620	1820
	CDD/CDF	6	09/12/91	1230	1512	1620	1820

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TABLE 2-1 (CONT'D). BORGESS MWI SAMPLING TEST LOG

SAMPLE LOCATION	SAMPLE TRAIN	RUN #	DATE	START	STOP	RESTART	END
Boiler Inlet	PM	7	09/13/91	948	1148	1245	1445
	CDD/CDF	7	09/13/91	945	1145	1246	1446
Baghouse Inlet	Mercury	7	09/13/91	947	1147	1245	1445
	PM/Metals	7	09/13/91	947	1147	1245	1445
	CDD/CDF	7	09/13/91	945	1145	1245	1445
Baghouse Outlet	Mercury	7	09/13/91	945	1145	1245	1445
	PM/Metals	7	09/13/91	945	1145	1245	1445
	CDD/CDF	7	09/13/91	945	1145	1245	1445
Boiler Inlet	PM	8	09/14/91	1015	1215	1425	1625
	CDD/CDF	8	09/14/91	1015	1215	1425	1625
Baghouse Inlet	Mercury	8	09/14/91	1015	1215	1425	1625
	PM/Metals	8	09/14/91	1015	1215	1425	1625
	CDD/CDF	8	09/14/91	1015	1215	1425	1625
Baghouse Outlet	Mercury	8	09/14/91	1015	1215	1425	1625
	PM/Metals	8	09/14/91	1015	1215	1425	1625
	BHO-D4	8	09/14/91	1015	1215	1425	1625
Boiler Inlet	PM	9	09/16/91	1030	1305	1415	1615
	CDD/CDF	9	09/16/91	1030	1305	1415	1615
Baghouse Inlet	Mercury	9	09/16/91	1030	1305	1416	1616
	PM/Metals	9	09/16/91	1030	1305	1416	1616
	CDD/CDF	9	09/16/91	1030	1305	1416	1616
Baghouse Outlet	Mercury	9	09/16/91	1030	1305	1416	1616
	PM/Metals	9	09/16/91	1030	1305	1416	1616
	BHO-D4	9	09/16/91	1030	1305	1416	1616

TABLE 2-2. SUMMARY OF CDD/CDF TESTS
(FLUE GAS)
BORGESS MEDICAL CENTER (1991)

AVERAGE DAILY EMISSION RATES

	Condition 1			Condition 2			Condition 3		
CONGENER	Boiler Inlet (ug/hr)	Baghouse Inlet (ug/hr)	Baghouse Outlet (ug/hr)	Boiler Inlet (ug/hr)	Baghouse Inlet (ug/hr)	Baghouse Outlet (ug/hr)	Boiler Inlet (ug/hr)	Baghouse Inlet (ug/hr)	Baghouse Outlet (ug/hr)
DIOXINS									
2378 TCDD	0.07	0.15	0.06	0.07	0.41	[0.04][a]	0.05	0.38	[0.04]
Other TCDD	0.66	1.18	0.67	4.66	3.58	0.05	1.57	2.97	[0.05]
12378 PCDD	0.23	0.45	0.26	0.27	0.99	[0.13]	0.30	0.90	[0.09]
Other PCDD	0.89	2.05	1.47	1.72	4.96	0.16	2.35	4.97	[0.10]
123478 HxCDD	0.16	0.52	0.47	0.19	1.32	[0.15]	0.35	1.21	[0.10]
123678 HxCDD	0.20	0.77	0.54	0.23	1.39	(0.21)	0.52	1.42	[0.06]
123789 HxCDD	0.35	1.45	0.91	0.44	2.45	0.36	1.07	2.73	[0.08]
Other HxCDD	1.17	4.36	3.68	1.73	8.17	0.83	3.53	9.02	0.20
1234678-HpCDD	1.92	11.63	7.09	2.51	19.98	1.60	6.60	20.24	0.62
Other Hepta-CDD	1.68	9.09	6.93	2.36	18.46	1.71	6.20	19.66	0.47
Octa-CDD	6.41	39.82	15.60	10.46	66.93	4.02	20.60	66.66	2.33
Total CDD	13.73	71.47	37.69	24.63	128.66	8.66	43.13	130.15	3.69
FURANS									
2378 TCDF	6.94	2.49	0.56	4.74	2.64	0.11	2.00	3.63	0.06
Other TCDF	12.65	17.49	15.17	17.24	40.69	1.41	20.48	31.63	0.74
12378 PCDF	1.41	1.90	1.23	1.44	3.84	(0.18)	1.62	3.45	0.09
23478 PCDF	1.58	3.08	2.48	1.86	6.81	0.25	2.59	6.08	0.11
Other PCDF	12.46	25.12	18.68	15.00	58.13	1.33	20.10	54.52	0.17
123478 HxCDF	4.38	16.72	10.11	5.02	26.50	1.06	10.13	25.53	0.34
123678 HxCDF	1.72	5.10	3.30	2.07	9.51	0.36	3.73	9.12	0.12
234678 HxCDF	3.11	17.43	11.79	4.44	27.29	1.18	9.39	25.28	0.41
123789 HxCDF	0.21	0.99	0.35	0.24	0.97	0.00	0.54	1.04	[0.08]
Other HxCDF	7.81	28.23	13.33	9.31	50.00	[0.12]	16.43	42.33	0.10
1234678-HpCDF	8.32	35.49	21.93	10.79	49.44	2.59	24.14	59.02	1.06
1234789-HpCDF	2.01	11.17	5.11	2.27	12.11	0.41	5.78	12.40	0.25
Other Hepta-CDF	8.85	42.13	24.03	10.73	51.75	2.30	22.86	53.26	0.75
Octa-CDF	16.46	46.22	35.70	20.81	122.41	2.94	48.68	118.46	2.40
Total CDF	87.91	253.56	163.75	105.98	462.08	15.15	188.47	445.76	6.55
Total CDF + CDF	101.6	325.03	201.44	130.60	590.74	23.80	231.60	575.92	10.24

[a] [] = Detection limit; () = Estimated maximum possible concentration

TABLE 2-2 (CONT'D). SUMMARY OF CDD/CDF TESTS
(INCINERATOR BOTTOM ASH AND BAGHOUSE ASH)
BORGESS MEDICAL CENTER (1991)

AVERAGE DAILY DISCHARGE RATES (ug/day)[a]

	Condition 1		Condition 2		Condition 3	
CONGENER	Incinerator Bottom Ash	Baghouse Ash	Incinerator Bottom Ash	Baghouse Ash	Incinerator Bottom Ash	Baghouse Ash
DIOXINS						
2378 TCDD	4.38	0.51	1.08	2.81	4.01	4.41
Other TCDD	249.36	6.08	54.17	47.89	260.45	104.92
12378 PCDD	27.03	3.39	6.82	18.25	25.43	22.43
Other PCDD	388.29	23.03	76.89	97.16	391.40	233.01
123478 HxCDD	44.42	6.91	6.87	21.15	32.92	53.05
123678 HxCDD	52.77	9.07	11.36	23.16	42.55	57.75
123789 HxCDD	111.86	17.32	16.43	47.25	82.71	114.99
Other HxCDD	588.79	69.41	84.89	222.94	497.80	690.82
1234678-HpCDD	435.17	168.24	95.74	329.90	348.94	957.49
Other Hepta-CDD	425.32	162.59	88.94	334.39	364.90	877.91
Octa-CDD	822.53	667.35	192.13	928.21	556.41	1,979.81
Total CDD	3,149.9	1,133.89	635.3	2,073.11	2,607.5	5,096.59
FURANS						
2378 TCDF	55.28	4.48	13.35	23.16	57.25	44.83
Other TCDF	1,974.16	126.17	458.13	699.28	1,933.02	1,662.17
12378 PCDF	76.41	12.36	16.66	55.31	67.30	108.52
23478 PCDF	186.56	29.68	38.56	98.54	144.64	232.94
Other PCDF	1,861.19	256.48	451.21	1,165.05	1,519.66	2,181.66
123478 HxCDF	690.34	96.80	109.46	326.92	335.35	892.13
123678 HxCDF	178.30	54.99	38.16	160.46	136.00	306.62
234678 HxCDF	380.86	108.22	90.57	267.00	231.62	658.52
123789 HxCDF	8.18	4.88	52.31	8.96	4.78	24.12
Other HxCDF	892.31	214.00	93.73	715.94	397.88	1,846.06
1234678-HpCDF	930.28	446.63	189.79	972.06	544.73	1,879.45
1234789-HpCDF	79.79	98.07	18.26	164.20	29.76	434.69
Other Hepta-CDF	478.26	450.72	100.27	910.14	288.63	1,932.58
Octa-CDF	500.79	1,132.11	125.62	1,898.27	287.90	3,021.15
Total CDF	8,292.7	3,035.6	1,796.1	7,465.3	6,125.6	15,225.5
Total CDF + CDF	11,442.6	4,169.5	2,431.4	9,538.4	8,733.1	20,322.0

[a] Baghouse ash discharge rate assumes 12 hr/day operation of the baghouse.

2.2.2 CDD/CDF Average Emission Results

Tables 2-3 through 2-6 present the average CDD/CDF emissions for the test program. Emission tests analyses were targeted for the tetra through octa 2378 substituted CDD/CDF isomers. Results are presented for each isomer as well as for each tetra through octa homologue total (total CDD, total CDF).

Average CDD/CDF gas concentrations measured at the boiler inlet and the baghouse outlet for the three test conditions are presented in Table 2-3. Stack gas concentrations of all target CDD/CDF congeners were detected during each test condition throughout the program at both the boiler inlet and baghouse inlet. Higher concentrations for the majority of congeners were observed at the baghouse inlet than at the boiler inlet, which indicates that CDD/CDF were formed in the boiler. Dioxins and furans are known to form through several chemical mechanisms. One mechanism is CDD/CDF formation from heavy organics and a chlorine donor (2). The optimum temperature window for this reaction is 500 to 600°F. At temperatures above 750°F, this reaction is slowed considerably (2). The CDD/CDF species may have formed inside the boiler where temperatures of 500 to 600°F occurred. The average boiler inlet temperature was about 1150°F, and the average baghouse inlet temperature was about 360°F. Thus, the flue gas passed through the temperature window of optimum CDD/CDF formation in the boiler.

Average CDD/CDF concentrations corrected to 7 percent O_2 are presented in Table 2-4. Average boiler inlet CDD/CDF concentrations ranged from 70.79 ng/dscm at Condition 1 to 134.9 ng/dscm for Condition 3.

Average total CDD/CDF concentrations at 7 percent O_2 at the baghouse inlet ranged from 237 ng/dscm at Condition 1 to 415 ng/dscm at Condition 3.

Average total CDD/CDF concentrations at 7 percent O_2 at the baghouse outlet ranged from 6.3 ng/dscm for Condition 3 to 131.9 ng/dscm for Condition 1, indicating significant reductions resulting from carbon injection.

TABLE 2-3. CDD/CDF AVERAGE FLUE GAS CONCENTRATIONS[a] AS MEASURED FOR CONDITION 1, 2, AND 3 BORGESS MEDICAL CENTER (1991)

CDD/CDF CONCENTRATION AS MEASURED (ng/dscm)[b]

	CONDITION 1			CONDITION 2			CONDITION 3		
	Boiler Inlet	Baghouse Inlet	Baghouse Outlet	Boiler Inlet	Baghouse Inlet	Baghouse Outlet	Boiler Inlet	Baghouse Inlet	Baghouse Outlet
CONGENER									
DIOXINS									[c]
2378 TCDD	0.023	0.053	0.016	0.021	0.138	[0.012]	0.014	0.135	[0.010]
Other TCDD	0.234	0.406	0.172	1.297	1.196	0.014	0.453	1.040	0.014
12378 PCDD	0.080	0.157	0.066	0.075	0.329	[0.033]	0.088	0.314	[0.022]
Other PCDD	0.308	0.725	0.376	0.484	1.663	0.042	0.677	1.754	0.023
123478 HxCDD	0.055	0.182	0.119	0.052	0.440	[0.039]	0.100	0.426	[0.022]
123678 HxCDD	0.069	0.269	0.138	0.066	0.464	0.053	0.150	0.498	0.014
123789 HxCDD	0.121	0.519	0.231	0.124	0.815	0.089	0.307	0.961	0.021
Other HxCDD	0.410	1.533	0.939	0.490	2.715	0.211	1.019	3.173	0.052
1234678-HpCDD	0.666	4.086	1.800	0.718	6.612	0.411	1.900	7.129	0.157
Other Hepta-CDD	0.577	3.117	1.759	0.674	6.114	0.436	1.787	6.918	0.120
Octa-CDD	2.200	14.022	3.964	3.013	21.965	1.047	5.899	23.516	0.598
Total CDD	4.742	25.069	9.581	7.014	42.451	2.232	12.394	45.862	0.944
FURANS									
2378 TCDF	2.282	0.868	0.143	1.366	0.866	0.028	0.581	1.303	0.015
Other TCDF	4.504	6.071	3.876	4.874	13.571	0.359	5.903	11.085	0.188
12378 PCDF	0.490	0.668	0.313	0.407	1.282	0.044	0.470	1.216	0.023
23478 PCDF	0.542	1.081	0.633	0.527	2.268	0.064	0.749	2.137	0.029
Other PCDF	4.371	8.781	4.772	4.246	19.370	0.338	5.803	19.250	0.043
123478 HxCDF	1.486	5.933	2.581	1.428	8.797	0.274	2.921	8.990	0.087
123678 HxCDF	0.592	1.797	0.843	0.586	3.165	0.092	1.076	3.211	0.030
234678 HxCDF	1.042	6.261	3.001	1.260	9.076	0.304	2.709	8.887	0.105
123789 HxCDF	0.072	0.359	0.088	0.069	0.322	[0.028]	0.155	0.368	[0.019]
Other HxCDF	2.719	9.925	3.402	2.640	16.608	0.279	4.745	14.967	0.024
1234678-HpCDF	2.811	12.532	5.578	3.079	16.292	0.670	6.952	20.800	0.269
1234789-HpCDF	0.688	3.978	1.300	0.649	3.966	0.108	1.668	4.370	0.064
Other Hepta-CDF	2.984	14.911	6.118	3.071	17.003	0.601	6.598	18.762	0.193
Octa-CDF	5.602	16.126	9.077	5.990	40.243	0.783	13.996	41.723	0.609
TOTAL CDF	30.184	89.291	41.726	30.191	152.829	3.921	54.325	157.069	1.663
TOTAL CDD+CDF	34.926	114.360	51.306	37.205	195.281	6.153	66.719	202.931	2.607

[a] Detection limits are not considered in the calculation of averages.

[b] Standard conditions are defined as 1 atm and 68 °F.

[c] [] = Average was calculated entirely from detection limits

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TABLE 2-4. CDD/CDF AVERAGE FLUE GAS CONCENTRATIONS[a] CORRECTED TO 7% O2 FOR CONDITIONS 1, 2, AND 3 BORGESS MEDICAL CENTER (1991)

CDD/CDF CONCENTRATION AT 7 PERCENT OXYGEN (ng/dscm @ 7% O2)[b]

	CONDITION 1			CONDITION 2			CONDITION 3		
	Boiler Inlet	Baghouse Inlet	Baghouse Outlet	Boiler Inlet	Baghouse Inlet	Baghouse Outlet	Boiler Inlet	Baghouse Inlet	Baghouse Outlet
CONGENER									
DIOXINS									
2378 TCDD	0.048	0.110	0.042	0.043	0.291	[0.030][c]	0.028	0.278	[0.026]
Other TCDD	0.481	0.860	0.440	2.718	2.513	0.036	0.924	2.168	0.036
12378 PCDD	0.164	0.327	0.168	0.158	0.691	[0.086]	0.180	0.651	[0.055]
Other PCDD	0.626	1.517	0.956	1.017	3.492	0.108	1.375	3.580	0.059
123478 HxCDD	0.111	0.378	0.308	0.110	0.925	[0.102]	0.203	0.875	[0.058]
123678 HxCDD	0.142	0.565	0.357	0.140	0.975	0.140	0.305	1.027	0.036
123789 HxCDD	0.247	1.058	0.596	0.262	1.714	0.117	0.618	1.971	[0.051]
Other HxCDD	0.829	3.177	2.428	1.031	5.712	0.553	2.099	6.524	0.125
1234678-HpCDD	1.354	8.593	4.636	1.515	13.924	1.073	3.823	14.613	0.380
Other Hepta-CDD	1.170	6.755	4.540	1.422	12.872	1.140	3.617	14.215	0.291
Octa-CDD	4.503	29.319	10.105	6.376	46.352	2.720	11.571	48.044	1.427
Total CDD	9.675	52.659	24.578	14.793	89.460	5.818	24.745	93.948	2.266
FURANS									
2378 TCDF	4.561	1.829	0.367	2.891	1.828	0.072	1.225	2.555	0.037
Other TCDF	9.216	12.775	10.022	10.256	28.521	0.940	11.959	22.993	0.465
12378 PCDF	1.005	1.373	0.802	0.856	2.693	0.116	0.970	2.496	0.059
23478 PCDF	1.103	2.255	1.628	1.109	4.767	0.168	1.549	4.403	0.070
Other PCDF	8.819	18.388	12.320	8.937	40.717	0.885	11.864	39.241	0.110
123478 HxCDF	3.025	12.262	6.681	3.012	18.509	0.715	5.931	18.450	0.210
123678 HxCDF	1.206	3.732	2.175	1.234	6.655	0.239	2.195	6.593	0.074
234678 HxCDF	2.124	12.856	7.792	2.653	19.088	0.792	5.509	18.329	0.251
123789 HxCDF	0.147	0.722	0.224	0.145	0.679	[0.073]	0.316	0.747	[0.047]
Other HxCDF	5.440	20.681	8.814	5.559	34.939	0.732	9.740	30.480	0.061
1234678-HpCDF	5.698	26.019	14.380	6.498	34.343	1.745	14.018	42.625	0.649
1234789-HpCDF	1.396	8.174	3.319	1.370	8.375	0.280	3.396	8.951	0.154
Other Hepta-CDF	6.024	31.006	15.728	6.486	35.869	1.562	13.454	38.476	0.456
Octa-CDF	11.349	32.226	23.085	12.671	84.887	2.022	27.995	85.561	1.464
TOTAL CDF	61.114	184.298	107.336	63.676	321.870	10.209	110.122	321.899	4.022
TOTAL CDD+CDF	70.789	236.957	131.914	78.469	411.330	16.028	134.867	415.847	6.288

[a] Detection limits are not considered when calculating averages.

[b] Standard conditions are defined as 1 atm and 68 °F.

[c] [] = Average was calculated entirely from detection limits.

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TABLE 2-5. CDD/CDF AVERAGE FLUE GAS TOXIC EQUIVALENCIES

a,b,c

2378 TOXIC EQUIVALENCY CONCENTRATIONS (ng/dscm adjusted to 7 percent O2)

		Condition 1			Condition 2			Condition 3		
CONGENER	2378 TCDD Toxic Equivalency Factor	Boiler Inlet (ng/dscm)	Baghouse Inlet (ng/dscm)	Baghouse Outlet (ng/dscm)	Boiler Inlet (ng/dscm)	Baghouse Inlet (ng/dscm)	Baghouse Outlet (ng/dscm)	Boiler Inlet (ng/dscm)	Baghouse Inlet (ng/dscm)	Baghouse Outlet (ng/dscm)
DIOXINS										
2378 TCDD	1.000	0.048	0.110	0.042	0.043	0.291	[0.030]	0.028	0.278	[0.026]
Other TCDD	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
12378 PCDD	0.500	0.082	0.163	0.084	0.079	0.346	[0.044]	0.090	0.326	[0.028]
Other PCDD	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
123478 HxCDD	0.100	0.011	0.038	0.031	0.011	0.092	[0.011]	0.020	0.088	[0.006]
123678 HxCDD	0.100	0.014	0.056	0.036	0.014	0.098	0.014	0.031	0.103	[0.004]
123789 HxCDD	0.100	0.025	0.106	0.060	0.026	0.171	0.023	0.062	0.197	[0.005]
Other HxCDD	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1234678-HpCDD	0.010	0.014	0.086	0.046	0.015	0.139	0.011	0.038	0.146	0.004
Other Hepta-CDD	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Octa-CDD	0.001	0.005	0.029	0.010	0.006	0.046	0.003	0.012	0.048	0.001
Total CDD		0.198	0.589	0.309	0.195	1.183	0.051	0.281	1.186	0.007
FURANS										
2378 TCDF	0.100	(0.456)	0.183	0.037	0.290	0.183	0.007	0.123	0.256	0.004
Other TCDF	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
12378 PCDF	0.050	0.044	0.069	0.040	0.043	0.135	0.006	0.049	0.125	0.003
23478 PCDF	0.500	0.465	1.127	0.814	0.555	2.384	0.084	0.775	2.202	0.035
Other PCDF	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
123478 HxCDF	0.100	0.263	1.226	0.668	0.301	1.851	0.071	0.593	1.845	0.021
123678 HxCDF	0.100	0.100	0.373	0.217	0.123	0.666	0.024	0.219	0.659	0.007
234678 HxCDF	0.100	0.197	1.286	0.779	0.265	1.909	0.079	0.551	1.833	0.025
123789 HxCDF	0.100	0.013	0.072	0.022	0.014	0.068	[0.007]	0.032	0.075	[0.005]
Other HxCDF	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1234678-HpCDF	0.010	0.047	0.260	0.144	0.065	0.343	0.017	0.140	0.426	0.006
1234789-HpCDF	0.010	0.011	0.082	0.033	0.014	0.084	0.003	0.034	0.090	0.002
Other Hepta-CDF	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Octa-CDF	0.001	0.009	0.032	0.023	0.013	0.085	0.002	0.028	0.086	0.001
TOTAL CDF		1.791	4.710	2.778	1.683	7.706	0.291	2.543	7.595	0.103
TOTAL CDD+CDF		1.988	5.299	3.087	1.878	8.890	0.342	2.824	8.781	0.110

a North Atlantic Treaty Organization, Committee on the Challenges of Modern Society. Pilot Study on International Information Exchange on Dioxins and Related Compounds: International Toxicity Equivalency Factor (I-TEF) Methods of Risk Assessment for Complex Mixtures of Dioxins and Related Compounds. Report No. 176, August 1988.

b Standard conditions are defined as 1 atm and 68°F.

c Non-detects are not included in the totals.

TABLE 2-6. CDD/CDF AVERAGE FLUE GAS EMISSIONS AND BAGHOUSE INLET TO BOILET INLET EMISSIONS RATIOS FOR CONDITIONS 1, 2, AND 3; BORGESS MEDICAL CENTER (1991)[a]

	Condition 1 (No Carbon Inj.)			Condition 2 (Carbon Inj. = 1 lb/hr)			Condition 3 (Carbon Inj. = 2.5 lb/hr)		
	Emissions			Emissions			Emissions		
CONGENER	Boiler Inlet (ug/hr)	Baghouse Inlet (ug/hr)	Baghouse/ Boiler Ratio	Boiler Inlet (ug/hr)	Baghouse Inlet (ug/hr)	Baghouse/ Boiler Ratio	Boiler Inlet (ug/hr)	Baghouse Inlet (ug/hr)	Baghouse/ Boiler Ratio
DIOXINS									
2378 TCDD	0.075	0.150	2.009	0.073	0.415	5.708	0.027	0.384	14.294
Other TCDD	0.749	1.175	1.569	4.658	3.581	0.769	1.077	2.975	2.763
12378 PCDD	0.256	0.446	1.743	0.266	0.987	3.715	0.214	0.896	4.182
Other PCDD	0.987	2.052	2.079	1.719	4.963	2.887	1.560	4.972	3.188
123478 HxCDD	0.175	0.519	2.972	0.185	1.320	7.119	0.228	1.210	5.313
123678 HxCDD	0.222	0.767	3.453	0.234	1.395	5.956	0.354	1.417	4.001
123789 HxCDD	0.389	1.455	3.744	0.437	2.452	5.612	0.651	2.729	4.189
Other HxCDD	1.310	4.363	3.330	1.728	8.170	4.729	2.611	9.019	3.454
1234678-HpCDD	2.136	11.634	5.447	2.515	19.981	7.945	4.010	20.238	5.047
Other Hepta-CDD	1.853	9.087	4.905	2.356	18.460	7.836	3.979	19.659	4.941
Octa-CDD	7.075	39.822	5.629	10.456	66.933	6.401	9.789	66.655	6.809
Total CDD	15.226	71.471	4.694	24.627	128.657	5.224	24.500	130.152	5.312
FURANS									
2378 TCDF	7.378	2.493	0.338	4.740	2.639	0.557	1.728	3.634	2.102
Other TCDF	14.381	17.490	1.216	17.242	40.693	2.360	13.194	31.626	2.397
12378 PCDF	1.573	1.899	1.207	1.441	3.841	2.665	1.208	3.454	2.858
23478 PCDF	1.741	3.083	1.770	1.863	6.805	3.654	1.953	6.082	3.115
Other PCDF	13.972	25.124	1.798	15.000	58.125	3.875	13.963	54.517	3.904
123478 HxCDF	4.787	16.716	3.492	5.020	26.500	5.279	6.631	25.529	3.850
123678 HxCDF	1.901	5.099	2.683	2.067	9.510	4.602	2.530	9.120	3.605
234678 HxCDF	3.365	17.430	5.179	4.442	27.291	6.144	6.214	25.276	4.068
123789 HxCDF	0.231	0.987	4.275	0.242	0.974	4.021	0.361	1.041	2.884
Other HxCDF	8.694	28.233	3.247	9.315	49.999	5.368	11.787	42.335	3.592
1234678-HpCDF	9.058	35.487	3.918	10.789	49.436	4.582	14.898	59.024	3.962
1234789-HpCDF	2.212	11.166	5.049	2.273	12.114	5.330	3.873	12.398	3.201
Other Hepta-CDF	9.614	42.128	4.382	10.730	51.745	4.822	15.475	53.261	3.442
Octa-CDF	18.025	46.225	2.565	20.813	122.413	5.882	27.964	118.465	4.236
TOTAL CDF	96.931	253.559	2.616	105.977	462.084	4.360	121.778	445.763	3.660
TOTAL CDD+CDF	112.156	325.030	2.898	130.604	590.741	4.523	146.278	575.916	3.937

[a] Detection limits are not considered when calculating averages.

Table 2-5 presents average corrected CDD/CDF gas concentrations in 2378 TCDD Toxic Equivalents. The concentration of each congener corrected to 7 percent O_2 was multiplied by its respective Toxic Equivalency Factor (TEF) to determine 2378 Toxic Equivalents. The TEF's used in this report are the international TEF (I-TEF) developed by the North Atlantic Treaty Organization Committee on the Challenges of Modern Society (NATO/CCMS) (1). The average 2378 Toxic Equivalent concentrations (TEC) for total CDD/CDF for Conditions 1, 2 and 3 at the baghouse outlet were 3.1 ng/dscm, 0.34 ng/dscm and 0.11 ng/dscm at 7 percent O_2, respectively.

Table 2-6 presents the boiler inlet and baghouse inlet average CDD/CDF mass emission rates. The ratio of baghouse inlet emissions divided by boiler inlet emissions indicates the amount of CDD/CDF formed in the boiler. This ratio ranges from 2.9 to 4.5 for total CDD/CDF; thus, approximately three to five times more CDD/CDF exited the boiler than entered the boiler.

Table 2-7 shows average CDD/CDF mass emission rates and removal efficiencies for the baghouse inlet and outlet. Total average CDD/CDF removal efficiency for Condition 1 is 38.0 percent, which may be attributable to CDD/CDF adsorption onto the lime and flyash particulate, and subsequent removal in the baghouse. For Conditions 2 and 3, removal efficiencies are 96.0 percent and 98.2 percent, respectively, which indicates improved removal due to carbon injection.

2.2.3 CDD/CDF Flue Gas Results for Each Run

Tables 2-8 through 2-13 present results for the individual CDD/CDF flue gas test runs (Runs 2 through 9). Table 2-8 presents uncorrected CDD/CDF flue gas concentrations at the boiler inlet, baghouse inlet, and baghouse outlet. All congeners were detected at the boiler inlet and baghouse inlet. For Condition 1 with no carbon injection, all congeners were also detected at the baghouse outlet. For Conditions 2 and 3, with carbon injection at 1 lb/hr and 2.5 lb/hr, respectively, several congeners were not detected. Fewer congeners were detected for Condition 3 than for Condition 2, indicating that the additional carbon injection improved removal efficiency for Condition 3. Table 2-9 presents the CDD/CDF flue gas concentrations corrected to 7 percent oxygen.

TABLE 2-7. CDD/CDF AVERAGE STACK EMISSIONS AND BAGHOUSE REMOVAL EFFICIENCIES[a] FOR CONDITIONS 1, 2, AND 3; BORGESS MEDICAL CENTER (1991)

CONGENER	Condition 1 (No Carbon Inj.) Emissions Baghouse Inlet (ug/hr)	Condition 1 Emissions Baghouse Outlet (ug/hr)	Condition 1 Removal Efficiency Ratio	Condition 2 (Carbon Inj. = 1 lb/hr) Emissions Baghouse Inlet (ug/hr)	Condition 2 Emissions Baghouse Outlet (ug/hr)	Condition 2 Removal Efficiency Ratio	Condition 3 (Carbon Inj. = 2.5 lb/hr) Emissions Baghouse Inlet (ug/hr)	Condition 3 Emissions Baghouse Outlet (ug/hr)	Condition 3 Removal Efficiency Ratio
DIOXINS					[b]				
2378 TCDD	0.150	0.064	57.3%	0.415	[0.045]	89.2%	0.384	[0.041]	89.3%
Other TCDD	1.175	0.672	42.8%	3.581	0.054	98.5%	2.975	0.055	98.2%
12378 PCDD	0.446	0.259	41.9%	0.987	[0.127]	87.1%	0.896	[0.090]	90.0%
Other PCDD	2.052	1.469	28.4%	4.963	0.161	96.8%	4.972	0.090	98.2%
123478 HxCDD	0.519	0.466	10.2%	1.320	[0.151]	88.6%	1.210	[0.096]	90.4%
123678 HxCDD	0.767	0.542	29.3%	1.395	0.214	84.7%	1.417	0.055	96.1%
123789 HxCDD	1.455	0.907	37.6%	2.452	0.179	92.7%	2.729	[0.084]	96.9%
Other HxCDD	4.363	3.682	15.6%	8.170	0.832	89.8%	9.019	0.203	97.7%
1234678-HpCDD	11.634	7.093	39.0%	19.981	1.600	92.0%	20.238	0.617	97.0%
Other Hepta-CDD	9.087	6.927	23.8%	18.460	1.708	90.7%	19.659	0.473	97.6%
Octa-CDD	39.822	15.604	60.8%	66.933	4.017	94.0%	66.655	2.330	96.5%
Total CDD	71.471	37.687	47.3%	128.657	8.657	93.3%	130.152	3.689	97.2%
FURANS									
2378 TCDF	2.493	0.560	77.5%	2.639	0.107	95.9%	3.634	0.060	98.3%
Other TCDF	17.490	15.166	13.3%	40.693	1.413	96.5%	31.626	0.744	97.6%
12378 PCDF	1.899	1.225	35.5%	3.841	0.178	95.4%	3.454	0.090	97.4%
23478 PCDF	3.083	2.477	19.6%	6.805	0.249	96.3%	6.082	0.114	98.1%
Other PCDF	25.124	18.679	25.7%	58.125	1.333	97.7%	54.517	0.175	99.7%
123478 HxCDF	16.716	10.108	39.5%	26.500	1.063	96.0%	25.529	0.342	98.7%
123678 HxCDF	5.099	3.303	35.2%	9.510	0.358	96.2%	9.120	0.120	98.7%
234678 HxCDF	17.430	11.794	32.3%	27.291	1.179	95.7%	25.276	0.413	98.4%
123789 HxCDF	0.987	0.346	65.0%	0.974	[0.108]	88.9%	1.041	[0.078]	92.5%
Other HxCDF	28.233	13.325	52.8%	49.999	1.110	97.8%	42.335	0.096	99.8%
1234678-HpCDF	35.487	21.928	38.2%	49.436	2.590	94.8%	59.024	1.061	98.2%
1234789-HpCDF	11.166	5.107	54.3%	12.114	0.410	96.6%	12.398	0.251	98.0%
Other Hepta-CDF	42.128	24.033	43.0%	51.745	2.303	95.5%	53.261	0.753	98.6%
Octa-CDF	46.225	35.702	22.8%	122.413	2.941	97.6%	118.465	2.395	98.0%
TOTAL CDF	253.559	163.753	35.4%	462.084	15.146	96.7%	445.763	6.554	98.5%
TOTAL CDD+CDF	325.030	201.439	38.0%	590.741	23.803	96.0%	575.916	10.243	98.2%

[a] Detection limits are not considered when calculating averages.

[b] [] = Average was calculated entirely from detection limits.

TABLE 2-8. CDD/CDF FLUE GAS CONCENTRATIONS AS MEASURED FOR CONDITION 1; BORGESS MEDICAL CENTER (1991)

CDD/CDF CONCENTRATIONS AS MEASURED (ng/dscm)[a]

CONGENER	Condition 1 (No Carbon Injection)											
	Boiler Inlet				Baghouse Inlet				Baghouse Outlet			
	RUN 2	RUN 3	RUN 4	AVG.	RUN 2	RUN 3	RUN 4	AVG.	RUN 2	RUN 3	RUN 4	AVG.
DIOXINS	b											
2378 TCDD	(0.020)	(0.031)	0.019	0.023	0.030	0.066	0.061	0.053	0.022	(0.013)	(0.014)	0.016
Other TCDD	0.166	0.362	0.174	0.234	0.109	0.597	0.513	0.406	0.220	0.172	0.123	0.172
12378 PCDD	0.062	0.116	0.061	0.080	0.109	0.181	0.179	0.157	0.094	0.066	(0.038)	0.066
Other PCDD	0.297	0.420	0.207	0.308	0.588	0.691	0.897	0.725	0.535	0.374	0.218	0.376
123478 HxCDD	0.046	0.080	0.038	0.055	0.126	0.230	0.190	0.182	0.117	0.150	0.090	0.119
123678 HxCDD	(0.062)	0.094	0.052	0.069	0.174	0.304	0.330	0.269	0.144	0.181	(0.090)	0.138
123789 HxCDD	0.114	0.170	0.080	0.121	0.566	0.523	0.467	0.519	0.256	0.286	0.152	0.231
Other HxCDD	0.395	0.595	0.240	0.410	1.093	1.909	1.597	1.533	1.011	1.101	0.706	0.939
1234678-HpCDD	0.652	0.894	0.452	0.666	2.657	4.361	5.240	4.086	1.753	3.126	0.521	1.800
Other Hepta-CDD	0.619	0.715	0.395	0.577	0.000	4.361	4.989	3.117	1.663	2.950	0.663	1.759
Octa-CDD	2.087	2.772	1.740	2.200	10.192	14.969	16.906	14.022	4.719	6.605	0.568	3.964
Total CDD	4.520	6.249	3.457	4.742	15.645	28.193	31.371	25.069	10.535	15.024	3.183	9.581
FURANS												
2378 TCDF	(3.554)	(1.833)	(1.458)	2.282	(0.375)	(1.151)	(1.077)	0.868	0.189	0.137	0.104	0.143
Other TCDF	3.261	7.242	3.010	4.504	2.308	8.653	7.251	6.071	4.396	3.782	3.449	3.876
12378 PCDF	0.424	0.671	0.376	0.490	0.523	0.872	0.610	0.668	0.409	0.313	0.218	0.313
23478 PCDF	0.554	0.671	0.400	0.542	0.697	1.326	1.220	1.081	0.764	0.661	0.474	0.633
Other PCDF	4.434	6.303	2.375	4.371	4.878	11.200	10.266	8.781	5.524	4.795	3.998	4.772
123478 HxCDF	1.630	1.699	1.129	1.486	5.618	5.792	6.389	5.933	2.831	2.686	2.226	2.581
123678 HxCDF	0.587	0.760	0.428	0.592	1.394	2.024	1.974	1.797	0.944	0.969	0.616	0.843
234678 HxCDF	1.206	1.073	0.847	1.042	7.709	4.396	6.676	6.261	2.742	4.271	1.990	3.001
123789 HxCDF	0.065	0.094	0.056	0.072	0.566	0.216	0.294	0.359	0.126	(0.101)	0.038	0.088
Other HxCDF	3.195	3.706	1.256	2.719	6.969	11.542	11.263	9.925	3.649	3.611	2.946	3.402
1234678-HpCDF	3.326	3.084	2.023	2.811	10.235	13.433	13.927	12.532	5.798	8.190	2.748	5.578
1234789-HpCDF	0.750	0.849	0.466	0.688	4.181	3.733	4.020	3.978	1.573	1.937	(0.388)	1.300
Other Hepta-CDF	3.750	3.174	2.027	2.984	12.848	14.655	17.229	14.911	6.787	8.631	2.937	6.118
Octa-CDF	6.423	6.527	3.857	5.602	10.976	31.193	6.210	16.126	11.416	14.443	1.374	9.077
TOTAL CDF	33.159	37.685	19.708	30.184	69.277	110.188	88.407	89.291	47.146	54.526	23.505	41.726
TOTAL CDD+CDF	37.679	43.934	23.165	34.926	84.922	138.381	119.778	114.360	57.681	69.550	26.688	51.306

[a] Standard conditions are defined as 1 atm and 68 °F.

[b] () = Estimated Maximum Possible Concentration

TABLE 2-8 (CONT'D). CDD/CDF FLUE GAS CONCENTRATIONS AS MEASURED FOR CONDITION 2; BORGESS MEDICAL CENTER (1991)

CDD/CDF CONCENTRATIONS AS MEASURED (ng/dscm)[a]

	Condition 2 (Carbon Injection = 1 lb/hr)								
	Boiler Inlet			Baghouse Inlet			Baghouse Outlet		[c]
CONGENER	RUN 5	RUN 6	AVERAGE	RUN 5	RUN 6	AVERAGE	RUN 5	RUN 6	AVERAGE
DIOXINS							[b]		
2378 TCDD	0.015	0.027	0.021	0.063	0.213	0.138	[0.013]	[0.010]	[0.012]
Other TCDD	0.147	2.448	1.297	0.507	1.885	1.196	0.013	0.015	0.014
12378 PCDD	0.044	0.106	0.075	0.168	0.490	0.329	[0.036]	[0.030]	[0.033]
Other PCDD	0.235	0.734	0.484	0.529	2.798	1.663	0.049	0.034	0.042
123478 HxCDD	0.034	0.071	0.052	0.215	0.665	0.440	[0.044]	[0.034]	[0.039]
123678 HxCDD	0.049	0.084	0.066	0.263	0.665	0.464	(0.053)	[0.020]	0.053
123789 HxCDD	0.103	0.146	0.124	0.475	1.154	0.815	0.089	[0.025]	0.089
Other HxCDD	0.352	0.627	0.490	1.548	3.882	2.715	0.324	0.098	0.211
1234678-HpCDD	0.684	0.751	0.718	4.655	8.569	6.612	0.533	0.290	0.411
Other Hepta-CDD	0.684	0.663	0.674	4.148	8.080	6.114	0.621	0.251	0.436
Octa-CDD	3.861	2.165	3.013	21.089	22.840	21.965	1.110	0.984	1.047
Total CDD	6.207	7.821	7.014	33.661	51.242	42.451	2.792	1.672	2.232
FURANS									
2378 TCDF	(1.760)	(0.972)	1.366	(0.823)	0.909	0.866	0.036	0.020	0.028
Other TCDF	3.030	6.717	4.874	6.365	20.776	13.571	0.542	0.177	0.359
12378 PCDF	0.239	0.574	0.407	0.570	1.994	1.282	(0.044)	[0.015]	0.044
23478 PCDF	0.347	0.707	0.527	1.108	3.428	2.268	(0.084)	0.044	0.064
Other PCDF	2.835	5.656	4.246	9.500	29.241	19.370	0.533	0.143	0.338
123478 HxCDF	1.222	1.635	1.428	5.351	12.242	8.797	0.342	0.207	0.274
123678 HxCDF	0.420	0.751	0.586	1.678	4.652	3.165	0.124	0.059	0.092
234678 HxCDF	0.929	1.591	1.260	5.035	13.116	9.076	0.382	(0.226)	0.304
123789 HxCDF	0.049	0.088	0.069	0.225	0.420	0.322	[0.031]	[0.025]	[0.028]
Other HxCDF	1.877	3.403	2.640	9.782	23.435	16.608	0.484	0.074	0.279
1234678-HpCDF	2.933	3.226	3.079	13.521	19.063	16.292	0.799	0.541	0.670
1234789-HpCDF	0.635	0.663	0.649	4.085	3.847	3.966	0.098	(0.118)	0.108
Other Hepta-CDF	3.226	2.916	3.071	15.643	18.363	17.003	0.613	0.590	0.601
Octa-CDF	7.429	4.551	5.990	36.415	44.071	40.243	0.533	1.033	0.783
TOTAL CDF	26.931	33.451	30.191	110.101	195.558	152.829	4.611	3.231	3.921
TOTAL CDD+CDF	33.138	41.272	37.205	143.762	246.800	195.281	7.402	4.904	6.153

[a] Standard conditions are defined as 1 atm and 68 °F.

[b] [] = Minimum detection limit; () = Estimated maximum possible concentration.

[c] Detection limits are not considered when calculating averages.

TABLE 2-8 (CONT'D). CDD/CDF FLUE GAS CONCENTRATIONS AS MEASURED FOR CONDITION 3; BORGESS MEDICAL CENTER (1991)

CDD/CDF CONCENTRATIONS AS MEASURED (ng/dscm)[a]

	Condition 3 (Carbon Injection = 2.5 lb/hr)											
	Boiler Inlet				Baghouse Inlet				Baghouse Outlet			
CONGENER	RUN 7	RUN 8	RUN 9	AVG.	RUN 7	RUN 8	RUN 9	AVG.	RUN 7	RUN 8	RUN 9	AVG.[c]
DIOXINS												
2378 TCDD	0.002	0.019	0.020	0.014	0.168	0.128	0.109	0.135	[0.017][b]	[0.009]	[0.005]	[0.010]
Other TCDD	0.394	0.514	0.451	0.453	1.402	1.039	0.680	1.040	[0.017]	(0.014)	[0.005]	0.014
12378 PCDD	0.092	0.090	0.083	0.088	0.392	0.317	0.233	0.314	[0.039]	[0.014]	[0.014]	[0.022]
Other PCDD	0.379	0.928	0.724	0.677	2.033	1.433	1.796	1.754	[0.039]	(0.023)	[0.014]	0.023
123478 HxCDD	0.077	0.114	0.110	0.100	0.464	0.437	0.376	0.426	[0.039]	[0.014]	[0.019]	[0.022]
123678 HxCDD	0.134	0.165	0.150	0.150	0.606	0.474	0.413	0.498	[0.022]	(0.014)	[0.010]	0.014
123789 HxCDD	0.225	0.315	0.381	0.307	1.034	0.948	0.902	0.961	[0.035]	[0.014]	[0.014]	0.021
Other HxCDD	0.728	1.491	0.838	1.019	3.602	3.099	2.817	3.173	(0.052)	0.051	0.053	0.052
1234678-HpCDD	1.337	1.987	2.376	1.900	7.917	6.744	6.724	7.129	0.161	0.161	0.149	0.157
Other Hepta-CDD	1.213	2.109	2.040	1.787	7.846	6.672	6.236	6.918	0.122	0.124	0.115	0.120
Octa-CDD	2.822	4.968	9.908	5.899	24.465	22.603	23.479	23.516	(0.522)	0.552	(0.719)	0.598
Total CDD	7.401	12.700	17.081	12.394	49.929	43.894	43.764	45.862	0.857	0.939	1.036	0.944
FURANS												
2378 TCDF	(0.792)	(0.703)	(0.247)	0.581	(0.963)	(0.729)	2.216	1.303	0.017	0.018	0.010	0.015
Other TCDF	4.653	6.374	6.680	5.903	13.873	11.192	8.189	11.085	0.200	0.258	0.106	0.188
12378 PCDF	0.520	0.509	0.381	0.470	1.355	1.167	1.127	1.216	[0.026]	0.023	[0.010]	0.023
23478 PCDF	0.792	0.873	0.583	0.749	2.675	1.896	1.841	2.137	0.030	(0.032)	0.024	0.029
Other PCDF	4.752	7.029	5.627	5.803	19.864	17.900	19.985	19.250	0.065	0.064	0.000	0.043
123478 HxCDF	2.624	2.933	3.206	2.921	9.736	8.968	8.264	8.990	0.100	0.083	0.077	0.087
123678 HxCDF	1.015	1.115	1.098	1.076	3.495	3.208	2.930	3.211	0.039	0.032	0.019	0.030
234678 HxCDF	2.475	2.739	2.914	2.709	9.237	10.062	7.363	8.887	0.126	0.074	0.115	0.105
123789 HxCDF	0.146	0.158	0.161	0.155	0.357	0.335	0.413	0.368	[0.035]	[0.009]	[0.014]	[0.019]
Other HxCDF	3.715	6.265	4.255	4.745	12.839	16.435	15.627	14.967	0.026	0.046	0.000	0.024
1234678-HpCDF	5.743	6.641	8.473	6.952	21.719	21.035	19.647	20.800	0.322	0.230	0.254	0.269
1234789-HpCDF	1.485	1.769	1.748	1.668	4.494	4.448	4.170	4.370	(0.065)	0.060	0.067	0.064
Other Hepta-CDF	6.238	6.786	6.770	6.598	20.150	18.629	17.506	18.762	0.200	0.124	0.254	0.193
Octa-CDF	10.569	12.433	18.987	13.996	46.362	39.738	39.068	41.723	0.697	0.506	0.624	0.609
TOTAL CDF	45.520	56.326	61.130	54.325	167.118	155.742	148.347	157.069	1.889	1.550	1.549	1.663
TOTAL CDD+CDF	52.921	69.026	78.212	66.719	217.047	199.635	192.111	202.931	2.746	2.489	2.585	2.607

a Standard conditions are defined as 1 atm and 68 °F.

b [] = Minimum detection limit; () = Estimated maximum possible concentration.

TABLE 2-9. CDD/CDF FLUE GAS CONCENTRATIONS CORRECTED TO 7% O2 FOR CONDITION 1; BORGESS MEDICAL CENTER (1991)

CDD/CDF CONCENTRATIONS CORRECTED TO 7 PERCENT 0XYGEN (ng/dscm @ 7% O2)[a]

	Condition 1 (No Carbon Injection)											
	Boiler Inlet				Baghouse Inlet				Baghouse Outlet			
CONGENER	RUN 2	RUN 3	RUN 4	AVG.	RUN 2	RUN 3	RUN 4	AVG.	RUN 2	RUN 3	RUN 4	AVG.
DIOXINS	[b]											
2378 TCDD	(0.037)	(0.062)	0.044	0.048	0.057	0.131	0.142	0.110	0.053	(0.034)	(0.039)	0.042
Other TCDD	0.309	0.729	0.405	0.481	0.202	1.183	1.195	0.860	0.523	0.456	0.342	0.440
12378 PCDD	0.115	0.234	0.142	0.164	0.202	0.360	0.418	0.327	0.224	0.175	(0.106)	0.168
Other PCDD	0.551	0.847	0.482	0.626	1.091	1.370	2.089	1.517	1.271	0.993	0.606	0.956
123478 HxCDD	0.085	0.162	0.088	0.111	0.234	0.457	0.443	0.378	0.278	0.397	0.250	0.308
123678 HxCDD	(0.115)	0.189	0.120	0.142	0.323	0.602	0.769	0.565	0.342	0.479	(0.250)	0.357
123789 HxCDD	0.212	0.342	0.186	0.247	1.051	1.038	1.086	1.058	0.609	0.759	0.421	0.596
Other HxCDD	0.732	1.198	0.559	0.829	2.029	3.784	3.719	3.177	2.403	2.920	1.962	2.428
1234678-HpCDD	1.210	1.801	1.051	1.354	4.930	8.648	12.201	8.593	4.165	8.293	1.449	4.636
Other Hepta-CDD	1.150	1.441	0.920	1.170	0.000	8.648	11.616	6.755	3.951	7.826	1.844	4.540
Octa-CDD	3.873	5.583	4.052	4.503	18.914	29.681	39.362	29.319	11.213	17.521	1.580	10.105
Total CDD	8.387	12.588	8.049	9.675	29.033	55.903	73.042	52.659	25.031	39.853	8.850	24.578
FURANS												
2378 TCDF	(6.596)	(3.693)	(3.395)	4.561	(0.696)	(2.282)	(2.508)	1.829	0.449	0.362	0.290	0.367
Other TCDF	6.051	14.589	7.009	9.216	4.284	17.158	16.881	12.775	10.444	10.034	9.587	10.022
12378 PCDF	0.787	1.351	0.876	1.005	0.970	1.730	1.421	1.373	0.972	0.829	0.606	0.802
23478 PCDF	1.029	1.351	0.931	1.103	1.293	2.629	2.841	2.255	1.815	1.752	1.317	1.628
Other PCDF	8.229	12.698	5.531	8.819	9.053	22.209	23.902	18.388	13.124	12.720	11.115	12.320
123478 HxCDF	3.025	3.422	2.628	3.025	10.427	11.485	14.876	12.262	6.728	7.125	6.189	6.681
123678 HxCDF	1.089	1.531	0.997	1.206	2.586	4.013	4.596	3.732	2.243	2.570	1.712	2.175
234678 HxCDF	2.239	2.161	1.971	2.124	14.307	8.717	15.544	12.856	6.514	11.330	5.531	7.792
123789 HxCDF	0.121	0.189	0.131	0.147	1.051	0.429	0.685	0.722	0.299	(0.268)	0.105	0.224
Other HxCDF	5.930	7.465	2.924	5.440	12.932	22.887	26.225	20.681	8.671	9.578	8.191	8.814
1234678-HpCDF	6.172	6.214	4.709	5.698	18.995	26.637	32.426	26.019	13.776	21.726	7.638	14.380
1234789-HpCDF	1.392	1.711	1.084	1.396	7.759	7.403	9.360	8.174	3.738	5.139	(1.079)	3.319
Other Hepta-CDF	6.959	6.394	4.720	6.024	23.844	29.058	40.114	31.006	16.125	22.894	8.165	15.728
Octa-CDF	11.920	13.148	8.980	11.349	20.369	61.853	14.458	32.226	27.125	38.312	3.819	23.085
TOTAL CDF	61.538	75.916	45.887	61.114	128.566	218.489	205.838	184.298	112.022	144.641	65.344	107.336
TOTAL CDD+CDF	69.925	88.504	53.937	70.789	157.599	274.392	278.88	236.957	137.054	184.49	74.194	131.914

[a] Standard conditions are defined as 1 atm and 68 °F.

[b] () = Estimated maximum possible concentration

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TABLE 2-9 (CONT'D). CDD/CDF FLUE GAS CONCENTRATIONS CORRECTED TO 7% O2 FOR CONDITION 2; BORGESS MEDICAL CENTER (1991)

CDD/CDF CONCENTRATIONS CORRECTED TO 7 PERCENT 0XYGEN (ng/dscm @ 7% O2)[a]

	Condition 2(Carbon Injection = 1 lb/hr)								
	Boiler Inlet			Baghouse Inlet			Baghouse Outlet		
CONGENER	RUN 5	RUN 6	AVERAGE	RUN 5	RUN 6	AVERAGE	RUN 5	RUN 6	AVERAGE[c]
DIOXINS									
2378 TCDD	0.031	0.056	0.043	0.135	0.447	0.291	[0.034][b]	[0.026]	[0.030]
Other TCDD	0.312	5.125	2.718	1.078	3.947	2.513	0.035	0.038	0.036
12378 PCDD	0.094	0.222	0.158	0.357	1.025	0.691	[0.095]	[0.077]	[0.086]
Other PCDD	0.499	1.536	1.017	1.126	5.858	3.492	0.129	0.088	0.108
123478 HxCDD	0.073	0.148	0.110	0.458	1.391	0.925	[0.116]	[0.087]	[0.102]
123678 HxCDD	0.104	0.176	0.140	0.559	1.391	0.975	(0.140)	[0.051]	0.140
123789 HxCDD	0.218	0.305	0.262	1.011	2.416	1.714	0.234	[0.064]	0.117
Other HxCDD	0.749	1.314	1.031	3.296	8.127	5.712	0.855	0.251	0.553
1234678-HpCDD	1.457	1.573	1.515	9.908	17.939	13.924	1.405	0.742	1.073
Other Hepta-CDD	1.457	1.388	1.422	8.830	16.914	12.872	1.639	0.641	1.140
Octa-CDD	8.219	4.533	6.376	44.891	47.813	46.352	2.927	2.514	2.720
Total CDD	13.213	16.373	14.793	71.651	107.268	89.460	7.363	4.273	5.818
FURANS									
2378 TCDF	(3.746)	(2.035)	2.891	(1.752)	1.904	1.828	0.094	0.050	0.072
Other TCDF	6.450	14.061	10.256	13.548	43.493	28.521	1.428	0.452	0.940
12378 PCDF	0.510	1.203	0.856	1.213	4.174	2.693	(0.116)	[0.038]	0.116
23478 PCDF	0.739	1.480	1.109	2.359	7.176	4.767	(0.222)	0.113	0.168
Other PCDF	6.034	11.841	8.937	20.221	61.212	40.717	1.405	0.364	0.885
123478 HxCDF	2.601	3.423	3.012	11.391	25.627	18.509	0.901	0.528	0.715
123678 HxCDF	0.895	1.573	1.234	3.572	9.738	6.655	0.328	0.151	0.239
234678 HxCDF	1.977	3.330	2.653	10.717	27.458	19.088	1.007	(0.577)	0.792
123789 HxCDF	0.104	0.185	0.145	0.479	0.879	0.679	[0.082]	[0.064]	[0.073]
Other HxCDF	3.995	7.123	5.559	20.821	49.058	34.939	1.276	0.189	0.732
1234678-HpCDF	6.242	6.753	6.498	28.782	39.905	34.343	2.107	1.383	1.745
1234789-HpCDF	1.353	1.388	1.370	8.695	8.054	8.375	0.258	(0.302)	0.280
Other Hepta-CDF	6.867	6.105	6.486	33.298	38.441	35.869	1.616	1.508	1.562
Octa-CDF	15.814	9.528	12.671	77.515	92.258	84.887	1.405	2.639	2.022
TOTAL CDF	57.326	70.026	63.676	234.365	409.376	321.870	12.162	8.257	10.209
TOTAL CDD+CDF	70.539	86.40	78.469	306.02	516.64	411.330	19.525	12.53	16.028

[a] Standard conditions are defined as 1 atm and 68 °F.

[b] [ ] = Detection limit; () = Estimated maximum possible concentration.

[c] Detection limits are not considered when calculating averages.

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TABLE 2-9 (CONT'D). CDD/CDF FLUE GAS CONCENTRATIONS CORRECTED TO 7% O2 FOR CONDITION 3; BORGESS MEDICAL CENTER (1991)

CDD/CDF CONCENTRATIONS CORRECTED TO 7 PERCENT OXYGEN (ng/dscm @ 7% O2)[a]

CONGENER	Condition 3 (Carbon Injection = 2.5 lb/hr)											
	Boiler Inlet				Baghouse Inlet				Baghouse Outlet			
	RUN 7	RUN 8	RUN 9	AVG.	RUN 7	RUN 8	RUN 9	AVG.	RUN 7	RUN 8	RUN 9	AVG.[c]
DIOXINS												
2378 TCDD	0.005	0.042	0.036	0.028	0.364	0.274	0.197	0.278	[0.043][b]	[0.023]	[0.011]	[0.026]
Other TCDD	0.855	1.104	0.814	0.924	3.044	2.232	1.229	2.168	[0.043]	(0.036)	[0.011]	0.036
12378 PCDD	0.199	0.193	0.150	0.180	0.852	0.681	0.421	0.651	[0.098]	[0.036]	[0.030]	[0.055]
Other PCDD	0.823	1.994	1.309	1.375	4.415	3.078	3.246	3.580	[0.098]	(0.059)	[0.030]	0.059
123478 HxCDD	0.167	0.245	0.199	0.203	1.007	0.940	0.679	0.875	[0.098]	[0.036]	[0.041]	[0.058]
123678 HxCDD	0.290	0.354	0.271	0.305	1.317	1.018	0.747	1.027	[0.055]	(0.036)	[0.022]	0.036
123789 HxCDD	0.489	0.677	0.689	0.618	2.246	2.036	1.630	1.971	[0.088]	[0.036]	[0.030]	[0.051]
Other HxCDD	1.581	3.202	1.515	2.099	7.823	6.657	5.093	6.524	(0.130)	0.131	0.114	0.125
1234678-HpCDD	2.903	4.270	4.295	3.823	17.195	14.490	12.154	14.613	0.403	0.416	0.320	0.380
Other Hepta-CDD	2.634	4.530	3.687	3.617	17.040	14.333	11.272	14.215	0.305	0.321	0.248	0.291
Octa-CDD	6.129	10.674	17.909	11.571	53.135	48.560	42.439	48.044	(1.305)	1.426	(1.549)	1.427
Total CDD	16.074	27.284	30.875	24.745	108.439	94.300	79.105	93.948	2.142	2.425	2.231	2.266
FURANS												
2378 TCDF	(1.720)	(1.510)	(0.446)	1.225	(2.092)	(1.566)	4.006	2.555	0.044	0.048	0.021	0.037
Other TCDF	10.107	13.694	12.075	11.959	30.131	24.045	14.803	22.993	0.501	0.666	0.227	0.465
12378 PCDF	1.129	1.093	0.689	0.970	2.943	2.506	2.037	2.496	[0.065]	0.059	[0.022]	0.059
23478 PCDF	1.720	1.874	1.053	1.549	5.809	4.073	3.327	4.403	0.076	(0.083)	0.052	0.070
Other PCDF	10.322	15.100	10.170	11.864	43.143	38.456	36.124	39.241	0.163	0.166	0.000	0.110
123478 HxCDF	5.698	6.300	5.794	5.931	21.146	19.267	14.938	18.450	0.250	0.214	0.165	0.210
123678 HxCDF	2.204	2.395	1.985	2.195	7.591	6.892	5.296	6.593	0.098	0.083	0.041	0.074
234678 HxCDF	5.376	5.884	5.267	5.509	20.061	21.617	13.309	18.329	0.316	0.190	0.248	0.251
123789 HxCDF	0.317	0.338	0.292	0.316	0.775	0.721	0.747	0.747	[0.088]	[0.023]	[0.030]	[0.047]
Other HxCDF	8.069	13.460	7.690	9.740	27.884	35.308	28.247	30.480	0.065	0.119	0.000	0.061
1234678-HpCDF	12.472	14.267	15.316	14.018	47.171	45.192	35.513	42.625	0.805	0.594	0.548	0.649
1234789-HpCDF	3.226	3.801	3.160	3.396	9.759	9.555	7.537	8.951	(0.163)	0.154	0.145	0.154
Other Hepta-CDF	13.547	14.579	12.237	13.454	43.763	40.023	31.642	38.476	0.501	0.321	0.548	0.456
Octa-CDF	22.955	26.712	34.319	27.995	100.693	85.371	70.618	85.561	1.741	1.307	1.344	1.464
TOTAL CDF	98.863	121.009	110.495	110.122	362.961	334.592	268.144	321.899	4.723	4.005	3.339	4.022
TOTAL CDD+CDF	114.937	148.293	141.37	134.867	471.40	428.89	347.249	415.847	6.866	6.429	5.57	6.288

a Standard conditions are defined as 1 atm and 68 °F.

b [ ] = Detection limit; () = Estimated maximum possible concentration.

c Detection limits are not considered when calculating averages.

TABLE 2-10. CDD/CDF FLUE GAS TOXIC EQUIVALENCIES FOR CONDITION 1

a,b,c

2378 TOXIC EQUIVALENCY CONCENTRATIONS (ng/dscm adjusted to 7 percent O2)

CONGENER	2378 TCDD Toxic Equivalency Factor	Condition 1 (No Carbon Injection)											
		Boiler Inlet				Baghouse Inlet				Baghouse Outlet			
		RUN 2	RUN 3	RUN 4	AVG.	RUN 2	RUN 3	RUN 4	AVG.	RUN 2	RUN 3	RUN 4	AVG.
DIOXINS													
2378 TCDD	1.000	(0.037)	(0.062)	0.044	0.048	0.057	0.131	0.142	0.110	0.053	(0.034)	(0.039)	0.042
Other TCDD	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
12378 PCDD	0.500	0.057	0.117	0.071	0.082	0.101	0.180	0.209	0.163	0.112	0.088	0.000	0.084
Other PCDD	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
123478 HxCDD	0.100	0.008	0.016	0.009	0.011	0.023	0.046	0.044	0.038	0.028	0.040	0.025	0.031
123678 HxCDD	0.100	(0.012)	0.019	0.012	0.014	0.032	0.060	0.077	0.056	0.034	0.048	0.000	0.036
123789 HxCDD	0.100	0.021	0.034	0.019	0.025	0.105	0.104	0.109	0.106	0.061	0.076	0.042	0.060
Other HxCDD	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1234678-HpCDD	0.010	0.012	0.018	0.011	0.014	0.049	0.086	0.122	0.086	0.042	0.083	0.014	0.046
Other Hepta-CDD	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Octa-CDD	0.001	0.004	0.006	0.004	0.005	0.019	0.030	0.039	0.029	0.011	0.018	0.002	0.010
Total CDD		0.152	0.272	0.169	0.198	0.387	0.637	0.742	0.589	0.378	0.386	0.122	0.309
FURANS													
2378 TCDF	0.100	(0.660)	(0.369)	(0.340)	0.456	(0.070)	(0.228)	(0.251)	0.183	0.045	0.036	0.029	0.037
Other TCDF	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
12378 PCDF	0.050	0.039	0.068	0.044	0.050	0.048	0.086	0.071	0.069	0.049	0.041	0.030	0.040
23478 PCDF	0.500	0.514	0.675	0.465	0.552	0.647	1.315	1.421	1.127	0.908	0.876	0.658	0.814
Other PCDF	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
123478 HxCDF	0.100	0.303	0.342	0.263	0.303	1.043	1.148	1.488	1.226	0.673	0.713	0.619	0.668
123678 HxCDF	0.100	0.109	0.153	0.100	0.121	0.259	0.401	0.460	0.373	0.224	0.257	0.171	0.217
234678 HxCDF	0.100	0.224	0.216	0.197	0.212	1.431	0.872	1.554	1.286	0.651	1.133	0.553	0.779
123789 HxCDF	0.100	0.012	0.019	0.013	0.015	0.105	0.043	0.069	0.072	0.030	0.000	0.011	0.022
Other HxCDF	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1234678-HpCDF	0.010	0.062	0.062	0.047	0.057	0.190	0.266	0.324	0.260	0.138	0.217	0.076	0.144
1234789-HpCDF	0.010	0.014	0.017	0.011	0.014	0.078	0.074	0.094	0.082	0.037	0.051	0.000	0.033
Other Hepta-CDF	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Octa-CDF	0.001	0.012	0.013	0.009	0.011	0.020	0.062	0.014	0.032	0.027	0.038	0.004	0.023
TOTAL CDF		1.949	1.935	1.489	1.791	3.890	4.496	5.745	4.710	2.782	3.363	2.152	2.778
TOTAL CDD+CDF		2.101	2.207	1.658	1.988	4.277	5.133	6.487	5.299	3.160	3.749	2.274	3.087

a North Atlantic Treaty Organization, Committee on the Challenges of Modern Society. Pilot Study on International Information Exchange on Dioxins and Related Compounds: International Toxicity Equivalency Factor (I-TEF) Methods of Risk Assessment for Complex Mixtures of Dioxins and Related Compounds. Report No. 176, August 1988.

b Standard conditions are defined as 1 atm and 68°F.

c Non-detects are not included in the totals.

TABLE 2-10 (CONT'D). CDD/CDF FLUE GAS TOXIC EQUIVALENCIES FOR CONDITION 2

a,b,c

2378 TOXIC EQUIVALENCY CONCENTRATIONS (ng/dscm adjusted to 7 percent O2)

CONGENER	2378 TCDD Toxic Equivalency Factor	Condition 2 (Carbon Injection = 1 lb/hr) BOILER INLET			BAGHOUSE INLET			BAGHOUSE OUTLET		
		RUN 5	RUN 6	AVERAGE	RUN 5	RUN 6	AVERAGE	RUN 5	RUN 6	AVERAGE
DIOXINS										
2378 TCDD	1.000	0.031	0.056	0.043	0.135	0.447	0.291	[0.034]	[0.026]	[0.030]
Other TCDD	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
12378 PCDD	0.500	0.047	0.111	0.079	0.179	0.513	0.346	[0.048]	[0.039]	[0.044]
Other PCDD	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
123478 HxCDD	0.100	0.007	0.015	0.011	0.046	0.139	0.092	[0.012]	[0.009]	[0.011]
123678 HxCDD	0.100	0.010	0.018	0.014	0.056	0.139	0.098	(0.014)	[0.005]	0.014
123789 HxCDD	0.100	0.022	0.031	0.026	0.101	0.242	0.171	0.023	[0.006]	0.023
Other HxCDD	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1234678-HpCDD	0.010	0.015	0.016	0.015	0.099	0.179	0.139	0.014	0.007	0.011
Other Hepta-CDD	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Octa-CDD	0.001	0.008	0.005	0.006	0.045	0.048	0.046	0.003	0.003	0.003
Total CDD		0.189	0.312	0.195	0.660	1.706	1.183	0.148	0.095	0.051
FURANS										
2378 TCDF	0.100	(0.375)	(0.204)	0.290	(0.175)	0.190	0.183	0.009	0.005	0.007
Other TCDF	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
12378 PCDF	0.050	0.025	0.060	0.043	0.061	0.209	0.135	[0.006]	[0.002]	0.006
23478 PCDF	0.500	0.369	0.740	0.555	1.180	3.588	2.384	[0.111]	0.057	0.084
Other PCDF	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
123478 HxCDF	0.100	0.260	0.342	0.301	1.139	2.563	1.851	0.090	0.053	0.071
123678 HxCDF	0.100	0.089	0.157	0.123	0.357	0.974	0.666	0.033	0.015	0.024
234678 HxCDF	0.100	0.198	0.333	0.265	1.072	2.746	1.909	0.101	(0.058)	0.079
123789 HxCDF	0.100	0.010	0.019	0.014	0.048	0.088	0.068	[0.008]	[0.006]	[0.007]
Other HxCDF	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1234678-HpCDF	0.010	0.062	0.068	0.065	0.288	0.399	0.343	0.021	0.014	0.017
1234789-HpCDF	0.010	0.014	0.014	0.014	0.087	0.081	0.084	0.003	[0.003]	0.003
Other Hepta-CDF	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Octa-CDF	0.001	0.016	0.010	0.013	0.078	0.092	0.085	0.001	0.003	0.002
TOTAL CDF		1.419	1.946	1.683	4.484	10.929	7.706	0.383	0.215	0.291
TOTAL CDD+CDF		1.609	2.258	1.878	5.144	12.635	8.890	0.531	0.310	0.342

a North Atlantic Treaty Organization, Committee on the Challenges of Modern Society. Pilot Study on International Information Exchange on Dioxins and Related Compounds: International Toxicity Equivalency Factor (I-TEF) Methods of Risk Assessment for Complex Mixtures of Dioxins and Related Compounds. Report No. 176, August 1988.

b Standard conditions are defined as 1 atm and 68°F.

c Non-detects are not included in the totals.

TABLE 2-10 (CONT'D). CDD/CDF FLUE GAS TOXIC EQUIVALENCIES FOR CONDITION 3

a,b,c

2378 TOXIC EQUIVALENCY CONCENTRATIONS (ng/dscm adjusted to 7 percent O2)

CONGENER	2378 TCDD Toxic Equivalency Factor	Condition 3 (Carbon Injection = 2.5 lb/hr)											
		BOILER INLET				BAGHOUSE INLET				BAGHOUSE OUTLET			
		RUN 7	RUN 8	RUN 9	AVG.	RUN 7	RUN 8	RUN 9	AVG.	RUN 7	RUN 8	RUN 9	AVG.
DIOXINS													
2378 TCDD	1.000	0.005	0.042	0.036	0.028	0.364	0.274	0.197	0.278	[0.043]	[0.023]	[0.011]	[0.026]
Other TCDD	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
12378 PCDD	0.500	0.099	0.096	0.075	0.090	0.426	0.341	0.210	0.326	[0.049]	[0.018]	[0.015]	[0.028]
Other PCDD	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
123478 HxCDD	0.100	0.017	0.024	0.020	0.020	0.101	0.094	0.068	0.088	[0.010]	[0.004]	[0.004]	[0.006]
123678 HxCDD	0.100	0.029	0.035	0.027	0.031	0.132	0.102	0.075	0.103	[0.006]	[0.004]	[0.002]	[0.004]
123789 HxCDD	0.100	0.049	0.068	0.069	0.062	0.225	0.204	0.163	0.197	[0.009]	[0.004]	[0.003]	[0.005]
Other HxCDD	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1234678-HpCDD	0.010	0.029	0.043	0.043	0.038	0.172	0.145	0.122	0.146	0.004	0.004	0.003	0.004
Other Hepta-CDD	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Octa-CDD	0.001	0.006	0.011	0.018	0.012	0.053	0.049	0.042	0.048	(0.001)	0.001	(0.002)	0.001
Total CDD		0.235	0.319	0.288	0.281	1.472	1.208	0.877	1.186	0.122	0.059	0.040	0.007
FURANS													
2378 TCDF	0.100	(0.172)	(0.151)	(0.045)	0.123	(0.209)	(0.157)	0.401	0.256	0.004	0.005	0.002	0.004
Other TCDF	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
12378 PCDF	0.050	0.056	0.055	0.034	0.049	0.147	0.125	0.102	0.125	[0.003]	0.003	[0.001]	0.003
23478 PCDF	0.500	0.860	0.937	0.527	0.775	2.905	2.036	1.664	2.202	0.038	[0.042]	0.026	0.035
Other PCDF	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
123478 HxCDF	0.100	0.570	0.630	0.579	0.593	2.115	1.927	1.494	1.845	0.025	0.021	0.017	0.021
123678 HxCDF	0.100	0.220	0.240	0.199	0.219	0.759	0.689	0.530	0.659	0.010	0.008	0.004	0.007
234678 HxCDF	0.100	0.538	0.588	0.527	0.551	2.006	2.162	1.331	1.833	0.032	0.019	0.025	0.025
123789 HxCDF	0.100	0.032	0.034	0.029	0.032	0.077	0.072	0.075	0.075	[0.009]	[0.002]	[0.003]	[0.005]
Other HxCDF	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1234678-HpCDF	0.010	0.125	0.143	0.153	0.140	0.472	0.452	0.355	0.426	0.008	0.006	0.005	0.006
1234789-HpCDF	0.010	0.032	0.038	0.032	0.034	0.098	0.096	0.075	0.090	[0.002]	0.002	0.001	0.002
Other Hepta-CDF	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Octa-CDF	0.001	0.023	0.027	0.034	0.028	0.101	0.085	0.071	0.086	0.002	0.001	0.001	0.001
TOTAL CDF		5.319	4.956	2.159	2.543	8.888	7.801	6.097	7.595	0.119	0.129	0.086	0.103
TOTAL CDD+CDF		5.554	5.275	2.447	2.824	10.360	9.009	6.974	8.781	0.241	0.188	0.126	0.110

a North Atlantic Treaty Organization, Committee on the Challenges of Modern Society. Pilot Study on International Information Exchange on Dioxins and Related Compounds: International Toxicity Equivalency Factor (I-TEF) Methods of Risk Assessment for Complex Mixtures of Dioxins and Related Compounds. Report No. 176, August 1988.

b Standard conditions are defined as 1 atm and 68°F.

c Non-detects are not included in the totals.

TABLE 2-11. CDD/CDF EMISSIONS WITH BAGHOUSE TO BOILER RATIOS BORGESS MEDICAL CENTER (1991)

CONGENER	RUN 2			RUN 3			RUN 4			RUN 5		
	Boiler Inlet (ug/hr)	Baghouse Inlet (ug/hr)	Baghouse/ Boiler Ratio (ug/hr)	Boiler Inlet (ug/hr)	Baghouse Inlet (ug/hr)	Baghouse/ Boiler Ratio (ug/hr)	Boiler Inlet (ug/hr)	Baghouse Inlet (ug/hr)	Baghouse/ Boiler Ratio (ug/hr)	Boiler Inlet (ug/hr)	Baghouse Inlet (ug/hr)	Baghouse/ Boiler Ratio (ug/hr)
DIOXINS												
2378 TCDD	(0.065)[a]	0.079	1.221	(0.096)	0.196	2.042	0.063	0.176	2.768	0.050	0.200	4.006
Other TCDD	0.541	0.283	0.524	1.119	1.764	1.576	0.587	1.478	2.517	0.498	1.596	3.205
12378 PCDD	0.201	0.283	1.407	0.359	0.536	1.493	0.206	0.517	2.505	0.149	0.529	3.539
Other PCDD	0.965	1.530	1.586	1.299	2.043	1.573	0.698	2.584	3.700	0.797	1.666	2.091
123478 HxCDD	0.148	0.329	2.215	0.249	0.681	2.738	0.127	0.548	4.314	0.116	0.678	5.838
123678 HxCDD	(0.202)	0.453	2.245	0.290	0.897	3.094	0.175	0.951	5.447	0.166	0.828	4.988
123789 HxCDD	0.371	1.474	3.971	0.525	1.547	2.948	0.270	1.344	4.980	0.349	1.496	4.293
Other HxCDD	1.283	2.845	2.218	1.837	5.643	3.071	0.809	4.600	5.682	1.195	4.878	4.081
1234678-HpCDD	2.121	6.915	3.261	2.763	12.895	4.667	1.524	15.091	9.904	2.324	14.664	6.310
Other Hepta-CDD	2.015	0.000	0.000	2.210	12.895	5.834	1.333	14.367	10.776	2.324	13.068	5.623
Octa-CDD	6.786	26.527	3.909	8.565	44.256	5.167	5.873	48.684	8.290	13.114	66.439	5.066
Total CDD	14.698	40.720	2.770	19.312	83.353	4.316	11.666	90.339	7.744	21.082	106.043	5.030
FURANS												
2378 TCDF	(11.558)	(0.976)	0.085	(5.665)	(3.403)	0.601	(4.920)	(3.101)	0.630	(5.978)	(2.593)	0.434
Other TCDF	10.603	6.008	0.567	22.380	25.584	1.143	10.158	20.879	2.055	10.292	20.051	1.948
12378 PCDF	1.378	1.360	0.987	2.072	2.579	1.245	1.270	1.757	1.384	0.813	1.796	2.208
23478 PCDF	1.803	1.814	1.006	2.072	3.920	1.892	1.349	3.514	2.605	1.179	3.492	2.962
Other PCDF	14.421	12.697	0.880	19.479	33.114	1.700	8.016	29.562	3.688	9.628	29.927	3.108
123478 HxCDF	5.302	14.624	2.758	5.250	17.125	3.262	3.809	18.399	4.830	4.150	16.859	4.062
123678 HxCDF	1.909	3.628	1.901	2.349	5.983	2.548	1.444	5.685	3.936	1.428	5.287	3.704
234678 HxCDF	3.923	20.065	5.114	3.316	12.998	3.920	2.857	19.226	6.729	3.154	15.862	5.029
123789 HxCDF	0.212	1.474	6.949	0.290	0.640	2.205	0.190	0.848	4.450	0.166	0.708	4.267
Other HxCDF	10.391	18.138	1.745	11.452	34.125	2.980	4.238	32.435	7.654	6.374	30.815	4.834
1234678-HpCDF	10.815	26.640	2.463	9.532	39.717	4.167	6.825	40.105	5.876	9.960	42.597	4.277
1234789-HpCDF	2.439	10.883	4.462	2.625	11.038	4.205	1.571	11.577	7.367	2.158	12.869	5.963
Other Hepta-CDF	12.194	33.442	2.743	9.808	43.327	4.417	6.841	49.614	7.253	10.956	49.280	4.498
Octa-CDF	20.889	28.567	1.368	20.170	92.225	4.572	13.015	17.882	1.374	25.232	114.722	4.547
TOTAL CDF	107.829	180.315	1.672	116.459	325.777	2.797	66.505	254.584	3.828	91.468	346.858	3.792
TOTAL CDD+CD	122.527	221.035	1.804	135.772	409.131	3.013	78.171	344.923	4.412	112.550	452.901	4.024

[a] [ ] = Detection limit; () = Estimated maximum possible concentration.

TABLE 2-11 (CONT'D). CDD/CDF EMISSIONS WITH BAGHOUSE TO BOILER RATIOS
BORGESS MEDICAL CENTER (1991)

	RUN 6			RUN 7			RUN 8			RUN 9		
CONGENER	Boiler Inlet (ug/hr)	Baghouse Inlet (ug/hr)	Baghouse/ Boiler Ratio (ug/hr)	Boiler Inlet (ug/hr)	Baghouse Inlet (ug/hr)	Baghouse/ Boiler Ratio (ug/hr)	Boiler Inlet (ug/hr)	Baghouse Inlet (ug/hr)	Baghouse/ Boiler Ratio (ug/hr)	Boiler Inlet (ug/hr)	Baghouse Inlet (ug/hr)	Baghouse/ Boiler Ratio (ug/hr)
DIOXINS												
2378 TCDD	0.095	0.630	6.596	0.008	0.491	58.153	0.067	0.366	5.493	0.071	0.294	4.121
Other TCDD	8.818	5.566	0.631	1.342	4.103	3.058	1.768	2.984	1.688	1.595	1.837	1.152
12378 PCDD	0.382	1.446	3.784	0.312	1.148	3.678	0.309	0.911	2.952	0.294	0.629	2.143
Other PCDD	2.642	8.261	3.127	1.291	5.950	4.610	3.194	4.115	1.288	2.564	4.851	1.892
123478 HxCDD	0.255	1.962	7.704	0.262	1.357	5.189	0.392	1.256	3.206	0.389	1.015	2.610
123678 HxCDD	0.302	1.962	6.488	0.456	1.775	3.895	0.567	1.361	2.400	0.532	1.116	2.100
123789 HxCDD	0.525	3.407	6.488	0.768	3.027	3.943	1.084	2.722	2.511	1.349	2.436	1.805
Other HxCDD	2.260	11.462	5.071	2.481	10.544	4.251	5.129	8.900	1.735	2.968	7.612	2.564
1234678-HpCDD	2.706	25.298	9.350	4.556	23.175	5.087	6.839	19.371	2.833	8.413	18.168	2.160
Other Hepta-CDD	2.387	23.852	9.991	4.134	22.966	5.555	7.255	19.161	2.641	7.222	16.848	2.333
Octa-CDD	7.799	67.427	8.646	9.618	71.613	7.445	17.096	64.918	3.797	35.080	63.434	1.808
Total CDD	28.172	151.272	5.370	25.227	146.149	5.793	43.700	126.066	2.885	60.477	118.242	1.955
FURANS	a											
2378 TCDF	(3.501)	2.685	0.767	(2.700)	(2.819)	1.044	(2.419)	(2.094)	0.866	(0.875)	5.988	6.844
Other TCDF	24.193	61.335	2.535	15.862	40.609	2.560	21.933	32.145	1.466	23.651	22.126	0.936
12378 PCDF	2.069	5.886	2.845	1.772	3.967	2.239	1.751	3.351	1.913	1.349	3.045	2.257
23478 PCDF	2.547	10.119	3.974	2.700	7.829	2.900	3.002	5.445	1.814	2.064	4.973	2.410
Other PCDF	20.373	86.323	4.237	16.199	58.147	3.589	24.185	51.411	2.126	19.921	53.995	2.710
123478 HxCDF	5.889	36.140	6.137	8.943	28.499	3.187	10.091	25.758	2.553	11.349	22.329	1.967
123678 HxCDF	2.706	13.733	5.076	3.459	10.230	2.957	3.836	9.214	2.402	3.889	7.917	2.036
234678 HxCDF	5.730	38.721	6.758	8.437	27.038	3.205	9.424	28.899	3.067	10.318	19.893	1.928
123789 HxCDF	0.318	1.239	3.893	0.498	1.044	2.097	0.542	0.963	1.777	0.571	1.116	1.954
Other HxCDF	12.256	69.182	5.645	12.664	37.581	2.968	21.558	47.201	2.190	15.064	42.222	2.803
1234678-HpCDF	11.619	56.275	4.843	19.574	63.575	3.248	22.851	60.415	2.644	30.001	53.082	1.769
1234789-HpCDF	2.387	11.358	4.758	5.062	13.153	2.598	6.088	12.774	2.098	6.191	11.266	1.820
Other Hepta-CDF	10.505	54.210	5.161	21.262	58.982	2.774	23.351	53.505	2.291	23.969	47.297	1.973
Octa-CDF	16.394	130.104	7.936	36.027	135.710	3.767	42.782	114.129	2.668	67.223	105.555	1.570
TOTAL CDF	120.486	577.310	4.792	155.159	489.183	3.153	193.814	447.303	2.308	216.434	400.804	1.852
TOTAL CDD+CDF	148.658	728.582	4.901	180.386	635.332	3.522	237.514	573.369	2.414	276.912	519.046	1.874

a

( ) = Estimated maximum possible concentration

TABLE 2-12. CDD/CDF BAGHOUSE INLET AND OUTLET EMISSIONS AND REMOVAL EFFICIENCIES FOR CONDITION 1; BORGESS MEDICAL CENTER (1991)

CONGENER	RUN 2 EMISSIONS			RUN 3 EMISSIONS			RUN 4 EMISSIONS		
	INLET (ug/hr)	OUTLET (ug/hr)	REMOVAL EFFICIENCY	INLET (ug/hr)	OUTLET (ug/hr)	REMOVAL EFFICIENCY	INLET (ug/hr)	OUTLET (ug/hr)	REMOVAL EFFICIENCY
DIOXINS					[a]				
2378 TCDD	0.08	0.087	-9.4%	0.20	(0.052)	74.0%	0.18	(0.054)	69.3%
Other TCDD	0.28	0.851	-200.2%	1.76	0.686	61.1%	1.48	0.479	67.6%
12378 PCDD	0.28	0.365	-28.7%	0.54	0.264	50.8%	0.52	(0.148)	71.5%
Other PCDD	1.53	2.066	-35.0%	2.04	1.494	26.9%	2.58	0.848	67.2%
123478 HxCDD	0.33	0.451	-37.3%	0.68	0.598	12.2%	0.55	0.350	36.1%
123678 HxCDD	0.45	0.556	-22.5%	0.90	0.721	19.7%	0.95	(0.350)	63.2%
123789 HxCDD	1.47	0.990	32.8%	1.55	1.143	26.2%	1.34	0.590	56.1%
Other HxCDD	2.85	3.907	-37.3%	5.64	4.394	22.1%	4.60	2.746	40.3%
1234678-HpCDD	6.92	6.772	2.1%	12.89	12.480	3.2%	15.09	2.027	86.6%
Other Hepta-CDD	0.00	6.425	NA	12.89	11.777	8.7%	14.37	2.580	82.0%
Octa-CDD	26.53	18.233	31.3%	44.26	26.366	40.4%	48.68	2.211	95.5%
Total CDD	40.72	40.703	0.0%	83.35	59.973	28.0%	90.34	12.383	86.3%
FURANS									
2378 TCDF	(0.976)	0.729	25.3%	(3.403)	0.545	84.0%	(3.101)	0.405	86.9%
Other TCDF	6.01	16.983	-182.7%	25.58	15.099	41.0%	20.88	13.416	35.7%
12378 PCDF	1.36	1.580	-16.2%	2.58	1.248	51.6%	1.76	0.848	51.8%
23478 PCDF	1.81	2.952	-62.8%	3.92	2.637	32.7%	3.51	1.843	47.6%
Other PCDF	12.70	21.342	-68.1%	33.11	19.142	42.2%	29.56	15.554	47.4%
123478 HxCDF	14.62	10.940	25.2%	17.12	10.722	37.4%	18.40	8.662	52.9%
123678 HxCDF	3.63	3.647	-0.5%	5.98	3.867	35.4%	5.68	2.396	57.9%
234678 HxCDF	20.07	10.593	47.2%	13.00	17.050	-31.2%	19.23	7.740	59.7%
123789 HxCDF	1.47	0.486	67.0%	0.64	(0.403)	37.0%	0.85	0.147	82.6%
Other HxCDF	18.14	14.100	22.3%	34.13	14.413	57.8%	32.44	11.463	64.7%
1234678-HpCDF	26.64	22.401	15.9%	39.72	32.694	17.7%	40.10	10.689	73.3%
1234789-HpCDF	10.88	6.078	44.2%	11.04	7.734	29.9%	11.58	(1.509)	87.0%
Other Hepta-CDF	33.44	26.221	21.6%	43.33	34.451	20.5%	49.61	11.426	77.0%
Octa-CDF	28.57	44.107	-54.4%	92.22	57.653	37.5%	17.88	5.344	70.1%
TOTAL CDF	180.3	182.158	-1.0%	325.8	217.658	33.2%	254.6	91.442	64.1%
TOTAL CDD+CDF	221.0	222.862	-0.8%	409.1	277.631	32.1%	344.9	103.825	69.9%

[a] [ ] = Detection limit; () = Estimated maximum possible concentration.

TABLE 2-13. CDD/CDF BAGHOUSE INLET AND OUTLET EMISSIONS AND REMOVAL REMOVAL EFFICIENCIES FOR CONDITION 2; BORGESS MEDICAL CENTER (1991)

	RUN 5 EMISSIONS			RUN 6 EMISSIONS		
CONGENER	INLET (ug/hr)	OUTLET (ug/hr)	REMOVAL EFFICIENCY	INLET (ug/hr)	OUTLET (ug/hr)	REMOVAL EFFICIENCY
DIOXINS		[a]				
2378 TCDD	0.20	[0.053]	73.5%	0.63	[0.036]	94.3%
Other TCDD	1.60	0.054	96.6%	5.57	0.053	99.0%
12378 PCDD	0.53	[0.145]	72.6%	1.45	[0.108]	92.6%
Other PCDD	1.67	0.197	88.2%	8.26	0.124	98.5%
123478 HxCDD	0.68	[0.178]	73.8%	1.96	[0.123]	93.7%
123678 HxCDD	0.83	(0.214)	74.2%	1.96	[0.072]	96.3%
123789 HxCDD	1.50	0.359	76.0%	3.41	[0.090]	97.4%
Other HxCDD	4.88	1.309	73.2%	11.46	0.355	96.9%
1234678-HpCDD	14.66	2.151	85.3%	25.30	1.048	95.9%
Other Hepta-CDD	13.07	2.510	80.8%	23.85	0.906	96.2%
Octa-CDD	66.44	4.481	93.3%	67.43	3.553	94.7%
Total CDD	106.04	11.274	89.4%	151.27	6.040	96.0%
FURANS						
2378 TCDF	(2.593)	0.143	94.5%	2.68	0.071	97.4%
Other TCDF	20.05	2.187	89.1%	61.33	0.640	99.0%
12378 PCDF	1.80	(0.178)	90.1%	5.89	[0.054]	99.1%
23478 PCDF	3.49	(0.339)	90.3%	10.12	0.160	98.4%
Other PCDF	29.93	2.151	92.8%	86.32	0.515	99.4%
123478 HxCDF	16.86	1.380	91.8%	36.14	0.746	97.9%
123678 HxCDF	5.29	0.502	90.5%	13.73	0.213	98.4%
234678 HxCDF	15.86	1.542	90.3%	38.72	(0.816)	100.0%
123789 HxCDF	0.71	[0.125]	82.4%	1.24	[0.090]	92.7%
Other HxCDF	30.82	1.954	93.7%	69.18	0.266	99.6%
1234678-HpCDF	42.60	3.227	92.4%	56.28	1.954	96.5%
1234789-HpCDF	12.87	0.394	96.9%	11.36	(0.426)	100.0%
Other Hepta-CDF	49.28	2.474	95.0%	54.21	2.132	96.1%
Octa-CDF	114.72	2.151	98.1%	130.10	3.731	97.1%
TOTAL CDF	346.9	18.622	94.6%	577.3	11.670	98.0%
TOTAL CDD+CDF	452.9	29.896	93.4%	728.6	17.710	97.6%

[a] [ ] = Detection limit; () = Estimated maximum possible concentration.

Table 2-10 presents 2378 TCDD TEC in the flue gas for the 3 conditions. Total CDD/CDF TECs at the boiler inlet range from 1.6 ng/dscm at 7 percent O_2 for Run 5 to 5.6 ng/dscm at 7 percent O_2 for Run 7. Baghouse inlet TECs at 7 percent O_2 ranged from 4.3 ng/dscm for Run 2 to 12.6 ng/dscm for Run 6. Baghouse outlet TEC values at 7 percent O_2 ranged from 0.13 ng/dscm for Run 9 to 3.7 ng/dscm at 7 percent O_2 for Run 3.

Table 2-11 presents the CDD/CDF mass emission rates for the boiler inlet and baghouse inlet. The ratio of baghouse inlet to boiler inlet is given to show the magnitude of CDD/CDF formation in the boiler.

Table 2-12 presents the flue gas CDD/CDF mass emission rates for the baghouse inlet and outlet at test Condition 1. Baghouse inlet and outlet mass rates are presented with removal efficiencies to show the effectiveness of CDD/CDF removal through the baghouse. For Condition 1, total removal efficiency ranged from no removal for Run 2 to almost 70 percent for Run 4.

Tables 2-13 and 2-14 present the CDD/CDF mass emission rates for the baghouse inlet and baghouse outlet at Conditions 2 and 3, respectively. As shown in Table 2-13, with carbon injection at 1 lb/hr, total CDD/CDF removal efficiency for Run 5 was 93.4 percent, and the removal efficiency for Run 6 was 97.6 percent. Table 2-14 shows total CDD/CDF removal efficiencies (with carbon injection at 2.5 lb/hr) over 98 percent for Runs 7, 8, and 9.

2.2.4 CDD/CDF Flue Gas Sample Parameters

The CDD/CDF flue gas sample parameters for each of the 8 runs at the 3 sampling locations are shown in Tables 2-15 through 2-17. Sampling rate, meter volume, stack gas temperature, gas O_2/CO/H_2O concentrations, stack gas flow rates, and isokinetic parameters are shown.

2.2.5 CDD/CDF Ash Results

Daily samples were taken of both the incinerator bottom ash and the baghouse ash.

TABLE 2-14. CDD/CDF BAGHOUSE INLET AND OUTLET EMISSIONS AND REMOVAL EFFICIENCIES FOR CONDITION 3; BORGESS MEDICAL CENTER (1991)

CONGENER	RUN 7 EMISSIONS			RUN 8 EMISSIONS			RUN 9 EMISSIONS		
	INLET (ug/hr)	OUTLET (ug/hr)	REMOVAL EFFICIENCY	INLET (ug/hr)	OUTLET (ug/hr)	REMOVAL EFFICIENCY	INLET (ug/hr)	OUTLET (ug/hr)	REMOVAL EFFICIENCY
DIOXINS		[a]							
2378 TCDD	0.49	[0.071]	85.5%	0.37	[0.035]	90.4%	0.29	[0.018]	93.9%
Other TCDD	4.10	[0.071]	98.3%	2.98	(0.055)	98.2%	1.84	[0.018]	99.0%
12378 PCDD	1.15	[0.163]	85.8%	0.91	[0.055]	94.0%	0.63	[0.052]	91.7%
Other PCDD	5.95	[0.163]	97.3%	4.11	(0.090)	97.8%	4.85	[0.052]	98.9%
123478 HxCDD	1.36	[0.163]	88.0%	1.26	[0.055]	95.6%	1.01	[0.070]	93.1%
123678 HxCDD	1.77	[0.092]	94.8%	1.36	(0.055)	96.0%	1.12	[0.037]	96.7%
123789 HxCDD	3.03	[0.146]	95.2%	2.72	[0.055]	98.0%	2.44	[0.052]	97.9%
Other HxCDD	10.54	(0.217)	97.9%	8.90	0.198	97.8%	7.61	0.194	97.4%
1234678-HpCDD	23.18	0.673	97.1%	19.37	0.629	96.8%	18.17	0.548	97.0%
Other Hepta-CDD	22.97	0.509	97.8%	19.16	0.486	97.5%	16.85	0.424	97.5%
Octa-CDD	71.61	(2.181)	97.0%	64.92	2.158	96.7%	63.43	(2.650)	95.8%
Total CDD	146.15	3.580	97.6%	126.07	3.671	97.1%	118.24	3.817	96.8%
FURANS									
2378 TCDF	(2.819)	0.073	97.4%	(2.094)	0.072	96.6%	5.99	0.035	99.4%
Other TCDF	40.61	0.837	97.9%	32.14	1.007	96.9%	27.13	0.389	98.2%
12378 PCDF	3.97	[0.109]	98.6%	3.35	0.090	97.3%	3.04	[0.037]	98.8%
23478 PCDF	7.83	0.127	98.4%	5.44	(0.125)	97.7%	4.97	0.088	98.2%
Other PCDF	58.15	0.273	99.5%	51.41	0.252	99.5%	54.00	0.000	100.0%
123478 HxCDF	28.50	0.418	98.5%	25.76	0.324	98.7%	22.33	0.283	98.7%
123678 HxCDF	10.23	0.164	98.4%	9.21	0.126	98.6%	7.92	0.071	99.1%
234678 HxCDF	27.04	0.527	98.0%	28.90	0.288	99.0%	19.89	0.424	97.9%
123789 HxCDF	1.04	[0.146]	91.4%	0.96	[0.035]	96.4%	1.12	[0.052]	95.3%
Other HxCDF	37.58	0.109	99.7%	47.20	0.180	99.6%	42.22	0.000	100.0%
1234678-HpCDF	63.57	1.346	97.9%	60.42	0.899	98.5%	53.08	0.937	98.2%
1234789-HpCDF	13.15	(0.272)	97.9%	12.77	0.234	98.2%	11.27	0.247	97.8%
Other Hepta-CDF	58.98	0.837	98.6%	53.50	0.486	99.1%	47.30	0.937	98.0%
Octa-CDF	135.71	2.910	97.9%	114.13	1.978	98.3%	105.55	2.298	97.8%
TOTAL CDF	489.2	7.892	98.4%	447.3	6.060	98.6%	400.8	5.710	98.6%
TOTAL CDD+CDF	635.3	11.472	98.2%	573.4	9.730	98.3%	519.0	9.526	98.2%

[a] [ ] = Detection limit; () = Estimated maximum possible concentration.

TABLE 2-15. CDD/CDF EMISSIONS SAMPLING AND FLUE GAS PARAMETERS AT THE BOILER INLET; BORGESS MEDICAL CENTER (1991)

	CONDITION 1			
RUN NUMBER DATE	Run 2 09/07/91	Run 3 09/09/91	Run 4 09/10/91	AVERAGE
Total Sampling Time (min.)	240	239	240	239.67
Average Sampling Rate (dscfm)	0.45	0.33	0.31	0.36
Metered Volume (dscf)	108.31	79	75.07	87.46
Metered Volume (dscm)	3.067	2.237	2.126	2.477
Average Stack Temperature (°F)	1377	1205	1122	1234
O2 Concentration (%V)*	13.4	14.0	14.9	14.1
CO2 Concentration (%V)*	5.0	5.0	4.1	4.7
Stack Gas Moisture (%V)	13.0	21.9	12.9	16.0
Volumetric Flow Rate (dscfm)	1914	1819	1986	1906
Volumetric Flow Rate (dscmm)	54.20	51.51	45.24	50.32
Percent Isokinetic	109.6	109.9	98.9	106.1
		CONDITION 2		
RUN NUMBER DATE		Run 5 09/11/91	Run 6 09/12/91	AVERAGE
Total Sampling Time (min.)		240	240	240.00
Average Sampling Rate (dscfm)		0.3	0.33	0.32
Metered Volume (dscf)		72.26	79.92	76.09
Metered Volume (dscm)		2.046	2.263	2.15
Average Stack Temperature (°F)		1127	1086	1106
O2 Concentration (%V)*		14.4	14.3	14.3
CO2 Concentration (%V)*		4.2	3.9	4.1
Stack Gas Moisture (%V)		13.1	15.1	14.1
Volumetric Flow Rate (dscfm)		1999	2120	2059
Volumetric Flow Rate (dscmm)		56.61	60.03	58.32
Percent Isokinetic		94.6	98.6	96.6
	CONDITION 3			
RUN NUMBER DATE	Run 7 09/13/91	Run 8 09/14/91	Run 9 09/16/91	AVERAGE
Total Sampling Time (min.)	240	240	240	240.00
Average Sampling Rate (dscfm)	0.59	0.61	0.66	0.62
Metered Volume (dscf)	142.67	145.7	157.51	148.63
Metered Volume (dscm)	4.04	4.126	4.461	4.209
Average Stack Temperature (°F)	1166	1166	1302	1211
O2 Concentration (%V)*	14.5	14.4	13.2	14.0
CO2 Concentration (%V)*	3.3	3.1	5.0	3.8
Stack Gas Moisture (%V)	13.5	13.6	15.9	14.3
Volumetric Flow Rate (dscfm)	2006	2025	2084	2038
Volumetric Flow Rate (dscmm)	56.81	57.35	59.01	57.72
Percent Isokinetic	92.9	94.0	98.8	95.2

* O2 and CO2 were measured at the baghouse inlet.

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TABLE 2-16. CDD/CDF EMISSIONS SAMPLING AND FLUE GAS PARAMETERS AT THE BAGHOUSE INLET; BORGESS MEDICAL CENTER (1991)

	CONDITION 1			
RUN NUMBER DATE	Run 2 09/07/91	Run 3 09/09/91	Run 4 09/10/91	AVERAGE
Total Sampling Time (min.)	240	240	240	240
Average Sampling Rate (dscfm)	0.34	0.42	0.41	0.39
Metered Volume (dscf)	81.07	101.19	98.36	93.54
Metered Volume (dscm)	2.296	2.866	2.786	2.649
Average Stack Temperature (°F)	365	359	357	360
O2 Concentration (%V)	13.4	13.9	14.9	14.1
CO2 Concentration (%V)	5.0	4.2	4.1	4.4
Stack Gas Moisture (%V)	12.3	12.5	12.1	12.3
Volumetric Flow Rate (dscfm)	1532	1740	1695	1655
Volumetric Flow Rate (dscmm)	43.38	49.28	48.00	46.88
Percent Isokinetic	104.6	102.7	102.5	103.3

	CONDITION 2		
RUN NUMBER DATE	Run 5 09/11/91	Run 6 09/12/91	AVERAGE
Total Sampling Time (min.)	240	240	240
Average Sampling Rate (dscfm)	0.46	0.42	0.44
Metered Volume (dscf)	111.51	100.96	106.24
Metered Volume (dscm)	3.158	2.859	3.01
Average Stack Temperature (°F)	359	369	364
O2 Concentration (%V)	14.4	14.3	14.3
CO2 Concentration (%V)	4.2	3.9	4.1
Stack Gas Moisture (%V)	12.4	13.5	13.0
Volumetric Flow Rate (dscfm)	1854	1737	1796
Volumetric Flow Rate (dscmm)	52.51	49.20	50.85
Percent Isokinetic	106.3	102.7	104.5

	CONDITION 3			
RUN NUMBER DATE	Run 7 09/13/91	Run 8 09/14/91	Run 9 09/16/91	AVERAGE
Total Sampling Time (min.)	240	240	240	240
Average Sampling Rate (dscfm)	0.41	0.40	0.39	0.40
Metered Volume (dscf)	99.01	96.86	93.98	96.62
Metered Volume (dscm)	2.804	2.743	2.662	2.736
Average Stack Temperature (°F)	368	360	373	367
O2 Concentration (%V)	14.5	14.4	13.2	14.0
CO2 Concentration (%V)	3.3	3.1	5.0	3.8
Stack Gas Moisture (%V)	13.1	13.3	15.1	13.8
Volumetric Flow Rate (dscfm)	1723	1690	1590	1668
Volumetric Flow Rate (dscmm)	48.79	47.69	45.03	47.17
Percent Isokinetic	101.5	101.2	104.4	102.4

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TABLE 2-17. CDD/CDF EMISSIONS SAMPLING AND FLUE GAS PARAMETERS AT THE BAGHOUSE OUTLET, BORGESS MEDICAL CENTER (1991)

	CONDITION 1			
RUN NUMBER DATE	Run 2 09/07/91	Run 3 09/09/91	Run 4 09/10/91	AVERAGE
Total Sampling Time (min.)	240	240	240	240.00
Average Sampling Rate (dscfm)	0.33	0.33	0.31	0.32
Metered Volume (dscf)	78.57	80.21	74.56	77.78
Metered Volume (dscm)	2.225	2.271	2.111	2.202
Average Stack Temperature (°F)	292	296	290	293
O2 Concentration (%V)	15.05	15.66	15.90	15.5
CO2 Concentration (%V)	4.69	4.19	4.19	4.4
Stack Gas Moisture (%V)	14.49	9.06	9.78	11.1
Volumetric Flow Rate (dscfm)	2274	2349	2290	2304
Volumetric Flow Rate (dscmm)	64.40	66.53	64.84	65.25
Percent Isokinetic	103.15	101.93	97.22	100.77
		CONDITION 2		
RUN NUMBER DATE		Run 5 09/11/91	Run 6 09/12/91	AVERAGE
Total Sampling Time (min.)		240	240	240.00
Average Sampling Rate (dscfm)		0.33	0.3	0.32
Metered Volume (dscf)		79.57	71.78	75.68
Metered Volume (dscm)		2.253	2.033	2.14
Average Stack Temperature (°F)		286	291	289
O2 Concentration (%V)		15.63	15.46	15.55
CO2 Concentration (%V)		4.23	4.42	4.33
Stack Gas Moisture (%V)		8.98	8.45	8.72
Volumetric Flow Rate (dscfm)		2376.76	2125.53	2251.15
Volumetric Flow Rate (dscmm)		67.31	60.195	63.75
Percent Isokinetic		99.94	100.82	100.38
	CONDITION 3			
RUN NUMBER DATE	Run 7 09/13/91	Run 8 09/14/91	Run 9 09/16/91	AVERAGE
Total Sampling Time (min.)	240	240	240	240.00
Average Sampling Rate (dscfm)	0.34	0.32	0.31	0.32
Metered Volume (dscf)	81.1	76.75	73.63	77.16
Metered Volume (dscm)	2.297	2.174	2.085	2.185
Average Stack Temperature (°F)	292	280	289	287
O2 Concentration (%V)	15.34	15.52	14.45	15.1
CO2 Concentration (%V)	4.45	4.48	5.2	4.7
Stack Gas Moisture (%V)	10.00	10.45	11.17	10.54
Volumetric Flow Rate (dscfm)	2458	2301	2169	2309
Volumetric Flow Rate (dscmm)	69.62	65.16	61.43	65.40
Percent Isokinetic	98.49	99.59	101.35	99.81

2.2.5.1 Incinerator Bottom Ash. All bottom ash was removed from the incinerator on the morning after each test day. A 50-gallon stainless steel drum was filled 2/3 full with ash, the lid was fastened, and the drum was rolled to mix the ash thoroughly. The lid was removed and three 1-liter bottles were filled with the ash. Two of these bottles were archived and one was sent to the laboratory for CDD/CDF analysis. Attempts were made to shovel representative portions of ash from all points of the incinerator. This procedure was performed for each test run.

Table 2-18 presents the CDD/CDF concentrations in the bottom ash for all runs. Total CDD/CDF concentrations range from approximately 6,000 ppt.wt for Run 6 to approximately 80,000 ppt.wt for Run 3. Table 2-19 presents the 2378 TCDD TEC in the bottom ash. Total CDD/CDF TEC's range from 169.5 ppt.wt to 2040.1 ppt.wt.

Table 2-20 presents the hourly discharge rate of CDD/CDF in the incinerator bottom ash based on the weight of the total ash collected from the incinerator. The total CDD/CDF generated ranged from 166 μg/hr to 1944 μg/hr.

2.2.5.2 Baghouse Ash. Baghouse ash was collected each test day during the test period. After each test period, a composite sample of the baghouse ash was mixed in a 55 gallon stainless steel drum. Three 1-liter bottles were filled with ash. Two of these were archived and one was sent to the laboratory for CDD/CDF analysis. This procedure was repeated for each test run.

Table 2-21 presents the CDD/CDF concentrations in the baghouse ash for all runs. Total CDD/CDF concentrations range from 10,420.6 ppt.wt for Run 2 to 62,084 ppt.wt for Run 7. Concentrations of CDD/CDF increase from Condition 1 to Condition 3 due to the removal of CDD/CDF in the baghouse. Table 2-22 presents the 2378-TCDD toxic equivalencies of the baghouse ash, which range from 117.2 ppt.wt to 1254.1 ppt.wt for total CDD/CDF.

Table 2-23 presents an estimate of the hourly discharge rate of CDD/CDF in the baghouse ash based on the weight of the ash collected from the baghouse during the test period. Total CDD/CDF ranges from 258 μg/hr to 1767 μg/hr.

TABLE 2-18. CDD/CDF CONCENTRATIONS IN THE INCINERATOR BOTTOM ASH; BORGESS MEDICAL CENTER (1991)

DATE:	09/07	09/09	09/10	09/11	09/12	09/13	09/14	09/16	AVERAGE
RUN NUMBER	2	3	4	5	6	7	8	9	
CONGENER	(ppt.wt)	(ppt.wt)	(ppt.wt)	(ppt.wt)	(ppt.wt)	(ppt.wt)	(ppt.wt)	(ppt.wt)	(ppt.wt)
2378 TCDD	14.0	29.9	12.1	4.0	3.2	11.7	14.7	13.7	12.9
Other TCDD	1,266.0	1,240.1	510.9	207.0	153.8	717.3	489.3	1,426.3	751.3
12378 PCDD	82.7	191.0	71.5	31.2	15.1	86.6	73.6	95.6	80.9
Other PCDD	1,267.3	2,639.0	1,038.5	285.8	224.9	993.4	784.4	2,174.4	1,176.0
123478 HxCDD	114.0	334.0	128.0	27.7	18.3	91.3	103.0	136.0	119.0
123678 HxCDD	169.0	372.0	127.0	54.4	23.2	141.0	106.0	182.0	146.8
123789 HxCDD	273.0	870.0	305.0	65.9	44.1	208.0	252.0	370.0	298.5
Other HxCDD	1,744.0	4,244.0	1,540.0	347.0	222.4	729.7	1,279.0	2,992.0	1,637.3
1234678-HpCDD	1,420.0	3,040.0	1,040.0	442.0	209.0	1,080.0	895.0	1,540.0	1,208.3
Other Hepta-CDD	1,290.0	3,030.0	1,110.0	412.0	193.0	1,040.0	925.0	1,710.0	1,213.8
Octa-CDD	3,240.0	5,110.0	1,890.0	873.0	431.0	1,840.0	1,710.0	2,040.0	2,141.8
Total CDD	10,880.0	21,100.0	7,773.0	2,750.0	1,538.0	6,939.0	6,632.0	12,680.0	8,786.5
FURANS									
2378 TCDF	144.0	408.0	167.0	51.0	37.9	181.0	159.0	236.0	173.0
Other TCDF	4,786.0	15,222.0	5,643.0	1,749.0	1,302.1	6,239.0	5,001.0	8,234.0	6,022.0
12378 PCDF	192.0	550.0	265.0	72.4	40.1	209.0	189.0	279.0	224.6
23478 PCDF	483.0	1,420.0	504.0	165.0	94.9	467.0	411.0	577.0	515.2
Other PCDF	5,585.0	12,920.0	5,481.0	2,022.6	1,035.0	4,874.0	3,950.0	6,484.0	5,294.0
123478 HxCDF	2,080.0	4,850.0	1,930.0	458.0	278.0	(1260.0)	1,370.0	1,960.0	1,773.3
123678 HxCDF	484.0	1,310.0	511.0	179.0	81.0	463.0	378.0	528.0	491.8
234678 HxCDF	1,450.0	2,460.0	827.0	379.0	230.0	858.0	588.0	890.0	960.3
123789 HxCDF	18.3	62.4	27.3	6.5	308.0	19.2	(15.90)	29.8	60.9
Other HxCDF	2,367.7	6,207.6	3,184.7	627.5	44.0	(500.2)	1,498.1	2,952.2	2,047.7
1234678-HpCDF	2,800.0	6,520.0	2,630.0	890.0	403.0	1,230.0	1,890.0	2,330.0	2,336.6
1234789-HpCDF	156.0	684.0	194.0	79.3	44.0	143.0	153.0	(241.0)	211.8
Other Hepta-CDF	1,194.0	3,606.0	1,426.0	450.7	229.0	767.0	947.0	1,179.0	1,224.8
Octa-CDF	1,980.0	2,970.0	1,350.0	556.0	294.0	1,100.0	734.0	1,070.0	1,256.8
TOTAL CDF	23,720.0	59,190.0	24,140.0	7,686.0	4,421.0	17,310.0	17,284.0	26,990.0	22,592.6
TOTAL CDD+CDF	34,600.0	80,290.0	31,913.0	10,436.0	5,959.0	24,249.0	23,916.0	39,670.0	31,379.1

a

ppt.wt = Parts per trillion by weight.

b

( ) = Estimated maximum possible concentration.

TABLE 2-19. CDD/CDF 2378 TCDD TOXIC EQUIVALENCY CONCENTRATIONS IN BOTTOM ASH; BORGESS MEDICAL CENTER (1991)

2378 TCDD TOXIC EQUIVALENCY (ppt.wt)[a,b]

CONGENER	2378 TCDD Toxic Equivalency Factor	Condition 1			Condition 2		Condition 3			Average
		Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	
DIOXINS										
2378 TCDD	1.000	14.0	29.9	12.1	4.0	3.2	11.7	14.7	13.7	12.9
Other TCDD	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12378 PCDD	0.500	41.4	95.5	35.8	15.6	7.6	43.3	36.8	47.8	40.5
Other PCDD	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
123478 HxCDD	0.100	11.4	33.4	12.8	2.8	1.8	9.1	10.3	13.6	11.9
123678 HxCDD	0.100	16.9	37.2	12.7	5.4	2.3	14.1	10.6	18.2	14.7
123789 HxCDD	0.100	27.3	87.0	30.5	6.6	4.4	20.8	25.2	37.0	29.9
Other HxCDD	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1234678-HpCDD	0.010	14.2	30.4	10.4	4.4	2.1	10.8	9.0	15.4	12.1
Other Hepta-CDD	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Octa-CDD	0.001	3.2	5.1	1.9	0.9	0.4	1.8	1.7	2.0	2.1
Total CDD		128.4	318.5	116.1	39.7	21.8	111.7	108.3	147.7	124.0
FURANS										
2378 TCDF	0.100	14.4	40.8	16.7	5.1	3.8	18.1	15.9	23.6	17.3
Other TCDF	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12378 PCDF	0.050	9.6	27.5	13.3	3.6	2.0	10.5	9.5	14.0	11.2
23478 PCDF	0.500	241.5	710.0	252.0	82.5	47.5	233.5	205.5	288.5	257.6
Other PCDF	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
123478 HxCDF	0.100	208.0	485.0	193.0	45.8	27.8	0.0	137.0	196.0	177.3
123678 HxCDF	0.100	48.4	131.0	51.1	17.9	8.1	46.3	37.8	52.8	49.2
234678 HxCDF	0.100	145.0	246.0	82.7	37.9	23.0	85.8	58.8	89.0	96.0
123789 HxCDF	0.100	1.8	6.2	2.7	0.7	30.8	1.9	0.0	3.0	6.1
Other HxCDF	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1234678-HpCDF	0.010	28.0	65.2	26.3	8.9	4.0	12.3	18.9	23.3	23.4
1234789-HpCDF	0.010	1.6	6.8	1.9	0.8	0.4	1.4	1.5	0.0	2.1
Other Hepta-CDF	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Octa-CDF	0.001	2.0	3.0	1.4	0.6	0.3	1.1	0.7	1.1	1.3
TOTAL CDF		700.3	1,721.6	641.1	203.7	147.7	410.9	485.6	691.2	641.5
TOTAL CDD+CDF		828.7	2,040.1	757.2	243.4	169.5	522.6	593.9	838.9	765.5

a North Atlantic Treaty Organization, Committee on the Challenges of Modern Society. Pilot Study on International Information Exchange on Dioxins and Related Compounds: International Toxicity Equivalency Factor (I-TEF) Methods of Risk Assessment for Complex Mixtures of Dioxins and Related Compounds. Report No. 176, August 1988.

b ppt.wt = Parts per trillion by weight.

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TABLE 2-20. CDD/CDF DISCHARGE RATE IN THE INCINERATOR BOTTOM ASH
BORGESS MEDICAL CENTER (1991)

DATE: RUN NUMBER CONGENER	09/07 2 (ug/hr)	09/09 3 (ug/hr)	09/10 4 (ug/hr)	09/11 5 (ug/hr)	09/12 6 (ug/hr)	09/13 7 (ug/hr)	09/14 8 (ug/hr)	09/16 9 (ug/hr)	AVERAGE (ug/hr)
2378 TCDD	1.69	3.22	0.82	0.43	0.36	1.59	1.34	1.74	1.40
Other TCDD	50.53	38.59	11.84	6.85	4.26	22.06	17.00	26.61	22.22
12378 PCDD	2.32	4.63	1.30	0.74	0.42	2.01	1.87	2.17	1.93
Other PCDD	35.48	63.91	18.91	6.74	6.26	23.03	19.88	49.32	27.94
123478 HxCDD	3.19	8.09	2.33	0.65	0.51	2.12	2.61	3.08	2.82
123678 HxCDD	4.73	9.01	2.31	1.28	0.65	3.27	2.69	4.13	3.51
123789 HxCDD	7.64	21.07	5.55	1.55	1.23	4.82	6.39	8.39	7.08
Other HxCDD	48.82	102.78	28.04	8.19	6.19	30.83	32.41	67.86	40.64
1234678-HpCDD	39.75	73.62	18.94	10.43	5.81	25.04	22.68	34.93	28.90
Other Hepta-CDD	36.11	73.38	20.21	9.72	5.37	24.12	23.44	38.78	28.89
Octa-CDD	90.70	123.75	34.41	20.60	11.99	42.67	43.33	46.27	51.71
Total CDD	304.57	510.99	141.52	64.88	42.79	181.56	168.06	287.58	212.75
FURANS									
2378 TCDF	4.03	9.88	3.04	1.20	1.05	4.20	4.03	5.35	4.10
Other TCDF	133.98	368.64	102.74	41.26	36.23	144.67	126.73	186.75	142.62
12378 PCDF	5.37	13.32	4.82	1.71	1.12	4.85	4.79	6.33	5.29
23478 PCDF	13.52	34.39	9.18	3.89	2.64	10.83	10.42	13.09	12.24
Other PCDF	156.34	312.89	99.79	47.72	28.79	113.02	100.10	147.06	125.71
123478 HxCDF	58.23	117.46	35.14	10.81	7.73	0.00	34.72	44.45	38.57
123678 HxCDF	13.55	31.73	9.30	4.22	2.25	10.74	9.58	11.98	11.67
234678 HxCDF	40.59	59.58	15.06	8.94	6.40	19.90	14.90	20.19	23.19
123789 HxCDF	0.51	1.51	0.50	0.15	8.57	0.45	0.00	0.68	1.55
Other HxCDF	66.28	150.33	57.98	14.80	1.22	37.56	37.96	66.96	54.14
1234678-HpCDF	78.38	157.90	47.88	21.00	11.21	28.52	47.89	52.84	55.70
1234789-HpCDF	4.37	16.56	3.53	1.87	1.22	3.32	3.88	0.00	4.34
Other Hepta-CDF	33.42	87.33	25.96	10.63	6.37	17.79	24.00	26.74	29.03
Octa-CDF	55.43	71.93	24.58	13.12	8.18	25.51	18.60	24.27	30.20
TOTAL CDF	664.01	1433.45	439.51	181.34	123.00	450.54	437.99	612.13	542.75
TOTAL CDD+CDF	968.58	1944.44	581.03	246.22	165.78	632.10	606.06	899.72	755.49

( ) = Estimated Maximum Possible Detection Limit.

TABLE 2-21. CDD/CDF CONCENTRATIONS IN BAGHOUSE ASH; BORGESS MEDICAL CENTER (1991)

DATE:	09/07	09/09	09/10	09/11	09/12	09/13	09/14	09/16	AVERAGE
RUN NUMBER	2	3	4	5	6	7	8	9	
CONGENER	(ppt.wt)	(ppt.wt)	(ppt.wt)	(ppt.wt)	(ppt.wt)	(ppt.wt)	(ppt.wt)	(ppt.wt)	(ppt.wt)
2378 TCDD	(0.740)[a]	1.5	(2.100)	4.6	11.7	15.5	12.7	(8.900)	7.22
Other TCDD	14.4	19.9	18.4	73.1	203.3	356.5	211.3	318.1	151.87
12378 PCDD	5.7	9.2	14.4	54.7	57.1	82.2	57.9	48.9	41.26
Other PCDD	47.8	56.0	97.6	133.3	423.9	849.8	488.1	631.1	340.95
123478 HxCDD	11.7	15.1	33.5	41.0	83.2	158.0	125.0	163.0	78.81
123678 HxCDD	18.8	21.4	39.2	43.6	92.1	167.0	122.0	197.0	87.64
123789 HxCDD	34.7	37.3	80.0	83.5	192.0	377.0	276.0	315.0	174.44
Other HxCDD	151.8	159.2	298.3	384.9	912.7	1938.0	1287.0	2595.0	965.86
1234678-HpCDD	417.0	407.0	656.0	689.0	1260.0	2350.0	1820.0	3880.0	1434.88
Other Hepta-CDD	388.0	396.0	644.0	721.0	1260.0	2230.0	1950.0	3190.0	1347.38
Octa-CDD	1990.0	1850.0	2040.0	2420.0	3180.0	5310.0	4650.0	6660.0	3512.50
Total CDD	3080.6	2972.6	3923.5	4648.7	7676.0	13834.0	11000.0	18007.0	8142.80
FURANS									
2378 TCDF	6.9	12.3	19.5	37.5	96.7	155.0	123.0	99.0	68.74
Other TCDF	199.1	278.7	621.5	982.5	3033.3	5195.0	4557.0	4201.0	2383.51
12378 PCDF	21.3	32.3	53.6	90.8	230.0	378.0	291.0	244.0	167.63
23478 PCDF	47.6	66.0	145.0	172.0	402.0	793.0	625.0	541.0	348.95
Other PCDF	445.1	598.7	1191.4	1697.2	5008.0	7359.0	5974.0	5005.0	3409.80
123478 HxCDF	205.0	214.0	431.0	470.0	1410.0	2760.0	2400.0	2330.0	1277.50
123678 HxCDF	93.3	126.0	260.0	298.0	641.0	975.0	814.0	787.0	499.29
234678 HxCDF	296.0	216.0	450.0	465.0	1090.0	2050.0	1560.0	1930.0	1007.13
123789 HxCDF	13.1	12.7	17.1	(17.80)	(34.90)	84.5	(46.70)	72.7	37.44
Other HxCDF	492.6	461.3	931.9	889.2	3194.1	5800.5	5019.3	4680.3	2683.65
1234678-HpCDF	972.0	1080.0	1860.0	2060.0	3690.0	5680.0	5120.0	4970.0	3179.00
1234789-HpCDF	231.0	246.0	383.0	442.0	552.0	1400.0	1010.0	1250.0	689.25
Other Hepta-CDF	987.0	1094.0	1867.0	2228.0	3228.0	5790.0	4940.0	5500.0	3204.25
Octa-CDF	3330.0	2850.0	3830.0	4980.0	6480.0	9830.0	8440.0	7100.0	5855.00
TOTAL CDF	7340.0	7288.0	12061.0	14830.0	29090.0	48250.0	40920.0	38710.0	24811.13
TOTAL CDD+CDF	10420.6	10260.6	15984.5	19478.7	36766.0	62084.0	51920.0	56717.0	32953.93

[a] ( ) = Estimated maximum possible concentration.

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TABLE 2-22. CDD/CDF 2378 TCDD TOXIC EQUIVALENCY CONCENTRATIONS IN BAGHOUSE ASH; BORGESS MEDICAL CENTER (1991)

2378 TCDD TOXIC EQUIVALENCY (ppt.wt)[a]

CONGENER	2378 TCDD Toxic Equivalency Factor	Condition 1			Condition 2		Condition 3		
		Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9
DIOXINS									
2378 TCDD	1.000	0.0	1.5	0.0	4.6	11.7	15.5	12.7	0.0
Other TCDD	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12378 PCDD	0.500	2.9	4.6	7.2	27.4	28.6	41.1	29.0	24.5
Other PCDD	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
123478 HxCDD	0.100	1.2	1.5	3.4	4.1	8.3	15.8	12.5	16.3
123678 HxCDD	0.100	1.9	2.1	3.9	4.4	9.2	16.7	12.2	19.7
123789 HxCDD	0.100	3.5	3.7	8.0	8.4	19.2	37.7	27.6	31.5
Other HxCDD	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1234678-HpCDD	0.010	4.2	4.1	6.6	6.9	12.6	23.5	18.2	38.8
Other Hepta-CDD	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Octa-CDD	0.001	2.0	1.9	2.0	2.4	3.2	5.3	4.7	6.7
Total CDD		15.5	19.4	31.1	58.1	92.8	155.6	116.8	137.4
FURANS									
2378 TCDF	0.100	0.7	1.2	2.0	3.8	9.7	15.5	12.3	9.9
Other TCDF	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12378 PCDF	0.050	1.1	1.6	2.7	4.5	11.5	18.9	14.6	12.2
23478 PCDF	0.500	23.8	33.0	72.5	86.0	201.0	396.5	312.5	270.5
Other PCDF	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
123478 HxCDF	0.100	20.5	21.4	43.1	47.0	141.0	276.0	240.0	233.0
123678 HxCDF	0.100	9.3	12.6	26.0	29.8	64.1	97.5	81.4	78.7
234678 HxCDF	0.100	29.6	21.6	45.0	46.5	109.0	205.0	156.0	193.0
123789 HxCDF	0.100	1.3	1.3	1.7	0.0	0.0	8.5	0.0	7.3
Other HxCDF	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1234678-HpCDF	0.010	9.7	10.8	18.6	20.6	36.9	56.8	51.2	49.7
1234789-HpCDF	0.010	2.3	2.5	3.8	4.4	5.5	14.0	10.1	12.5
Other Hepta-CDF	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Octa-CDF	0.001	3.3	2.9	3.8	5.0	6.5	9.8	8.4	7.1
TOTAL CDF		101.7	108.8	219.2	247.6	585.2	1,098.5	886.5	873.9
TOTAL CDD+CDF		117.2	128.2	250.3	305.7	677.9	1,254.1	1,003.3	1,011.3

[a] ppt.wt = Parts per trillion by weight

NOTE: Condition 1: No Carbon Injection
Condition 2: Carbon Injection = 1 lb/hr
Condition 3: Carbon Injection = 2.5 lb/hr

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TABLE 2-23. CDD/CDF DISCHARGE RATE IN THE BAGHOUSE ASH
BORGESS MEDICAL CENTER (1991)

CDD/CDF Discharge Rate (ug/hr)

	Condition 1				Condition 2			Condition 3			
CONGENER	Run 2	Run 3	Run 4	Avg.	Run 5	Run 6	Avg.	Run 7	Run 8	Run 9	Avg.
2378 TCDD	0.02	0.05	0.06	0.04	0.11	0.36	0.23	0.44	0.40	0.27	0.37
Other TCDD	0.36	0.64	0.52	0.51	1.71	6.27	3.99	10.15	6.61	9.47	8.74
12378 PCDD	0.14	0.30	0.41	0.28	1.28	1.76	1.52	2.34	1.81	1.46	1.87
Other PCDD	1.18	1.81	2.76	1.92	3.12	13.08	8.10	24.19	15.27	18.79	19.42
123478 HxCDD	0.29	0.49	0.95	0.58	0.96	2.57	1.76	4.50	3.91	4.85	4.42
123678 HxCDD	0.46	0.69	1.11	0.76	1.02	2.84	1.93	4.75	3.82	5.87	4.81
123789 HxCDD	0.86	1.21	2.27	1.44	1.95	5.92	3.94	10.73	8.64	9.38	9.58
Other HxCDD	3.75	5.15	8.45	5.78	9.00	28.15	18.58	55.16	40.27	77.28	57.57
1234678-HpCDD	10.31	13.16	18.58	14.02	16.12	38.86	27.49	66.89	56.94	115.54	79.79
Other Hepta-CDD	9.60	12.81	18.24	13.55	16.87	38.86	27.87	63.47	61.01	94.99	73.16
Octa-CDD	49.22	59.83	57.79	55.61	56.61	98.09	77.35	151.14	145.48	198.33	164.98
Total CDD	**76.19**	**96.14**	**111.14**	**94.49**	**108.75**	**236.76**	**172.76**	**393.76**	**344.16**	**536.23**	**424.72**
FURANS											
2378 TCDF	0.17	0.40	0.55	0.37	0.88	2.98	1.93	4.41	3.85	2.95	3.74
Other TCDF	4.92	9.01	17.61	10.51	22.99	93.56	58.27	147.87	142.58	125.10	138.51
12378 PCDF	0.53	1.04	1.52	1.03	2.12	7.09	4.61	10.76	9.10	7.27	9.04
23478 PCDF	1.18	2.13	4.11	2.47	4.02	12.40	8.21	22.57	19.55	16.11	19.41
Other PCDF	11.01	19.36	33.75	21.37	39.71	154.47	97.09	209.46	186.91	149.04	181.80
123478 HxCDF	5.07	6.92	12.21	8.07	11.00	43.49	27.24	78.56	75.09	69.38	74.34
123678 HxCDF	2.31	4.08	7.37	4.58	6.97	19.77	13.37	27.75	25.47	23.44	25.55
234678 HxCDF	7.32	6.99	12.75	9.02	10.88	33.62	22.25	58.35	48.81	57.47	54.88
123789 HxCDF	0.32	0.41	0.48	0.41	0.42	1.08	0.75	2.41	1.46	2.16	2.01
Other HxCDF	12.18	14.92	26.40	17.83	20.80	98.52	59.66	165.10	157.04	139.37	153.84
1234678-HpCDF	24.04	34.93	52.69	37.22	48.19	113.82	81.00	161.67	160.19	148.00	156.62
1234789-HpCDF	5.71	7.96	10.85	8.17	10.34	17.03	13.68	39.85	31.60	37.22	36.22
Other Hepta-CDF	24.41	35.38	52.89	37.56	52.12	99.57	75.84	164.80	154.56	163.78	161.05
Octa-CDF	82.36	92.17	108.49	94.34	116.50	199.87	158.19	279.80	264.06	211.43	251.76
TOTAL CDF	**181.5**	**235.7**	**341.7**	**253.0**	**346.9**	**897.3**	**622.1**	**1,373.4**	**1,280.3**	**1,152.7**	**1,268.8**
TOTAL CDD+CDF	**257.7**	**331.8**	**452.8**	**347.5**	**455.7**	**1,134.0**	**794.9**	**1,767.1**	**1,624.4**	**1,689.0**	**1,693.5**

( ) = Estimated Maximum Possible Detection Limit.

2.3 TOXIC METALS EMISSIONS

2.3.1 Overview

A single sampling train was used to determine emission rates of a series of 13 metals [aluminum (Al), antimony (Sb), arsenic (As), barium (Ba), beryllium (Be), cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), mercury (Hg), nickel (Ni), silver (Ag), thallium (Tl)], and particulate matter (PM). Mercury was also sampled by Method 101A and will be discussed in Section 2.5. Two to three sampling runs were performed under each of the three test conditions (without carbon injection, carbon injection at 1 lb/hr, and carbon injection at 2.5 lb/hr) to ensure representative test results.

Sampling for metals was conducted at the fabric filter inlet and fabric filter outlet. The average metals emission rates and removal efficiencies are summarized in Section 2.3.2. The results for each individual run are presented in Section 2.3.4. Concentrations at dry, standard conditions are shown, both actual and adjusted to 7 percent O_2. Emission rates are also shown. The metals to PM ratios are presented in Section 2.3.5, flue gas metals by sample fraction are presented in Section 2.3.6, and metals concentrations in ash samples are presented in Section 2.3.7.

A summary of the Borgess Hospital toxic metals sampling results is presented in Table 2-24. Inlet mass emission rates ranged from not detected for Be and Tl to 21.6 g/hr for Hg. Outlet emissions ranged from not detected for As, Be, Ag, and Tl to 17.4 g/hr for Hg. The associated removal efficiencies were above 30 percent for the test runs without carbon injection, above 40 percent for test runs with carbon injection at 1 lb/hr, and above 27 percent for test runs with carbon injection at 2.5 lb/hr.

2.3.2 Metals Data Reduction

The values tabulated in the toxic metals test report section include detection limits for samples in which specific metals were not detected. Since the samples were analyzed in three separate fractions (see Section 5 for details), guidelines for mathematically handling detection limits were required. The guidelines used for this report are:

Table 2-24

SUMMARY OF TOXIC METALS FLUE GAS EMISSION RATES AND METALS IN ASH - BORGESS MEDICAL CENTER (1991)

	Without Carbon			Carbon Injection @ 1 lb/hr			Carbon Injection @ 2.5 lb/hr			Baghouse Ash		Bottom Ash	
Metals	Inlet (g/hr)	Outlet (g/hr)	RE (%)	Inlet (g/hr)	Outlet (g/hr)	RE (%)	Inlet (g/hr)	Outlet (g/hr)	RE (%)	Average Conc. (mg/kg)	Average Discharge (g/day)	Average Conc. (mg/kg)	Average Discharge (g/day)
Aluminum	1.42	0.341	76.1%	1.12	0.347	69.1%	0.982	0.329	66.4%	692	79.6	48500	12200
Antimony	0.448	0.0237	94.7%	0.788	0.0174	97.8%	0.313	0.0168	94.6%	32.6	3.77	15.2	5.04
Arsenic	0.0100	0.00131	91.3%	0.0101	0.00234	76.8%	0.00645	[0.00139]	> 78.4%	1.29	0.149	47.5	11.8
Barium	0.155	0.00826	94.7%	0.218	0.00773	96.5%	0.167	0.00898	94.6%	13.6	1.57	2880	824
Beryllium	0.00100	[0.000355]	> 64.5%	[0.000306]	[0.000350]	NA	[0.000296]	0.000897	NA	0.260	0.0326	0.268	0.0939
Cadmium	0.612	0.00274	99.6%	3.00	0.00380	99.9%	1.07	0.0174	98.4%	154	18.7	12.0	3.44
Chromium	0.0510	0.0333	34.8%	0.0768	0.0249	67.6%	0.0627	0.0182	70.9%	13.8	1.58	39.7	10.7
Copper	1.47	0.147	90.0%	1.55	0.0308	98.0%	1.18	0.0306	97.4%	157	18.0	30800	11600
Lead	2.32	0.00708	99.7%	3.21	0.00840	99.7%	2.26	0.0124	99.5%	116	13.4	162	38.9
Mercury	10.7	12.5	-16.6%	11.3	1.52	86.5%	14.5	0.714	95.1%	270	30.9	11.2	2.67
Nickel	0.0720	0.0504	30.1%	0.161	0.0250	84.4%	0.0548	0.0395	27.9%	4.37	0.503	47.1	12.5
Silver	0.0151	0.00791	47.5%	0.0188	0.0113	39.9%	0.0193	0.00975	49.6%	3.52	0.405	3.52	0.970
Thallium	[0.0311]	[0.0362]	NA	[0.0306]	[0.0350]	NA	[0.0296]	[0.0349]	NA	[20.0]	[2.30]	[20.0]	[5.44]

NA = Not Applicable

[ ] = Minimum Detection Limit

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- If a metal was detected in one or more fractions of the sample train but not in all fractions, only the detected values were used to determine total sample mass (i.e., non detects = zero)

- If a metal was not detected in any fraction of a sample train, the sum of the non-detects for each fraction was used as the overall sample detection limit.

For the purpose of calculating average results:

- If a metal was detected in one or more of the test runs but not all, only those runs for which the metal was detected were used in calculating the average. Runs where the metal was not detected were not included for averaging.

- If the metal was not detected in any of the three runs, then the average result was reported as "not detected" at the average detection limit.

The ash samples were analyzed for the same series of metals as the emission test samples. These results are reported in Section 2.3.7.

2.3.3 Metals Emissions

Tables 2-25 through 2-27 present the metals emissions results for each test condition. During the emission tests without carbon injection, Hg had the highest average mass rate at the inlet with 10.7 g/hr, followed by Pb with 2.32 g/hr. Beryllium and Tl were not collected in detectable amounts for any of the runs at the inlet or outlet during these emissions test conditions. Mercury was the most prevalent element collected for the three runs at the outlet during this condition with an average emission rate of 12.5 g/hr, followed by Al with 0.341 g/hr. Sample results for Ag showed negative removal efficiencies for two of the three runs. Analysis of samples from Run 2 indicated a substantially higher mass emission rate of Ag at the outlet of 0.0140 g/hr versus 0.00750 g/hr at the inlet. Run 4 showed similar outlet and inlet mass emission rates of Ag of 0.00726 g/hr and 0.00517 g/hr , respectively. Chromium showed a negative removal efficiency in Run 4 with inlet and outlet mass rates of 0.00343 g/hr

Table 2-25

AVERAGE METALS EMISSION RATES AND REMOVAL EFFICIENCIES FOR- BORGESS MEDICAL CENTER (1991)

*** WITHOUT CARBON INJECTION ***

Condition	Without Carbon Injection											
	Run 2			Run 3			Run 4			Average Burn Emissions		
Location	Inlet (g/hr)	Outlet (g/hr)	RE (%)	Inlet (g/hr)	Outlet (g/hr)	RE (%)	Inlet (g/hr)	Outlet (g/hr)	RE (%)	Inlet (g/hr)	Outlet (g/hr)	RE (%)
Aluminum	1.22	0.328	73.1%	1.82	0.342	81.2%	1.23	0.352	71.3%	1.42	0.341	76.1%
Antimony	0.214	0.0267	87.5%	0.631	0.0239	96.2%	0.500	0.0205	95.9%	0.448	0.0237	94.7%
Arsenic	0.00839	[0.00148]	> 82.4%	0.0119	0.000782	93.5%	0.00977	0.00184	81.2%	0.0100	0.00131	86.9%
Barium	0.139	0.00697	95.0%	0.234	0.00900	96.1%	0.0934	0.00880	90.6%	0.155	0.00826	94.7%
Beryllium	[0.000312]	[0.000370]	NA	0.00100	[0.000329]	> 67.1%	[0.000311]	[0.000365]	NA	0.00100	[0.000355]	>64.5%
Cadmium	0.623	0.00161	99.7%	0.595	0.00285	99.5%	0.619	0.00377	99.4%	0.612	0.00274	99.6%
Chromium	0.0431	0.0152	64.8%	0.0756	0.0502	33.6%	0.0343	0.0344	-0.238%	0.0510	0.0333	34.8%
Copper	1.20	0.284	76.3%	2.00	0.0919	95.4%	1.20	0.0637	94.7%	1.47	0.147	90.0%
Lead	1.50	0.00501	99.7%	3.57	0.00496	99.9%	1.91	0.0113	99.4%	2.32	0.00708	99.7%
Mercury	15.1	17.4	-15.5%	11.9	14.1	-18.4%	5.23	6.06	-15.9%	10.7	12.5	-16.6%
Nickel	0.0521	0.0290	44.4%	0.0849	0.0550	35.2%	0.0790	0.0672	15.0%	0.0720	0.0504	30.1%
Silver	0.00750	0.0140	-87.3%	0.0325	0.00241	92.6%	0.00517	0.00726	-40.3%	0.0151	0.00791	47.5%
Thallium	[0.0312]	[0.0369]	NA	[0.0311]	[0.0352]	NA	[0.0311]	[0.0365]	NA	[0.0311]	[0.0362]	NA

NA = Not Applicable

[ ] = Minimum Detection Limit

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Table 2-26

AVERAGE METALS EMISSION RATES AND REMOVAL EFFICIENCIES FOR- BORGESS MEDICAL CENTER (1991)

*** CARBON INJECTION AT 1 lb/hr ***

Condition	Carbon Injection at 1 lb/hr								
	Run 5			Run 6			Average Burn Emissions		
Location	Inlet (g/hr)	Outlet (g/hr)	RE (%)	Inlet (g/hr)	Outlet (g/hr)	RE (%)	Inlet (g/hr)	Outlet (g/hr)	RE (%)
Aluminum	1.30	0.356	72.7%	0.941	0.338	64.1%	1.12	0.347	69.1%
Antimony	0.944	0.0177	98.1%	0.633	0.0171	97.3%	0.788	0.0174	97.8%
Arsenic	0.00995	[0.00148]	> 85.1%	0.0102	0.00234	77.0%	0.0101	0.00234	76.8%
Barium	0.187	0.00704	96.2%	0.249	0.00842	96.6%	0.218	0.00773	96.5%
Beryllium	[0.000306]	[0.000362]	NA	[0.000306]	[0.000338]	NA	[0.000306]	[0.000350]	NA
Cadmium	0.517	0.00376	99.3%	5.48	0.00384	99.9%	3.00	0.00380	99.9%
Chromium	0.0518	0.0175	66.2%	0.102	0.0324	68.2%	0.0768	0.0249	67.6%
Copper	1.88	0.0312	98.3%	1.22	0.0304	97.5%	1.55	0.0308	98.0%
Lead	3.89	0.0108	99.7%	2.52	0.00603	99.8%	3.21	0.00840	99.7%
Mercury	9.43	1.39	85.3%	13.2	1.66	87.4%	11.3	1.52	86.5%
Nickel	0.116	0.0206	82.2%	0.205	0.0294	85.7%	0.161	0.0250	84.4%
Silver	0.0201	[0.00217]	> 89.2%	0.0175	0.0113	35.8%	0.0188	0.0113	39.9%
Thallium	[0.0306]	[0.0362]	NA	[0.0306]	[0.0338]	NA	[0.0306]	[0.0350]	NA

NA = Not Applicable

[ ] = Minimum Detection Limit

Table 2-27

AVERAGE METALS EMISSION RATES AND REMOVAL EFFICIENCIES FOR- BORGESS MEDICAL CENTER (1991)

*** CARBON INJECTION AT 2.5 lb/hr ***

Condition Location	Carbon Injection at 2.5 lb/hr									Average Burn Emissions		
	Run 7			Run 8			Run 9					
	Inlet (g/hr)	Outlet (g/hr)	RE (%)	Inlet (g/hr)	Outlet (g/hr)	RE (%)	Inlet (g/hr)	Outlet (g/hr)	RE %	Inlet (g/hr)	Outlet (g/hr)	RE (%)
Aluminum	0.843	0.304	64.0%	1.24	0.392	68.4%	0.862	0.293	66.0%	0.982	0.329	66.4%
Antimony	0.116	0.0175	84.9%	0.500	0.0171	96.6%	0.323	0.0158	95.1%	0.313	0.0168	94.6%
Arsenic	0.00236	[0.00144]	> 39.0%	0.00771	[0.00135]	> 82.5%	0.00927	[0.00141]	> 84.8%	0.00645	[0.00139]	> 78.4%
Barium	0.0603	0.00774	87.2%	0.301	0.00956	96.8%	0.138	0.00963	93.0%	0.167	0.00898	94.6%
Beryllium	[0.000292]	[0.000360]	NA	[0.000307]	[0.000336]	NA	[0.000290]	0.000897	NA	[0.000296]	0.000897	NA
Cadmium	0.341	0.00172	99.5%	1.74	0.0468	97.3%	1.12	0.00357	99.7%	1.07	0.0174	98.4%
Chromium	0.0746	0.0159	78.7%	0.0790	0.0193	75.5%	0.0344	0.0195	43.2%	0.0627	0.0182	70.9%
Copper	0.271	0.0228	91.6%	1.59	0.0528	89.1%	1.68	0.0161	99.0%	1.18	0.0306	97.4%
Lead	0.652	0.00350	99.5%	3.28	0.0185	99.4%	2.86	0.0152	99.5%	2.26	0.0124	99.5%
Mercury	12.0	1.36	88.7%	9.83	0.174	98.2%	21.6	0.603	97.2%	14.5	0.714	95.1%
Nickel	0.0495	0.0503	-1.52%	0.0687	0.0328	52.2%	0.0461	0.0354	23.3%	0.0548	0.0395	27.9%
Silver	0.0135	0.0166	-23.0%	0.0293	0.00281	90.4%	0.0152	0.00983	35.3%	0.0193	0.00975	49.6%
Thallium	[0.0292]	[0.0360]	NA	[0.0307]	[0.0336]	NA	[0.0290]	[0.0352]	NA	[0.0296]	[0.0349]	NA

NA = Not Applicable

[ ] = Minimum Detection Limit

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and 0.00344 g/hr, respectively. The differences can be attributed to round-off error. Analytical values for Ag and Cr showed values less than five times the detection limit. The test results also showed negative Hg removal efficiencies.

During the emission tests with carbon injection at 1 lb/hr, Hg had the highest average mass rate for the inlet runs with 11.3 g/hr, followed by Pb with 3.21 g/hr. As with the emission tests without carbon injection, Be and Tl were not collected in detectable amounts for any of the runs at the inlet and outlet. Mercury was emitted at the highest rate for the runs at the outlet during this condition, with an average emission rate of 1.52 g/hr.

During the emission tests with carbon injection at 2.5 lb/hr, Hg had the highest average mass rate for the inlet runs at 14.5 g/hr, followed by Pb at 2.26 g/hr. As with the conditions above, Be and Tl were not collected in detectable amounts for any of the runs at the inlet and outlet. Mercury was again emitted at the highest rate for these runs at the outlet with an average emission rate of 0.714 g/hr. Sample results for Ag and Ni showed negative removal efficiencies for Run 7. Results for Ag showed a substantially higher mass rate at the outlet of 0.0166 g/hr versus 0.0135 g/hr at the inlet. Results for Ni showed similar outlet and inlet mass rates of 0.0503 g/hr at the outlet, and 0.0495 g/hr at the inlet.

The average removal efficiencies calculated for Cr increased with increasing carbon injection from 34.8 percent without carbon, to 67.6 percent with carbon injection at 1 lb/hr, to 70.9 percent with carbon injection at 2.5 lb/hr. The removal efficiencies calculated for Hg increased from -16.6 percent without carbon, to 87.0 percent with carbon injection at 1 lb/hr, to 95.1 percent with carbon injection at 2.5 lb/hr. For the other metals analyzed, the removal efficiencies did not change significantly with carbon injection rates.

2.3.4 Metals Flue Gas Concentrations

Metal concentrations, mass rates, and removal efficiencies are presented for each run in Tables 2-28 through 2-35. Also shown for each run are the location, date, metered volume, O_2 concentration, and flow rate. Flue gas concentrations are given in

Table 2-28

METALS CONCENTRATION EMISSION RATES AND REMOVAL EFFICIENCIES FOR RUN 2 - BORGESS MEDICAL CENTER (1991) WITHOUT CARBON INJECTION

Location		Inlet	Outlet	Removal
Date		09/07/91	09/07/91	Efficiencies
Metered Volume (dscm)		3.354	2.394	(%)
O2 Concentration (%V)		13.41	15.05	
Flow Rate (dscmm)		48.643	69.208	
Aluminum	(ug/dscm)	417	78.9	
	(ug/dscm @ 7% O2)	775	188	
	(g/hr)	1.22	0.328	73.1%
Antimony	(ug/dscm)	73.3	6.43	
	(ug/dscm @ 7% O2)	136	15.3	
	(g/hr)	0.214	0.0267	87.5%
Arsenic	(ug/dscm)	2.87	[0.356]	
	(ug/dscm @ 7% O2)	5.33	[.846]	
	(g/hr)	0.00839	[0.00148]	> 82.4%
Barium	(ug/dscm)	47.7	1.68	
	(ug/dscm @ 7% O2)	88.5	3.99	
	(g/hr)	0.139	0.00697	95.0%
Beryllium	(ug/dscm)	[0.107]	[0.089]	
	(ug/dscm @ 7% O2)	[0.198]	[0.211]	
	(g/hr)	[0.000312]	[0.000370]	NA
Cadmium	(ug/dscm)	213	0.388	
	(ug/dscm @ 7% O2)	396	0.923	
	(g/hr)	0.623	0.00161	99.7%
Chromium	(ug/dscm)	14.8	3.65	
	(ug/dscm @ 7% O2)	27.4	8.67	
	(g/hr)	0.0431	0.0152	64.8%
Copper	(ug/dscm)	411	68.5	
	(ug/dscm @ 7% O2)	764	163	
	(g/hr)	1.20	0.284	76.3%
Lead	(ug/dscm)	513	1.21	
	(ug/dscm @ 7% O2)	952	2.87	
	(g/hr)	1.50	0.00501	99.7%
Mercury	(ug/dscm)	5160	4180	
	(ug/dscm @ 7% O2)	9580	9930	
	(g/hr)	15.1	17.4	-15.5%
Nickel	(ug/dscm)	17.9	6.98	
	(ug/dscm @ 7% O2)	33.1	16.6	
	(g/hr)	0.0521	0.0290	44.4%
Silver	(ug/dscm)	2.57	3.38	
	(ug/dscm @ 7% O2)	4.77	8.04	
	(g/hr)	0.00750	0.0140	-87.3%
Thallium	(ug/dscm)	[10.7]	[8.90]	
	(ug/dscm @ 7% O2)	[19.8]	[21.1]	
	(g/hr)	[0.0312]	[0.0369]	NA

NA = Not Applicable

[ ] = Minimum Detection Limit

Table 2-29
METALS CONCENTRATION EMISSION RATES AND REMOVAL EFFICIENCIES
FOR RUN 3 - BORGESS MECICAL CENTER (1991)
WITHOUT CARBON INJECTION

Location		Inlet	Outlet	Removal
Date		09/07/91	09/07/91	Efficiencies
Metered Volume (dscm)		3.719	2.579	(%)
O2 Concentration (%V)		13.89	15.66	
Flow Rate (dscmm)		54.055	72.453	
Aluminum	(ug/dscm)	562	78.7	
	(ug/dscm @ 7% O2)	1110	209	
	(g/hr)	1.82	0.342	81.2%
Antimony	(ug/dscm)	195	5.51	
	(ug/dscm @ 7% O2)	386	14.6	
	(g/hr)	0.631	0.0239	96.2%
Arsenic	(ug/dscm)	3.68	0.180	
	(ug/dscm @ 7% O2)	7.30	0.477	
	(g/hr)	0.0119	0.000782	93.5%
Barium	(ug/dscm)	72.1	2.07	
	(ug/dscm @ 7% O2)	143	5.49	
	(g/hr)	0.234	0.00900	96.1%
Beryllium	(ug/dscm)	0.309	[0.0810]	
	(ug/dscm @ 7% O2)	0.613	[0.215]	
	(g/hr)	0.00100	[0.000329]	> 67.1%
Cadmium	(ug/dscm)	183	0.655	
	(ug/dscm @ 7% O2)	364	1.74	
	(g/hr)	0.595	0.00285	99.5%
Chromium	(ug/dscm)	23.3	11.6	
	(ug/dscm @ 7% O2)	46.2	30.7	
	(g/hr)	0.0756	0.0502	33.6%
Copper	(ug/dscm)	616	21.1	
	(ug/dscm @ 7% O2)	1220	56.1	
	(g/hr)	2.00	0.0919	95.4%
Lead	(ug/dscm)	1100	1.14	
	(ug/dscm @ 7% O2)	2180	3.02	
	(g/hr)	3.57	0.00496	99.9%
Mercury	(ug/dscm)	3680	3250	
	(ug/dscm @ 7% O2)	7300	8620	
	(g/hr)	11.9	14.1	-18.4%
Nickel	(ug/dscm)	26.2	12.6	
	(ug/dscm @ 7% O2)	51.9	33.5	
	(g/hr)	0.0849	0.0550	35.2%
Silver	(ug/dscm)	10.0	0.554	
	(ug/dscm @ 7% O2)	19.9	1.47	
	(g/hr)	0.0325	0.00241	92.6%
Thallium	(ug/dscm)	[9.60]	[8.10]	
	(ug/dscm @ 7% O2)	[19.0]	[21.5]	
	(g/hr)	[0.0311]	[0.0352]	NA

NA = Not Applicable
[ ] = Minimum Detection Limit

081

Table 2-30
METALS CONCENTRATION EMISSION RATES AND REMOVAL EFFICIENCIES
FOR RUN 4 - BORGESS MEDICAL CENTER (1991)
WITHOUT CARBON INJECTION

Location		Inlet	Outlet	
Date		09/07/91	09/07/91	Removal
Metered Volume (dscm)		3.702	2.619	Efficiencies
O2 Concentration (%V)		14.93	15.9	(%)
Flow Rate (dscmm)		53.829	76.539	
Aluminum	(ug/dscm)	381	76.7	
	(ug/dscm @ 7% O2)	887	213	
	(g/hr)	1.23	0.352	71.3%
Antimony	(ug/dscm)	155	4.47	
	(ug/dscm @ 7% O2)	360	12.4	
	(g/hr)	0.500	0.0205	95.9%
Arsenic	(ug/dscm)	3.03	0.401	
	(ug/dscm @ 7% O2)	7.04	1.11	
	(g/hr)	0.00977	0.00184	81.2%
Barium	(ug/dscm)	28.9	1.92	
	(ug/dscm @ 7% O2)	67.3	5.33	
	(g/hr)	0.0934	0.00880	90.6%
Beryllium	(ug/dscm)	[0.0962]	[0.0794]	
	(ug/dscm @ 7% O2)	[0.224]	[0.221]	
	(g/hr)	[0.000311]	[0.000365]	NA
Cadmium	(ug/dscm)	192	0.821	
	(ug/dscm @ 7% O2)	447	2.28	
	(g/hr)	0.619	0.00377	99.4%
Chromium	(ug/dscm)	10.6	7.48	
	(ug/dscm @ 7% O2)	24.7	20.8	
	(g/hr)	0.0343	0.0344	-0.238%
Copper	(ug/dscm)	373	13.9	
	(ug/dscm @ 7% O2)	868	38.5	
	(g/hr)	1.20	0.0637	94.7%
Lead	(ug/dscm)	592	2.46	
	(ug/dscm @ 7% O2)	1377	6.83	
	(g/hr)	1.91	0.0113	99.4%
Mercury	(ug/dscm)	1620	1320	
	(ug/dscm @ 7% O2)	3770	3670	
	(g/hr)	5.23	6.06	-15.9%
Nickel	(ug/dscm)	24.5	14.6	
	(ug/dscm @ 7% O2)	57.0	40.7	
	(g/hr)	0.0790	0.0672	15.0%
Silver	(ug/dscm)	1.60	1.58	
	(ug/dscm @ 7% O2)	3.73	4.39	
	(g/hr)	0.00517	0.00726	-40.3%
Thallium	(ug/dscm)	[9.62]	[7.94]	
	(ug/dscm @ 7% O2)	[22.4]	[22.1]	
	(g/hr)	[0.0311]	[0.0365]	NA

NA = Not Applicable
[ ] = Minimum Detection Limit

Table 2-31
METALS CONCENTRATION EMISSION RATES AND REMOVAL EFFICIENCIES
FOR RUN 5 - BORGESS MEDICAL CENTER (1991)
CARBON INJECTION @ 1 lb/hr.

Location		Inlet	Outlet	Removal
Date		09/07/91	09/07/91	Efficiencies
Metered Volume (dscm)		3.714	2.747	(%)
O2 Concentration (%V)		14.37	15.63	
Flow Rate (dscmm)		53.117	79.401	
Aluminum	(ug/dscm)	409	74.6	
	(ug/dscm @ 7% O2)	871	197	
	(g/hr)	1.30	0.356	72.7%
Antimony	(ug/dscm)	296	3.71	
	(ug/dscm @ 7% O2)	630	9.79	
	(g/hr)	0.944	0.0177	98.1%
Arsenic	(ug/dscm)	3.12	[0.310]	
	(ug/dscm @ 7% O2)	6.65	[0.818]	
	(g/hr)	0.00995	[0.00148]	> 85.1%
Barium	(ug/dscm)	58.7	1.48	
	(ug/dscm @ 7% O2)	125	3.90	
	(g/hr)	0.187	0.00704	96.2%
Beryllium	(ug/dscm)	[0.0961]	[0.0761]	
	(ug/dscm @ 7% O2)	[0.205]	[0.201]	
	(g/hr)	[0.000306]	[0.000362]	NA
Cadmium	(ug/dscm)	162	0.790	
	(ug/dscm @ 7% O2)	346	2.08	
	(g/hr)	0.517	0.00376	99.3%
Chromium	(ug/dscm)	16.3	3.68	
	(ug/dscm @ 7% O2)	34.6	9.70	
	(g/hr)	0.0518	0.0175	66.2%
Copper	(ug/dscm)	590	6.55	
	(ug/dscm @ 7% O2)	1255	17.3	
	(g/hr)	1.88	0.0312	98.3%
Lead	(ug/dscm)	1220	2.26	
	(ug/dscm @ 7% O2)	2600	5.96	
	(g/hr)	3.89	0.0108	99.7%
Mercury	(ug/dscm)	2960	291	
	(ug/dscm @ 7% O2)	6300	767	
	(g/hr)	9.43	1.39	85.3%
Nickel	(ug/dscm)	36.3	4.33	
	(ug/dscm @ 7% O2)	77.4	11.4	
	(g/hr)	0.116	0.0206	82.2%
Silver	(ug/dscm)	6.30	[0.455]	
	(ug/dscm @ 7% O2)	13.4	[1.20]	
	(g/hr)	0.0201	[0.00217]	> 89.2%
Thallium	(ug/dscm)	[9.61]	[7.61]	
	(ug/dscm @ 7% O2)	[20.5]	[20.1]	
	(g/hr)	[0.0306]	[0.0362]	NA

NA = Not Applicable
[ ] = Minimum Detection Limit

Table 2-32

METALS CONCENTRATION EMISSION RATES AND REMOVAL EFFICIENCIES
FOR RUN 6 - BORGESS MEDICAL CENTER (1991)
CARBON INJECTION @ 1 lb/hr.

Location		Inlet	Outlet	Removal
Date		09/07/91	09/07/91	Efficiencies
Metered Volume (dscm)		3.814	2.506	(%)
O2 Concentration (%V)		14.26	15.46	
Flow Rate (dscmm)		54.406	67.901	
Aluminum	(ug/dscm)	288	83.0	
	(ug/dscm @ 7% O2)	604	212	
	(g/hr)	0.941	0.338	64.1%
Antimony	(ug/dscm)	194	4.19	
	(ug/dscm @ 7% O2)	406	10.7	
	(g/hr)	0.633	0.0171	97.3%
Arsenic	(ug/dscm)	3.12	0.575	
	(ug/dscm @ 7% O2)	6.53	1.47	
	(g/hr)	0.0102	0.00234	77.0%
Barium	(ug/dscm)	76.3	2.07	
	(ug/dscm @ 7% O2)	160	5.28	
	(g/hr)	0.249	0.00842	96.6%
Beryllium	(ug/dscm)	[0.0939]	[0.0830]	
	(ug/dscm @ 7% O2)	[0.196]	[0.212]	
	(g/hr)	[0.000306]	[0.000338]	NA
Cadmium	(ug/dscm)	1680	0.942	
	(ug/dscm @ 7% O2)	3520	2.41	
	(g/hr)	5.48	0.00384	99.9%
Chromium	(ug/dscm)	31.2	7.94	
	(ug/dscm @ 7% O2)	65.3	20.3	
	(g/hr)	0.102	0.0324	68.2%
Copper	(ug/dscm)	372	7.46	
	(ug/dscm @ 7% O2)	779	19.1	
	(g/hr)	1.22	0.0304	97.5%
Lead	(ug/dscm)	773	1.48	
	(ug/dscm @ 7% O2)	1620	3.78	
	(g/hr)	2.52	0.00603	99.8%
Mercury	(ug/dscm)	4040	407	
	(ug/dscm @ 7% O2)	8460	1040	
	(g/hr)	13.2	1.66	87.4%
Nickel	(ug/dscm)	62.9	7.22	
	(ug/dscm @ 7% O2)	132	18.5	
	(g/hr)	0.205	0.0294	85.7%
Silver	(ug/dscm)	5.37	2.77	
	(ug/dscm @ 7% O2)	11.3	7.07	
	(g/hr)	0.0175	0.0113	35.8%
Thallium	(ug/dscm)	[9.36]	[8.30]	
	(ug/dscm @ 7% O2)	[19.6]	[21.2]	
	(g/hr)	[0.0306]	[0.0338]	NA

NA = Not Applicable
[ ] = Minimum Detection Limit

Table 2-33
METALS CONCENTRATION EMISSION RATES AND REMOVAL EFFICIENCIES
FOR RUN 7 - BORGESS MEDICAL CENTER (1991)
CARBON INJECTION @ 2.5 lb/hr.

Location		Inlet	Outlet	Removal
Date		09/07/91	09/07/91	Efficiencies
Metered Volume (dscm)		3.765	2.619	(%)
O2 Concentration (%V)		14.5	15.34	
Flow Rate (dscmm)		51.381	74.922	
Aluminum	(ug/dscm)	274	67.6	
	(ug/dscm @ 7% O2)	594	169	
	(g/hr)	0.843	0.304	64.0%
Antimony	(ug/dscm)	37.7	3.89	
	(ug/dscm @ 7% O2)	81.9	9.74	
	(g/hr)	0.116	0.0175	84.9%
Arsenic	(ug/dscm)	0.765	[0.320]	
	(ug/dscm @ 7% O2)	1.66	[0.800]	
	(g/hr)	0.00236	[0.00144]	> 39.0%
Barium	(ug/dscm)	19.6	1.72	
	(ug/dscm @ 7% O2)	42.5	4.31	
	(g/hr)	0.0603	0.00774	87.2%
Beryllium	(ug/dscm)	[0.0948]	[0.0802]	
	(ug/dscm @ 7% O2)	[0.206]	[0.200]	
	(g/hr)	[0.000292]	[0.000360]	NA
Cadmium	(ug/dscm)	111	0.382	
	(ug/dscm @ 7% O2)	241	0.955	
	(g/hr)	0.341	0.00172	99.5%
Chromium	(ug/dscm)	24.2	3.53	
	(ug/dscm @ 7% O2)	52.6	8.83	
	(g/hr)	0.0746	0.0159	78.7%
Copper	(ug/dscm)	87.9	5.08	
	(ug/dscm @ 7% O2)	191	12.7	
	(g/hr)	0.271	0.0228	91.6%
Lead	(ug/dscm)	211	0.779	
	(ug/dscm @ 7% O2)	459	1.95	
	(g/hr)	0.652	0.00350	99.5%
Mercury	(ug/dscm)	3904	304	
	(ug/dscm @ 7% O2)	8480	759	
	(g/hr)	12.0	1.36	88.7%
Nickel	(ug/dscm)	16.1	11.2	
	(ug/dscm @ 7% O2)	34.9	28.0	
	(g/hr)	0.0495	0.0503	-1.52%
Silver	(ug/dscm)	4.38	3.70	
	(ug/dscm @ 7% O2)	9.52	9.24	
	(g/hr)	0.0135	0.0166	-23.0%
Thallium	(ug/dscm)	[9.48]	[8.02]	
	(ug/dscm @ 7% O2)	[20.6]	[20.0]	
	(g/hr)	[0.0292]	[0.0360]	NA

NA = Not Applicable
[ ] = Minimum Detection Limit

Table 2-34
METALS CONCENTRATION EMISSION RATES AND REMOVAL EFFICIENCIES
FOR RUN 8 - BORGESS MEDICAL CENTER (1991)
CARBON INJECTION @ 2.5 lb/hr.

Location		Inlet	Outlet	Removal
Date		09/07/91	09/07/91	Efficiencies
Metered Volume (dscm)		3.588	2.63	(%)
O2 Concentration (%V)		14.43	15.52	
Flow Rate (dscmm)		51.501	71.24	
Aluminum	(ug/dscm)	401	91.6	
	(ug/dscm @ 7% O2)	862	237	
	(g/hr)	1.24	0.392	68.4%
Antimony	(ug/dscm)	162	3.99	
	(ug/dscm @ 7% O2)	347	10.3	
	(g/hr)	0.500	0.0171	96.6%
Arsenic	(ug/dscm)	2.49	[0.316]	
	(ug/dscm @ 7% O2)	5.36	[0.815]	
	(g/hr)	0.00771	[0.00135]	> 82.5%
Barium	(ug/dscm)	97.5	2.24	
	(ug/dscm @ 7% O2)	210	5.78	
	(g/hr)	0.301	0.00956	96.8%
Beryllium	(ug/dscm)	[0.0995]	[0.0787]	
	(ug/dscm @ 7% O2)	[0.214]	[0.203]	
	(g/hr)	[0.000307]	[0.000336]	NA
Cadmium	(ug/dscm)	563	11.0	
	(ug/dscm @ 7% O2)	1210	28.3	
	(g/hr)	1.74	0.0468	97.3%
Chromium	(ug/dscm)	25.6	4.52	
	(ug/dscm @ 7% O2)	54.9	11.7	
	(g/hr)	0.0790	0.0193	75.5%
Copper	(ug/dscm)	516	12.4	
	(ug/dscm @ 7% O2)	1110	31.9	
	(g/hr)	1.59	0.0528	89.1%
Lead	(ug/dscm)	1060	4.33	
	(ug/dscm @ 7% O2)	2280	11.2	
	(g/hr)	3.28	0.0185	99.4%
Mercury	(ug/dscm)	3180	40.7	
	(ug/dscm @ 7% O2)	6830	105	
	(g/hr)	9.83	0.174	98.2%
Nickel	(ug/dscm)	22.2	7.68	
	(ug/dscm @ 7% O2)	47.8	19.8	
	(g/hr)	0.0687	0.0328	52.2%
Silver	(ug/dscm)	9.48	0.658	
	(ug/dscm @ 7% O2)	20.4	1.70	
	(g/hr)	0.0293	0.00281	90.4%
Thallium	(ug/dscm)	[9.95]	[7.87]	
	(ug/dscm @ 7% O2)	[21.4]	[20.3]	
	(g/hr)	[0.0307]	[0.0336]	NA

NA = Not Applicable
[ ] = Minimum Detection Limit

Table 2-35
METALS CONCENTRATION EMISSION RATES AND REMOVAL EFFICIENCIES
FOR RUN 9 - BORGESS MEDICAL CENTER (1991)
CARBON INJECTION @ 2.5 lb/hr.

Location		Inlet	Outlet	Removal
Date		09/07/91	09/07/91	Efficiencies
Metered Volume (dscm)		3.616	2.545	(%)
O2 Concentration (%V)		13.21	14.45	
Flow Rate (dscmm)		49.014	71.42	
Aluminum	(ug/dscm)	293	68.4	
	(ug/dscm @ 7% O2)	530	147	
	(g/hr)	0.862	0.293	66.0%
Antimony	(ug/dscm)	110	3.69	
	(ug/dscm @ 7% O2)	198	7.95	
	(g/hr)	0.323	0.0158	95.1%
Arsenic	(ug/dscm)	3.15	[0.328]	
	(ug/dscm @ 7% O2)	5.70	[0.707]	
	(g/hr)	0.00927	[0.00141]	> 84.8%
Barium	(ug/dscm)	47.0	2.25	
	(ug/dscm @ 7% O2)	85.0	4.84	
	(g/hr)	0.138	0.00963	93.0%
Beryllium	(ug/dscm)	[0.0987]	0.2094	
	(ug/dscm @ 7% O2)	[0.178]	0.451	
	(g/hr)	[0.000290]	0.000897	NA
Cadmium	(ug/dscm)	382	0.833	
	(ug/dscm @ 7% O2)	690	1.80	
	(g/hr)	1.12	0.00357	99.7%
Chromium	(ug/dscm)	11.7	4.56	
	(ug/dscm @ 7% O2)	21.1	9.82	
	(g/hr)	0.0344	0.0195	43.2%
Copper	(ug/dscm)	572	3.77	
	(ug/dscm @ 7% O2)	1040	8.12	
	(g/hr)	1.68	0.0161	99.0%
Lead	(ug/dscm)	973	3.54	
	(ug/dscm @ 7% O2)	1760	7.63	
	(g/hr)	2.86	0.0152	99.5%
Mercury	(ug/dscm)	7330	141	
	(ug/dscm @ 7% O2)	13200	303	
	(g/hr)	21.6	0.603	97.2%
Nickel	(ug/dscm)	15.7	8.25	
	(ug/dscm @ 7% O2)	28.3	17.8	
	(g/hr)	0.0461	0.0354	23.3%
Silver	(ug/dscm)	5.17	2.29	
	(ug/dscm @ 7% O2)	9.35	4.95	
	(g/hr)	0.0152	0.00983	35.3%
Thallium	(ug/dscm)	[9.87]	[8.21]	
	(ug/dscm @ 7% O2)	[17.8]	[17.7]	
	(g/hr)	[0.0290]	[0.0352]	NA

NA = Not Applicable
[ ] = Minimum Detection Limit

terms of μg/dscm, both with and without correction to 7 percent O_2. Oxygen concentrations were calculated from CEM data, which were averaged over the time period in which manual testing was performed.

2.3.5 Flue Gas Metals to PM Ratios

A summary of the ratio of metals to PM for the emission tests without carbon injection is presented in Table 2-36. Metals to PM ratios are given in units of milligrams of metal to grams of PM collected by the sampling train. The inlet values range from 0.0208 mg Ag per gram of PM during Run 4 to 57.2 mg Hg per gram during Run 2. Mercury had the highest inlet ratios for Runs 3 and 4 also, with 39.9 and 21.0 mg metal/gram PM, respectively. Outlet values range from 0.0912 mg Cd per gram of PM during Run 2 to 2270 mg Hg per gram of PM during Run 3. High Hg-to-PM ratios can be misleading, however, since most Hg is in a volatile form at the particulate filter temperature, and is, therefore, not associated with PM, but is captured in the back-half impinger solutions.

Table 2-37 presents a summary of the ratio by weight of metals to PM for the emission tests with carbon injection at 1 lb/hr. Inlet values range from 0.037 mg As per gram of PM in Run 5 to 53.4 mg Hg per gram of PM in Run 6. Mercury had the highest ratio for Run 5 also, with 34.9 mg metal per gram of PM. Values at the outlet range from 0.293 mg of As per gram of PM in Run 6 to 316 mg of Hg per gram of PM in Run 5. Mercury also had the highest outlet ratio for Run 6 with 208 mg of metal per gram of PM.

Table 2-38 presents a summary of the ratio by weight of metals to PM for the emission tests with carbon injection at 2.5 lb/hr. Inlet values range from 0.009 mg As per gram of PM in Run 7 to 86.3 mg Hg per gram of PM in Run 9. Mercury also had the highest ratio for Runs 7 and 8 with 46.4 and 34.3 mg Hg per gram of PM, respectively. Outlet values range from 0.188 mg Ag per gram of PM in Run 8 to 172 mg of Hg per gram of PM in Run 7. Aluminum had the highest ratio in Run 8 with 26.2 mg metal per gram of PM, and Hg in Run 9, with 87.4 mg metal per gram of PM.

Table 2-36

RATIO OF METALS TO PARTICULATE MATTER - BORGESS MEDICAL CENTER (1991)

*** WITHOUT CARBON INJECTION ***

METALS/PARTICULATE RATIO (mg metal per gram of particulate)								
Location	INLET				OUTLET			
Run	Run 2 (mg/g)	Run 3 (mg/g)	Run 4 (mg/g)	Average (mg/g)	Run 2 (mg/g)	Run 3 (mg/g)	Run 4 (mg/g)	Average (mg/g)
Aluminum	4.63	6.10	4.94	5.22	18.5	55.0	47.1	40.2
Antimony	0.814	2.11	2.01	1.65	1.51	3.85	2.74	2.70
Arsenic	0.0319	0.0400	0.0393	0.0370	[0.0837]	0.126	0.246	0.186
Barium	0.529	0.782	0.375	0.562	0.394	1.45	1.18	1.01
Beryllium	[0.00118]	0.00336	[0.00125]	0.00336	[0.0209]	[0.0529]	[0.488]	[0.187]
Cadmium	2.37	1.99	2.49	2.28	0.0912	0.458	0.504	0.351
Chromium	0.164	0.253	0.138	0.185	0.857	8.08	4.59	4.51
Copper	4.56	6.68	4.84	5.36	16.1	14.8	8.50	13.1
Lead	5.69	11.9	7.68	8.43	0.283	0.797	1.51	0.862
Mercury	57.2	39.9	21.0	39.4	984	2270	810	1354
Nickel	0.198	0.284	0.318	0.267	1.64	8.84	8.97	6.48
Silver	0.0285	0.109	0.0208	0.0527	0.794	0.388	0.970	0.717
Thallium	[0.118]	[0.104]	[0.125]	[0.116]	[2.08]	[5.66]	[4.88]	[4.20]

[ ] = Minimum Detection Limit

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Table 2-37

RATIO OF METALS TO PARTICULATE MATTER - BORGESS MEDICAL CENTER (1991)

*** CARBON INJECTION AT 1 lb/hr ***

METALS/PARTICULATE RATIO (mg metal per gram of particulate)						
Location	INLET			OUTLET		
Run	Run 5 (mg/g)	Run 6 (mg/g)	Average (mg/g)	Run 5 (mg/g)	Run 6 (mg/g)	Average (mg/g)
Aluminum	4.83	3.81	4.32	81.1	42.3	61.7
Antimony	3.49	2.56	3.03	4.04	2.14	3.09
Arsenic	0.0369	0.0412	0.0391	[0.338]	0.293	0.293
Barium	0.693	1.01	0.851	1.61	1.05	1.33
Beryllium	[0.00113]	[0.00147]	[0.00130]	[0.0698]	[0.0423]	[0.0560]
Cadmium	1.92	22.2	12.1	0.859	0.480	0.670
Chromium	0.192	0.412	0.302	4.00	4.05	4.02
Copper	6.96	4.92	5.94	7.12	3.81	5.46
Lead	14.4	10.2	12.3	2.46	0.755	1.61
Mercury	34.9	53.4	44.2	316	208	262
Nickel	0.429	0.832	0.630	4.71	3.69	4.20
Silver	0.0743	0.0708	0.0726	[0.495]	1.41	1.41
Thallium	[0.113]	[0.147]	[0.130]	[6.98]	[4.23]	[5.60]

[ ] = Minimum Detection Limit

Table 2-38

RATIO OF METALS TO PARTICULATE MATTER - BORGESS MEDICAL CENTER (1991)

*** CARBON INJECTION AT 2.5 lb/hr ***

METALS/PARTICULATE RATIO (mg metal per gram of particulate)								
Location	INLET				OUTLET			
Run	Run 7 (mg/g)	Run 8 (mg/g)	Run 9 (mg/g)	Average (mg/g)	Run 7 (mg/g)	Run 8 (mg/g)	Run 9 (mg/g)	Average (mg/g)
Aluminum	3.25	4.34	3.45	3.68	38.4	26.2	42.5	35.7
Antimony	0.448	1.75	1.29	1.16	2.21	1.14	2.29	1.88
Arsenic	0.00909	0.0269	0.0371	0.0244	[0.182]	[0.0902]	[0.204]	[0.159]
Barium	0.233	1.05	0.554	0.613	0.978	0.639	1.40	1.00
Beryllium	[0.00112]	[0.00107]	[0.00116]	[0.00112]	[0.0455]	[0.0224]	0.130	0.130
Cadmium	1.32	6.08	4.49	3.96	0.217	3.13	0.517	1.29
Chromium	0.288	0.276	0.138	0.234	2.01	1.29	2.83	2.04
Copper	1.04	5.57	6.74	4.45	2.89	3.53	2.34	2.92
Lead	2.51	11.4	11.5	8.47	0.443	1.24	2.20	1.29
Mercury	46.4	34.3	86.3	55.7	172	11.6	87.4	90.5
Nickel	0.191	0.240	0.185	0.205	6.36	2.19	5.13	4.56
Silver	0.0521	0.102	0.0609	0.0718	2.10	0.188	1.43	1.24
Thallium	[0.112]	[0.107]	[0.116]	[0.111]	[4.55]	[2.24]	[5.10]	[3.97]

[ ] = Minimum Detection Limit

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2.3.6 Flue Gas Metals by Sample Fraction and Sample Parameters

Table 2-39 presents the metal amounts in the inlet flue gas samples by fraction for each run. The highest proportion of Hg was consistently collected in the nitric acid impingers (Impingers 1-3). All other metals detected, except Cr in Runs 2, 7, and 8, and Ni in Runs 2 and 3, were collected in the highest proportions in the front half (filter, nozzle/probe rinse).

The amounts of metals in the outlet flue gas samples are presented in Table 2-40 by sample fraction. As in the inlet, the highest proportion of Hg was collected in the nitric acid impingers for all runs. Other metals were collected in the highest proportions in the front half fraction, except for Cr in Run 2, As, Cr, Cu, and Ni in Run 3, Ba, Cr, and Cu in Run 4, Cr and Cu in Runs 5 and 7, As, Cr, Cr, Ni, and Ag in Run 6, and Cr in Runs 8 and 9. Laboratory analytical results for each sample fraction are presented in detail in Appendix E.

Sampling and flue gas parameters for the PM/metals runs at the three sampling locations are shown in Tables 2-41 through 2-43. Total sampling times, sample volume and isokinetic results for each sampling run are presented. Appendix A contains a complete listing of these and additional sampling and flue gas parameters for each run, along with the field data sheets.

2.3.7 Metals in Ash

A sample of the baghouse ash was collected in the afternoon following each test day. Incinerator bottom ash was collected in the morning following its respective test run. Concentrations of the metals in the ash in units of mg/kg were determined by microwave digesting a half gram in acid and hydrogen peroxide and diluting the solution to 100 mL. The analyses were then completed as discussed in Section 5.

The metals in the ash are shown in Table 2-44. Aluminum was the metals with the highest concentration in the baghouse ash for every run. Beryllium and Tl were not detected in any of the baghouse ash samples. Copper was the most prevalent metal in the bottom ash from Day 6 with 232,000 mg/kg. Aluminum showed the highest concentration of metals in the ash for the other runs sampled. Thallium was not detected in any of the bottom ash samples.

Table 2-39
METALS AMOUNT IN INLET FLUE GAS - SAMPLES BY SAMPLE FRACTION
BORGESS MEDICAL CENTER (1991)

METALS	Run 2				Run 3				Run 4			
	Front Half (Total ug)	Impinger 1,2,3 (Total ug)	Impinger 4,5,6 (Total ug)	Total ug	Front Half (Total ug)	Impinger 1,2,3 (Total ug)	Impinger 4,5,6 (Total ug)	Total ug	Front Half (Total ug)	Impinger 1,2,3 (Total ug)	Impinger 4,5,6 (Total ug)	Total ug
Aluminum	1300	98.6		1400	2010	79.0		2090	1330	83.4		1410
Antimony	187	58.8		246	669	55.0		724	548	24.8		573
Arsenic	9.13	0.511		9.64	12.8	0.891		13.7	9.65	1.56		11.2
Barium	153	6.76		160	263	4.79		268	106	0.819		107
Beryllium	[0.250]	[0.108]		[0.358]	[0.250]	1.15		1.15	[0.250]	[0.106]		[0.356]
Cadmium	715	0.986		716	680	2.44		682	710	[0.213]		710
Chromium	18.1	31.4		49.5	53.8	32.9		86.7	23.7	15.6		39.3
Copper	1350	33.8		1380	2190	97.7		2290	1350	31.3		1380
Lead	1720	2.55		1720	4090	0.601		4090	2190	0.734		2190
Mercury	7.38	17200	78.9	17300	[2.45]	13700	16.6	13700	[2.45]	5960	46.2	6000
Nickel	29.3	30.6		59.9	92.8	4.51		97.3	38.8	51.8		90.6
Silver	4.85	3.77		8.62	6.35	30.9		37.3	5.93	[0.638]		5.93
Thallium	[25.0]	[10.8]		[35.8]	[25.0]	[10.7]		[35.7]	[25.0]	[10.6]		[35.6]

NOTE: Impingers 4,5, and 6 sample fractions analyzed for mercury content only.

[ ]= Minimum Detection Limit

0 9 3

Table 2-39 (Continued)
METALS AMOUNT IN INLET FLUE GAS - SAMPLES BY SAMPLE FRACTION
BORGESS MEDICAL CENTER (1991)

METALS	Run 5				Run 6				Field Blank			
	Front Half (Total ug)	Impinger 1,2,3 (Total ug)	Impinger 4,5,6 (Total ug)	Total ug	Front Half (Total ug)	Impinger 1,2,3 (Total ug)	Impinger 4,5,6 (Total ug)	Total ug	Front Half (Total ug)	Impinger 1,2,3 (Total ug)	Impinger 4,5,6 (Total ug)	Total ug
Aluminum	1340	176		1520	887	208		1100	468	22.0		490
Antimony	1040	63.9		1100	640	98.9		739	30.0	[1.85]		30.0
Arsenic	11.0	0.601		11.6	11.2	0.696		11.9	[1.00]	0.655		0.655
Barium	208	9.90		218	288	2.62		291	15.8	1.03		16.8
Beryllium	[0.250]	[0.107]		[0.357]	[0.250]	[0.107]		[0.357]	[0.250]	[0.124]		[0.374]
Cadmium	601	2.34		603	6420	0.522		6420	8.93	[0.247]		8.93
Chromium	43.3	17.1		60.4	61.0	58.3		119	47.5	4.21		51.7
Copper	2160	36.5		2200	1400	22.6		1420	46.5	9.65		56.2
Lead	4520	0.601		4520	2950	0.464		2950	27.3	0.538		27.8
Mercury	3.25	11000	19.6	11000	12.0	15400	43.8	15500	[2.45]	20.0	30.6	50.6
Nickel	111	23.6		135	184	56.3		240	59.5	3.49		63.0
Silver	23.4	[0.641]		23.4	15.8	4.67		20.5	[1.50]	[0.742]		[2.24]
Thallium	[25.0]	[10.7]		[35.7]	[25.0]	[10.7]		[35.8]	[25.0]	[12.4]		[37.4]

NOTE: Impingers 4,5, and 6 sample fractions analyzed for mercury content only.

[ ]= Minimum Detection Limit

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Table 2-39 (Continued)
METALS AMOUNT IN INLET FLUE GAS - SAMPLES BY SAMPLE FRACTION
BORGESS MEDICAL CENTER (1991)

METALS	Run 7				Run 8				Run 9			
	Front Half (Total ug)	Impinger 1,2,3 (Total ug)	Impinger 4,5,6 (Total ug)	Total ug	Front Half (Total ug)	Impinger 1,2,3 (Total ug)	Impinger 4,5,6 (Total ug)	Total ug	Front Half (Total ug)	Impinger 1,2,3 (Total ug)	Impinger 4,5,6 (Total ug)	Total ug
Aluminum	940	92.9		1030	1330	105		1440	939	123		1060
Antimony	93.0	48.7		142	528	52.3		580	251	146		397
Arsenic	2.18	0.701		2.88	8.50	0.454		8.95	10.8	0.649		11.4
Barium	72.5	1.21		73.7	349	1.17		350	163	7.27		170
Beryllium	[0.250]	[0.107]		[0.357]	[0.250]	[0.107]		[0.357]	[0.250]	[0.107]		[0.357]
Cadmium	417	0.344		417	2010	5.91		2020	1380	[0.213]		1380
Chromium	44.5	46.6		91.1	27.5	64.2		91.7	23.6	18.7		42.3
Copper	328	3.38		331	1830	20.8		1850	2070	4.44		2070
Lead	795	0.878		796	3800	6.06		3810	3520	0.464		3520
Mercury	4.38	14700	10.7	14700	7.38	11400	29.3	11400	22.0	26400	44.8	26500
Nickel	49.5	11.0		60.5	61.3	18.5		79.8	48.3	8.39		56.7
Silver	15.1	1.43		16.5	34.0	[0.640]		34.0	18.7	[0.640]		18.7
Thallium	[25.0]	[10.7]		[35.7]	[25.0]	[10.7]		[35.7]	[25.0]	[10.7]		[35.7]

NOTE: Impingers 4,5, and 6 sample fractions analyzed for mercury content only.

[ ]= Minimum Detection Limit

0 9 5

Table 2-40

METALS AMOUNTS IN OUTLET FLUE GAS - SAMLES BY SAMPLE FRACTION - BORGESS MEDICAL CENTER (1991)

METALS	Run 2				Run 3				Run 4			
	Front Half (Total ug)	Impinger 1,2,3 (Total ug)	Impinger 4,5,6 (Total ug)	Total ug	Front Half (Total ug)	Impinger 1,2,3 (Total ug)	Impinger 4,5,6 (Total ug)	Total ug	Front Half (Total ug)	Impinger 1,2,3 (Total ug)	Impinger 4,5,6 (Total ug)	Total ug
Aluminum	171	17.5		189	172	30.9		203	179	22.2		201
Antimony	11.8	3.56		15.4	11.7	2.45		14.2	11.7	[1.62]		11.7
Arsenic	[0.400]	[0.452]		[0.852]	[0.400]	0.464		0.464	[0.400]	1.05		1.05
Barium	3.65	0.373		4.02	4.83	0.511		5.34	4.64	0.379		5.02
Beryllium	[0.100]	[0.113]		[0.213]	[0.100]	[0.109]		[0.209]	[0.100]	[0.108]		[0.208]
Cadmium	0.930	[0.226]		0.930	1.07	0.620		1.69	1.73	0.422		2.15
Chromium	4.10	4.64		8.74	5.14	24.7		29.8	4.00	15.6		19.6
Copper	141	22.7		164	19.6	34.9		54.5	9.37	26.9		36.3
Lead	2.18	0.708		2.89	1.78	1.16		2.94	5.61	0.816		6.43
Mercury	[0.980]	9970	51.3	10000	[0.980]	8340	45.8	8390	[0.980]	3460	9.43	3470
Nickel	12.3	4.40		16.7	7.11	25.5		32.6	22.2	16.1		38.3
Silver	4.83	3.27		8.10	1.43	[0.653]		1.43	4.14	[0.649]		4.14
Thallium	[10.0]	[11.3]		[21.3]	[10.0]	[10.9]		[20.9]	[10.0]	[10.8]		[20.8]

NOTE: Impingers 4,5, and 6 sample fractions analyzed for mercury content only,

[ ]= Minimum Detection Limit

Table 2-40 (Continued)
METALS AMOUNTS IN OUTLET FLUE GAS - SAMLES BY SAMPLE FRACTION - BORGESS MEDICAL CENTER (1991)

METALS	Run 5				Run 6				Field Blank			
	Front Half (Total ug)	Impinger 1,2,3 (Total ug)	Impinger 4,5,6 (Total ug)	Total ug	Front Half (Total ug)	Impinger 1,2,3 (Total ug)	Impinger 4,5,6 (Total ug)	Total ug	Front Half (Total ug)	Impinger 1,2,3 (Total ug)	Impinger 4,5,6 (Total ug)	Total ug
Aluminum	186	18.5		205	176	31.8		208	152	23.2		175
Antimony	10.2	[1.64]		10.2	10.5	[1.62]		10.5	10.2	[1.71]		10.2
Arsenic	[0.400]	[0.436]		[0.852]	[0.400]	1.44		1.44	[0.400]	[0.457]		[0.857]
Barium	3.77	0.294		4.06	4.69	0.486		5.18	3.79	0.503		4.29
Beryllium	[0.100]	[0.109]		[0.209]	[0.100]	[0.108]		[0.208]	[0.100]	[0.114]		[0.214]
Cadmium	1.54	0.633		2.17	1.89	0.465		2.36	0.490	0.263		0.753
Chromium	2.89	7.21		10.1	4.61	15.3		19.9	4.90	6.63		11.5
Copper	8.00	10.0		18.0	6.44	12.3		18.7	16.2	79.8		96.0
Lead	5.04	1.17		6.21	2.83	0.884		3.71	2.62	1.04		3.66
Mercury	[0.980]	786	13.1	799	[0.980]	1010	4.68	1020	[0.980]	18.5	[0.529]	18.5
Nickel	5.97	5.88		11.9	7.80	10.3		18.1	94.3	6.48		101
Silver	[0.600]	[0.655]		[1.25]	0.710	6.22		6.93	4.72	0.800		5.52
Thallium	[10.0]	[10.9]		[20.9]	[10.0]	[10.8]		[20.8]	[10.0]	[11.4]		[21.4]

NOTE: Impingers 4,5, and 6 sample fractions analyzed for mercury content only.

[ ]= Minimum Detection Limit

Table 2-40 (Continued)
METALS AMOUNTS IN OUTLET FLUE GAS - SAMLES BY SAMPLE FRACTION -
BORGESS MEDICAL CENTER (1991)

METALS	Run 7				Run 8				Run 9			
	Front Half (Total ug)	Impinger 1,2,3 (Total ug)	Impinger 4,5,6 (Total ug)	Total ug	Front Half (Total ug)	Impinger 1,2,3 (Total ug)	Impinger 4,5,6 (Total ug)	Total ug	Front Half (Total ug)	Impinger 1,2,3 (Total ug)	Impinger 4,5,6 (Total ug)	Total ug
Aluminum	159	18.0		177	220	20.5		241	147	27.2		174
Antimony	10.2	[1.64]		10.2	10.5	[1.61]		10.5	9.39	[1.63]		9.39
Arsenic	[0.400]	[0.438]		[0.838]	[0.400]	[0.430]		[0.830]	[0.400]	[0.435]		[0.835]
Barium	4.16	0.351		4.51	5.50	0.376		5.88	3.63	2.09		5.72
Beryllium	[0.100]	[0.110]		[0.210]	[0.100]	[0.107]		[0.207]	[0.100]	0.533		0.533
Cadmium	1.00	[0.219]		1.00	28.8	[0.215]		28.8	1.01	1.11		2.12
Chromium	3.12	6.13		9.25	3.39	8.47		11.9	7.93	3.62		11.6
Copper	4.93	8.36		13.3	19.8	12.7		32.5	5.46	4.13		9.59
Lead	2.04	[0.329]		2.04	10.7	0.741		11.4	8.68	0.334		9.01
Mercury	[0.980]	788	6.82	795	[0.980]	107	[0.686]	107	[0.980]	358	[0.796]	358
Nickel	27.4	1.93		29.3	17.2	3.00		20.2	18.5	2.51		21.0
Silver	8.79	0.888		9.68	1.73	[0.644]		1.73	5.06	0.783		5.84
Thallium	[10.0]	[11.0]		[21.0]	[10.0]	[10.7]		[20.7]	[10.0]	[10.9]		[20.9]

NOTE: Impingers 4,5, and 6 sample fractions analyzed for mercury content only.

[ ]= Minimum Detection Limit

0 9 8 0

Table 2-41

METALS/PM EMISSIONS SAMPLING AND FLUE GAS PARAMETERS AT THE BOILER INLET BORGESS MEDICAL CENTER (1991)

Run No. Date	Run 2 09/07/91	Run 3 09/09/91	Run 4 09/10/91	Run 5 09/11/91	Run 6 09/12/91	Run 7 09/13/91	Run 8 09/14/91	Run 9 09/16/91	Average
Total Sampling Time (min)	240	241	240	240	240	240	240	240	NA
Average Sampling Rate (dscfm)	0.62	0.34	0.35	0.33	0.28	0.26	0.26	0.27	0.34
Metered Volume (dscf)	148.38	81.45	85.14	78.17	66.55	62.60	62.52	65.56	81.30
Metered Volume (dscm)	4.202	2.31	2.411	2.214	1.885	1.773	1.770	1.857	2.302
Average Stack Temperature (F)	1329	1255	1082	1230	1272	1206	1216	1247	1230
O2 Concentration (%V)	13.4	13.9	14.9	14.4	14.3	14.5	14.4	13.2	14.1
CO2 Concentration (%V)	5.0	4.2	4.1	4.2	3.9	3.3	3.1	5.0	4.1
Stack Gas Moisture (%V)	13.9	11.7	15.0	12.6	14.7	13.4	13.5	15.8	13.8
Volumetric Flow Rate (dscfm)	1923	2132	1960	1959	1941	1979	1947	1963	1976
Volumetric Flow Rate (dscmm)	54.47	60.39	55.50	55.49	54.98	56.05	55.13	55.59	55.95
Percent Isokinetic	95.6	133.3	109.5	104.4	89.7	108.0	109.6	114.0	NA
Particulate Catch (grams)	1.0073	0.4649	0.2839	0.3577	0.2469	0.1567	0.3064	0.291	0.3894

NA = Not Applicable

* O2 and CO2 values were obtained form the baghouse inlet.

Table 2-42

METALS/PM EMISSIONS SAMPLING AND FLUE GAS PARAMETERS AT BAGHOUSE INLET BORGESS MEDICAL CENTER (1991)

Run No. Date	Run 2 09/07/91	Run 3 09/09/91	Run 4 09/10/91	Run 5 09/11/91	Run 6 09/12/91	Run 7 09/13/91	Run 8 09/14/91	Run 9 09/16/91	Average
Total Sampling Time (min)	240	240	240	240	240	240	240	240	NA
Average Sampling Rate (dscfm)	0.49	0.55	0.54	0.55	0.56	0.55	0.53	0.53	0.54
Metered Volume (dscf)	118.42	131.32	130.71	131.16	134.67	132.93	126.70	127.68	129.20
Metered Volume (dscm)	3.354	3.719	3.702	3.714	3.814	3.765	3.588	3.616	3.659
Average Stack Temperature (F)	361	356	354	357	369	363	357	372	361
O2 Concentration (%V)	13.4	13.9	14.9	14.4	14.3	14.5	14.4	13.2	14.1
CO2 Concentration (%V)	5.0	4.2	4.1	4.2	3.9	3.3	3.1	5.0	4.1
Stack Gas Moisture (%V) *	12.8	11.7	12.0	12.2	13.4	12.8	13.0	14.8	12.8
Volumetric Flow Rate (dscfm)	1718	1909	1901	1876	1921	1814	1819	1731	1836
Volumetric Flow Rate (dscmm)	48.64	54.06	53.83	53.12	54.41	51.38	51.50	49.01	51.99
Percent Isokinetic	95.3	97.3	95.8	97.4	96.2	100.6	95.6	101.3	NA
Particulate Catch (grams)	0.3023	0.3427	0.2852	0.3148	0.2885	0.3168	0.3322	0.3071	0.3112

NA = Not Applicable

* Moisture values are average values from the CDD/CDF and M101A sampling trains. Moisture data obtained from the metals trains was determined to be inaccurate.

Table 2-43

METALS/PM EMISSIONS SAMPLING AND FLUE GAS PARAMETERS AT OUTLET

BORGESS MEDICAL CENTER (1991)

Run No. Date	Run 2 09/07/91	Run 3 09/09/91	Run 4 09/10/91	Run 5 09/11/91	Run 6 09/12/91	Run 7 09/13/91	Run 8 09/14/91	Run 9 09/16/91	Average
Total Sampling Time (min)	240	240	240	240	240	240	240	240	NA
Average Sampling Rate (dscfm)	0.35	0.38	0.39	0.40	0.37	0.39	0.39	0.37	0.38
Metered Volume (dscf)	84.52	91.08	92.48	96.99	88.48	92.48	92.88	89.86	91.10
Metered Volume (dscm)	2.394	2.579	2.619	2.747	2.506	2.619	2.630	2.545	2.580
Average Stack Temperature (F)	294.42	295.60	292.25	288.98	293.33	295.42	282.44	292.52	291.87
O2 Concentration (%V)	15.05	15.66	15.90	15.63	15.46	15.34	15.52	14.45	15.38
CO2 Concentration (%V)	4.69	4.19	4.19	4.23	4.42	4.45	4.48	5.20	4.48
Stack Gas Moisture (%V)	10.56	12.84	9.14	9.20	15.03	10.20	15.76	11.59	11.79
Volumetric Flow Rate (dscfm)	2443.77	2558.37	2702.66	2803.72	2397.63	2645.55	2515.55	2521.88	2573.64
Volumetric Flow Rate (dscmm)	69.208	72.453	76.539	79.401	67.901	74.922	71.240	71.420	72.886
Percent Isokinetic	103.26	106.28	102.15	103.28	110.17	104.36	110.23	106.38	NA
Particulate Catch (grams)	0.0102	0.0037	0.0044	0.0058	0.0049	0.0046	0.0092	0.0041	0.0059

NA = Not Applicable

Table 2-44
METALS IN ASH CONCENTRATIONS
BAGHOUSE ASH AND BOTTOM ASH - BORGESS MEDICAL CENTER (1991)

Metal	Run 2 (mg/kg)	Run 3 (mg/kg)	Run 4 (mg/kg)	Run 5 (mg/kg)	Run 6 (mg/kg)	Run 7 (mg/kg)	Run 8 (mg/kg)	Run 9 (mg/kg)	Average Runs 2-9 (mg/kg)
BAGHOUSE ASH									
Aluminum	682	692	583	654	591	835	760	742	692
Antimony	22.6	41.2	25.8	46.4	31.0	18.8	51.8	23.4	32.6
Arsenic	1.30	1.16	0.976	1.16	0.976	1.44	1.71	1.62	1.29
Barium	12.0	12.6	8.40	12.5	16.0	18.7	16.5	12.3	13.6
Beryllium	[0.200]	[0.200]	[0.200]	[0.200]	[0.200]	[0.200]	0.260	[0.200]	0.260
Cadmium	22.2	27.4	40.0	23.4	829	144	84.0	65.4	154
Chromium	13.6	13.2	13.1	13.1	13.0	13.1	13.4	17.7	13.8
Copper	178	196	135	169	132	154	143	147	157
Lead	85.2	151	80.0	146	98.4	117	142	112	116
Mercury	7.80	6.32	4.84	476	354	385	336	594	270
Nickel	4.16	3.26	3.06	4.14	3.88	4.26	5.18	7.04	4.37
Silver	3.40	5.36	1.98	4.30	3.86	4.62	2.96	1.70	3.52
Thallium	[20.0]	[20.0]	[20.0]	[20.0]	[20.0]	[20.0]	[20.0]	[20.0]	[20.0]
BOTTOM ASH									
Aluminum	56500	55600	59100	23900	23200	57500	48800	63400	48500
Antimony	[3.00]	[3.00]	[3.00]	[3.00]	26.2	[3.00]	4.16	[3.00]	15.2
Arsenic	60.0	51.8	60.0	20.6	19.5	56.4	46.0	65.6	47.5
Barium	2350	2510	1460	3580	1640	5150	3860	2490	2880
Beryllium	0.400	0.400	0.400	[0.200]	[0.200]	0.340	0.300	0.300	0.268
Cadmium	6.00	5.68	5.58	1.32	43.0	12.7	5.20	16.9	12.0
Chromium	58.8	44.0	34.2	19.5	18.6	46.8	52.0	44.0	39.7
Copper	4000	3200	462	537	232000	2860	2030	1530	30800
Lead	105	246	87.6	116	72.8	224	152	290	162
Mercury	[1.96]	11.2	[1.96]	[1.96]	[1.96]	[1.96]	[1.96]	[1.96]	11.2
Nickel	37.4	191.0	18.8	9.3	13.6	32.0	37.6	37.0	47.1
Silver	3.80	3.00	2.02	6.02	4.04	2.24	[1.20]	[1.20]	3.52
Thallium	[20.0]	[20.0]	[20.0]	[20.0]	[20.0]	[20.0]	[20.0]	[20.0]	[20.0]

[ ] = Minimum Detection Limit

Table 2-45 shows the hourly mass rate of each metal removed from the incinerator in the baghouse ash and the daily mass rate of metals removed from the incinerator in the bottom ash.

2.4 PARTICULATE MATTER EMISSIONS

Particulate matter emissions were determined from the same sampling train used for metals determinations at the baghouse inlet and outlet. At the boiler inlet, PM emissions were sampled with a standard Method 5 train. Before metals analysis, PM collected in the filter and in the front half acetone rinse (probe, nozzle, filter holder) was analyzed gravimetrically as discussed in Section 5.

The average PM stack gas concentrations and mass rates for the boiler and baghouse inlets and baghouse outlet are presented in Table 2-46. Uncorrected concentrations and concentrations adjusted to 7 percent O_2 are shown. As shown, average removal efficiency, based on the mass rates at the baghouse inlet and outlet, is 96.5 percent.

Particulate matter concentrations, emission rates, and removal efficiencies for the individual runs are summarized in Table 2-47. Run 2 showed the highest PM concentration and emission rate at the outlet with 0.00426 g/dscm and 0.0177 kg/hr, respectively. Removal efficiencies ranged from 93.3 percent for Run 2 to 98.4 percent for Run 5.

A brief summary of the sampling and flue gas parameters for the PM runs is given in Table 2-41 and 2-42. Appendix A.2 presents a detailed listing of the parameters for each sampling run. Appendix E.2 shows the gravimetric PM analytical results.

2.5 MERCURY EMISSIONS BY METHOD 101A

A Method 101A train was used to sample Hg because a toxic metals train cannot be used if particulate sampling is run in conjunction with the multi-metal trains. A comparison of the Method 101A Hg values to the multi-metals train is discussed in more detail in Section 2.5.6.

Table 2-45.

METALS DAILY DISCHARGE RATES IN THE ASH STREAM

BAGHOUSE ASH AND BOTTOM ASH BORGESS MEDICAL CENTER (1991)

Run	2	3	4	5	6	7	8	9	Average Runs 2-9
BAGHOUSE ASH	(g/hr)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	(g/hr)
Aluminum	12.7	13.9	12.3	11.6	11.8	17.9	14.6	14.6	13.7
Antimony	0.420	0.828	0.542	0.821	0.622	0.402	0.994	0.459	0.636
Arsenic	0.0242	0.0233	0.0205	0.0205	0.0196	0.0308	0.0328	0.0318	0.0254
Barium	0.223	0.253	0.177	0.221	0.321	0.400	0.317	0.241	0.269
Beryllium	[0.00371]	[0.00402]	[0.00420]	[0.00355]	[0.00405]	[0.00428]	0.00499	[0.00393]	0.00499
Cadmium	0.413	0.551	0.841	0.414	16.6	3.08	1.61	1.28	3.10
Chromium	0.253	0.265	0.275	0.232	0.261	0.280	0.257	0.347	0.271
Copper	3.31	3.94	2.84	2.99	2.65	3.29	2.74	2.88	3.08
Lead	1.58	3.03	1.68	2.58	1.97	2.50	2.73	2.20	2.29
Mercury	0.145	0.127	0.102	8.42	7.10	8.24	6.45	11.7	5.28
Nickel	0.0774	0.0655	0.0643	0.0732	0.0778	0.0911	0.0994	0.1381	0.0859
Silver	0.0632	0.108	0.0416	0.0761	0.0774	0.0988	0.0568	0.0334	0.0694
Thallium	[0.371]	[0.402]	[0.420]	[0.355]	[0.401]	[0.428]	[0.384]	[0.378]	[0.349]
Total Ash Collected (lb)	218.1	285.2	249.8	206.3	272.0	251.0	275.9	262.6	252.6
BOTTOM ASH	(g/day)	(g/day)	(g/day)	(g/day)	(g/day)	(g/day)	(g/day)	(g/day)	(g/day)
Aluminum	16600	13300	9350	6590	7760	16700	15300	NA	12200
Antimony	[0.884]	[0.716]	[0.475]	[0.828]	8.77	[0.871]	1.30	NA	1.73
Arsenic	17.7	12.4	9.49	5.68	6.52	16.4	14.4	NA	11.8
Barium	692	599	231	988	549	1500	1210	NA	824
Beryllium	0.118	0.0955	0.0633	[0.0552]	[0.0669]	0.0988	0.0940	NA	0.0739
Cadmium	1.77	1.36	0.883	0.364	14.4	3.69	1.63	NA	3.44
Chromium	17.3	10.5	5.41	5.38	6.22	13.6	16.3	NA	10.7
Copper	1178	764	73.1	148	77600	831	636	NA	11604
Lead	30.9	58.7	13.9	32.0	24.4	65.1	47.6	NA	38.9
Mercury	0.577	2.67	0.310	0.541	0.656	0.569	0.614	NA	0.849
Nickel	11.0	45.6	2.97	2.57	4.55	9.29	11.8	NA	12.5
Silver	1.12	0.716	0.320	1.66	1.35	0.651	0.376	NA	0.885
Thallium	[5.89]	[4.77]	[3.16]	[5.52]	[6.69]	[5.81]	[6.26]	NA	[4.76]
Total Ash Collected (lb)	648	525	348	607	736	639	689	NA	524

[ ] = Minimum Detection Limits

NA = Not Applicable; Sample bottle broke before a weight was determined.

Table 2-46

AVERAGE PARTICULATE MATTER CONCENTRATIONS, EMISSION RATES, AND REMOVAL EFFICIENCY - BORGESS MEDICAL CENTER (1991)

Concentrations	Boiler Inlet Average	Baghouse Inlet Average	Baghouse Outlet Average	Removal Efficiency (%)
grains/dscf	0.0694	0.0372	0.00100	
grains/dscf @ 7% O2	0.141	0.0767	0.00252	
grams/dscm	0.159	0.0852	0.00213	
grams/dscm @ 7% O2	0.323	0.175	0.00535	
EMISSION RATES				
lb/hr	1.17	0.584	0.0202	
kg/hr	0.533	0.265	0.00919	96.5%

NOTE: Removal Efficiency based on emission rate.

TABLE 2-47. PARTICULATE MATTER CONCENTRATIONS AND EMISSIONS; BORGESS MEDICAL CENTER

Run Number	Date	Flue Gas Concentration				Flue Gas Emission Rate		Carbon Injection[a] (lb/hr)	Removal Efficiency[b] (%)
		grains/dscf	grains/dscf @ 7% O_2	grams/dscm	grams/dscm @ 7% O_2	lb/hr	kg/hr		
Boiler Inlet									
2	9/07/91	0.105	0.194	0.240	0.445	1.72	0.783		
3	9/09/91	0.0881	0.175	0.202	0.400	1.61	0.730		
4	9/10/91	0.0515	0.120	0.177	0.273	0.860	0.391		
5	9/11/91	0.0706	0.150	0.162	0.344	1.18	0.538		
6	9/12/91	0.0573	0.120	0.131	0.274	0.951	0.432		
7	9/13/91	0.0386	0.0839	0.0880	0.192	0.654	0.297		
8	9/14/91	0.0756	0.163	0.173	0.372	1.26	0.572		
9	9/16/91	0.0685	0.124	0.157	0.283	1.15	0.523		
Average		0.0694	0.141	0.159	0.323	1.17	0.533		
Baghouse Inlet									
2	9/7/91	0.0394	0.0731	0.0901	0.167	0.579	0.263	0.0	
3	9/9/91	0.0403	0.0799	0.0922	0.183	0.658	0.299	0.0	
4	9/10/91	0.0337	0.0784	0.0771	0.179	0.547	0.249	0.0	
5	9/11/91	0.0370	0.0789	0.0848	0.180	0.594	0.270	1.07	
6	9/12/91	0.0331	0.0692	0.0756	0.158	0.543	0.247	1.06	
7	9/13/91	0.0368	0.0799	0.0842	0.183	0.571	0.259	2.60	
8	9/14/91	0.0405	0.0869	0.0926	0.199	0.629	0.286	2.87	
9	9/16/91	0.0371	0.0671	0.0849	0.154	0.549	0.250	2.85	
Average		0.0372	0.0767	0.0852	0.175	0.584	0.265		
Baghouse Outlet									
2	9/7/91	0.00186	0.00443	0.00426	0.0101	0.0389	0.0177		93.3
3	9/9/91	0.000630	0.00166	0.00143	0.00379	0.0137	0.00622		97.9
4	9/10/91	0.000730	0.00204	0.00163	0.00453	0.0165	0.00749		97.0
5	9/11/91	0.000920	0.00243	0.000920	0.00243	0.00964	0.00438		99.4
6	9/12/91	0.000850	0.00218	0.00196	0.00501	0.0176	0.00799		98.9
7	9/13191	0.000770	0.00192	0.00176	0.00440	0.0174	0.00791		99.5
8	9/14/91	0.00153	0.00395	0.00350	0.00904	0.0329	0.0150		99.1
9	9/16/91	0.000700	0.00152	0.00161	0.00347	0.0152	0.00690		99.6
Average		0.00100	0.00252	0.00213	0.00535	0.0202	0.00919		98.1

[a]Carbon was injected at the baghouse inlet only.

[b]Removal efficiency = (1 - [outlet rate/ (inlet rate + carbon injection rate)]) x 100.

2.5.1 Overview

A single sampling train was used to determine emission rates of Hg by Method 101A. Two to three sampling runs were performed under each of the three test conditions (without carbon injection, carbon injection at 1 lb/hr, and carbon injection at 2.5 lb/hr) to ensure representative test results. Sampling locations, method, and QA/QC are discussed in Sections 4, 5, and 6, respectively. The average Hg emission rates and removal efficiencies are summarized in Section 2.5.3. The results for each individual run are presented in Section 2.5.4. Concentrations at dry standard conditions, adjusted to 7 percent O_2, and emission rates are shown. A comparison of the Hg collected in Method 101A versus the toxic metals trains is presented in Section 2.5.6.

2.5.2 Mercury Data Reduction

The following mercury results were calculated using the same guidelines outlined for the metals in Section 2.3.2.

2.5.3 Mercury Emissions

Table 2-48 presents the mercury emission rate results for each test condition. No Hg removal was observed during the emission tests without carbon injection. The removal efficiencies during the emission tests with carbon injection at 1 lb/hr were higher, at an average of 86.4 percent. Average emission rates were 10.3 g/hr at the inlet and 1.40 g/hr at the outlet. The removal efficiencies during the emission tests with carbon injection at 2.5 lb/hr were even higher, at an average 96.3 percent. Average emission rates were 14.9 g/hr at the inlet and 0.557 g/hr at the outlet.

2.5.4 Mercury Flue Gas Concentrations

Mercury concentrations, mass rates, and removal efficiencies are presented for each run in Table 2-49. Also shown for each run are the location, date, metered volume, O_2 concentration, and flow rate. Flue gas concentrations are given in terms of μg/dscm, both with and without correction to 7 percent O_2. Oxygen concentrations were calculated from CEM data.

Table 2-48

MERCURY 101A EMISSION RATES AND REMOVAL EFFICIENCIES

BORGESS MEDICAL CENTER (1991)

Condition	Run	Inlet (g/hr)	Outlet (g/hr)	RE (%)
Without Carbon Injection	2	12.8	12.9	-0.781%
	3	11.5	11.5	0.0%
	4	5.18	5.19	-0.193%
	Average	9.83	9.87	-0.407%
Carbon Injection @ 1 lb/hr	5	8.41	1.25	85.1%
	6	12.1	1.55	87.2%
	Average	10.3	1.40	86.4%
Carbon Injection @ 2.5 lb/hr	7	12.9	0.880	93.2%
	8	10.3	0.180	98.2%
	9	21.5	0.610	97.2%
	Average	14.9	0.557	96.3%

Table 2-49
MERCURY 101A CONCENTRATIONS AND EMISSION RATES BY RUNS
BORGESS MEDICAL CENTER (1991)

Run	Location	Date	Time (min.)	O2 Conc. (%V)	Flow Rate (dscmm)	Mercury Concentration (ug/dscm)	Mercury Concentration @ 7% O2 (ug/dscm)	Emission Rate (g/hr)	Removal Efficiencies (%)
2	Inlet	09/07/91	240	13.41	48.483	4410	8180	12.8	
	Outlet	09/07/91	240	15.05	69.787	3080	7320	12.9	-0.781%
3	Inlet	09/07/91	240	13.89	53.533	3580	7100	11.5	
	Outlet	09/07/91	240	15.66	75.021	2560	6790	11.5	0.0%
4	Inlet	09/10/91	240	14.93	52.595	1640	3820	5.18	
	Outlet	09/10/91	240	15.90	76.567	1130	3140	5.19	-0.193%
5	Inlet	09/11/91	240	14.37	51.940	2700	5750	8.41	
	Outlet	09/11/91	240	15.63	79.491	262	690	1.25	85.1%
6	Inlet	09/12/91	240	14.26	51.741	3910	8180	12.1	
	Outlet	09/12/91	240	15.46	67.287	385	983	1.55	87.2%
7	Inlet	09/13/91	240	14.50	51.467	4190	9100	12.9	
	Outlet	09/13/91	240	15.34	74.774	196	490	0.880	93.2%
8	Inlet	09/14/91	240	14.43	49.864	3430	7370	10.3	
	Outlet	09/14/91	240	15.52	75.352	39.9	103	0.180	98.2%
9	Inlet	09/15/91	240	13.21	49.074	7310	13200	21.5	
	Outlet	09/15/91	240	14.45	71.343	142	307	0.610	97.2%

2.5.5 Flue Gas Mercury by Sample and Sample Parameters

Table 2-50 presents the amounts of Hg in the inlet and outlet flue gas samples for the emission tests. Sampling and flue gas parameters for Hg at the inlet are shown in Table 2-51, and Table 2-52 presents the parameters for the runs at the outlet. Total sampling times, sample volume, and isokinetic results for each sampling run are presented. Appendix A.4 contains a complete listing of these and additional sampling and flue gas parameters for each run, as well as the field data sheets.

2.5.6 Mercury Emissions Comparison

Table 2-53 presents the comparison of Hg emission rates and removal efficiencies for Method 101A to multi-metal trains. During the emission tests without carbon injection, most values are fractionally higher for the multi-metals trains with the exception of Run 2 inlet. For the emission tests with carbon injection at 1 lb/hr, all of the multi-metal runs are also slightly higher than the Method 101A samples. For the emission tests with carbon injection at 2.5 lb/hr, the multi-metal values are lower on the inlet on Run 7 and 8, and the outlet on Runs 8 and 9.

The table shows an increasing Hg removal efficiency as the carbon injection rate is increased, showing that adding carbon to the process increases the removal of Hg.

2.6 HALOGEN GAS EMISSIONS

Hydrogen chloride, HF, and HBr gas concentrations were manually sampled at the baghouse inlet and the baghouse outlet following EPA Method 26 procedures. In this method, flue gas is extracted from the sample location and passed through acidified water. The HCl dissociates and form ions in acidified water. Ion chromatography was used to detect the chloride ions (Cl-), bromide ions (Br-), and fluoride ions (F-) present in the sample. Testing was conducted on eight test days at operating conditions described previously.

TABLE 2-50

MERCURY 101A AMOUNTS IN FLUE GAS SAMPLES - BORGESS MEDICAL CENTER (1991)

Location	Run 2 (total ug)	Run 3 (total ug)	Run 4 (total ug)	Run 5 (total ug)	Run 6 (total ug)	Run 7 (total ug)	Run 8 (total ug)	Run 9 (total ug)
Inlet	13900	12500	5760	9550	14400	15200	12200	26000
Outlet	7310	6470	2990	719	955	517	106	361

Table 2-51

MERCURY 101A SAMPLING AND FLUE GAS PARAMETERS AT INLET - BORGESS MEDICAL CENTER (1991)

Run No. Date	Run 2 09/07/91	Run 3 09/09/91	Run 4 09/10/91	Run 5 09/11/91	Run 6 09/12/91	Run 7 09/13/91	Run 8 09/14/91	Run 9 09/16/91	Average
Total Sampling Time (min)	240	240	240	240	240	240	240	240	NA
Average Sampling Rate (dscfm)	0.46	0.51	0.52	0.52	0.54	0.53	0.52	0.52	0.52
Metered Volume (dscf)	111.26	123.30	123.98	124.90	130.09	128.17	125.52	125.54	124.10
Metered Volume (dscm)	3.151	3.492	3.511	3.537	3.684	3.630	3.555	3.555	3.514
Average Stack Temperature (F)	361.02	355.52	354.40	356.90	369.15	363.13	357.29	371.67	361.14
O2 Concentration (%V)	13.41	13.89	14.93	14.37	14.26	14.50	14.43	13.21	14.12
CO2 Concentration (%V)	5.01	4.18	4.05	4.20	3.90	3.33	3.10	4.98	4.09
Stack Gas Moisture (%V)	13.39	10.90	11.93	12.02	13.25	12.47	12.67	14.47	12.64
Volumetric Flow Rate (dscfm)	1711.99	1890.29	1857.15	1834.05	1827.01	1817.34	1760.73	1732.84	1803.92
Volumetric Flow Rate (dscmm)	48.483	53.533	52.595	51.940	51.741	51.467	49.864	49.074	51.087
Percent Isokinetic	93.31	95.09	97.32	99.28	103.80	102.81	103.92	105.61	NA

Table 2-52

MERCURY 101A SAMPLING AND FLUE GAS PARAMETERS AT OUTLET - BORGESS MEDICAL CENTER(1991)

Run No. Date	Run 2 09/07/91	Run 3 09/09/91	Run 4 09/10/91	Run 5 09/11/91	Run 6 09/12/91	Run 7 09/13/91	Run 8 09/14/91	Run 9 09/16/91	Average
Total Sampling Time (min)	240	240	240	240	240	240	240	240	NA
Average Sampling Rate (dscfm)	0.35	0.37	0.39	0.40	0.37	0.39	0.39	0.37	0.38
Metered Volume (dscf)	83.91	89.06	93.06	97.00	87.63	93.13	93.78	89.47	90.88
Metered Volume (dscm)	2.376	2.522	2.636	2.747	2.482	2.637	2.656	2.534	2.574
Average Stack Temperature (F)	294.44	295.40	292.25	288.98	293.33	295.42	282.44	292.52	291.85
O2 Concentration (%V)	15.05	15.66	15.90	15.63	15.46	15.34	15.52	14.45	15.38
CO2 Concentration (%V)	4.69	4.19	4.19	4.23	4.42	4.45	4.48	5.20	4.48
Stack Gas Moisture (%V)	9.64	9.08	9.10	9.07	15.95	10.14	9.82	11.70	10.56
Volumetric Flow Rate (dscfm)	2464.22	2649.04	2703.63	2806.89	2375.96	2640.32	2660.74	2519.18	2602.50
Volumetric Flow Rate (dscmm)	69.787	75.021	76.567	79.491	67.287	74.774	75.352	71.343	73.703
Percent Isokinetic	100.37	101.01	101.46	101.87	108.72	104.63	104.56	105.35	NA

Table 2-53

COMPARISON FOR MERCURY EMISSION RATES AND REMOVAL EFFICIENIES

BORGESS MEDICAL CENTER (1991)

Condition	Method 101A				Toxic Metal Trains		
	RUN	Inlet (g/hr)	Outlet (g/hr)	RE (%)	Inlet (g/hr)	Outlet (g/hr)	RE (%)
Without Carbon Injection	2	12.8	12.9	-0.781%	15.1	17.4	-15.5%
	3	11.5	11.5	0.00%	11.9	14.1	-18.4%
	4	5.18	5.19	-0.193%	5.23	6.06	-15.9%
	Average	9.83	9.87	-0.407%	10.7	12.5	-16.6%
Carbon Injection @ 1 lb/hr	5	8.41	1.25	85.1%	9.43	1.39	85.3%
	6	12.1	1.55	87.2%	13.2	1.66	87.4%
	Average	10.3	1.40	86.4%	11.3	1.52	86.5%
Carbon Injection @ 2.5 lb/hr	7	12.9	0.880	93.2%	12.0	1.36	88.7%
	8	10.3	0.180	98.2%	9.83	0.174	98.2%
	9	21.5	0.610	97.2%	21.6	0.603	97.2%
	Average	14.9	0.557	96.3%	14.5	0.714	95.1%

2.6.1 Halogen Gas Emissions Results

Table 2-54 provides a summary of the HCl results at the baghouse inlet. Concentrations are reported in mg/dscm and ppmv, both at measured conditions and corrected to a 7 percent O_2 basis. The HCl concentrations at 7 percent O_2 ranged from 341.1 ppmv to 3591.0 ppmv with a mean of 1912.3 ppmv. The calculated emission rates ranged from 1.62 lb/hr to 17.57 lb/hr with a mean of 9.55 lb/hr.

Table 2-55 provides a summary of the HCl results at the baghouse outlet. The HCl concentrations at 7 percent O_2 ranged from 1.4 ppmv to 204.3 ppmv with a mean of 49.9 ppmv. Emission rates ranged from 0.007 lb/hr to 1.16 lb/hr at the baghouse outlet.

Table 2-56 presents a summary of HCl inlet and outlet concentrations and emission rates determined by manual sampling and provides the HCl removal efficiencies across the baghouse. Twenty-four runs were completed during eight days of testing. The removal efficiency for Run 8A could not be properly validated because the inlet and outlet sampling was not conducted at the same time. Hydrogen chloride removal efficiencies ranged from 82.4 percent to 99.9 percent with a mean of 96.6 percent.

Table 2-57 presents a summary of HF results obtained through sampling at the baghouse inlet. Noticeable concentrations of HF were detected during all the runs. The HF concentrations at 7 percent O_2 ranged from 6.0 ppmv to 49.6 ppmv with a mean of 18.3 ppmv. Calculated emission rates for HF ranged from 0.015 lb/hr to 0.147 lb/hr and averaged 0.051 lb/hr.

Table 2-58 provides the HF results at the baghouse outlet for all of the runs conducted. Detectable quantities of HF were present in only 2 of the 24 samples. Within the 24 runs, the concentrations at 7 percent O_2 ranged from 0.39 ppmv to 2.7 ppmv with a mean of 0.73 ppmv. Hydrogen fluoride emission rates recorded at the baghouse outlet ranged from 0.001 lb/hr to 0.009 lb/hr with an average of 0.002 lb/hr.

TABLE 2-54. MEASURED HYDROGEN CHLORIDE CONCENTRATIONS AND EMISSION RATES FOR THE BAGHOUSE INLET

TEST RUN NUMBER		MEASURED CONCENTRATIONS				EMISSION RATES	
		(mg/dscm)	(mg/dscm @7% O2)	(ppmv)	(ppmv @7% O2)	(g/hr)	(lb/hr)[b]
2	A	1825	3388	1204	2235	5310	11.707
	B	838	1555	553	1026	2437	5.373
	C	1297	2408	856	1588	3774	8.320
AVERAGE		1320	2450	871	1616	3840	8.467
3	A	930	1844	613	1216	2986	6.584
	B	1860	3688	1227	2433	5975	13.172
	C	1727	3425	1139	2259	5548	12.231
AVERAGE		1506	2986	993	1969	4836	10.662
4	A	317	737	209	486	1000	2.204
	B	910	2118	600	1397	2871	6.329
	C	1551	3610	1023	2381	4893	10.788
AVERAGE		926	2155	611	1422	2921	6.440
5	A	969	2062	639	1360	3019	6.655
	B	2128	4529	1403	2988	6631	14.619
	C	2558	5444	1687	3591	7971	17.572
AVERAGE		1885	4012	1243	2646	5873	12.949
6	A	1100	2303	726	1519	3415	7.530
	B	1469	3075	969	2029	4561	10.055
	C	1370	2869	904	1892	4254	9.379
AVERAGE		1313	2749	866	1813	4077	8.988
7	A[a]	238	517	157	341	735	1.621
	B	1708	3709	1126	2447	5274	11.626
	C	1481	3216	977	2121	4573	10.081
AVERAGE		1142	2481	753	1636	3527	7.776
8	A	854	1834	563	1210	2554	5.631
	B	1628	3497	1074	2306	4869	10.735
	C	2116	4545	1395	2998	6329	13.954
AVERAGE		1532	3292	1011	2171	4584	10.106
9	A	2428	4389	1602	2895	7150	15.762
	B	1196	2163	789	1426	3523	7.767
	C	1469	2656	969	1752	4327	9.539
AVERAGE		1698	3069	1120	2025	5000	11.023

a The results for Runs 7B and 7C were originally reported as baghouse outlet results.

b An average of the flow rates determined by the Method 101A sampling trains was used for HCl emission rate calcultions.

TABLE 2-55. MEASURED HYDROGEN CHLORIDE CONCENTRATIONS AND EMISSION RATES FOR THE BAGHOUSE OUTLET

TEST RUN NUMBER		MEASURED CONCENTRATIONS				EMISSION RATE	
		(mg/dscm)	(mg/dscm @7% O2)	(ppmv)	(ppmv @7% O2)	(g/hr)	(lb/hr)[b]
2	A	124.9	296.7	82.36	195.69	522.81	1.153
	B	62.92	149.5	41.50	98.62	263.47	0.581
	C	8.797	20.90	5.803	13.79	36.83	0.081
AVERAGE		65.53	155.7	43.22	102.70	274.37	0.605
3	A	116.8	309.8	77.02	204.32	525.63	1.159
	B	8.816	23.38	5.815	15.42	39.68	0.087
	C	40.78	108.2	26.90	71.35	183.54	0.405
AVERAGE		55.45	147.1	36.58	97.03	249.62	0.550
4	A	2.446	6.799	1.613	4.485	11.24	0.025
	B	3.813	10.60	2.515	6.991	17.52	0.039
	C	7.943	22.08	5.239	14.564	36.49	0.080
AVERAGE		4.734	13.16	3.122	8.680	21.75	0.048
5	A	7.368	19.43	4.860	12.82	35.14	0.077
	B	74.10	195.4	48.88	128.9	353.41	0.779
	C	25.62	67.56	16.90	44.57	122.17	0.269
AVERAGE		35.69	94.15	23.54	62.10	170.24	0.375
6	A	0.828	2.115	0.546	1.395	3.343	0.007
	B	4.551	11.63	3.002	7.670	18.37	0.041
	C	6.494	16.59	4.284	10.95	26.22	0.058
AVERAGE		3.958	10.11	2.610	6.670	15.98	0.035
7	A[a]	8.016	20.04	5.288	13.22	35.96	0.079
	B	32.95	82.37	21.732	54.33	147.82	0.326
	C	14.85	37.12	9.795	24.49	66.62	0.147
AVERAGE		18.60	46.51	12.272	30.68	83.47	0.184
8	A	3.360	8.681	2.216	5.73	15.19	0.033
	B	8.145	21.04	5.373	13.88	36.83	0.081
	C	22.39	57.84	14.766	38.15	101.21	0.223
AVERAGE		11.30	29.19	7.452	19.25	51.08	0.113
9	A	42.06	90.65	27.75	59.79	180.06	0.397
	B	87.80	189.2	57.91	124.81	375.84	0.829
	C	22.66	48.84	14.95	32.22	97.01	0.214
AVERAGE		50.84	109.6	33.54	72.27	217.64	0.480

a The results for Runs 7B and 7C were originally reported as baghouse inlet results.

b An average of the flow rates determined by the Method 101A sampling trains was used for HCl emission rate calcultions.

TABLE 2-56. HYDROGEN CHLORIDE REMOVAL EFFICIENCY
BORGESS MEDICAL CENTER (1991)

RUN NO.	DATE	BAGHOUSE INLET			BAGHOUSE OUTLET			REMOVAL EFFICIENCY (%)
		SAMPLING TIME	GAS CONC. (ppmV)	EMISSION RATE a (lb/hr)	SAMPLING TIME	GAS CONC. (ppmV)	EMISSION RATE (lb/hr)	
2 A	9/7/91	12:15-13:15	1204.1	11.707	12:15-13:15	82.36	1.153	90.2
2 B	9/7/91	15:15-16:15	552.6	5.373	15:15-16:15	41.50	0.581	89.2
2 C	9/7/91	16:25-17:25	855.7	8.320	16:25-17:25	5.803	0.081	99.0
AVERAGE			870.8	8.467		43.22	0.605	92.8
3 A	9/9/19	11:41-12:44	613.3	6.584	11:32-12:44	77.02	1.159	82.4
3 B	9/9/19	15:30-16:30	1227.0	13.172	15:30-16:30	5.815	0.087	99.3
3 C	9/9/19	16:40-17:49	1139.3	12.231	16:40-17:46	26.90	0.405	96.7
AVERAGE			993.2	10.662		36.58	0.550	92.8
4 A	9/10/91	12:05-13:05	208.9	2.204	12:05-13:05	1.613	0.025	98.9
4 B	9/10/91	15:00-16:00	600.1	6.329	15:00-16:00	2.515	0.039	99.4
4 C	9/10/91	16:16-17:16	1022.8	10.788	16:16-17:16	5.239	0.080	99.3
AVERAGE			610.6	6.440		3.122	0.048	99.2
5 A	9/11/91	11:15-12:15	638.9	6.655	11:15-12:15	4.860	0.077	98.8
5 B	9/11/91	14:05-15:05	1403.5	14.619	14:05-15:05	48.88	0.779	94.7
5 C	9/11/91	15:14-16:15	1687.0	17.572	15:15-16:15	16.90	0.269	98.5
AVERAGE			1243.1	12.949		23.54	0.375	97.3
6 A	9/12/91	12:30-14:11	725.7	7.530	12:30-14:07	0.546	0.007	99.9
6 B	9/12/91	16:10-17:15	969.0	10.055	16:10-17:10	3.002	0.041	99.6
6 C	9/12/91	17:20-18:20	903.9	9.379	17:20-18:20	4.284	0.058	99.4
AVERAGE			866.2	8.988		2.610	0.035	99.6
7 A b	9/13/91	09:45-10:45	157.1	1.621	09:45-10:45	5.288	0.079	95.1
7 B	9/13/91	12:35-13:35	1126.5	11.626	12:35-13:35	21.73	0.326	97.2
7 C	9/13/91	13:45-14:45	976.7	10.081	13:45-14:45	9.795	0.147	98.5
AVERAGE			753.4	7.776		12.27	0.184	96.9
8 A	9/14/91	12:15-13:15	563.1	5.631	10:15-11:15	2.216	0.033	*99.4
8 B	9/14/91	14:15-15:15	1073.5	10.735	14:15-15:15	5.373	0.081	99.2
8 C	9/14/91	15:25-16:25	1395.4	13.954	15:25-16:25	14.77	0.223	98.4
AVERAGE			1010.7	10.106		7.452	0.113	99.0
9 A	9/16/91	10:30-11:30	1601.6	15.762	10:30-11:30	27.75	0.397	97.5
9 B	9/16/91	14:06-15:06	789.2	7.767	14:06-15:06	57.91	0.829	89.3
9 C	9/16/91	15:16-16:16	969.3	9.539	15:16-16:16	14.95	0.214	97.8
AVERAGE			1120.0	11.023		33.54	0.480	94.9

a An average of the flow rates determined by the Method 101A sampling trains was used for HCl emission rate calculations.

b The results for Runs 7B and 7C were originally recorded as results at opposite locations.

* Run 8A at the inlet and outlet was not conducted at the same time.

TABLE 2-57. MEASURED HYDROGEN FLOURIDE CONCENTRATIONS AND EMISSION RATES FOR THE BAGHOUSE INLET

TEST RUN NUMBER		MEASURED CONCENTRATIONS				EMISSION RATE	
		(mg/dscm)	(mg/dscm @7% O2)	(ppmv)	(ppmv @7% O2)	(g/hr)	(lb/hr)[b]
2	A	2.781	5.160	3.343	6.203	8.089	0.018
	B	3.406	6.320	4.094	7.598	9.907	0.022
	C	9.542	17.71	11.47	21.29	27.76	0.061
AVERAGE		5.243	9.729	6.302	11.70	15.25	0.034
3	A	4.403	8.731	5.293	10.50	14.14	0.031
	B	20.81	41.27	25.02	49.61	66.85	0.147
	C	12.85	25.49	15.45	30.64	41.29	0.091
AVERAGE		12.69	25.16	15.25	30.25	40.76	0.090
4	A	2.509	5.841	3.016	7.021	7.916	0.017
	B	5.206	12.12	6.259	14.57	16.43	0.036
	C	3.990	9.291	4.797	11.17	12.59	0.028
AVERAGE		3.902	9.085	4.690	10.92	12.31	0.027
5	A	8.107	17.26	9.746	20.75	25.27	0.056
	B	10.25	21.81	12.32	26.22	31.93	0.070
	C	4.026	8.570	4.840	10.30	12.55	0.028
AVERAGE		7.460	15.88	8.968	19.09	23.25	0.051
6	A	7.256	15.19	8.722	18.26	22.53	0.050
	B	9.638	20.18	11.59	24.25	29.92	0.066
	C	8.474	17.74	10.19	21.32	26.31	0.058
AVERAGE		8.456	17.70	10.16	21.28	26.25	0.058
7[a]	A	4.554	9.890	5.474	11.89	14.06	0.031
	B	7.393	16.057	8.888	19.30	22.83	0.050
	C	4.147	9.007	4.985	10.83	12.81	0.028
AVERAGE		5.365	11.65	6.449	14.01	16.57	0.037
8	A	2.323	4.990	2.792	5.998	6.949	0.015
	B	7.585	16.29	9.118	19.59	22.69	0.050
	C	4.543	9.759	5.461	11.73	13.59	0.030
AVERAGE		4.817	10.35	5.790	12.44	14.41	0.032
9	A	17.50	31.64	21.04	38.03	51.54	0.114
	B	11.17	20.19	13.43	24.27	32.89	0.073
	C	8.390	15.16	10.09	18.23	24.70	0.054
AVERAGE		12.35	22.33	14.85	26.84	36.38	0.080

a The results for Runs 7B and 7C were originally reported as baghouse outlet results.

b An average of the flow rates determined by the Method 101A sampling trains was used for HF emission rate calculations.

TABLE 2-58. MEASURE HYDROGEN FLOURIDE CONCENTRATIONS AND EMISSION RATES FOR THE BAGHOUSE OUTLET

TEST RUN NUMBER	MEASURED CONCENTRATIONS (mg/dscm)	(mg/dscm @7% O2)	(ppmv)	(ppmv @7% O2)	EMISSION RATES (g/hr)	(lb/hr)[b]
2 A	[0.194][c]	[0.461]	[0.233]	[0.554]	[0.813]	[0.002]
2 B	[0.219]	[0.519]	[0.263]	[0.624]	[0.915]	[0.002]
2 C[d]	[0.218]	[0.519]	[0.263]	[0.624]	[0.914]	[0.002]
AVERAGE	[0.210]	[0.500]	[0.253]	[0.601]	[0.881]	[0.002]
3 A	[0.184]	[0.488]	[0.221]	[0.587]	[0.828]	[0.002]
3 B	[0.211]	[0.560]	[0.254]	[0.673]	[0.950]	[0.002]
3 C	[0.208]	[0.553]	[0.250]	[0.664]	[0.938]	[0.002]
AVERAGE	[0.201]	[0.534]	[0.242]	[0.641]	[0.905]	[0.002]
4 A	(0.198)	(0.550)	(0.238)	(0.661)	(0.909)	(0.002)
4 B	[0.211]	[0.587]	[0.254]	[0.706]	[0.970]	[0.002]
4 C	[0.191]	[0.532]	[0.230]	[0.639]	[0.879]	[0.002]
AVERAGE	0.198	0.550	0.238	0.661	0.909	0.002
5 A	[0.169]	[0.445]	[0.203]	[0.535]	[0.805]	[0.002]
5 B	0.865	2.281	1.040	2.742	4.125	0.009
5 C	0.816	2.151	0.980	2.586	3.890	0.009
AVERAGE	0.840	2.216	1.010	2.664	4.007	0.009
6 A	(0.180)	(0.460)	(0.216)	(0.553)	(0.727)	(0.002)
6 B	[0.255]	[0.652]	[0.307]	[0.784]	[1.030]	[0.002]
6 C	[0.180]	[0.459]	[0.216]	[0.552]	[0.725]	[0.002]
AVERAGE	0.180	0.460	0.216	0.553	0.727	0.002
7 A[a]	(0.204)	(0.510)	(0.245)	(0.613)	(0.916)	(0.002)
7 B	[0.151]	[0.377]	[0.181]	[0.453]	[0.676]	[0.001]
7 C	[0.163]	[0.407]	[0.196]	[0.490]	[0.731]	[0.002]
AVERAGE	0.204	0.510	0.245	0.613	0.916	0.002
8 A	[0.156]	[0.404]	[0.188]	[0.486]	[0.707]	[0.002]
8 B	[0.125]	[0.324]	[0.151]	[0.390]	[0.567]	[0.001]
8 C	[0.126]	[0.325]	[0.151]	[0.390]	[0.568]	[0.001]
AVERAGE	[0.135]	[0.351]	[0.163]	[0.422]	[0.614]	[0.001]
9 A	[0.157]	[0.339]	[0.189]	[0.407]	[0.673]	[0.001]
9 B	[0.156]	[0.335]	[0.187]	[0.403]	[0.666]	[0.001]
9 C	[0.156]	[0.336]	[0.187]	[0.404]	[0.667]	[0.001]
AVERAGE	[0.156]	[0.336]	[0.188]	[0.404]	[0.668]	[0.001]

a The results for Runs 7B and 7C were originally reported as baghouse inlet results.

b An average of the flow rates determined by the CDD/CDF sampling trains was used for HBr emission rate calculations.

c [] = Detection limit; () = Estimated maximum possible concentration

d Detection limits are not considered when calculating averages.

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Table 2-59 presents a summary of HF inlet and outlet concentrations, emission rates, and removal efficiencies determined by manual sampling. The removal efficiency for Run 8A is not valid because inlet and outlet samples were not conducted at the same time. The baghouse removal efficiencies for HF ranged from 69.0 percent to 99.4 percent with a mean of 94.1 percent.

Table 2-60 displays the HBr manual sampling results at the baghouse inlet. Measurable quantities were detected in 20 of the 24 samples taken. The concentrations of HBr in the samples, corrected to 7 percent O_2, ranged from 0.027 ppmv to 5.37 ppmv with a mean of 2.0 ppmv.

Table 2-61 summarizes the HBr manual sampling results from the baghouse outlet. Detectable quantities of HBr were found in 6 of the 21 valid runs. Of these six detectable quantities, only one measured greater than five times the detection limit. The concentrations of HBr corrected to 7 percent O_2 ranged from 0.0295 ppmv to 0.2667 ppmv. The average of the detected concentrations is 0.19 ppmv at 7 percent O_2.

Table 2-62 summarizes the HBr inlet and outlet concentrations, emission rates, and removal efficiencies for the baghouse. The results from Runs 16, 17, and 18 are invalid due to reasons discussed previously. All of the runs exhibited removal efficiencies greater than 80 percent except the 3 runs conducted on the last day of testing. No HBr was detected at either the inlet or the outlet sampling location during these runs. On runs when HBr was detected, the HBr removal efficiencies ranged from 81.1 percent to 91.1 percent, with an average of 93.9 percent.

2.7 CEM RESULTS

Continuous emissions monitoring was conducted at the inlet and outlet to the APCS during eight days of testing (test runs). Concentrations of O_2, CO_2, CO, NO_x, and SO_2 were determined on a dry basis by extracting the gas from the flue, transferring it to the CEM trailer through heated teflon tubing (heat trace), passing it through gas conditioners to remove moisture and directing it to each respective analyzer. A full description of Radian's CEM system and methods is given in Section 5. Concentrations of THC and HCl were also monitored with gas concentrations determined on a wet basis. This was accomplished on the THC system by allowing a slipstream from each

TABLE 2-59. HYDROGEN FLUORIDE REMOVAL EFFICIENCY
BORGESS MEDICAL CENTER (1991)

RUN NO.	DATE	INLET SAMPLING TIME	INLET GAS CONC. (ppmV)	INLET EMISSION RATE a (lb/hr)	OUTLET SAMPLING TIME	OUTLET GAS CONC. (ppmV) c	OUTLET EMISSION RATE (lb/hr)	REMOVAL EFFICIENCY (%)
A	9/7/91	12:15-13:15	3.343	0.018	12:15-13:15	[0.233]	[0.002]	90.0
2 B	9/7/91	15:15-16:15	4.094	0.022	15:15-16:15	[0.263]	[0.002]	90.8
C d	9/7/91	16:25-17:25	11.470	0.061	16:25-17:25	[0.263]	[0.002]	96.7
AVERAGE			6.302	0.034		[0.253]	[0.002]	92.5
A	9/9/19	11:41-12:44	5.293	0.031	11:32-12:44	[0.221]	[0.002]	94.1
3 B	9/9/19	15:30-16:30	25.019	0.147	15:30-16:30	[0.254]	[0.002]	98.6
C	9/9/19	16:40-17:49	15.452	0.091	16:40-17:46	[0.250]	[0.002]	97.7
AVERAGE			15.255	0.090		[0.242]	[0.002]	96.8
A	9/10/91	12:05-13:05	3.016	0.017	12:05-13:05	(0.238)	(0.002)	88.5
4 B	9/10/91	15:00-16:00	6.259	0.036	15:00-16:00	[0.254]	[0.002]	94.1
C	9/10/91	16:16-17:16	4.797	0.028	16:16-17:16	[0.230]	[0.002]	93.0
AVERAGE			4.690	0.027		0.238	0.002	91.9
A	9/11/91	11:15-12:15	9.746	0.056	11:15-12:15	[0.203]	[0.002]	96.8
5 B	9/11/91	14:05-15:05	12.318	0.070	14:05-15:05	1.040	0.009	87.1
C	9/11/91	15:14-16:15	4.840	0.028	15:15-16:15	0.980	0.009	69.0
AVERAGE			8.968	0.051		1.010	0.009	84.3
A	9/12/91	12:30-14:11	8.722	0.050	12:30-14:07	(0.216)	(0.002)	96.8
6 B	9/12/91	16:10-17:15	11.586	0.066	16:10-17:10	[0.307]	[0.002]	96.6
C	9/12/91	17:20-18:20	10.186	0.058	17:20-18:20	[0.216]	[0.002]	97.2
AVERAGE			10.165	0.058		0.216	0.002	96.9
b								
A	9/13/91	09:45-10:45	5.474	0.031	09:45-10:45	(0.245)	(0.002)	93.5
7 B	9/13/91	12:35-13:35	8.888	0.050	12:35-13:35	[0.181]	[0.001]	97.0
C	9/13/91	13:45-14:45	4.985	0.028	13:45-14:45	[0.196]	[0.002]	94.3
AVERAGE			6.449	0.037		0.245	0.002	94.9
A	9/14/91	12:15-13:15	2.792	0.015	10:15-11:15	[0.188]	[0.002]	*99.4
8 B	9/14/91	14:15-15:15	9.118	0.050	14:15-15:15	[0.151]	[0.001]	97.5
C	9/14/91	15:25-16:25	5.461	0.030	15:25-16:25	[0.151]	[0.001]	95.8
AVERAGE			5.790	0.032		[0.163]	[0.001]	96.7
A	9/16/91	10:30-11:30	21.041	0.114	10:30-11:30	[0.189]	[0.001]	98.7
9 B	9/16/91	14:06-15:06	13.428	0.073	14:06-15:06	[0.187]	[0.001]	98.0
C	9/16/91	15:16-16:16	10.085	0.054	15:16-16:16	[0.187]	[0.001]	97.3
AVERAGE			14.851	0.080		[0.188]	[0.001]	98.0

a An average of the flow rates determined by the Method 101A sampling trains was used for HF emission rate calculations.

b The results for Runs 7B and 7C were originally recorded as results at the opposite location

c [] = Detection limit; () = Estimated maximum possible concentration

d Detection limits are not considered in the calculation of averages.

* The Runs 8A at the inlet and outlet were not conducted at the same time.

TABLE 2-60. MEASURED HYDROGEN BROMIDE CONCENTRATIONS AND EMISSION RATES FOR THE BAGHOUSE INLET

TEST RUN NUMBER	MEASURED CONCENTRATIONS (mg/dscm)	(mg/dscm @7% O2)	(ppmv)	(ppmv @7% O2)	EMISSION RATE (g/hr)	(lb/hr)[b]
2 A	3.425	6.356	1.018	1.889	9.963	0.022
2 B	2.965	5.503	0.881	1.636	8.625	0.019
2 C [d]	2.609	4.841	0.775	1.439	7.589	0.017
AVERAGE	3.000	5.567	0.892	1.655	8.726	0.019
3 A	0.520	1.032	0.155	0.307	1.671	0.004
3 B	3.288	6.519	0.977	1.938	10.560	0.023
3 C	3.024	5.997	0.899	1.782	9.714	0.021
AVERAGE	2.277	4.516	0.677	1.342	7.315	0.016
4 A	3.502	8.154	1.041	2.424	11.051	0.024
4 B	2.386	5.554	0.709	1.651	7.528	0.017
4 C	2.648	6.164	0.787	1.832	8.355	0.018
AVERAGE	2.845	6.624	0.846	1.969	8.978	0.020
5 A	4.786	10.187	1.423	3.028	14.915	0.033
5 B	5.601	11.923	1.665	3.544	17.456	0.038
5 C	1.846	3.930	0.549	1.168	5.753	0.013
AVERAGE	4.078	8.680	1.212	2.580	12.708	0.028
6 A	6.218	13.016	1.848	3.869	19.303	0.043
6 B	4.547	9.519	1.352	2.829	14.117	0.031
6 C	2.322	4.860	0.690	1.445	7.208	0.016
AVERAGE	4.362	9.132	1.297	2.714	13.543	0.030
7 A[a]	3.112	6.758	0.925	2.009	9.609	0.021
7 B	[0.0519]	[0.1128]	[0.0154]	[0.0335]	[0.1603]	[0.0004]
7 C	8.318	18.065	2.472	5.370	25.685	0.057
AVERAGE	5.715	12.412	1.699	3.689	17.647	0.039
8 A	4.620	9.926	1.373	2.950	13.823	0.030
8 B	6.167	13.250	1.833	3.938	18.452	0.041
8 C	6.389	13.727	1.899	4.080	19.116	0.042
AVERAGE	5.726	12.301	1.702	3.656	17.130	0.038
9 A	[0.057][c]	[0.102]	[0.017]	[0.030]	[0.166]	[0.0004]
9 B	[0.050]	[0.090]	[0.015]	[0.027]	[0.146]	[0.0003]
9 C	[0.058]	[0.105]	[0.017]	[0.031]	[0.170]	[0.0004]
AVERAGE	[0.055]	[0.099]	[0.016]	[0.029]	[0.161]	[0.0004]

a The results for Runs 7B and 7C were originally reported as baghouse outlet results.

b An average of the flow rates determined by the Method 101A sampling trains was used for HBr emission rate calculations.

c [] = Detection limit; () = Estimated maximum possible concentration

d Detection limits are not considered when calculating averages.

TABLE 2-61. MEASURED HYDROGEN BROMIDE CONCENTRATIONS AND EMISSION RATES FOR THE BAGHOUSE OUTLET

TEST RUN NUMBER		MEASURED CONCENTRATIONS				EMISSION RATE	
		(mg/dscm)	(mg/dscm @7% O2)	(ppmv)	(ppmv @7% O2)	(g/hr)	(lb/hr)[b]
		[c]					
	A	[0.0547]	[0.1301]	[0.0163]	[0.0387]	[0.2292]	[0.0005]
2	B	0.378	0.897	0.112	0.267	1.582	0.003
	C [d]	(0.178)	(0.424)	(0.053)	(0.126)	(0.747)	(0.002)
AVERAGE		0.278	0.661	0.083	0.196	1.164	0.003
	A	[0.0486]	[0.1290]	[0.0145]	[0.0384]	[0.2190]	[0.0005]
3	B	[0.0645]	[0.1710]	[0.0192]	[0.0508]	[0.2901]	[0.0006]
	C	(0.224)	(0.593)	(0.066)	(0.176)	(1.006)	(0.002)
AVERAGE		0.224	0.593	0.066	0.176	1.006	0.002
	A	[0.0578]	[0.1606]	[0.0172]	[0.0477]	[0.2654]	[0.0006]
4	B	[0.0645]	[0.1793]	[0.0192]	[0.0533]	[0.2963]	[0.0007]
	C	[0.0584]	[0.1624]	[0.0174]	[0.0483]	[0.2683]	[0.0006]
AVERAGE		[0.0602]	[0.1674]	[0.0179]	[0.0498]	[0.2767]	[0.0006]
	A	(0.213)	(0.563)	(0.063)	(0.167)	(1.017)	(0.002)
5	B	(0.295)	(0.778)	(0.088)	(0.231)	(1.406)	(0.003)
	C	(0.230)	(0.607)	(0.068)	(0.180)	(1.097)	(0.002)
AVERAGE		0.246	0.649	0.073	0.193	1.174	0.003
	A	[0.0529]	[0.1351]	[0.0157]	[0.0401]	[0.2134]	[0.0005]
6	B	[0.0779]	[0.1990]	[0.0232]	[0.0592]	[0.3145]	[0.0007]
	C	[0.0548]	[0.1401]	[0.0163]	[0.0416]	[0.2214]	[0.0005]
AVERAGE		[0.0619]	[0.1581]	[0.0184]	[0.0470]	[0.2498]	[0.0006]
	[a] A	[0.0622]	[0.1555]	[0.0185]	[0.0462]	[0.2791]	[0.0006]
7	B	[0.0460]	[0.1149]	[0.0137]	[0.0342]	[0.2062]	[0.0005]
	C	[0.0498]	[0.1245]	[0.0148]	[0.0370]	[0.2235]	[0.0005]
AVERAGE		[0.0527]	[0.1316]	[0.0157]	[0.0391]	[0.2363]	[0.0005]
	A	[0.0478]	[0.1235]	[0.0142]	[0.0367]	[0.2160]	[0.0005]
8	B	[0.0383]	[0.0990]	[0.0114]	[0.0294]	[0.1733]	[0.0004]
	C	[0.0384]	[0.0993]	[0.0114]	[0.0295]	[0.1738]	[0.0004]
AVERAGE		[0.0415]	[0.1073]	[0.0123]	[0.0319]	[0.1877]	[0.0004]
	A	[0.0478]	[0.1031]	[0.0142]	[0.0306]	[0.2048]	[0.0005]
9	B	[0.0475]	[0.1023]	[0.0141]	[0.0304]	[0.2032]	[0.0004]
	C	[0.0487]	[0.1049]	[0.0145]	[0.0312]	[0.2084]	[0.0005]
AVERAGE		[0.0480]	[0.1034]	[0.0143]	[0.0307]	[0.2055]	[0.0005]

a The results for Runs 7B and 7C were originally reported as baghouse inlet results.

b An average of the flow rates determined by the Method 101A sampling trains was used for HBr emission rate calculations.

c [] = Detection limit; () = Estimated maximum possible concentration

d Detection limits are not considered when calculating averages.

TABLE 2-62. HYDROGEN BROMIDE REMOVAL EFFICIENCY
BORGESS MEDICAL CENTER (1991)

RUN NO.	DATE	INLET SAMPLING TIME	INLET GAS CONC. (ppmV)	INLET EMISSION RATE [a] (lb/hr)	OUTLET SAMPLING TIME	OUTLET GAS CONC. (ppmV)	OUTLET EMISSION RATE (lb/hr)	REMOVAL EFFICIENCY (%)
A	9/7/91	12:15-13:15	1.018	0.022	12:15-13:15	[0.0163]	[0.0005]	97.7
2 B	9/7/91	15:15-16:15	0.881	0.019	15:15-16:15	0.112	0.003	81.7
C [d]	9/7/91	16:25-17:25	0.775	0.017	16:25-17:25	(0.053)	(0.002)	90.2
AVERAGE			0.892	0.019		0.083	0.003	89.8
A	9/9/19	11:41-12:44	0.155	0.004	11:32-12:44	[0.0145]	[0.0384]	86.9
3 B	9/9/19	15:30-16:30	0.977	0.023	15:30-16:30	[0.0192]	[0.0006]	97.3
C	9/9/19	16:40-17:49	0.899	0.021	16:40-17:46	(0.066)	(0.002)	89.6
AVERAGE			0.677	0.016		0.066	0.002	91.3
A	9/10/91	12:05-13:05	1.041	0.024	12:05-13:05	[0.0172]	[0.0006]	97.6
4 B	9/10/91	15:00-16:00	0.709	0.017	15:00-16:00	[0.0192]	[0.0007]	96.1
C	9/10/91	16:16-17:16	0.787	0.018	16:16-17:16	[0.0174]	[0.0006]	96.8
AVERAGE			0.846	0.020		[0.0179]	[0.0006]	96.8
A	9/11/91	11:15-12:15	1.423	0.033	11:15-12:15	(0.063)	(0.002)	93.2
5 B	9/11/91	14:05-15:05	1.665	0.038	14:05-15:05	(0.088)	(0.003)	91.9
C	9/11/91	15:14-16:15	0.549	0.013	15:15-16:15	(0.068)	(0.002)	80.9
AVERAGE			1.212	0.028		0.073	0.003	88.7
A	9/12/91	12:30-14:11	1.848	0.043	12:30-14:07	[0.0157]	[0.0005]	98.9
6 B	9/12/91	16:10-17:15	1.352	0.031	16:10-17:10	[0.0232]	[0.0007]	97.8
C	9/12/91	17:20-18:20	0.690	0.016	17:20-18:20	[0.0163]	[0.0005]	96.9
AVERAGE			1.297	0.030		[0.0184]	[0.0006]	97.9
A [b]	9/13/91	09:45-10:45	0.925	0.021	09:45-10:45	[0.0185]	[0.0006]	97.1
7 B	9/13/91	12:35-13:35	[0.0154]	[0.0004]	12:35-13:35	[0.0137]	[0.0005]	NA
C	9/13/91	13:45-14:45	2.472	0.057	13:45-14:45	[0.0148]	[0.0005]	99.1
AVERAGE			1.699	0.039		[0.0157]	[0.0005]	55.9
A	9/14/91	12:15-13:15	1.373	0.030	10:15-11:15	[0.0142]	[0.0005]	*98.4
8 B	9/14/91	14:15-15:15	1.833	0.041	14:15-15:15	[0.0114]	[0.0004]	99.1
C	9/14/91	15:25-16:25	1.899	0.042	15:25-16:25	[0.0114]	[0.0004]	99.1
AVERAGE			1.702	0.038		[0.0123]	[0.0004]	98.9
A	9/16/91	10:30-11:30	[0.017] [c]	[0.0004]	10:30-11:30	[0.0142]	[0.0005]	NA [e]
9 B	9/16/91	14:06-15:06	[0.015]	[0.0003]	14:06-15:06	[0.0141]	[0.0004]	NA
C	9/16/91	15:16-16:16	[0.017]	[0.0004]	15:16-16:16	[0.0145]	[0.0005]	NA
AVERAGE			[0.016]	[0.0004]		[0.0143]	[0.0005]	NA

a An average of the flow rates determined by the Method 101A sampling trains was used for HBr emission rate calculations.

b The results for Runs 7B and 7C were originally recorded as results at opposite locations.

c [] = Detection limit; () = Estimated maximum possible concentration

d Detection limits are not considered in the calculation of averages.

e NA = Results at the inlet and outlet are detection limits.

* Run 8A at the inlet and outlet was not conducted at the same time.

respective heated sample line (inlet or outlet sample location) to bypass the sample conditioners so that the wet flue gas was directed to the analyzer as it exited the flue. The HCl CEM system employed a dilution probe and sample gas transfer system separate from the other CEMs. In this way, the stack gas was diluted by a known amount using quartz critical orifice (500 ml at the outlet, 100 ml at the inlet) and delivered to the analyzer without removing the moisture.

The following CEM analyzers shown below with their respective units of concentration were employed during the Borgess MWI test program:

Baghouse Inlet	Baghouse Outlet
O_2/CO_2 - %V/dry	O_2/CO_2 - %V/dry
CO - ppmv/dry	CO - ppmv/dry
NO_x - ppmv/dry	NO_x - ppmv/dry (offline 9/14 & 16)
SO_2 - ppmv/dry	SO_2 - ppmv/dry
THC - ppmv/wet	THC - ppmv/wet (online 9/7 only)
HCl - ppmv/wet	HCl - ppmv/wet

All CEM data were recorded as 30-second averages from multiple readings per second by Radian's CEM data acquisition system (DAS). The resulting CEM data files were averaged over the duration of each test run. The averages are presented in the following section. The 30-second data are included in Appendix C along with the following additional CEM information:

	LOCATION	CEM DATA TYPE
•	Appendix C.1	CEM Inlet/Outlet Graphs
•	Appendix C.2	CEM 30-second averages
•	Appendix C.3	CEM Calibration Drift Summary
•	Appendix C.4	CEM Daily Cals and QC Gas Responses

- Appendix C.5 CEM Response Time & NO_x Converter Checks
- Section 6.5 CEM Coefficients of Variation

The CEM run averages are presented In Table 2-63. Both inlet and outlet concentrations are given. Moisture contents are also presented because these values were used to correct the wet CEM values to a dry basis in the following tables. Inlet O_2 run averages varied from 12.9 to 14.9, while outlet values were 1 to 2 percent higher by volume. Inlet CO_2 values were approximately 4 to 5 percent by volume, except for Runs 6 through 8 which averaged near 3 percent. These latter values are lower than the corresponding outlet averages. All QA/QC criterion for that monitor were met.

Nitrogen oxides concentrations were approximately 60 to 80 ppmv, dry at the inlet and somewhat lower (approximately 40 to 70 ppmv dry) at the outlet. As detailed in Section 6, the NO_x converter for the inlet instrument used for Runs 2 through 7 only showed about 50 percent conversion efficiency. When comparing the inlet NO_x data to the outlet NO_x data, the lower NO_x conversion efficiency did not appear to have affected the quality of the inlet data. It is postulated that the majority of NO_x in a flue gas stream is typically in the form of NO and, therefore, does not need to be converted from NO_2 to NO for accurate measurement.

Average values for SO_2 are also presented in Table 2-63. Both inlet and outlet values were typically lower than 10 ppmv.

Concentrations of THC were also monitored, with the resulting inlet concentrations consistently below 5 ppmv/wet. Outlet concentrations were only monitored for one day with the resulting run average equaling 1.9 ppmv/wet.

Concentrations of HCl were monitored and determined using EPA Reference Method 26. Averages for the inlet concentrations ranged from approximately 500 to 800 ppmv/wet. Outlet concentrations ranged from 10 to 40 ppmv/wet. Hydrogen chloride removal efficiencies based on the reference method results were presented in Section 2.5.3.

TABLE 2-63. CONTINUOUS EMISSIONS MONITORING DAILY TEST AVERAGES FOR ACTUAL CONCENTRATIONS. BORGESS MEDICAL CENTER (1991)

DATE	RUN NO.	TEST TIME	H2O a (%V,wet by manual methods)		O2 (%V,dry)		CO2 (%V,dry)		CO (ppmv,dry)		NOx (ppmv,dry)		SO2 (ppmv,dry)		THC (ppmv,wet)		HCl (ppmv,wet)	
			Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet
9/7	2	12:15-17:25	12.8	11.9	13.5	15.1	4.9	4.7	6.5	0.9	75.7	69.8	5.4	4.8	4.2	1.9	753	39.4
9/9	3	11:32-17:48	11.7	10.3	13.8	15.6	4.2	4.2	8.1	2.9	76.6	71.9	3.8	5.7	5.6	NR	797	39.2
9/10	4	12:07-17:18	12.0	9.3	14.9	15.9	4.0	4.2	4.9	0.6	59.3	56.7	0.4	0.4	2.3	NR	515	9.7
9/11	5	11:17-16:17	12.2	9.1	14.4	15.6	4.2	4.3	4.6	0.2	67.9	61.5	2.5	3.9	2.2	NR	612	26.3
9/12	6	12:30-16:22	13.4	13.8	14.3	15.5	b 2.2	4.4	3.9	0.7	66.3	38.8	2.2	11.1	1.6	NR	486	10.6
9/13	7	09:47-14:45	12.8	10.1	14.4	15.3	3.2	4.5	3.6	0.9	63.8	57.4	4.5	5.9	2.0	NR	625	16.1
9/14	8	10:15-16:25	13.0	12.0	14.4	15.5	3.1	4.5	4.6	0.3	69.6	NR	2.1	5.3	1.8	NR	627	19.6
9/16	9	10:30-16:16	14.8	11.5	12.9	14.4	5.3	5.3	4.3	0.2	97.8	NR	6.4	8.6	1.5	NR	777	29.5

a Average moisture value from the CDD/CDF and 101A trains.

b Inlet CO2 values appear low in runs 6 - 8. All CEM QA/QC criteria for that monitor were met however the CEM operator expressed lower confidence in that instrument.

NC = Data not compiled yet.

NR = Not recorded (instrument was inoperative for these test runs).

All CEM average data are presented corrected to a 7 percent O_2/dry basis in Table 2-64. Each 30-second CEM reading was corrected to 7 percent O_2 based on the corresponding O_2 value. Averages of the corrected values were then calculated. For HCl and THC, the corrected values incorporated a correction to a dry basis by dividing the average corrected result by the average moisture content for that sample location. The average moisture content was calculated from the Method 4 results from the CDD/CDF, PM/Metals, and the Hg 101A sampling trains. The corrected run averages show trends similar to those presented in the previous table.

Table 2-65 shows pollutant concentrations measured during a typical burndown period (Run 4). During the burndown period, charging of waste into the incinerator is stopped, and combustion continues until all combustible waste in the incinerator is consumed. The data show that emissions of SO_2, CO, HCl, and THC all decrease significantly after the first hour, when most of the easily combusted material is oxidized. Nitrogen oxide emissions decrease after the third hour of burndown. Oxygen content of the flue gas approaches ambient concentrations during the last three hours of burndown, as little combustion is taking place and combustion air continues to be fed at normal operating rates. The pollutant concentrations are not corrected to 7 percent O_2 for this reason.

Comparisons of the manual HCl test results and the CEM HCl results are contained in Tables 2-66 and 2-67. The CEM results are data averages that correspond to the actual manual run time. These results were originally wet and were corrected to a dry basis.

Results at the baghouse inlet showed an average relative percent difference (RPD) between the manual and CEM measurements of 48 percent. Correlation between the two measurement methods at the inlet was poor.

The average RPD of the manual and CEM measurements at the outlet was 66 percent, however, daily average values of HCl concentrations differed by less than 16 ppm between the two methods. The correlation coefficient of the measurements made during individual tests was 0.97, showing a relatively high correlation between the two measurement methods at the baghouse outlet.

TABLE 2-64. CONTINUOUS EMISSIONS MONITORING DAILY TEST AVERAGES CORRECTED TO 7 PERCENT OXYGEN, DRY. BORGESS MEDICAL CENTER (1991)

DATE	RUN NO.	TEST TIME	H2O a (%V,wet by manual methods)		O2 b (%V,dry)		CO2 (%V,dry)	CO (ppmv,dry)		NOx (ppmv,dry)		SO2 (ppmv,dry)		THC (ppmv,dry)		HCl (ppmv,dry)	
			Inlet	Outlet	Inlet	Outlet		Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet
9/7	2	12:15-17:25	13.1	11.9	13.5	15.1	NA	12.4	2.2	141	165	9.8	10.9	9.2	5.3	1,644	103.4
9/9	3	11:32-17:48	11.0	10.3	13.8	15.6	NA	16.0	7.5	150	188	7.5	14.9	12.7	NR	1,766	116.3
9/10	4	12:07-17:18	11.2	9.3	14.9	15.9	NA	11.4	1.6	138	156	0.8	1.2	6.1	NR	1,350	29.2
9/11	5	11:17-16:17	11.3	9.1	14.4	15.6	NA	10.0	0.4	143	160	5.0	9.3	5.3	NR	1,457	72.1
9/12	6	12:30-16:22	11.5	13.8	14.3	15.5	NA	8.3	1.9	138	100	4.3	28.6	3.9	NR	1,160	31.4
9/13	7	09:47-14:45	12.9	10.1	14.4	15.3	NA	7.9	2.4	137	144	9.6	15.0	5.1	NR	1,561	46.5
9/14	8	10:15-16:25	11.7	12.0	14.4	15.5	NA	10.0	0.7	150	NR	4.5	13.8	4.4	NR	1,540	58.2
9/16	9	10:30-16:16	14.8	11.5	12.9	14.4	NA	7.6	0.4	171	NR	10.8	18.0	2.7	NR	1,351	71.6

a Values not corrected to 7% Oxygen. Average moisture value from the CDD/CDF, PM/Metals and 101A trains.

b Values not corrected to 7% Oxygen.

NOTE: Values calculated by correcting each 30 second CEM concentration to 7 % O2 and averaging the values over the duration of the test. Moisture corrections were completed for THC and HCl by deviding the 7 % value by 1 minus the moisture fraction.

NR = Not recorded (instrument was inoperative for these test runs).

NA = Not Applicable.

Table 2-65. Hourly Averages of Actual CEM Measurements
Run 4 Burndown
Borgess Medical Center (1991)

Time	O2 %V		SO2 ppmV		CO ppmV		CO2 %V		NOx ppmV		HCl ppmV		THC ppmV
	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	Inlet
1800-1859	6.89	7.06	12.1	11.1	7.9	7.5	2.10	2.22	16.5	16.3	200.5	19.8	9.2
1900-1959	15.80	17.43	-1.0	-0.5	4.3	1.4	2.29	2.42	18.6	18.0	141.4	6.7	1.9
2000-2059	15.94	17.60	-1.1	-0.2	4.2	1.4	2.06	2.19	20.4	19.8	63.2	5.7	1.7
2100-2159	17.48	19.48	-0.7	-0.1	5.1	3.2	0.96	0.90	8.3	7.1	38.8	3.7	2.4
2200-2259	18.53	20.69	-0.1	-0.4	3.8	2.0	0.19	0.10	1.3	0.7	36.8	1.3	3.0
2300-2332	18.61	20.69	-0.1	-0.6	3.9	2.1	0.12	0.05	0.5	0.2	37.4	0.6	3.0

Note: THC concentrations were not measured at the baghouse outlet location.

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TABLE 2-66. COMPARISON OF MANUAL AND CEM HCl RESULTS
BAGHOUSE INLET SAMPLING LOCATION
BORGESS MEDICAL CENTER (1991)

TEST RUN NUMBER		MANUAL HCl RESULTS (ppmV)	MANUAL HCl RESULTS (ppmV @7% O2)	CEM HCl RESULTS a,b (ppmV)	CEM HCl RESULTS (ppmV @7% O2)
	A	1204.1	2234.6	990.9	1843.3
2	B	552.6	1025.6	964.0	1721.2
	C	855.7	1588.0	748.1	1362.4
AVERAGE		870.8	1616.1	901.0	1642.3
	A	613.3	1216.0	960.2	1778.7
3	B	1227.0	2432.9	753.9	1531.1
	C	1139.3	2259.1	818.8	1752.6
AVERAGE		993.2	1969.3	844.3	1687.5
	A	208.9	486.4	487.2	1115.3
4	B	600.1	1397.1	504.6	1170.8
	C	1022.8	2381.4	623.4	1447.3
AVERAGE		610.6	1421.6	538.4	1244.5
	A	638.9	1360.0	533.9	1114.8
5	B	1403.5	2987.5	907.5	1742.1
	C	1687.0	3591.1	492.9	1084.2
AVERAGE		1243.1	2646.2	644.8	1313.7
	A	725.7	1519.1	558.8	1183.1
6	B	969.0	2028.5	326.1	781.0
	C	903.9	1892.2	NA	NA
AVERAGE		866.2	1813.3	442.5	982.0
	A	157.1	341.1	496.8	1049.3
7	B	1126.5	2446.5	732.2	1716.8
	C	976.7	2121.4	616.6	1309.6
AVERAGE		753.4	1636.3	615.2	1358.6
	A	563.1	1209.7	NA	NA
8	B	1073.5	2306.3	693.1	1518.1
	C	1395.4	2997.9	733.3	1463.4
AVERAGE		1010.7	2171.3	475.5	993.8
	A	1601.6	2895.0	958.9	1499.3
9	B	789.2	1426.5	686.5	1356.4
	C	969.3	1752.0	NA	NA
AVERAGE		1120.0	2024.5	822.7	1427.9

NA = No results are available.

a CEM Run concentrations are calculated as averages over the same time period as the manual sampling.

b CEM daily concentrations are an average of the three test run concentrations.

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TABLE 2-67. COMPARISON OF MANUAL AND CEM HCl RESULTS
BAGHOUSE OUTLET SAMPLING LOCATION
BORGESS MEDICAL CENTER (1991)

TEST RUN NUMBER		MANUAL HCl RESULTS (ppmV)	MANUAL HCl RESULTS (ppmV @7% O2)	CEM HCl RESULTS a,b (ppmV)	CEM HCl RESULTS (ppmV @7% O2)
	A	82.36	195.7	79.22	173.1
2	B	41.50	98.62	41.31	96.78
	C	5.803	13.79	19.45	46.20
AVERAGE		43.22	102.7	46.66	105.4
	A	77.02	204.3	63.07	156.7
3	B	5.815	15.42	18.99	52.17
	C	26.90	71.35	40.11	119.3
AVERAGE		36.58	97.03	40.72	109.4
	A	1.613	4.485	7.411	20.28
4	B	2.515	6.991	10.50	28.59
	C	5.239	14.56	14.17	38.31
AVERAGE		3.122	8.680	10.70	29.06
	A	4.860	12.82	13.20	35.20
5	B	48.88	128.9	59.74	135.4
	C	16.90	44.57	17.16	46.56
AVERAGE		23.54	62.10	30.03	72.39
	A	0.546	1.395	8.724	23.28
6	B	3.002	7.670	9.000	24.50
	C	4.284	10.95	10.87	27.52
AVERAGE		2.610	6.670	9.531	25.10
	A	5.288	13.22	8.460	21.04
7	B	21.73	54.33	26.64	74.72
	C	9.795	24.49	18.31	45.09
AVERAGE		12.27	30.68	17.80	46.95
	A	2.216	5.726	15.82	41.22
8	B	5.373	13.88	21.06	57.65
	C	14.77	38.15	26.91	63.81
AVERAGE		7.452	19.25	21.26	54.23
	A	27.75	59.79	28.68	54.05
9	B	57.91	124.8	53.68	119.5
	C	14.95	32.22	18.90	46.06
AVERAGE		33.54	72.27	33.75	73.20

NA = No results are available.

a CEM Run concentrations are calculated as averages over the same time period as the manual sampling.

b CEM daily concentrations are an average of the three test run concentrations.

2.8 ASH ANALYSIS FOR LOSS-ON-IGNITION AND CARBON

Both baghouse ash and bottom ash were analyzed for loss-on-ignition (LOI) and carbon content. Analysis for LOI was performed using procedures based on ASTM Methods D3174. Method 3174 was modified to include an additional intermediate weight measurement after heating for 1 hour at 410°F to drive off hydrated water. Carbon content was determined using ASTM Method D3174.

Table 2-68 shows LOI and carbon content analysis results for the bottom ash. Moisture content of the bottom ash was high variable between samples because of intermittent use of the water spray ash quenching system by plant operators. The LOI values varied from 5 to 11 percent during the test period. Carbon content of the bottom ash on a dry basis varied from 1.4 to 5.9 percent.

Table 2-69 presents LOI and carbon content analysis results for the baghouse ash. Carbon injection rates are shown for each sampling run for comparison with LOI and carbon content values. Moisture content of the baghouse ash was less than 1 percent for all samples. The LOI values ranged from 17.6 percent with no carbon injection to 22.3 percent at the highest carbon injection rate. Carbon content on a dry basis ranged from 0.5 percent with no carbon injection, to 4.3 percent at the highest rate of carbon injection.

TABLE 2-68. BOTTOM ASH LOI AND CARBON CONTENT
BORGESS MEDICAL CENTER (1991)

Run Number	Moisture (%)	Hydrated Water (%)	LOI (%)	Total Loss (%)	Carbon	
					As Received (%)	Dry (%)
2	22.08	1.51	8.57	29.84	3.34	4.29
3	18.35	1.24	5.12	23.49	1.15	1.41
4	0.47	0.46	6.28	7.15	3.66	3.68
5	42.38	2.66	10.55	49.83	1.32	2.29
6	35.92	1.64	10.22	43.41	3.37	5.26
7	14.56	1.38	9.96	24.13	4.60	5.38
8	15.39	2.14	8.44	24.19	1.55	1.83
9	19.08	0.91	9.61	27.53	4.79	5.92

TABLE 2-69. BAGHOUSE ASH LOI AND CARBON CONTENT
BORGESS MEDICAL CENTER (1991)

Run Number	Moisture (%)	Hydrated Water (%)	LOI (%)	Total Loss (%)	Carbon		Carbon Injection Rate (lb/hr)
					As Received (%)	Dry (%)	
2	0.60	0.91	17.63	18.87	0.52	0.52	0
3	0.76	0.89	18.45	19.79	0.67	0.68	0
4	0.57	0.90	21.27	22.42	1.07	1.08	0
5	0.43	0.86	20.51	21.54	1.35	1.36	1.07
6	0.58	0.95	20.53	21.74	1.81	1.82	1.06
7	0.63	0.89	21.42	22.61	3.04	3.06	2.60
8	0.90	1.06	22.32	23.83	4.29	4.33	2.87
9	0.97	1.09	22.30	23.89	2.36	2.38	2.85

3. PROCESS DESCRIPTION AND SUMMARY OF PROCESS OPERATION DURING TESTING AT BORGESS MEDICAL CENTER

3.1 INTRODUCTION

The Borgess Medical Center is located in Kalamazoo, Michigan, and comprises approximately 500 beds. Wastes generated at Borgess, including red bag and general waste but excluding cafeteria waste, are incinerated in an on-site incineration facility. This incineration facility consists of a Cleaver Brooks Model 780-A/31 MWI followed by a Cleaver Brooks waste heat recovery boiler and dry lime injection system, and a MicroPul pulse-jet baghouse.

This chapter presents both a description of the MWI process at Borgess and a summary of the process operation during the emission test program. Section 3.2 describes the history of the test program at Borgess and presents the emission test protocol. Section 3.3 describes the system tested including the equipment involved (charging system, primary, secondary, and tertiary chambers, air handling system, auxiliary burners, ash removal system, waste heat boiler, dry lime injection system, and baghouse) and the processes involved including the daily operation by the operators, the combustion process in each of the MWI chambers, the solids transfer process in the primary chamber (charging and stoking), and the APCS process. Section 3.4 describes the typical operating schedule for the MWI system. Finally, Section 3.5 describes the test program at the facility by providing a summary of the MWI and APCS process data collected and presents test run summaries that describe the operation of the system during each test run and any process anomalies that occurred.

3.2 TEST PROGRAM HISTORY AND TEST PROTOCOL

3.2.1 Test Program History

This section describes the Borgess test program history including the previous test program conducted in 1990, the results in general terms of the previous test program, and the reasons for returning to Borgess to conduct this test program.

During April, May, and June 1990, a comprehensive emissions testing program sponsored by EPA and the State of Michigan was conducted at Borgess. This test program comprised 7 test conditions and a total of 23 test runs. Concentrations of PM,

metals, CDD/CDF, and HCl were measured simultaneously at the inlet and outlet of the APCS using manual sampling trains. Indicator spore sampling was also conducted at the APCS inlet. Additionally, CEMs measured the stack gas concentrations of CO, CO_2, SO_2, HCl, NO_x, O_2, and THC. Prior to the start of the 1990 test program, a significant amount of time and effort was expended in solving test-related issues on the MWI system, in performing a pretest, and in preparing the facility to ensure the success of the test program. These issues and site preparation activities are described in detail in the final test report entitled "Michigan Hospital Incinerator Emissions Test Program, Volume II: Site Summary Report, Borgess Medical Center Incinerator, April 15, 1991."

The results from the 1990 test showed that little or no control of CDD/CDF was observed across the DI/FF. In fact, many of the test runs showed that the outlet CDD/CDF concentrations were higher than the inlet CDD/CDF concentrations indicating that formation of CDD/CDF was occurring across the DI/FF system. Additionally, the percent reduction in Hg emissions measured at this facility was less than 45 percent for all test runs.

Prior to the 1990 test program, it was anticipated that the DI/FF system would provide significant control (approximately 70 percent) of CDD/CDF and that some level of control (although small) of Hg would be realized. The results of the 1990 test showed that, against expectations, CDD/CDF concentrations actually increased across the DI/FF and that as expected a low level of control of Hg was found. Based on these results, on similar findings from other emission performance tests on MWIs with DI/FF APCSs, and on some European test data that showed significant control of both CDD/CDF and HG when activated carbon was injected into the duct along with the hydrated lime, EPA made the decision to return to Borgess and conduct another series of tests with and without activated carbon injection.

3.2.2 Borgess MWI/DI/FF Operating Protocol for Emissions Testing

The following operating protocol was developed and proposed based on the experience of the previous test program conducted in April and May, 1990. This protocol is similar to the protocol developed for the previous test program.

3.2.2.1 Incinerator Operating Cycle. During the test, the following incinerator operating cycles will be used:

- Charging period: 8 to 11 hours
- Burndown period: 6 hours
- Cooldown period: 5 to 8 hours
- Ash removal/preheat: 2 hours

The proposed operating schedule and key sampling events are summarized in Table 3-1. Sampling will not commence within 2 hours of initiating charging of waste to the incinerator.

3.2.2.2 Charge Rate. Based on previous experience, the incinerator will be charged at a rate of 245 to 263 kg/hr (540 to 580 lb/hr) for a period of 8 to 11 hours. This charge rate corresponds to charging 7 to 9 charges per hour with each charge weighing approximately 32 kg (70 lb). The total weight of waste charged per day will be limited to 2,722 kg (6,000 lb).

3.2.2.3 Incinerator Temperatures

Primary Chamber --

The primary chamber temperature will be allowed to vary within its normal operating range of 593° to 760°C (1100° to 1400°F). Testing will be stopped only if a very unusual temperature condition occurs in the primary chamber. The temperature setpoint for the primary chamber quench water spray will be 704°C (1300°F).

Retention Chamber --

During testing, the setpoint temperature on the control panel will be set at 1010°C (1850°F). The retention chamber temperature will be maintained within ±28°C (50°F) of the setpoint. If the temperature exceeds ±28°C (±50°F) of the setpoint, 5 minutes will be allowed for the trend to reverse prior to stopping the test. If the trend reverses within 5 minutes, an additional 5 minutes will be allowed for the temperature to return within the ±28°C (50°F) range prior to stopping the test.

TABLE 3-1. DAILY OPERATING SCHEDULE
BORGESS MEDICAL CENTER

Time	Incinerator	Fabric Filter
0500-0600	Clean out ash	
0600-0630	Check hearth	
0630-0730	Preheat; weigh bottom ash	Fill lime hopper; fill carbon hopper; check lime injection; check carbon injection; set lime rate; set carbon rate; check baghouse hopper
0730	Charge unit; establish setpoints; boiler auxiliary burner off	Begin lime injection
0730-0930	Line-out unit	
0930	Begin test	
1530	Complete test	
1530-1630		Check lime level; calculate lime rate; reset lime rate; calculate carbon rate
1630-1730	Summarize process data	
1930	Stop charging	
1930-0130	Burndown	
0130-0500	Cooldown; boiler auxiliary burner on when baghouse temperature drops to 300°F	

Baghouse --

The pressure drop across the baghouse will be maintained between 747 and 1,992 Pa (1 and 8 in. w.c.).

The baghouse inlet temperature will be maintained within a range of 149° to 326°C (300° to 350°F).

3.2.2.4 Lime Injection Rate. The lime injection rate will be set to achieve better than 95 percent removal (as measured by the HCL continuous emission monitoring systems). Based upon the results of the previous test, the stoichiometric ratio (SR) required to achieve 95 percent removal will be greater than 3:1. For this test program, it is expected that a lime injection rate of 18 kg/hr (40 lb/yr) will be adequate.

The lime injection rate will be set just prior to initiating charging. The rate will be adjusted after the first hour of charging, if necessary, to maintain a lime flow rate of 18 kg/hr (40 lb/hr). The lime injection rate will not be varied during the test; i.e., the lime injection rate will not be varied during the test in an attempt to match a varying HCl emission rate. Upon the completion of each emission test run, the lime injection rate will be reset to the facility's normal injection rate (7.7 kg/hr [17 lb/hr]).

3.2.2.5 Carbon Injection System. The test contractor will make arrangements for the installation of the activated carbon injection system. The system will be installed downstream of the last pair of inlet ports to the DI/FF and just upstream of the lime injection port. Based on information obtained from vendors and emissions tests at other facilities, activated carbon injection rates of 0.45 and 1.13 kg/hr (1.0 and 2.5 lb/hr) has been established. During the test program, the emission test runs without carbon injection will be completed first. The carbon injection system will be operated continuously before, during, and after the emission test runs with carbon injection in order to maintain a carbon cake on the FF bags.

Calibration of the carbon injection rate will be accomplished during the 2-hour line-out period prior to testing to ensure that the target carbon injection rates are maintained.

3.2.2.6 Boiler Auxiliary Burner. The boiler auxiliary burner will be off throughout each day's test. The auxiliary burner will not be turned on until the point in

the incinerator cooldown period when the high temperature lockout is activated and the incinerator is switched to bypass, or until the baghouse inlet temperature drops below 149°C (300°F), whichever occurs first.

3.3 INCINERATOR SYSTEM PROCESS DESCRIPTION

Figures 3-1 and 3-2 are simplified schematics of the incinerator and APCS, respectively. The key components of the system including the incinerator, the heat recovery boiler, and the APCS are discussed in the sections that follow.

3.3.1 Incinerator

The Model 780-A/31 incinerator is a controlled (starved) -air unit that consists of a primary chamber, thermal reactor (secondary chamber), and a retention chamber (tertiary chamber). The incinerator is designed for intermittent duty and the unit must be shut down and the primary chamber opened in order to remove the bottom ash from the chamber. The incinerator is rated at a heat input rate of 5.8×10^6 kg/hr (5.5×10^6 Btu/hr). This heat input rate roughly corresponds to a capacity of 295 kg/hr (650 lb/hr) for waste with a higher heating value (HHV) of 19,800 KG/kg (8,500 Btu/lb).

The primary chamber is cylindrical in shape with refractory-lined walls. Eight cast-iron plates supported by the frame of the primary chamber form the hearth. Gaps between the plates and the refractory walls are sealed using a heat resistant ceramic packing (rope).

The primary chamber combustion air is distributed as underfire air through small, approximately 3 millimeter (mm) (0.125 inch [in.])-diameter holes in the cast-iron hearth plates. The underfire combustion air holes are evenly distributed across the entire surface of the hearth. A single primary air blower provides the air to the primary chamber. The air damper controlling the air flow to the primary chamber is manually set (i.e., the airflow rate to the primary chamber is not automatically modulated during operation). Steam can be injected into the underfire air system (steam injection was used during the test). Steam is used to help prevent clinker buildup and slagging that could plug the underfire air ports. Steam injection was employed during the test because this process is a normal function of the MWI system that helps maintain combustion air

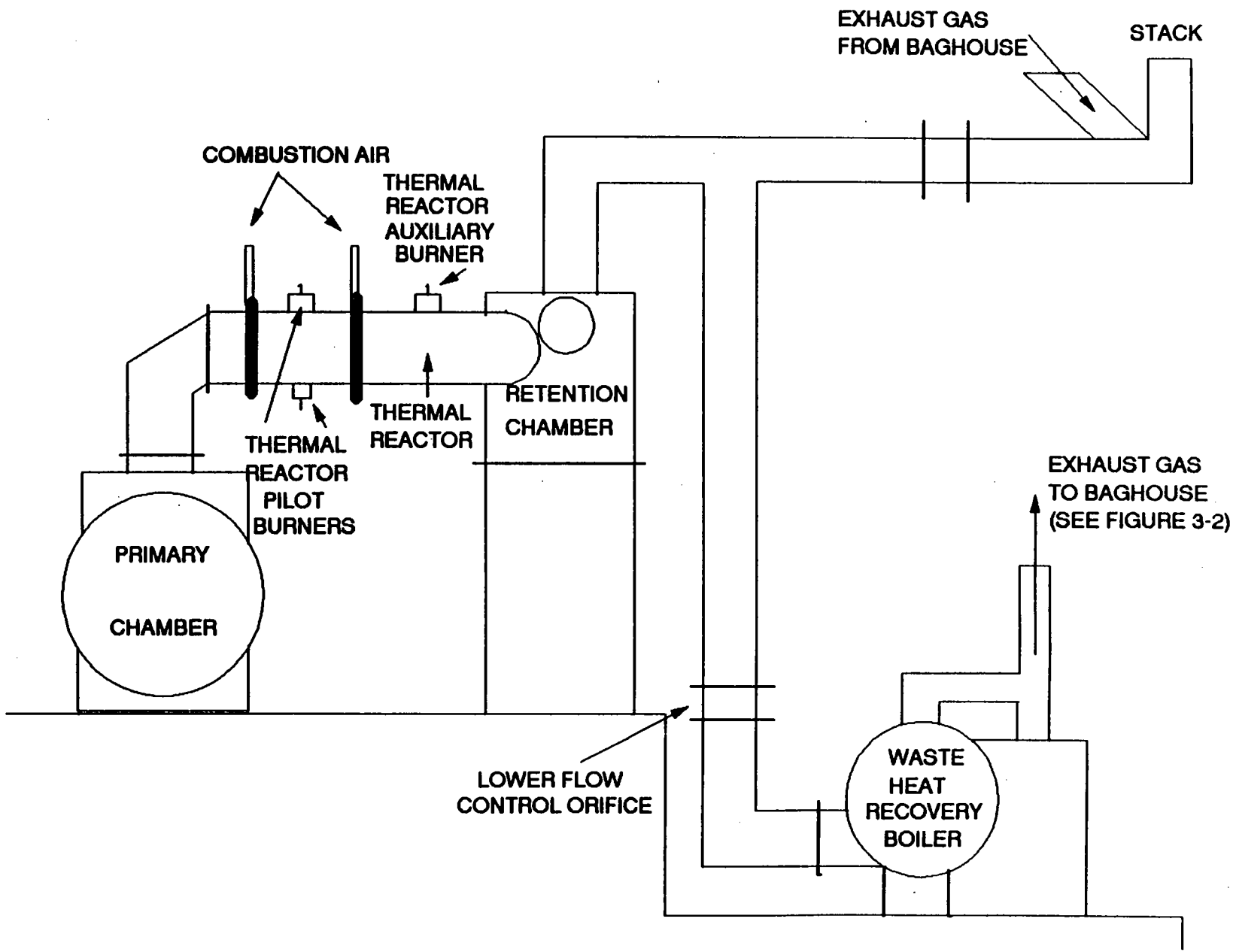


FIGURE 3-1. SCHEMATIC OF MEDICAL WASTE INCINERATOR/WASTE HEAT BOILER SYSTEM AT BORGESS MEDICAL CENTER.

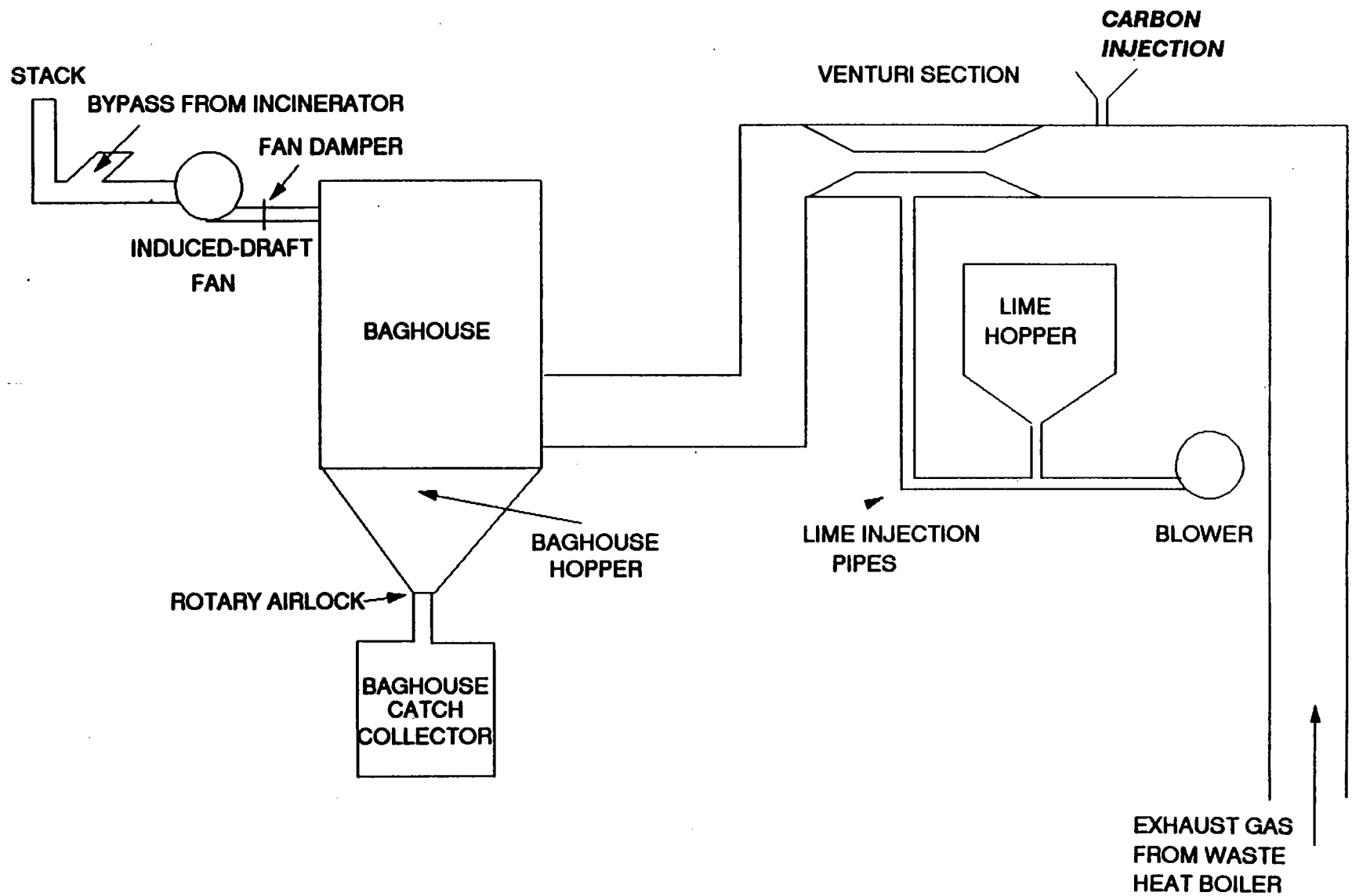


FIGURE 3-2. SCHEMATIC OF DRY LIME INJECTION/FABRIC FILTER AIR POLLUTION CONTROL SYSTEM AT BORGESS MEDICAL CENTER.

flow to the primary chamber. Design combustion air requirements comprise a total airflow of 50 dscm/min (1,750 scfm) with 30 percent of the air distributed as underfire air to the primary chamber and 70 percent distributed to the secondary chamber.

The primary chamber is equipped with a thermocouple and a water spray that is activated when the primary chamber temperature exceeds a preset value. A differential pressure gauge is used to monitor the primary chamber pressure.

The primary chamber is equipped with an ash ram that is used to help push the bottom ash from the chamber during ash removal. The ash ram is also used by the operators to stoke the ash bed during operation. The bed is either "automatically stoked" by activating an automatic stoke cycle that moves the ram into the chamber about two thirds the length of the chamber or the bed is "manually stoked" by manually activating the ram and moving it several feet into the chamber along the length of the hearth (the distance depends upon the length of time the operator activates the ram). Typically, the operators activate the ram until it reaches the end of the hearth during "manual stoking."

The thermal reactor (secondary chamber) is cylindrical in shape and has a volume of 1.1 cubic meters (m^3) (38.1 cubic feet [ft^3]). The thermocouple for the thermal reactor is located just after the auxiliary thermal reactor burner. The thermal reactor has three auxiliary burners. Two burners, Pilot Burner No. 1 and Pilot Burner No. 2, are relatively small burners located near the entrance of the thermal reactor and are used to provide a flame front and to help maintain a minimum temperature in the thermal reactor. Each burner is controlled separately; each burner is automatically turned on when the thermal reactor temperature falls below the preselected on/off setpoint for that burner. The third burner, the Thermal Reactor Auxiliary Burner, is a larger fully modulated burner used to maintain a minimum temperature within the retention chamber. The rate of firing of this auxiliary burner is modulated by establishing set points of a proportional controller keyed to the temperature measured at the outlet of the retention chamber.

Secondary combustion air is supplied to the thermal reactor in two places. "Premix" air is provided at the entrance of the thermal reactor just prior to the two pilot

burners; this air is supplied at a constant rate from the primary combustion air blower. Additional secondary combustion air is provided from a separate secondary combustion air blower and is injected into the thermal reactor just before the auxiliary thermal reactor burner. The output of the secondary air blower is fully modulated using a damper that is controlled using a proportional controller keyed to the retention chamber temperature. Combustion air for the two pilot burners is provided by the primary air blower at a constant rate. The auxiliary thermal reactor burner has its own combustion air blower.

The retention (tertiary) chamber is cylindrical in shape and has a volume of 2.8 m^3 (99.9 ft^3). The retention chamber does not have any burners nor is additional combustion air added to the chamber. The retention chamber thermocouple is located just after the chamber in the duct leading to the waste heat boiler. Both the retention chamber and the refractory-lined duct connecting the retention chamber and the boiler provide additional residence time for the hot gases; the duct is 5.3 m (11.75 ft) long and has a volume of 0.8 m^3 (28.2 ft^3).

Total residence time for the gases includes the combined residence times of the thermal reactor, retention chamber, and ductwork leading to the boiler. Residence times based on the design air flow of 210 m^3/min (7,462 acfm) at 980°C (1800°F) are as follows:

	Volume, m^3	Volume, ft^3	Residence time, sec
Thermal reactor	1.1	38.1	0.31
Retention chamber	2.8	99.9	0.80
Duct to boiler	0.8	28.2	0.23
TOTAL	4.7	166.2	1.34

3.3.2 Charging System

The primary chamber of the incinerator is fitted with a mechanical hopper/ram charging system. The wastes are transported to the incinerator in identical plastic carts. Each cart load is weighed individually on a scale that is tared to account for the weight of the cart and the net weight is recorded in a daily log. The incinerator is equipped

with an automatic cart dumper to lift each cart and dump the load into the hopper of the hopper/ram charging system. Each charge consists of a single cartload typically weighing between 27 and 39 kg (60 and 85 lb). During the tests, the weight of each charge was controlled.

3.3.3 Bottom Ash Removal System

Ash from the incinerator is removed manually from the primary chamber the morning after the burn. The rear of the incinerator has a refractory-lined door that is opened by sliding straight upward while remaining in position against the end of the chamber. The rear of the incinerator also is hinged on one side and can be opened by pulling the back end away from the chamber and pivoting the door assembly on the hinges. An ash cart is placed against the rear of the incinerator such that the top of the open cart is below the level of the hearth. The rear door assembly includes a three-sided shroud that can be hydraulically lowered over the cart. The shroud contains a row of water sprays which can be manually activated to wet the ash as it is being discharged to the ash cart. (The water sprays were not used during testing so that the dry ash could be weighed). During ash removal, the rear door assembly is raised such that there is about a 0.9 m (2 ft) high opening along the width of the hearth; this opening between the hearth and the ash cart is covered by the shroud. The ash ram is used to push ash through the opening into the ash cart. Once the ash ram is no longer effective at removing the ash, the rear door is unlatched and swung open exposing the primary chamber hearth to the operator. The operator, wearing protective clothing and a full face respirator, rakes the remaining ash from the hearth into the shrouded cart. After all the ash is raked off of the hearth, the shroud is lifted and the cart rolled away from the rear of the incinerator. A hoist is used to lift the cart and to dump the ash into a large dumpster located outside. During the tests, the ash carts containing the bottom ash from each run were weighed prior to dumping.

3.3.4 Waste Heat Boiler

The waste heat boiler is a 1,960 kilowatt (kW) (200 horsepower [hp]) Cleaver Brooks unit rated at 3,090 kg (6,800 lb) of steam per hour. The waste heat boiler design includes an auxiliary gas burner, which is capable of providing about half of the rated

output. The boiler can be operated in the waste heat recovery mode, auxiliary fuel mode, or dual mode. During the tests, the boiler was operated in the waste heat recovery mode only, i.e., the auxiliary burner was turned off during all testing so that emissions from the boiler burner would not interfere with the emissions from the MWI. The boiler is equipped with an automatic, continuous-cycle soot blowing system. The soot blower was operated normally throughout the testing.

3.3.5 Air Pollution Control System

The APCS consists of dry lime injection for hydrochloric acid gas control followed by a fabric filter baghouse for PM control.

3.3.5.1 Dry Lime Injection. Hydrated lime (Mississippi Lime Company) is injected into the flue gas duct between the waste heat boiler and the baghouse. Lime is received in 22.7 kg (50 lb) bags. The lime is dumped by the operator, as needed, into a feed hopper. The lime is discharged via gravity from the bottom of the feed hopper into a flexible pipe that is connected to the discharge end of an air blower rated at 2.8 scm/min (98 scfm). The lime discharged from the hopper is blown through the pipe by the blower (as well as pulled through the pipe by the draft created by the baghouse induced-draft fan) and is injected into a venturi section of the duct about 15 m (50 ft) upstream of the baghouse.

The rate of discharge of lime from the lime hopper is controlled by a rotary air lock valve. To assist with gravity flow of the lime, the hopper is vibrated and a screw auger is used within the hopper. Operation of the vibrator, auger, and rotary valve are all controlled by a programmable microprocessor system. The primary control for the feed rate is the frequency and duration of the operation of the rotary valve. The injector system is designed to feed reagent in the range of 2.3 to 14 kg/hr (5 to 30 lb/hr). However, during the previous test program, lime injection rates greater than 27 kg/hr (60 lb/hr) were achieved. During the latest test program (September 1991), lime injection rates of greater than 18 kg/hr (40 lb/hr) were achieved.

One of the major drawbacks to this lime injection system discovered during the previous test program was the piping system used to transport the lime to the inlet duct. The lime feed hopper is located on the mezzanine adjacent to the waste heat boiler

inside the MWI building and the inlet duct is located on the roof of the building. Therefore, the lime has to travel down from the hopper to the piping where it is blown and pulled through the piping up to the roof (approximately 4.6 m [15 ft]). Previously, the piping system used to transport the lime to the inlet duct consisted of 5-centimeter (2-inch) ID metal pipe with seven 90° bends before it reached the inlet duct. This configuration and the vertical orientation of the pipe created a high potential for lime pluggage in the piping. The higher the lime rate was, the greater was the potential for pluggage. A hammer was rapped on the pipes several times during the previous test program to dislodge lime from the inside surface of the pipe to prevent pluggage. Since the completion of the previous test program, Borgess installed a flexible pipe to replace 5 of the 90° bends inside the building. Additionally, prior to this year's test program, EPA requested that Borgess also install a flexible pipe on the roof to eliminate the remaining two 90° bends prior to injection into the duct. The addition of these flexible ducts prevented pluggage during the test program.

3.3.5.2 Activated Carbon Injection. During this test program, activated carbon was injected (for five of the eight runs) into the inlet duct to the baghouse just prior to the venturi section where the lime is injected. The activated carbon injection system was comprised of a screw feeder system that metered the activated carbon to a funnel welded to the inlet duct. The activated carbon was drawn into the duct by the draft created by the ID fan. The rate at which carbon was injected was adjusted using a controller that adjusted the voltage and, thereby, the speed of the screw feeder. During this test program, a coal-based thermally-activated carbon was used. This activated carbon has an average surface area of 950 m^2/gram (4.64 x 10^6 ft^2/lb), an average pore radius of 1.5 nm (5.9 x 10^{-8} in.), a particle size of 97.1 percent less than 200 mesh and 72.8 percent less than 325 mesh, and a tamp density of 687.2 kg/m^3 (42.9 lb/ft^3).

3.3.5.3 Fabric Filter Baghouse. The fabric filter baghouse is a MicroPul pulse-jet baghouse operated under negative pressure. The design specifications for the baghouse are presented in Table 3-2. The baghouse is a single compartment baghouse with continuous cleaning. Each row of bags is cleaned every 80 seconds, resulting in a complete cleaning cycle about every 19 minutes. The system is designed such that a

TABLE 3-2. FABRIC FILTER DESIGN PARAMETERS
BORGESS MEDICAL CENTER

Design	
Fabric Filter Type[a]	Pulse Jet
Construction Material[a]	Carbon Steel
Number of Compartments	One
Filter Bag Material[a]	Fiberglass, Teflon®-coated
Bag Material Maximum Temperature[a]	475°F
Number of Filter Bags[a b]	168
Bag Size[a]	10 ft x 4.5 in diameter
Cloth Area[a]	11.77 ft^2/bag
Total Cloth Area[a]	1977 ft^2
Design Air:Cloth Ratio[b]	3:1
Pressure Differential Range	1 to 6 in. w.c.

[a]Source of Information: MikroPul Owner's Manual and specifications.
[b]Source of Information: Notes from trip to facility.

relatively constant differential pressure across the baghouse in the range of 249 to 1,245 pascals (1 to 5 inch water column [in. w.c.]) is maintained. Draft through the system is maintained by a single ID fan downstream of the baghouse; an automatically controlled damper on the ID fan is used for airflow control.

The ID-fan damper is controlled by a proportional controller based on the measurement of primary chamber draft. Since the previous test, a new controller had been installed. This new controller made adjustments to the ID-fan damper too quickly and overcompensated for each change in primary chamber draft. As a result, the ID-fan damper tended to fluctuate significantly as the proportional controller tried to maintain the primary chamber draft within the upper and lower draft setpoints. This fluctuation in the ID-fan damper also caused fluctuations in stack gas flow rate and baghouse pressure drop. As a result of these fluctuations, a decision was made to remove the ID-fan damper controller linkage and to tighten down the damper in one position that produced the system design stack gas flow rate. Prior to testing each day, the flow rate was measured and the damper position adjusted, as necessary, to maintain the design stack gas flow rate.

The baghouse residue is continuously discharged from the collection hopper through a rotary air lock valve into a 132.5 liter (L) (35 gallon [gal]) container. The containers are lined with plastic bags and when a container is full, the bag is removed by the operator, sealed, and discarded into a dumpster and later removed to a hazardous waste landfill. The residue has a high lead content that classifies the waste as hazardous under the Resource Conservation and Recovery Act.

3.4 TYPICAL OPERATING SCHEDULE

At the beginning of each day, the ash from the previous burn cycle is removed from the incinerator. After the ash is removed, the hearth is covered with cardboard and the chamber is sealed. The cardboard provides an ash bed that inhibits clinker formation and slagging on the hearth. The thermal reactor burners are turned on to preheat the thermal reactor and the retention chamber. After a minimum temperature is achieved in the retention chamber, typically 968°C (1800°F), the primary chamber burner is started and the waste bed ignited. The first three charges to the incinerator

are cartloads of cardboard (to assist in developing a good ash bed) and are made in rapid succession. The fourth charge is medical waste. Once the waste bed is ignited, the primary chamber burner is no longer needed because combustion is self-sustaining. Subsequent charges are made at regular intervals so that seven to eight charges per hour are typically made. The charging is continued for up to 12 hours, but the manufacturer recommends that not more than a total of 2,727 kg (6,000 lb) is charged during any single burn cycle. When charging is completed for the day, the incinerator is put into an automatic burndown cycle. During the 6-hour burndown period, the large auxiliary thermal reactor burner remains operational for 3 hours while the remaining two thermal reactor pilot burners operate for the entire 6-hour period. The operating permit specifies that tertiary chamber temperatures be maintained at a minimum of 871°C (1600°F) during burndown while any waste is still burning. The combustion air blowers continue to operate until the unit is shut down for ash removal. After the incinerator has gone through the burndown cycle and the primary chamber has cooled (usually about 4 to 6 hours after the burndown cycle is completed), the ash removal process begins.

During operation, the operators stoke the waste bed on a regular basis through operation of the ash ram. The purpose of stoking is to agitate the waste bed thereby exposing all waste surfaces to heat and air and resulting in improved burnout. Stoking is initiated by the operator after every six charges. The first two stokes of each trio of stokes are automatic stokes where the ash ram travels approximately two-thirds of the length of the waste bed. Every third stoke is a manual stoke where the ash ram is manually operated such that the ash ram travels to the end of the waste bed. The results of stoking are increased temperatures in all three chambers as waste burns and volatiles are released. The temperature surges in the tertiary chamber were unpredictable. However, manual stokes typically caused larger temperature increases than automatic stokes. Typically, manual stokes were not conducted during testing because manual stokes tended to boost tertiary chamber temperature above the target temperature range. Automatic stokes were conducted in some cases. The stoking cycles used during testing are described in the test run summaries in Section 3.5.3.

3.5 PROCESS OPERATION DURING TESTING

3.5.1 Introduction

The test program at Borgess consisted of three test conditions (eight test runs). For each test condition, the MWI and DI/FF systems were operated at the same operating conditions as indicated in the test protocol in Section 3.2.2. The only difference between the three test conditions was the carbon injection rate. In Condition 1, no activated carbon was injected (three test runs). In Condition 2, activated carbon was injected at a rate of 0.45 kg/hr (1 lb/hr) (two test runs). In Condition 3, activated carbon was injected at a rate of 3.1 kg/hr (2.5 lb/hr) (three test runs).

During each test run, charges of approximately 32 kg (70 lb) were made every 7.5 minutes to maintain a consistent charge rate of approximately 254 kg/hr (560 lb/hr). Every attempt was made to maintain the charge rate for each test conditions. However, the primary process parameter in this test program was tertiary chamber temperature. The main objective during each test run was to maintain tertiary chamber temperatures in the 982° to 1038°C (1800° to 1900°F) range. Therefore, if temperatures exceeded this temperature range, then waste charging would be suspended until such time as the temperature dropped back into the range. Specific guidelines for the length of time testing could continue at temperatures outside the target range are presented in the test protocol in Section 3.2.2. In almost all cases, these high temperature excursions were short-lived (i.e., less than 10 minutes), and testing continued without interruption. Obviously, when charging was suspended because of high tertiary chamber temperatures, the charge rate for the test period was lower than the target charge rate.

Another goal of the test program was to achieve the high HCl removal rates obtained during the previous test program. Based on the results of the previous test program, a target lime injection rate of 18 kg/hr (40 lb/hr) was used during each of the test runs on this test program. While the microprocessor controller could be set to establish the target lime injection rate, the actual lime injection rate achieved could be more or less than the target rate.

Because of the potential for pluggage of the lime injection system, the system was disconnected, inspected, and cleaned, as necessary, before each test run. Typically, very little lime buildup was observed during these inspections as a direct result of the installation of the flexible lime transport pipes.

Prior to each test, the main control panel was checked to make sure that the waste heat recovery boiler was operating in the waste heat recovery mode only. However, at the end of the test, the boiler operator was instructed to place the waste heat recovery boiler into dual mode so that in addition to receiving heat input from the MWI, the boiler would also receive heat from the auxiliary fuel burner. The main reason for switching to dual mode was to maintain a baghouse inlet temperature of about 150°C (300°F) thereby preventing moisture condensation in the baghouse and blinded bags.

Other activities were conducted on a daily basis. Once the ash had been removed, the air pressure from the combustion air ports was measured, and any ports plugged with ash were rodded out. The hearth seals were inspected for air in-leakage and any substantial leaks were repaired by tamping ceramic rope packing into the leaking area. Other activities performed prior to testing included: checking the baghouse hopper for bridging; checking to make sure that the waste heat boiler soot blower was on and that the boiler auxiliary burner was off (i.e., that the boiler was in its waste heat recovery only mode); and blowing back the various system draft pressure lines.

The remainder of this section provides details of the process operation during testing and for those days where CEMs were operated all night to measure emissions during MWI startup and shutdown. Section 3.5.2 summarizes the MWI and DI/FF process operation during each of the test runs conducted and during the all-night CEM operation. Section 3.5.3 provides test run summaries that describe any process anomalies that occurred during each test run. Section 3.5.4 describes the process operation during the all-night CEM operation.

3.5.2 Summary of Process Operation

For the most part, the MWI system at Borgess performed well during the test program. The most common process problem was high temperature excursions that required withholding waste charges to allow the system to cool. Additionally, because stoking generally caused high temperature excursions over 1038°C (1900°F), stoking was often conducted during the port change. As a result, charging was not conducted during the port change when temperatures exceeding 1038°C (1900°F) were experienced. Therefore, in reporting the process data for each of the test runs, both total test period (period of time from the beginning of the test to the end of the test including the port change) and actual sampling period (same as the total test period with the process data removed for the port change and for any sampling or process anomalies) process data sets were developed. These data are presented in Appendix _____ along with graphs of the chamber temperature profiles during testing.

Tables 3-3 and 3-4 show the MWI process and DI/FF process data generated during each of the test runs conducted at Borgess. The process data presented are averages of all of the data collected during the actual sampling period of each test run. Therefore, the averages do not include data taken during port changes or any anomalies where sampling did not occur.

3.5.3 Test Run Summaries

The following paragraphs briefly summarize each test run by describing the quantity of waste charged during both the total test period and the actual sampling period, the weight of charges to the incinerator, and any process anomalies such as stoppages and high temperature excursions. The high temperature excursions were those periods of time when temperatures in the tertiary chamber exceeded the 982° to 1038°C (1800° to 1900°F) target temperature range. Typically, manual stoking was not conducted during testing. However, automatic stokes were conducted except where tertiary chamber temperatures were close to the upper limit of the target temperature range.

3.5.3.1 Test No. 1. Test No. 1 was conducted on September 6, 1991. Because of problems with one of the sampling trains, this test was aborted.

TABLE 3-3. INCINERATOR PROCESS DATA
BORGESS MEDICAL CENTER

Run Number	Date	Testing Charge Rate (lb/hr)		Daily Operation Charging			Ash (%)	Average Chamber Temperature (°F)			Boiler Inlet Temperature (°F)
		TTP	ASP	hr	lb	lb/hr		Primary	Secondary	Tertiary	
2	9/07/91	548	577	9.8	5176	528	12.5	1281	1854	1839	1406
3	9/09/92	443	506	9.8	4690	479	11.2	1220	1888	1846	1236
4	9/10/91	510	565	8.6	4270	497	8.1	1291	1860	1831	1172
5	9/11/91	523	554	11.6	6075	524	10	1298	1856	1836	1280
6	9/12/91	484	551	11.3	6051	535	12.2	1289	1883	1866	1335
7	9/13/91	526	591	12.1	6085	503	10.5	1294	1846	1827	1293
8	9/14/91	454	528	12.2	5880	482	11.7	1293	1850	1819	1240
9	9/16/91	522	525	13	6720	517	NA	1305	1848	1823	1452

NA = Not Available.

TABLE 3-4. LIME INJECTION/CARBON INJECTION/ FABRIC FILTER PROCESS DATA BORGESS MEDICAL CENTER

Run Number	Date	Fabric Filter Inlet Temperature (°F)			Fabric Filter Pressure (in. W.C.)	Lime Injection Rate[a] (lb/hr)	Carbon Injection Rate[b] (lb/hr)
		Average	Maximum	Minimum			
2	9/07/91	332	340	304	1.19	40.5	c
3	9/09/91	334	339	320	1.20	43.9	c
4	9/10/91	329	337	309	1.23	42.4	c
5	9/11/91	326	335	283	1.04	41.2	1.0
6	9/12/91	338	350	306	1.19	43.8	1.0
7	9/13/91	335	344	322	1.23	42.2	2.5
8	9/14/91	326	339	303	1.16	40.0	2.5
9	9/16/91	336	343	327	1.16	40.4	2.5

[a]Target lime rate is 40 lb/hr.
[b]For Runs 5 and 6, the target carbon injection rate is 1.0 lb/hr. For Runs 7, 8, and 9, the target carbon injection rate is 2.5 lb/hr.
[c]No activated carbon injection.

3.5.3.2 Test No. 2. Test No. 2 was conducted on September 7, 1991. The entire lime system was plugged this morning. During the velocity traverse prior to testing, a rag was drawn into the inlet duct, was lodged momentarily in the venturi section of the duct, and ended up fouling the rotary air lock at the baghouse discharge. The average charge rate for the total test period was 248.7 kg/hr (548.2 lb/hr), while that for the actual sampling period was 261.5 kg/hr. (576.5 lb/hr). Charges were maintained between 31 and 34 kg/charge (69 and 75 lb/charge) during testing with most charges weighing 32 kg (70 lb). Stoking was not conducted during this test. However, a manual stoke was conducted during the port change.

3.5.3.3 Test No. 3. Test No. 3 was conducted on September 9, 1991. The average charge rate for the total test period was 201.1 kg/hr (443.3 lb/hr), while that for the actual sampling period was 229.4 kg/hr (505.8 lb/hr). Charges were maintained at 32 kg/charge (70 lb/charge) throughout testing. All three scheduled automatic stokes were conducted during the first traverse. A manual stoke was conducted during the port change. Two of the three automatic stokes scheduled during the second traverse were skipped.

3.5.3.4 Test No. 4. Test No. 4 was conducted on September 10, 1991. The average charge rate for the total test period was 231.3 kg/hr (509.9 lb/hr), while that for the actual sampling period was 256.5 kg/hr (565.4 lb/hr). Charges were maintained at 32 kg/charge (70 lb/charge) throughout testing. Two of the three scheduled automatic stokes were conducted during the first traverse. A manual stoke was conducted during the port change. Two of the three automatic stokes scheduled during the second traverse were skipped.

3.5.3.5 Test No. 5. Test No. 5 was conducted on September 11, 1991. The average charge rate for the total test period was 237.2 kg/hr (522.9 lb/hr) while that for the actual sampling period was 251.4 kg/hr (554.2 lb/hr). Charges were maintained between 31 and 34 kg/charge (69 and 75 lb/charge) during testing with most charges weighing 32 kg (70 lb). One of the three scheduled automatic stokes was conducted during the first traverse. A manual stoke was conducted during the port change. One of the two scheduled automatic stokes was conducted during the second traverse.

3.5.3.6 Test No. 6. Test No. 6 was conducted on September 12, 1991. The average charge rate for the total test period was 219.6 kg/hr (484.1 lb/hr), while that for the actual sampling period was 249.7 kg/hr (550.6 lb/hr). Charges were maintained between 31 and 33 kg/charge (69 and 73 lb/charge) during testing. Of the two automatic stokes and one manual stoke scheduled during the first traverse, one of the automatic stokes was conducted. A manual stoke was conducted during the port change. One of the three scheduled automatic stokes was conducted during the second traverse.

3.5.3.7 Test No 7. Test No. 7 was conducted on September 13, 1991. The average charge rate for the total test period was 238.7 kg/charge (526.2 lb/hr), while that for the actual sampling period was 267.6 kg/hr (590.5 lb/hr). Charges were maintained between 32 and 34 kg/charge (70 and 74 lb/charge) during testing with most charges weighing 32 kg (70 lb). Two of the three scheduled automatic stokes were conducted during the first traverse. A manual stoke was conducted during the port change. One of the two scheduled automatic stokes was conducted during the second traverse.

3.5.3.8 Test No. 8. Test No. 8 was conducted on September 14, 1991. The average charge rate for the total test period was 206.0 kg/hr (454.1 lb/hr), while that for the actual sampling period was 239.4 kg/hr (527.8 lb/hr). Charges were maintained between 32 and 35 kg/charge (70 and 78 lb/charge) with most charges weighing between 32 and 33 kg/charge (70 and 72 lb/charge). During the port change, another rag was drawn through the baghouse system and was jammed in the rotary air lock. This incident caused the rotary air lock fuses to be blown and testing to be delayed for about an hour. The fuses were replaced and the system was placed back in operation. Stoking was not conducted during this test. However, a manual stoke was conducted during the port change.

3.5.3.9 Test No. 9. Test No. 9 was conducted on September 16, 1991. The average charge rate for the total test period was 236.8 kg/hr (522.0 lb/hr), while that for the actual sampling period was 238.1 kg/hr (525.0 lb/hr). Charges were maintained at 32 kg/charge (70 lb/charge) throughout testing. During the first traverse, two scheduled automatic stokes and one scheduled manual stoke were conducted. A manual and an

automatic stoke were conducted during the port change. One of the two scheduled automatic stokes was conducted during the second traverse.

3.5.4 Process Operation During 24-Hour CEM Operation

In addition to operating the CEMS during the testing periods, several attempts were made early in the test program to operate the CEMS for 24-hour periods in order to measure emissions during the startup, burndown, and cooldown periods of the MWI operating cycle. However, on each of these occasions, the system ID fan would shutdown during burndown causing MWI exhaust gases to flow through the bypass system instead of through the waste heat boiler and DI/FF system. Several different hypotheses were postulated to explain the ID fan failure. The following paragraphs explain the problem and solution in detail.

As explained earlier, when the system goes into burndown, the large auxiliary thermal reactor burner and Pilot Burners No. 1 and No. 2 cycle on and off to maintain their setpoint temperatures. After hours, the large auxiliary burner cycles off and remains off while the two smaller pilot burners continue to cycle on and off to maintain set point temperatures. During the early attempts to perform 24-hour CEMS monitoring, the ID fan would shutdown a few minutes after the large auxiliary burner cycled off for good (approximately 3 hours into the burndown period). The two small pilot burners cannot maintain the approximately 982° to 1010°C (1800° to 1850°F) setpoint temperatures without the auxiliary burner. Therefore, the secondary and tertiary chamber temperatures drop quickly when the auxiliary burner remains off. While several solutions were postulated regarding the ID fan shutdown, the problem turned out to be the improper setting of the high temperature setpoint on the retention chamber.

Almost all setpoints are adjusted using proportional controllers located behind the main control panel. The exceptions include the high temperature setpoint and the minimum temperature lockout for the retention chamber, and the high and low setpoints for the fabric filter. These setpoints are adjusted using the retention chamber and fabric filter LED readouts/controllers. These readouts/controllers are located on the front of the control panel and are accessed by removing the plastic view-glass. The LED readout

ordinarily displays the instantaneously measured temperature (i.e., retention chamber or fabric filter). The high or low read/reset buttons must be depressed to display the appropriate setpoint on the LED readout. The setpoints can be adjusted using the appropriate adjusting screw.

On Friday evening, September 13, 1991, the high temperature setpoint for the retention chamber was found to be 1614°F. Therefore, on the previous attempts to perform 24-hour CEMS monitoring, when the large auxiliary burner cycled off, the two pilot burners could not maintain setpoint temperatures, and when the thermal reactor temperature dropped below 1614°F, the ID fan shut off allowing the MWI exhaust gases to flow to bypass. With the waste heat boiler burner off, the 1614°F temperature is the temperature above which the boiler recovers heat from the MWI and below which the ID fan shuts off. Because testing was conducted with the waste boiler burner off, the 1614°F setpoint temperature controlled the operation of the ID fan.

For the 24-hour CEMS operation on Friday, September 13, 1991, the high temperature setpoint for the retention chamber was adjusted from 1614°F to 1206°F using the adjusting screw on the LED readout panel. This temperature closely paralleled the 1215°F setpoint that was used during the previous test program. At this setpoint temperature, even after the auxiliary burner shutdown, the ID fan stayed on, the waste heat boiler continued to recover heat, and the CEMS continued to monitor the MWI exhaust gases. At the conclusion of the burndown period (i.e., after the two pilot burners had shutdown), temperatures dropped rapidly below the 1206°F setpoint temperature causing the ID fan to shutdown again. The operator was asked to start up the waste boiler burner (i.e., dual mode) after the end of burndown but before the tertiary chamber temperature fell below 1206°F. Unfortunately there was a problem with the boiler flame sensor that prevented the boiler from coming on line. As a result of the ID fan shutdown, CEMs were measured only through the end of burndown and for a short period afterwards.

4. SAMPLING LOCATIONS

The sampling locations used during the emission testing program at the Borgess Medical Center MWI are described in this section. Flue gas samples were collected at three sampling locations.

Flue gas samples for CDD/CDF and PM were collected at the boiler inlet. This was a refractory-lined 21-inch ID duct with a gas temperature of approximately 1,400°F. Two 3-inch ports were used to access the duct. A total of 20 sampling points were used. A general schematic of this location is shown in Figure 4-1. The traverse point layout for this location is shown in Figure 4-2.

Flue gas was also sampled at the baghouse inlet which consisted of a horizontal 16-inch ID duct located on top of the roof of the facility. There were three sets of two 4-inch port nipples used to gain access to the flue gas. A general schematic is shown in Figure 4-3. Figure 4-4 gives the traverse point layout for this location.

The third sampling location was at the baghouse outlet. A schematic is presented in Figure 4-5. Figure 4-6 depicts the traverse point layout for the baghouse outlet. There were four sets of two ports (4-inch nipples) on this horizontal duct located on the roof of the facility. A total of 24 sampling points was used at this location.

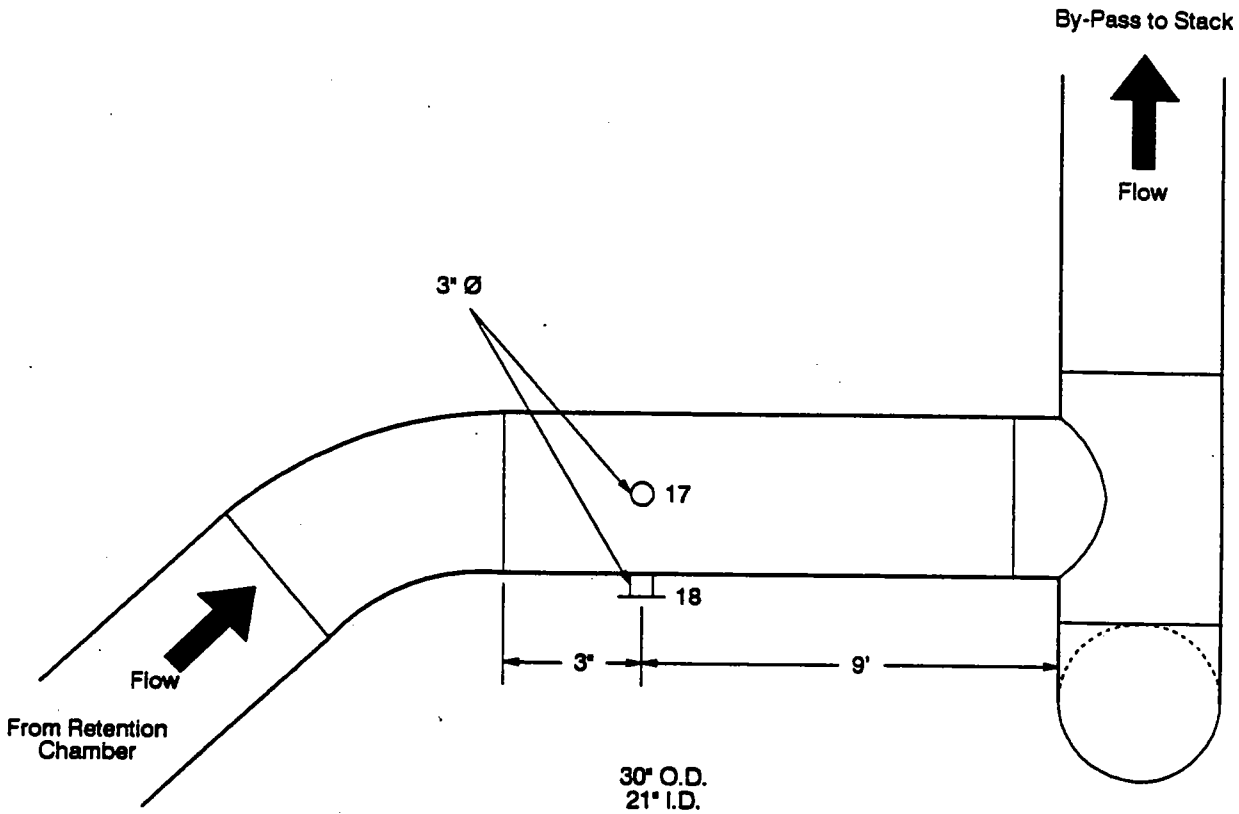
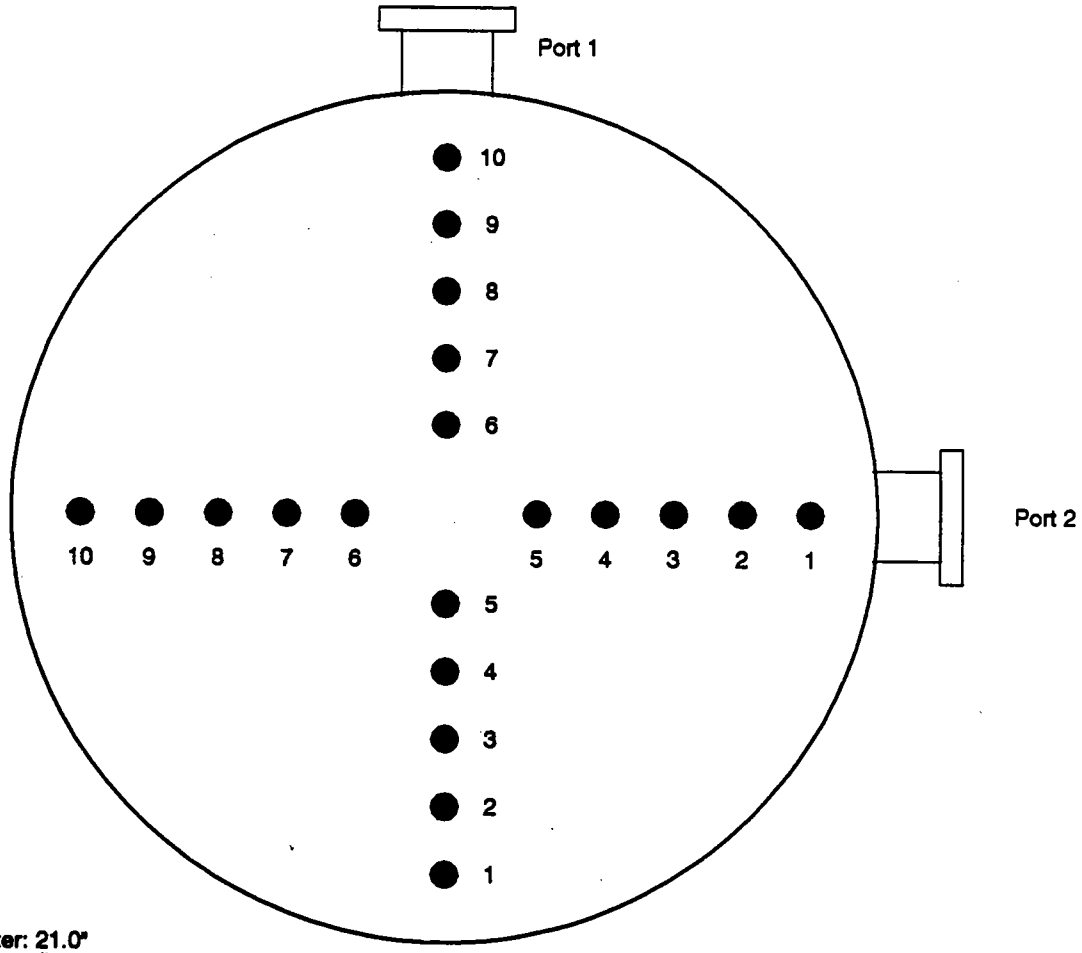


Figure 4-1. Borgess MWI Boiler Inlet Location

5316219R



Duct Diameter: 21.0"
Wall Thickness (including port length): 4"
Port Diameter: 3"

Point	% of Diameter	Distance from Inner Wall (inches)	Distance from Outside of Port (inches)
1	2.6	0.5	4.5
2	8.2	1.7	5.7
3	14.6	3.1	7.1
4	22.6	4.7	8.7
5	34.2	7.2	11.2
6	65.8	13.8	17.8
7	77.4	16.3	20.3
8	85.4	17.9	21.9
9	91.8	19.3	23.3
10	97.4	20.5	24.5

5316218R

Figure 4-2. Traverse Point Layout - Boiler Inlet

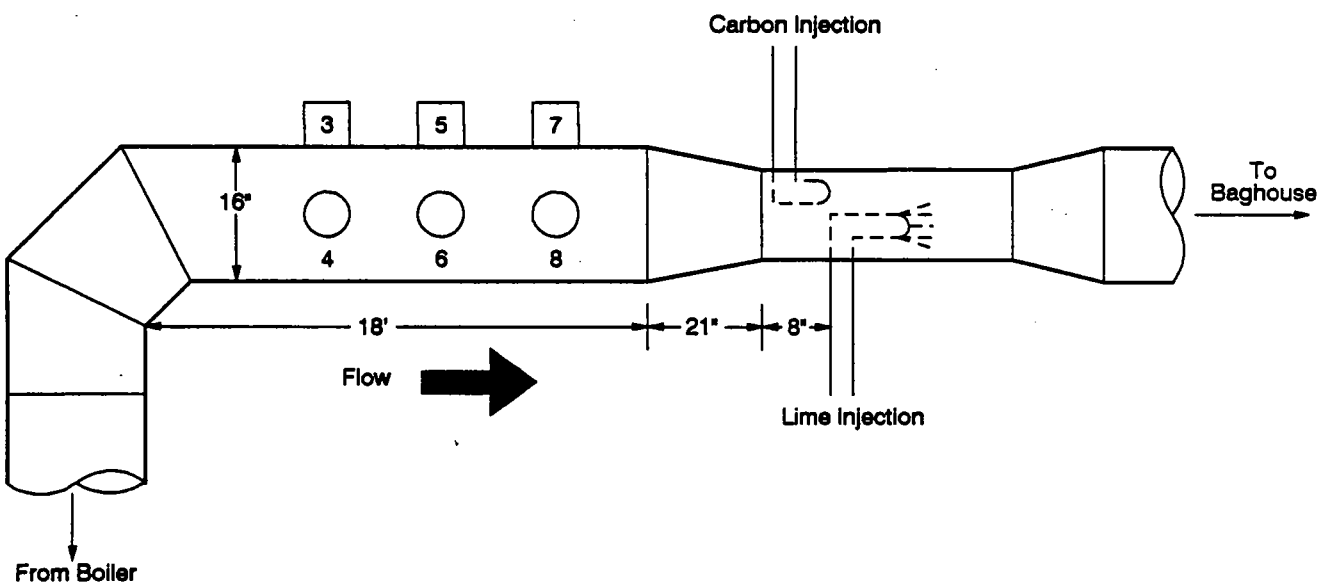
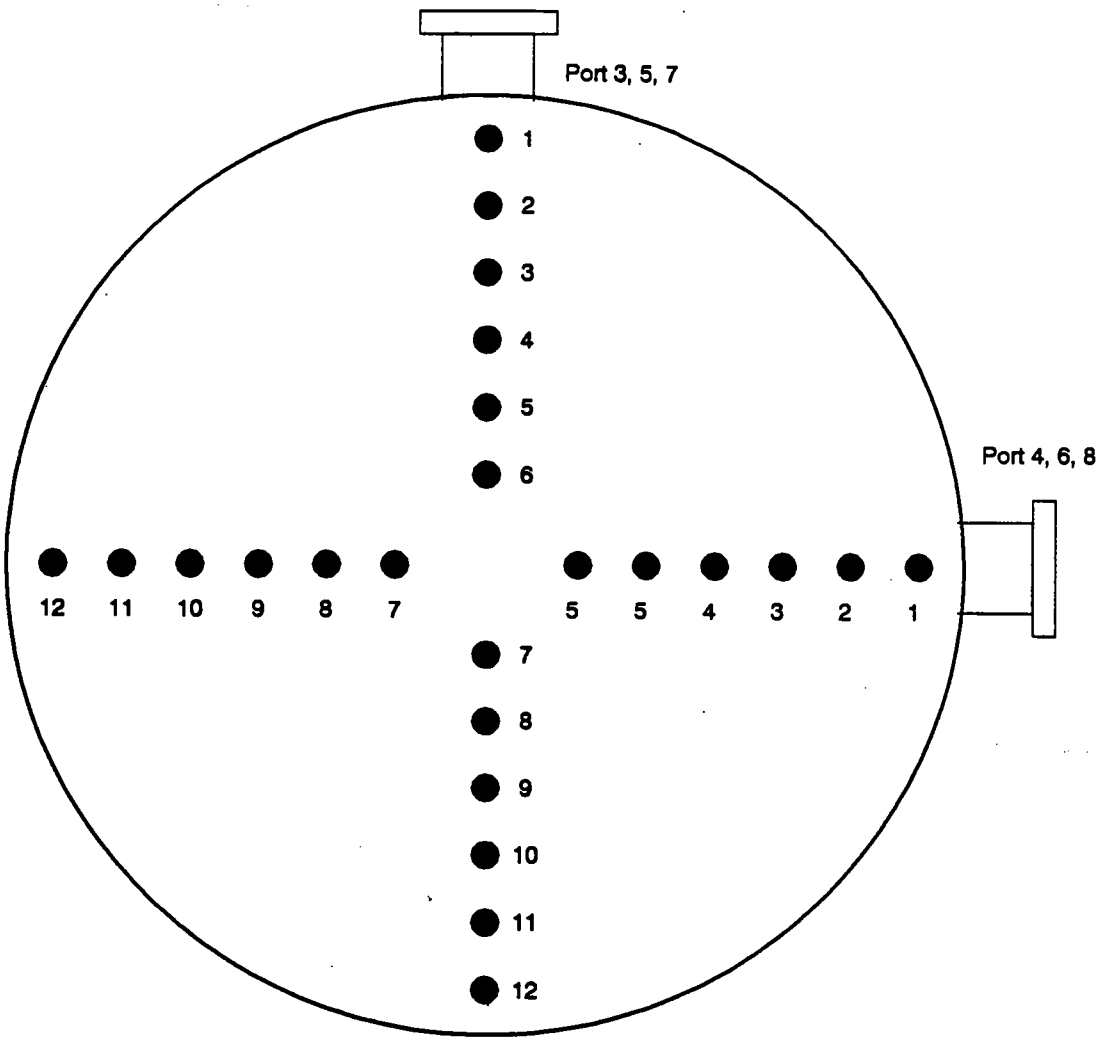


Figure 4-3. Borgess MWI Baghouse Inlet Location

5316215R



Duct Diameter: 16"
Wall Thickness (including port length): 4"
Port Diameter: 4"

Point	% of Diameter	Distance from Inner Wall (inches)	Distance from Outside of Port (inches)
1	2.1	0.5	4.5
2	6.7	1.0	5.0
3	11.8	1.8	5.8
4	17.7	2.7	6.7
5	25.0	3.9	7.9
6	35.6	5.5	9.5
7	64.4	10.0	14.0
8	75.0	11.6	15.6
9	82.3	12.8	16.8
10	88.2	13.7	17.7
11	93.3	14.5	18.5
12	97.9	15.0	19.0

5316217R

Figure 4-4. Traverse Point Layout - Baghouse Inlet

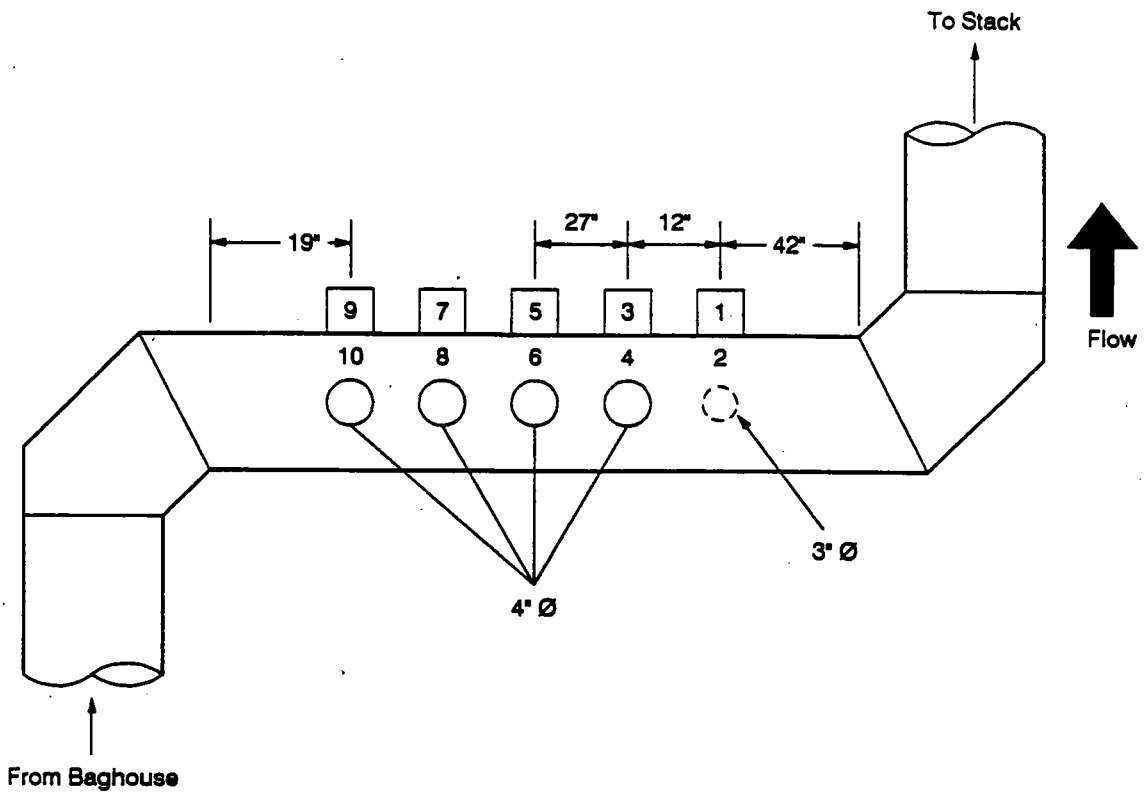
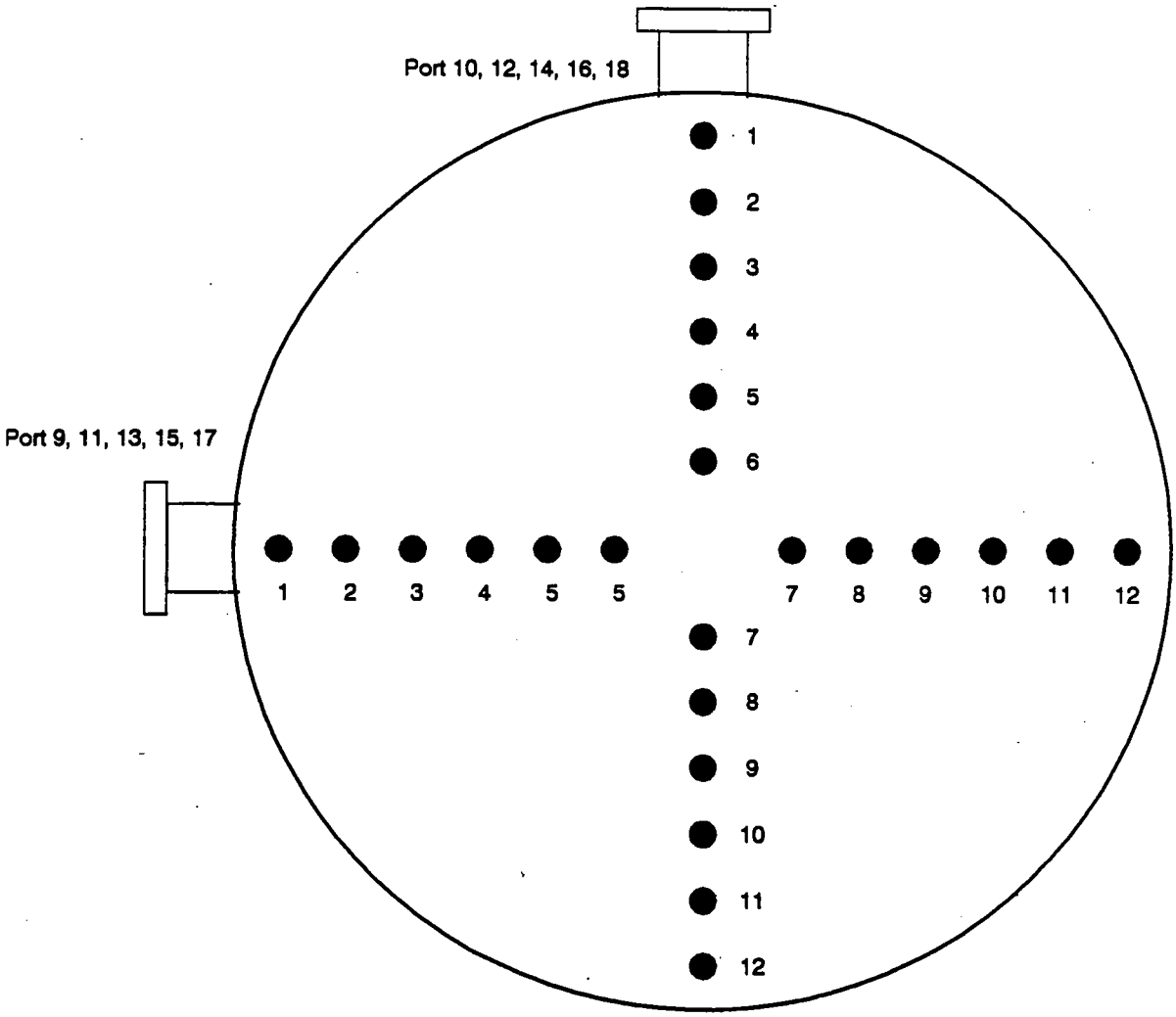


Figure 4-5. Borgess MWI Baghouse - Outlet Location

5316214R



Duct Diameter: 26.5"
Wall Thickness (including port length): 4"
Port Diameter: 4"

Point	% of Diameter	Distance from Inner Wall (inches)	Distance from Outside of Port (inches)
1	2.1	1.0	5.0
2	6.7	1.8	5.8
3	11.8	3.1	7.1
4	17.7	4.7	8.7
5	25.0	6.6	10.6
6	35.6	9.4	13.4
7	64.4	17.1	21.1
8	75.0	19.9	23.9
9	82.3	21.8	25.8
10	88.2	23.4	27.4
11	93.3	24.7	28.7
12	97.9	25.5	29.5

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Figure 4-6. Traverse Point Layout - Baghouse Outlet

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5. SAMPLING AND ANALYTICAL PROCEDURES

The sampling and analytical procedures used for the Borgess Medical Center MWI test program were the most recent revisions of the published EPA methods. Where published methods were not available, state-of-the-art sampling and analytical methods were used. In this section, descriptions of each sampling and analytical method are presented by analyte.

A summary of the sampling methods that were used is included in Table 5-1. Sampling times, minimum sampling volumes, and detection limits are summarized for the manual sampling methods in Table 5-2.

5.1 CDD/CDF EMISSIONS TESTING METHOD

The sampling and analytical method for determining flue gas emissions of CDD/CDF is EPA Proposed Method 23. This methodology is a combination of the American Society of Mechanical Engineers (ASME) 1984 draft protocol and the EPA Method 8290. The analytical method is designated as Method 8290X by Triangle Laboratories, Inc., Research Triangle Park (RTP), North Carolina, who performs the analyses. (For proprietary reasons, Triangle Laboratories has requested that a copy of their standard operating procedures not be included in this test report.)

Sample recovery techniques incorporated the latest EPA development of replacing the methylene chloride rinses with toluene rinses.

5.1.1 CDD/CDF Sampling Equipment

The CDD/CDF sampling method used the sampling train shown in Figure 5-1. Basically, the sampling system was similar to a Method 5 train with the exception of the following:

- All components (quartz probe/nozzle liner, all other glassware, filters) are pre-cleaned using solvent rinses and extraction techniques; and
- A condensing coil and XAD-II® resin absorption module are located between the filter and impinger train.

All sampling equipment specifications are detailed in the reference method shown in the Appendices.

TABLE 5-1. TEST METHODS BORGESS MEDICAL CENTER MWI

Analyte	Method
CDD/CDF	EPA Proposed Method 23 with GC/MS Method 8290
Mercury	EPA Method 101A
Particulates Lead Mercury Arsenic Nickel Cadmium Chromium Beryllium Antimony Barium Silver Thallium	EPA/EMSL Multi-Metals Train
SO_2	EPA Instrument Methods 6C
O_2/CO_2	3A
CO	10
NO_x	7E
THC	25A
HCl	NDIR CEM Analyzer
HCl	EPA Draft Method 26
HBr	EPA Draft Method 26
HF	EPA Draft Method 26
Loss-On-Ignition	ASTM D3174
Carbon	ASTM D 3178

TABLE 5-2. SAMPLING TIMES, MINIMUM SAMPLING VOLUMES AND DETECTION LIMITS FOR THE BORGESS MEDICAL CENTER MWI TESTS

Sampling Train	Sampling Time (hours)	Minimum Sample Volume (dscf)	Analyte	Detection Limit: Flue Gas[a] (μg/dscm)	Detection Limit: Analytical (μg/ml)
CDD/CDF	4[b]	120	CDD/CDF	0.3 ng/dscm	0.01 ng[c]
PM/Metals	4[b]	60	PM	0.006 gr/dscf	25-50 mg
			As	3.2	0.002
			CD	1.2	0.006
			CR	1.8	0.015
			Pb	4.9	0.002
			Hg	2.2	0.25
			Ni	4.2	0.015
			Be	0.4	0.0003
			Ba	0.7	0.002
			Sb	13.6	0.032
			Ag	6.9	0.007
			Tl	11.8	0.040
101A	4	60	Hg	2.2	0.02
HCl/HBr/HF	1	120 liters[d]	Cl^-	28	0.11
			Br^-	32	0.127
			F^-	100	0.40[e]

[a]Flue gas detection limit is calculated conservatively by summing the front half and back half detection limits. Solution volume for front half and back half fractions are typically 300 ml and 150 ml, respectively.
[b]An average sampling rate of 0.5 ft^3/min was used to calculate sampling time.
[c]Based on average detection limits for tetra-octa CDD/CDF congeners.
[d]An average sampling rate of 2 liters/min was used to calculate the sample volume.
[e]Detection limit based on 100 ml aliquot. Method is still under development. Actual limit may vary.

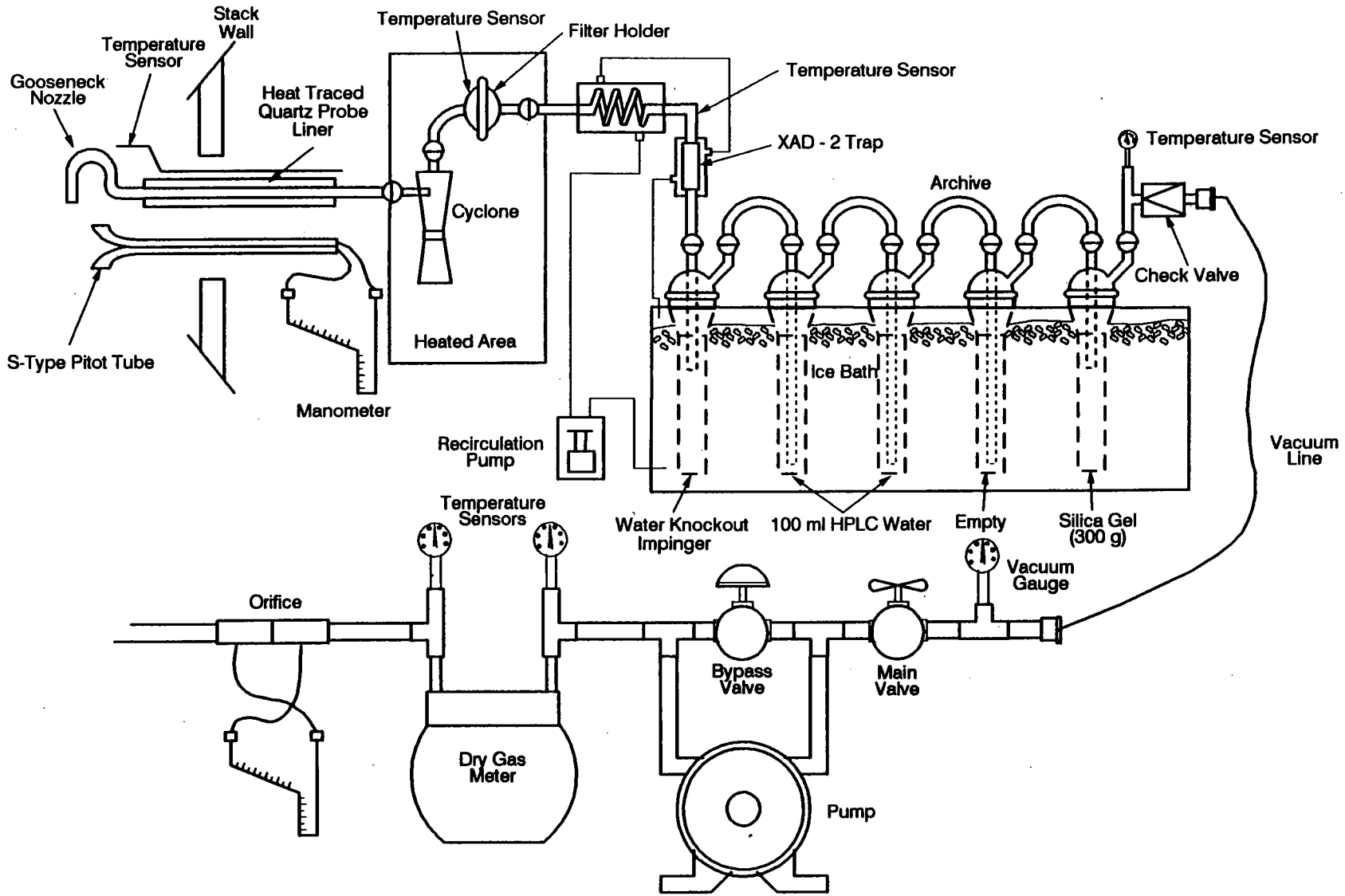

Figure 5-1. CDD/CDF Sampling Train Configuration

5.1.2 CDD/CDF Equipment Preparation

In addition to the standard EPA Method 5 requirements, the CDD/CDF sampling method includes several unique preparation steps which ensure that the sampling train components are not contaminated with organics that could interfere with analysis. The glassware, glass fiber filters and absorbing resin were cleaned, and the filters and resin were checked for residuals before they were packed.

5.1.2.1 Glassware Preparation. Glassware was cleaned as shown in Table 5-3. Glassware was washed in soapy water, rinsed with distilled water, baked and then rinsed with acetone followed by methylene chloride. Clean glassware was loosely covered with foil and allowed to dry under a hood to prevent laboratory contamination. Once the glassware was dry, the ends exposed to air were sealed with methylene chloride-rinsed aluminum foil. All the glass components of the sampling train, including the glass nozzles and any sample bottles, flasks, petri dishes, graduated cylinders and pipets that were used during sampling and recovery, were cleaned according to this procedure. Non-glass components (such as the Teflon®-coated filter screens and seals, tweezers, Teflon® squeeze bottles, nylon probe brushes and nylon nozzle brushes) were cleaned following the same procedure, except that no baking was performed (Step 4 omitted).

This cleaning procedure deviates from the EPA proposed method. However, Radian believes that the use of chromic acid solution may result in analytical interferences with the compounds of interest.

5.1.2.2 XAD-II® Resin and Filters Preparation. XAD-II® absorbing resin and glass fiber filters were pre-cleaned by separate procedures according to the specified method. Only pesticide grade solvents and HPLC grade water were used to prepare for organic sampling and to recover these samples. The lot number, manufacturer and grade of each reagent used was recorded in the laboratory notebook.

To prepare the filters, a batch of 50 filters were placed in a soxhlet pre-cleaned by extraction with toluene. The soxhlet was charged with fresh toluene and reflexed for 16 hours. After the extraction, the toluene was analyzed as described in Sections 5.2 and 5.3 of the reference method for the presence of tetrachloro dibenzo-p-dioxins (TCDD) or tetrachloro dibenzofurans (TCDF). (If these analytes are found, the filters are re-extracted until no TCDD or TCDF is detected.) The filters were then dried

TABLE 5-3. CDD/CDF GLASSWARE CLEANING PROCEDURE (Train Components, Sample Containers and Laboratory Glassware)

NOTE: USE VITON® GLOVES AND ADEQUATE VENTILATION WHEN RINSING WITH SOLVENTS

1. Soak all glassware in hot soapy water (Alconox®).
2. Tap water rinse to remove soap.
3. Rinse with distilled/deionized H_2O (X3).[a]
4. Bake at 450°F for 2 hours.[b]
5. Rinse with acetone (X3), (pesticide grade).
6. Rinse with methylene chloride (X3), (pesticide grade).
7. Cap glassware with clean glass plugs or methylene chloride rinsed aluminum foil.
8. Mark cleaned glassware with color-coded identification sticker.
9. Immediately rinse glassware before using with acetone and methylene chloride (laboratory proof).

[a] (X3) = three times.
[b] Step (4) has been added to the cleanup procedure to replace the dichromate soak specified in the reference method. Radian has demonstrated in the past that baking sufficiently removes organic artifacts. Baking is not used for probe liners and non-glass components of the train that cannot withstand 450°F (i.e., teflon-coated filter screen and seals, tweezers, teflon squeeze bottles, nylon probe and nozzle brushes).

completely under a clean nitrogen (N_2) gas stream. Each filter was individually checked for holes, tears, creases or discoloration. If any had been found, the filter would have been discarded. Acceptable filters were stored in a pre-cleaned petri dish, labeled by date of analyses and sealed with Teflon® tape.

To prepare the absorbing resin, the XAD-II® resin was cleaned in the following sequential order:

- Rinse with HPLC grade water, discard water;
- Soak in HPLC grade water overnight, discard water;
- Extract in soxhlet with HPLC grade water for 8 hours, discard water;
- Extract with methanol for 22 hours, discard solvent;
- Extract with methylene chloride for 22 hours, discard solvent;
- Extract with methylene chloride for 22 hours, retain an aliquot of solvent for gas chromatography analysis of TCDD and TCDF; and
- Dry resin under a clean N_2 stream.

Once the resin was completely dry, it was checked for the presence of methylene chloride, TCDD and TCDF as described in Section 3.1.2.3.1 of the reference method. (If TCDD or TCDF are found, the resin is re-extracted. If methylene chloride is found, the resin is dried until the excess solvent is removed.) The absorbent was used within four weeks of cleaning as specified by the method.

The cleaned XAD-II® resin was spiked with five CDD/CDF internal standards. Due to the special handling considerations required for the CDD/CDF internal standards, the spiking was performed by Triangle Laboratories. For convenience and to minimize contamination, Triangle Laboratories also performed the resin and filter cleanup procedures and loaded the resin into the glass traps.

5.1.2.3 <u>CDD/CDF Method 5 Equipment Preparation</u>. The remaining preparation included calibration and leak checking of all sampling train equipment. This included: meterboxes, thermocouples, nozzles, pitot tubes, and umbilicals. Referenced calibration procedures were followed. The results were properly documented in a

laboratory notebook and retained. The techniques used to calibrate this equipment followed EPA guidelines.

5.1.3 CDD/CDF Sampling Operations

5.1.3.1 Preliminary Measurements. Prior to sampling, preliminary measurements were required to ensure isokinetic sampling. These included determining the traverse point locations and performing a preliminary velocity traverse, cyclonic flow check and moisture determination. These measurements were then used to calculate a K factor. The K factor was used to determine an isokinetic sampling rate from stack gas flow readings taken during sampling.

Measurements were made of the duct inside diameter, port nozzle length, and the distances to the nearest upstream and downstream flow disturbances. These measurements were used to determine sampling point locations by EPA Reference Method 1 guidelines. The distances were then marked on the sampling probe with an indelible marker.

5.1.3.2 Assembling the Train. Assembly of the CDD/CDF sampling train components was completed in the recovery trailer, and final train assembly was performed at the stack location. First, the empty, clean impingers were assembled and laid out in the proper order in the recovery trailer. Each ground glass joint was carefully inspected for hairline cracks. The first impinger was a knockout impinger which had a short tip. The purpose of this impinger was to collect condensate which forms in the coil and XAD-II® resin trap. The next two impingers were modified tip impingers which each contained 100 ml of HPLC grade water. The fourth impinger was empty, and the fifth impinger contained 200 to 300 grams of blue indicating silica gel. After the impingers were loaded, each impinger was weighed and the initial weight and contents of each impinger was recorded on a recovery data sheet. The impingers were connected using clean glass U-tube connectors and were arranged in the impinger bucket as shown in Figure 5-2. All the impingers were approximately the same height to obtain a leak-free seal. The open ends of the train were sealed with methylene chloride-rinsed aluminum foil or clean ground-glass caps.

The second step was to load the filter into the filter holder in the recovery trailer. The filter holder was capped and placed with the resin trap and condenser coil (capped)

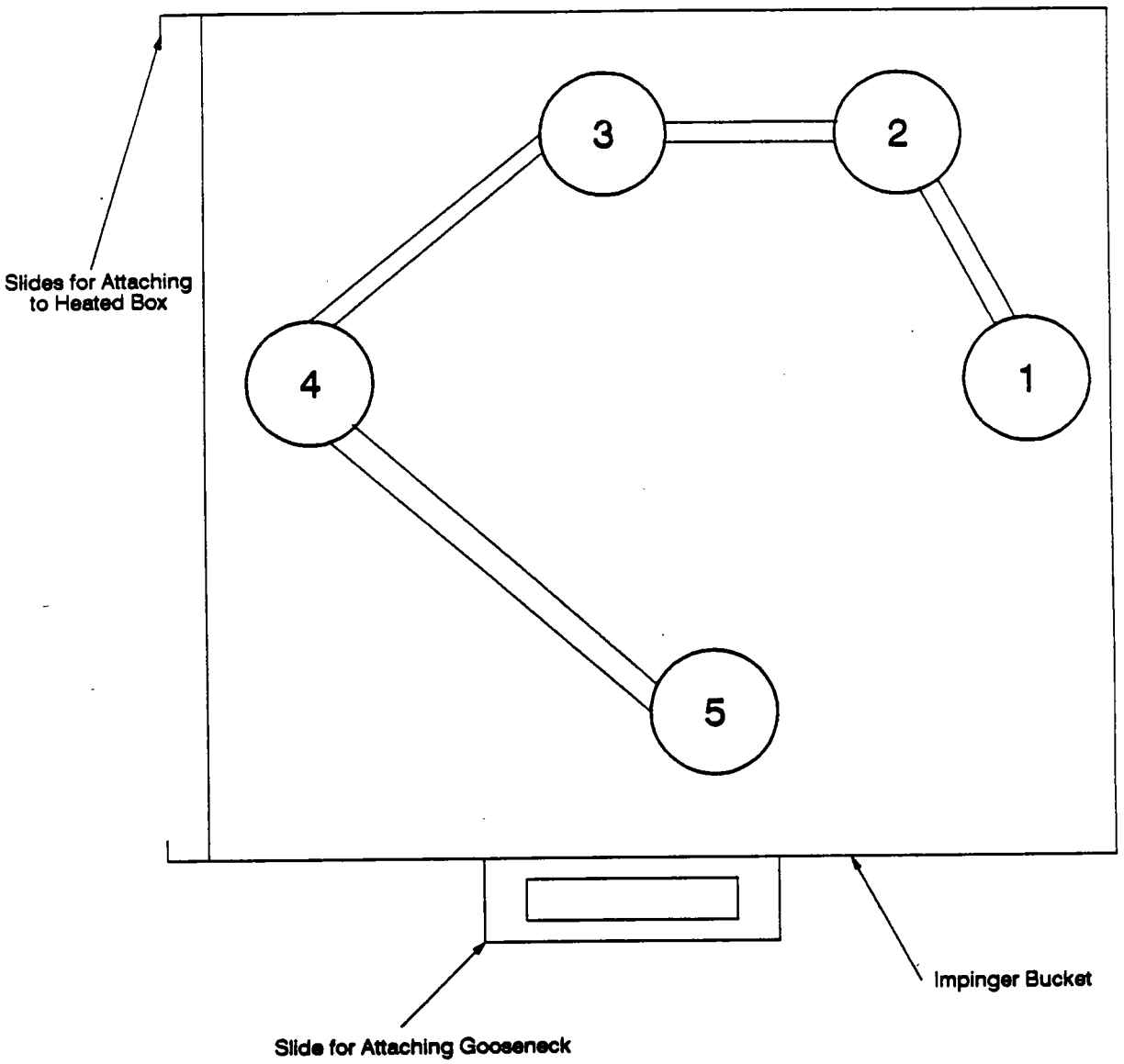

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Figure 5-2. Impinger Configuration for CDD/CDF Sampling
(optional knock out impinger not shown)

into the impinger bucket. A supply of pre-cleaned foil and socket joints was also placed in the bucket in a clean plastic bag for use by the samplers. Sealing greases were not used to avoid contamination of the sample. The train components were transferred to the sampling location and assembled as shown in Figure 5-1.

5.1.3.3 Sampling Procedures. After the train was assembled, the probe liner and filter box heaters and the sorbent module/condenser coil recirculating pump were turned on. When the system reached the appropriate temperatures, the sampling train was ready for pre-test leak checking. The temperature of the sorbent module resin must not exceed 50°C (120°F) at any time, and during testing it must not exceed 20°C (68°F). The filter skin temperature was maintained at 120 ±14°C (248 ±25°F). The probe temperature was maintained above 100°C (212°F).

The sampling trains were leak checked at the start and finish of sampling. (Method 5/23 protocol only requires post-test leak checks and recommends pre-test leak checks.) Radian protocol incorporates leak checks before and after every port change. An acceptable pre-test leak rate was less than 0.02 acfm (ft^3/min) at approximately 15 inches of Hg. If a piece of glassware needed to be emptied or replaced during testing, a leak check was performed before the glassware piece was removed and after the train was re-assembled.

To leak check the assembled train, the nozzle end was capped off and a vacuum of 15 inches Hg was pulled in the system. When the system was evacuated, the volume of gas flowing through the system was timed for 60 seconds. After the leak rate was determined, the cap was slowly removed from the nozzle end until the vacuum subsided, and then the pump was turned off. If the leak rate requirement was not met, the train was systematically checked by capping the train first at the filter, then at the first impinger, etc., until the leak was located and corrected.

After a successful pre-test leak check had been conducted and all train components were at their specified temperatures, initial data were recorded (DGM reading) and the test was initiated. Sampling train data were recorded periodically on

standard data forms. A checklist for CDD/CDF sampling is included in Table 5-4. A sampling requirement unique to CDD/CDF sampling is that the gas temperature entering the resin trap must be below 68°F. The gas was cooled by a water jacket condenser which circulated water at 0°C (32°F).

The leak rates and sampling start and stop times were recorded on the sampling log. Any events occurring during sampling that could potentially affect sampling results were also recorded on the sampling log.

At the conclusion of the test run, the sample pump (or flow) was turned off, the probe was removed from the duct, a final DGM reading was taken, and a post-test leak check was completed. The procedure was identical to the pre-test procedure, except that the vacuum pulled was at least one inch Hg higher than the highest vacuum attained during sampling. A leak rate of less than 4 percent of the average sample rate or 0.02 acfm (whichever is lower) is acceptable. If a final leak rate did not meet the acceptable level, the test run could still be accepted upon approval of the EPA Test Administrator. If approved, the measured leak rate was reduced by subtracting the allowable leak rate and then multiplying by the period of time in which the leak occurred. This "leaked volume" was then subtracted from the measured gas volume to determine the final gas sample volume.

5.1.4 CDD/CDF Sample Recovery

To facilitate transfer from the sampling location to the recovery trailer, the sampling train was disassembled into the following sections: the probe liner, filter holder, filter to condenser glassware, condenser sorbent module, and the impingers in their bucket. Each of these sections was capped with methylene chloride-rinsed aluminum foil or ground glass caps before removal to the recovery trailer. Once in the trailer, field recovery followed the scheme shown in Figure 5-3. The samples were recovered and stored in cleaned amber glass bottles to prevent light degradation.

For the Borgess Medical Center test program, all CDD/CDF recovery rinses were completed using toluene instead of methylene chloride. This is the most recent development in EPA CDD/CDF testing methodology. The solvents used for train recovery were all pesticide grade. The use of the highest grade reagents for train

TABLE 5-4. CDD/CDF SAMPLING CHECKLIST

Pretest:

1. Check impinger set to verify the correct order, orientation and number of impingers. Verify probe markings, and remark if necessary.

2. Check that you have all the correct pieces of glassware. Have a spare probe liner, probe sheath, meter box and filter ready to go at location.

3. Obtain data sheets and record barometric pressure on log sheet.

4. Bag sampling equipment for CO_2/O_2 needs to be ready if not using CEMs for CO_2/O_2 determinations.

5. Examine the meter box - level it, zero the manometers and confirm that the pump is operational.

6. Verify the filter is loaded correctly and as tight as possible; place filter in line with the train and leak check at 15 inches Hg.

7. Add probe to train.

8. Check thermocouples - make sure they are reading correctly.

9. Conduct pitot leak check, recheck manometer zero.

10. Do final leak check; record leak rate and vacuum on sampling log sheet.

11. Turn on variacs and verify that the heat is increasing.

12. Check that cooling water is flowing and on. Add ice to impinger buckets.

13. Check isokinetic K-factor - make sure it is correct. (Refer to previous results to confirm assumptions). (Two people should calculate this independently to double check it.)

TABLE 5-4. CDD/CDF SAMPLING CHECKLIST, continued

Test:

1. Notify crew chief of any sampling problems immediately. The meterbox operator must fill in sampling log and document any abnormalities.

2. Perform simultaneous/concurrent testing with other locations (if applicable). Maintain filter temperature between 248°F ±25°F. Keep temperature as steady as possible. Maintain the resin trap and impinger temperatures below 68°F. Maintain probe temperature above 212°F.

3. Leak check between ports and record on sampling log. Leak check if the test is stopped to change silica gel, to decant condensate, or to change filters.

4. Record sampling times, rate, and location for the fixed gas bag sampling (CO, CO_2, O_2), if applicable.

5. Blow back pitot tubes periodically if moisture entrapment is expected.

6. Stop test and change filter if vacuum suddenly increases or exceeds 15 inches Hg.

7. Check impinger solutions every 1/2 hour; if the knockout impinger is approaching full, stop test and empty it into a pre-weighed bottle and reinstate it in the train.

8. Check silica gel impinger every 1/2 hour; if indicator color begins to fade, request a pre-filled, pre-weighed impinger from the recovery trailer, stop test and replace silica gel impinger.

9. Check the ice in the impinger bucket frequently. If the stack gas temperatures are high, the ice will melt at the bottom rapidly. Maintain condenser coil and silica gel impinger gas temperatures below 68°F.

Post-test:

1. Record final meter reading and record on log sheet.

2. Do final leak check of sampling train at maximum vacuum during test and record on log sheet.

3. Do final pitot leak check.

TABLE 5-4. CDD/CDF SAMPLING CHECKLIST, continued

4. Check completeness of data sheet(s). Verify that impinger bucket identification is recorded on the data sheets. Note any abnormal conditions experienced during the test.

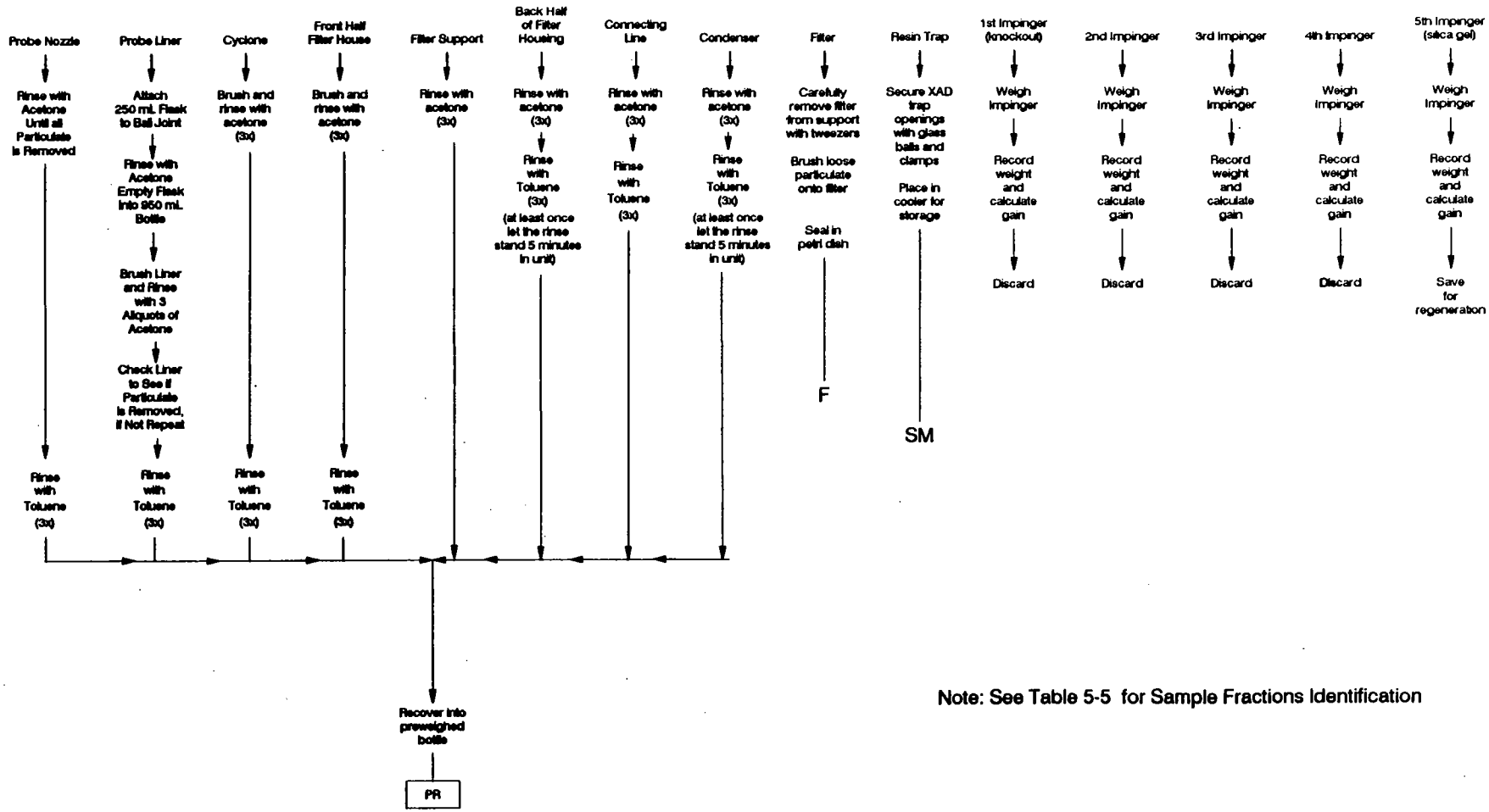
5. Leak check function (level, zero, etc.) of the pitot tubes and inspect for tip damage.

6. Disassemble train, cap sections, and take each section and all data sheets to the recovery trailer.

7. Probe recovery (use clean 950 ml bottles)
   a) Bring probes into recovery trailer (or other enclosed area).
   b) Wipe the exterior of the probe to remove any loose material that could contaminate the sample.
   c) Carefully remove the nozzle/probe liner and cap it with pre-rinsed aluminum foil. (Rinsed with methylene chloride.)
   d) For acetone rinses (all trains)
      - Attach precleaned cyclone flask to probe to catch rinses
      - Wet all sides of probe interior with acetone
      - While holding the probe in an inclined position, put precleaned probe brush down into probe and brush it in and out
      - Rinse the brush, while in the probe, with acetone
      - Do this at least 3 times until all the particulate has been recovered.
      - Recover acetone into a pre-weighed, pre-labeled sample container
   e) Follow the procedure outlined in (d) using toluene, except do not brush. Recover the solvent into the same acetone recovery bottle.

8. Cap both ends of nozzle/probe liner for the next day, and store in dry safe place.

9. Make sure data sheets are completely filled out, legible, and give them to the Field Test Leader.



Note: See Table 5-5 for Sample Fractions Identification

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Figure 5-3. CDD/CDF Field Recovery Scheme

recovery is essential to prevent the introduction of chemical impurities which interfere with the quantitative analytical determinations.

Field recovery resulted in the sample components listed in Table 5-5. The sorbent module was stored on ice in coolers at all times. The samples were shipped with written analysis instructions to the analytical laboratory by truck.

5.1.5 CDD/CDF Analytical Procedures

The analytical procedure used to obtain CDD/CDF concentrations from a single flue gas sample was HRGC and HRMS (resolution from 8000-10000 m/e). The target CDD/CDF congeners are listed in Table 5-6. The analyses were performed by Triangle Laboratories, Inc., by Method 8290X.

The flue gas samples were analyzed in two fractions according to the scheme in Figure 5-4. One fraction is the total train toluene and acetone rinses, filter(s) and sorbent module; the other fraction is composed of the toluene rinse of applicable portions of the sampling train. For the CDD/CDF analysis, isotopically-labeled surrogate compounds and internal standards were added to the samples before the extraction process was initiated. The internal standards and surrogates that were used are described in detail in EPA Method 23.

Data from the mass spectrometer were recorded and stored on a computer file and on paper. Results for the amount detected, detection limit, retention time, and internal standard and surrogate standard recoveries were calculated by computer. The chromatograms were retained by the analytical laboratory and were also included in the analytical report delivered to Radian Corporation.

5.1.5.1 Preparation of Samples for Extraction. Upon receiving the sample shipment, the samples were checked against the Chain-of-Custody forms and then assigned an analytical laboratory sample number. Each sample component was reweighed to determine if leakage occurred during travel. Color, appearance, and other particulars of the samples were noted. Samples were extracted within 21 days of collection.

5.1.5.2 Calibration of GC/MS System. A five-point calibration of the GC/MS system was performed to demonstrate instrument linearity over the concentration range of interest. Relative response factors were calculated for each congener or compound of

TABLE 5-5. CDD/CDF SAMPLE FRACTIONS SHIPPED TO ANALYTICAL LABORATORY

Container/ Component	Code	Fraction
1	F	Filter(s)
2	PR[a]	Acetone and toluene rinses of nozzle/probe, front half/back half filter holder, filter support, connecting glassware, condenser
3	SM	XAD-II® resin trap (sorbent module)

[a] Rinses include acetone and toluene recovered into the same sample bottle.

TABLE 5-6. CDD/CDF CONGENERS ANALYZED

DIOXINS:

2,3,7,8 tetrachlorodibenzo-p-dioxin (2,3,7,8 TCDD)
Total tetrachlorinated dibenzo-p-dioxins (TCDD)
1,2,3,7,8 pentachlorodibenzo-p-dioxin (1,2,3,7,8 PeCDD)
Total pentachlorinated dibenzo-p-dioxins (PeCDD)
1,2,3,4,7,8 hexachlorodibenzo-p-dioxin (1,2,3,4,7,8 HxCDD)
1,2,3,6,7,8 hexachlorodibenzo-p-dioxin (1,2,3,6,7,8 HxCDD)
1,2,3,7,8,9 hexachlorodibenzo-p-dioxin (1,2,3,7,8,9 HxCDD)
Total hexachlorinated dibenzo-p-dioxins (HxCDD)
1,2,3,4,6,7,8 heptachlorodibenzo-p-dioxin (1,2,3,4,6,7,8 HpCDD)
Total heptachlorinated dibenzo-p-dioxins (HpCDD)
Total octachlorinated dibenzo-p-dioxins (OCDD)

FURANS:

2,3,7,8 tetrachlorodibenzofurans (2,3,7,8 TCDF)
Total tetrachlorinated dibenzofurans (TCDF)
1,2,3,7,8 pentachlorodibenzofuran (1,2,3,7,8 PeCDF)
2,3,4,7,8 pentachlorodibenzofuran (2,3,4,7,8 PeCDF)
Total pentachlorinated dibenzofurans (PeCDF)
1,2,3,4,7,8 hexachlorodibenzofuran (1,2,3,4,7,8 HxCDF)
1,2,3,6,7,8 hexachlorodibenzofuran (1,2,3,6,7,8 HxCDF)
2,3,4,6,7,8 hexachlorodibenzofuran (2,3,4,6,7,8 HxCDF)
1,2,3,7,8,9 hexachlorodibenzofuran (1,2,3,7,8,9 HxCDF)
Total hexachlorinated dibenzofurans (HxCDF)
1,2,3,4,6,7,8 heptachlorodibenzofuran (1,2,3,4,6,7,8 HpCDF)
1',2,3,4,7,8,9 heptachlorodibenzofuran (1',2,3,4,7,8,9 HpCDF)
Total heptachlorinated dibenzofurans (HpCDF)
Total octachlorinated dibenzofurans (OCDF)

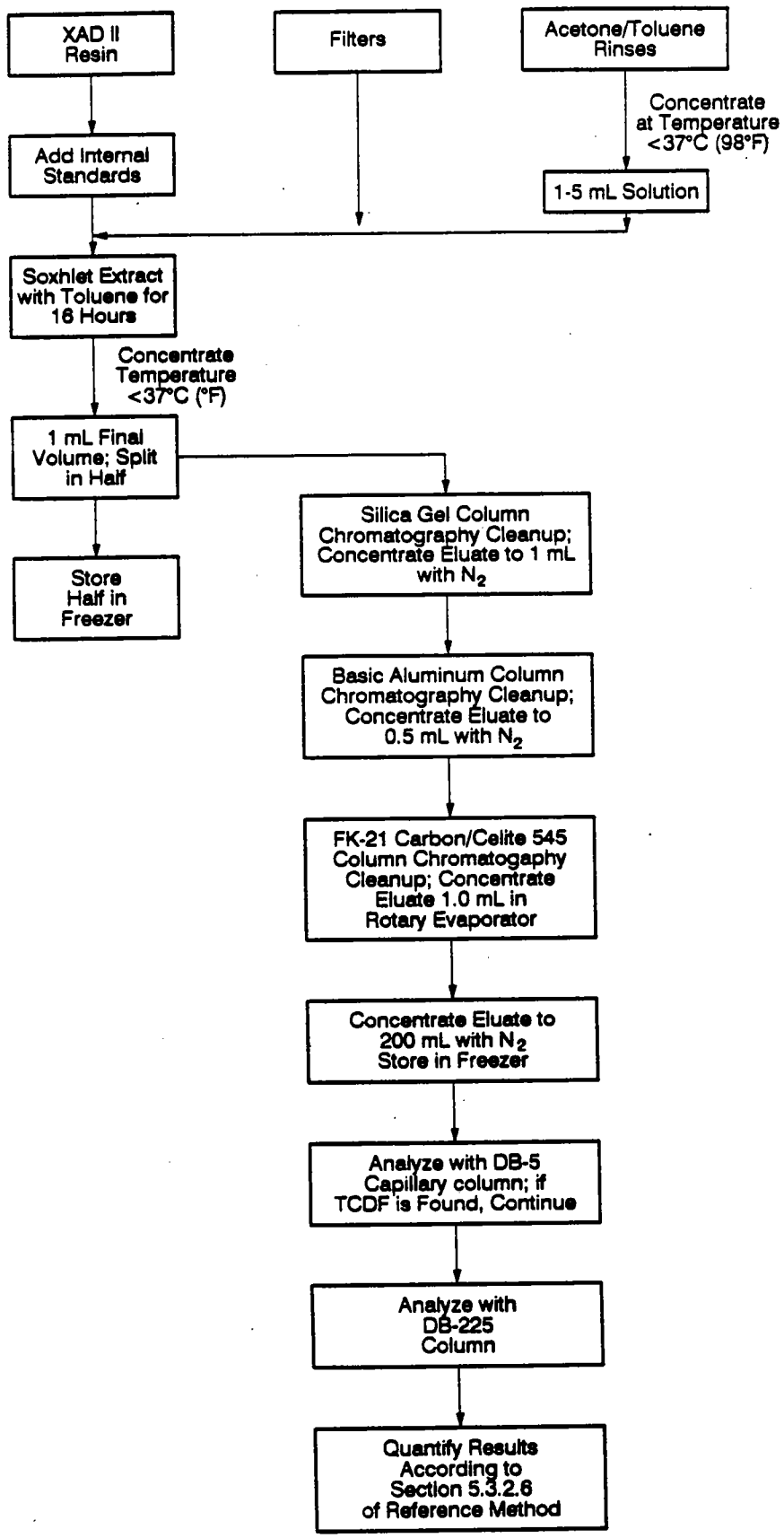

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Figure 5-4. Extraction and Analysis Schematic for CDD/CDF Samples

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interest. The response factors were verified on a daily basis using a continuing calibration standard consisting of a mid-level mixed isomer standard. The instrument performance is acceptable only if the measured response factors for the labeled and unlabeled compounds and the ion-abundance ratios are within the allowable limits specified in the method (52200, 52201 FR 891220).

5.1.6 CDD/CDF Analytical Quality Control

All quality control procedures specified in the test method were followed. Blanks were used to determine analytical contamination; calibration standards were used for instrument calibration and linearity checks; internal standards were used to determine isomer recoveries and adjust response factors for matrix effects; surrogate standards were used to measure the collection efficiency of the sampling methodology; and an alternate standard was used as a column efficiency check.

5.1.6.1 CDD/CDF Quality Control Blanks. Three different types of sample blanks were analyzed for CDD/CDF concentrations. The type of blanks that were required are shown in Table 5-7.

Reagent blanks of 1,000 ml of each reagent used at the test site were saved for analysis. Each reagent blank was of the same lot used during the sampling program. Each lot number and reagent grade was recorded on the field blank label and in the laboratory notebook.

A field blank was collected from a set of CDD/CDF glassware that had been used to collect at least one sample and had been recovered. The train was re-loaded and left at a sampling location during a test run. The train was then recovered. The purpose of the field blank is to measure the level of contamination that occurs from handling, loading, recovering, and transporting the sampling train. The field blanks were analyzed with the flue gas samples. If they were unsatisfactory in terms of contamination, reagent blanks were analyzed to determine the specific source of contamination.

In addition to the two types of blanks that are required for the sampling program, the analytical laboratory analyzed a method blank with each set of flue gas samples. This consists of preparing and analyzing reagent water by the exact procedure used for

TABLE 5-7. CDD/CDF BLANKS COLLECTED

Blank	Collection	Analysis
Field Blanks	One run collected and analyzed for each sampling location.	Analyze with flue gas samples.
Method Blank	At least one for each analytical batch	Analyze with each analytical batch of flue gas samples
Reagent Blanks	One 1000 ml sample for each reagent and lot.	Archive for potential analysis.

the samples analysis. The purpose of this procedure was to verify that there is no laboratory contamination of the field samples.

5.1.6.2 Quality Control Standards and Duplicates. Recoveries of the internal standards must be between 40 to 130 percent for the tetra- through hexachlorinated compounds and 25 to 130 percent for the hepta- and octachlorinated homologues. Surrogate standard recoveries must be between 70 to 130 percent. If these requirements are not met, the data will be acceptable if the signal to noise ratio is greater than or equal to ten. If these requirements are met, the results for the native sampled species are adjusted according to the internal standard recoveries.

If the recoveries of all standards are less than 70 percent, the project director is notified immediately to determine if the surrogate results can be used to adjust the results of the native species.

Duplicate analysis was performed for every ten samples. The purpose of duplicate analysis was to evaluate the precision of the combined sample preparation and analytical methodology.

5.2 PARTICULATE MATTER AND METALS EMISSIONS TESTING METHOD

Sampling for PM and metals was performed according to an EPA Emission Measurement Branch (EMB) draft protocol entitled "Methodology for the Determination of Metals Emissions in Exhaust Gases from Incineration Processes." The protocol is presented in Appendix I. This method is applicable for the determination of PM and Pb, Ni, zinc (Zn), phosphorus (P), Cr, Cu, manganese (Mn), selenium (Se), Be, Tl, Ag, Sb, Ba, Cd, As, and Hg emissions from various types of incinerators. Analyses of the Borgess Medical Center MWI test samples was performed for Al, As, Cd, Cr, Cu, Hg, Ni, Pb, Sb, Ag, Ba, Be, and Tl.

The PM emissions were also determined from this sampling train. Particulate concentrations were based on the weight gain of the filter and the front half acetone rinses (probe, nozzle, and filter holder). After the gravimetric analyses were completed, the sample fractions were analyzed for the target metals as discussed in Section 5.2.5.

5.2.1 PM/Metals Sampling Equipment

The methodology uses the sampling train shown in Figure 5-5. The 5-impinger train consists of a quartz nozzle/probe liner followed by a heated filter assembly with a Teflon® filter support, a series of impingers, and the standard EPA Method 5 meterbox and vacuum pump. The sample is not exposed to any metal surfaces in this train. The contents of the sequential impingers are: two impingers with a 5 percent HNO_3/10 percent H_2O_2 solution, two impingers with a 4 percent $KMnO_4$/10 percent sulfuric acid (H_2SO_4) solution, and an impinger containing silica gel. (An optional empty knockout impinger may be added if the moisture content of the flue gas is high.) The second impinger containing HNO_3/H_2O_2 was of the Greenburg-Smith design; the other impingers had straight tubes. The impingers were connected with clean glass U-tube connectors and arranged in an impinger bucket as shown in Figure 5-6. Sampling train components were recovered and analyzed in separate front and back half fractions according to the described method.

5.2.2 PM/Metals Sampling Equipment Preparation

5.2.2.1 Glassware Preparation. Glassware was washed in hot soapy water, rinsed three times (3X) with tap water, and then rinsed with deionized distilled water (3X). The glassware was then subjected to the following series of soaks and rinses:

- Soaked in a 10 percent HNO_3 solution for a minimum of 4 hours;
- Rinsed with deionized distilled water (3X); and
- Rinsed with acetone.

The cleaned glassware was allowed to air dry in a contamination-free environment. The ends were then covered with parafilm. All glass components of the sampling train plus any sample bottles, pipets, Erlenmeyer flasks, petri dishes, graduated cylinders, and other laboratory glassware used during sample preparation, recovery, and analysis were cleaned using this procedure.

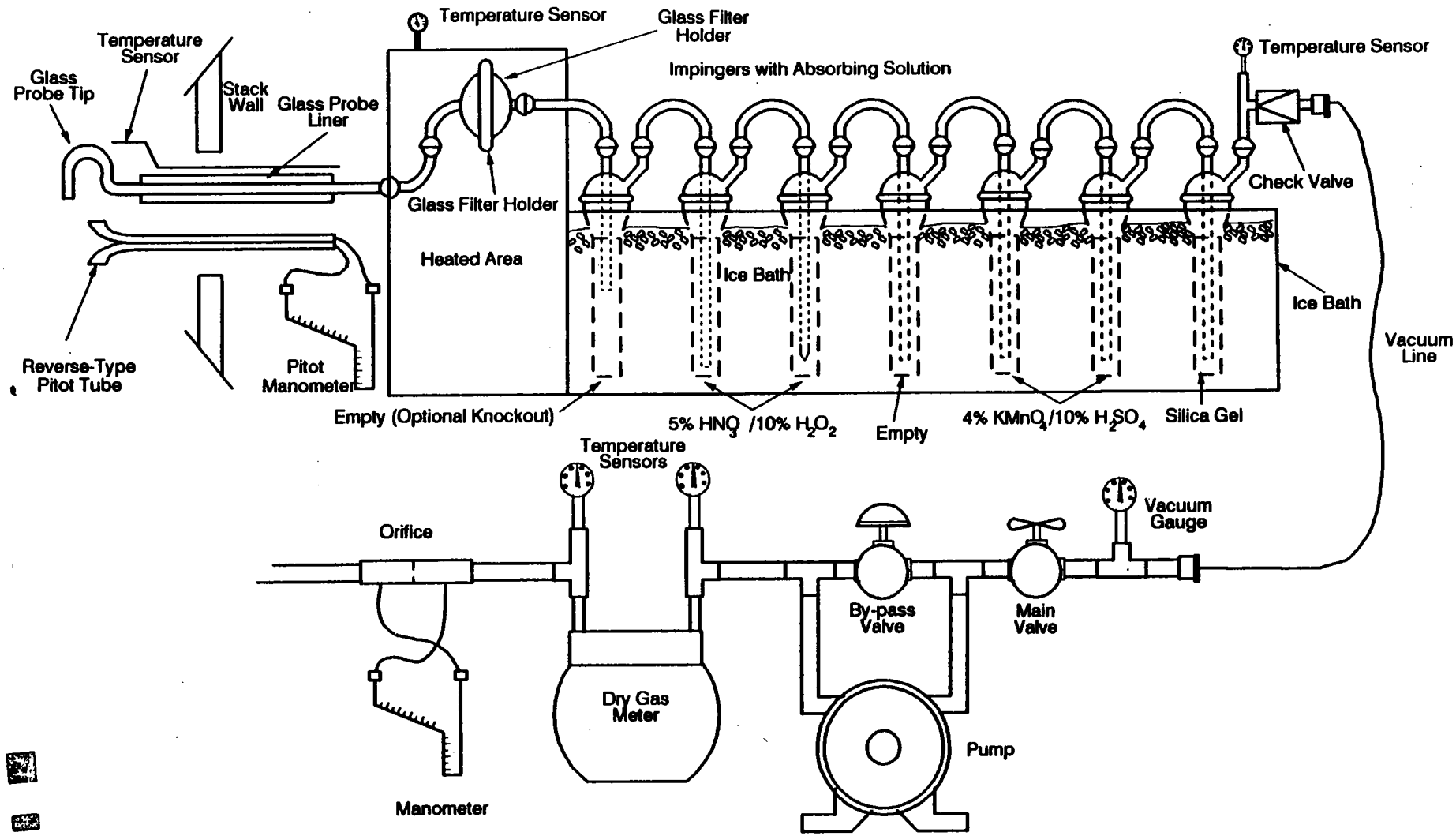

Figure 5-5. Schematic of Multiple Metals Sampling Train

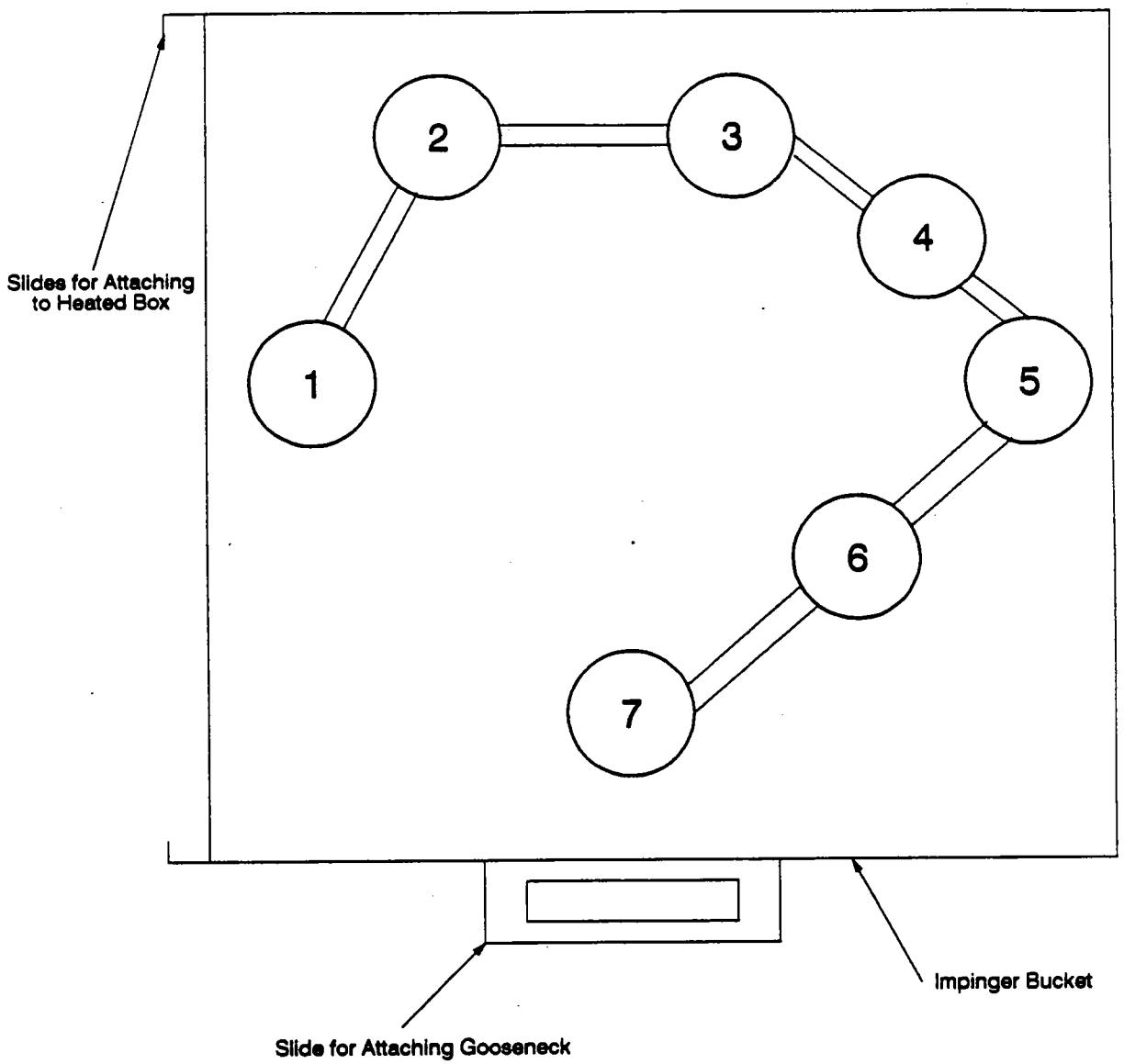

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Figure 5-6. Impinger Configuration for PM/Metals Sampling
(optional knock out impinger not shown)

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5.2.2.2 Reagent Preparation. The sample train filters were Pallflex Tissuequartz 2500QAS filters. The acids and H_2O_2 were Baker "Instra-analyzed" grade or equivalent. The H_2O_2 was purchased specifically for this test site and was kept cold until it was opened.

The reagent water was Baker "Analyzed HPLC" grade or equivalent. The lot number, manufacturer, and grade of each reagent used was recorded in the laboratory notebook.

Fresh HNO_3/H_2O_2 absorbing solution and acidic $KMnO_4$ absorbing solution were prepared daily according to Sections 4.2.1 and 4.2.2 of the reference method. The analyst wore safety glasses and protective gloves when the reagents were mixed and handled. Each reagent had its own designated transfer and dilution glassware. This glassware was marked for identification with a felt tip glass marking pen and used only for the designated reagent.

The analyst saved time preparing the acidic $KMnO_4$ solution each day by observing the following procedure, beginning at least one day before the reagent was needed.

- Quantitatively measured 400 ml from a 4 liter bottle of Baker "Analyzed HPLC" water into a clean glass bottle. Labeled this bottle 4.4 percent $KMnO_4$ in water.

- Quantitatively added 160 g of $KMnO_4$ crystals to the bottle; stirred with a Teflon® stirring bar and stirring plate as thoroughly as possible. This reagent was stored on the counter in a plastic tub at all times.

- Each morning the acidic reagent was needed, decanted 900 ml of $KMnO_4$ solution into a 1000 ml volumetric flask. Carefully added 100 ml of concentrated H_2SO_4 and mixed. This reagent was volatile and was mixed cautiously. By holding the flask cap on the flask, it was mixed once and vented quickly. Completed the mixing slowly until the mixture was homogenous. Allowed the solution to cool and brought the final volume to 1000 ml with H_2O.

- Carefully filtered this reagent through Wattman 541 filter paper into another volumetric flask or 2 liter amber bottle. Labeled this bottle 4 percent acidic $KMnO_4$ absorbing solution. Vented the top and stored the reagent in a plastic tub at all times.

5.2.2.3 Equipment Preparation. The remaining preparation included calibration and leak checking of all train equipment as specified in EPA Method 5. This equipment included the probe nozzles, pitot tubes, metering system, probe heater, temperature gauges, leak check metering system, and barometer. A laboratory field notebook was maintained to record these calibration values.

5.2.3 PM/Metals Sampling Operations

The sampling operations used for PM/Metals testing were virtually the same as those for the CDD/CDF tests discussed in Section 5.1.2. The only differences were that there was no condenser coil (so coil temperatures were not recorded) and glass caps, Teflon® tape, or parafilm was used to seal the sample train components instead of foil. Detailed instructions for assembling the metals sampling train can be found beginning on page 14 of the reference method.

5.2.4 PM/Metals Sample Recovery

Recovery procedures began as soon as the probe was removed from the stack and the post-test leak check was completed.

To facilitate transfer from the sampling location to the recovery trailer, the sampling train was disassembled into three sections: the nozzle/probe liner, filter holder, and impingers in their bucket. Each of these sections was capped with Teflon® tape or parafilm before removal to the recovery trailer.

Once in the trailers, the sampling train was recovered as separate front and back half fractions. A diagram illustrating front half and back half sample recovery procedures is shown in Figure 5-7. No equipment with exposed metal surfaces was used in the sample recovery procedures. The weight gain in each of the impingers was recorded to determine the moisture content in the flue gas. Following weighing of the impingers, the front half of the train, which includes the filter and all sample-exposed surfaces upstream of the filter was recovered. The probe liner was rinsed with acetone by tilting and rotating the probe while squirting acetone into the higher end to wet all inside surfaces. The acetone was quantitatively collected into the appropriate bottle. This rinse was followed by additional brush/rinse procedures using a non-metallic brush; the probe was held in an inclined position and acetone was squirted into the higher end as the brush was pushed through with a twisting action. All of the acetone and PM were

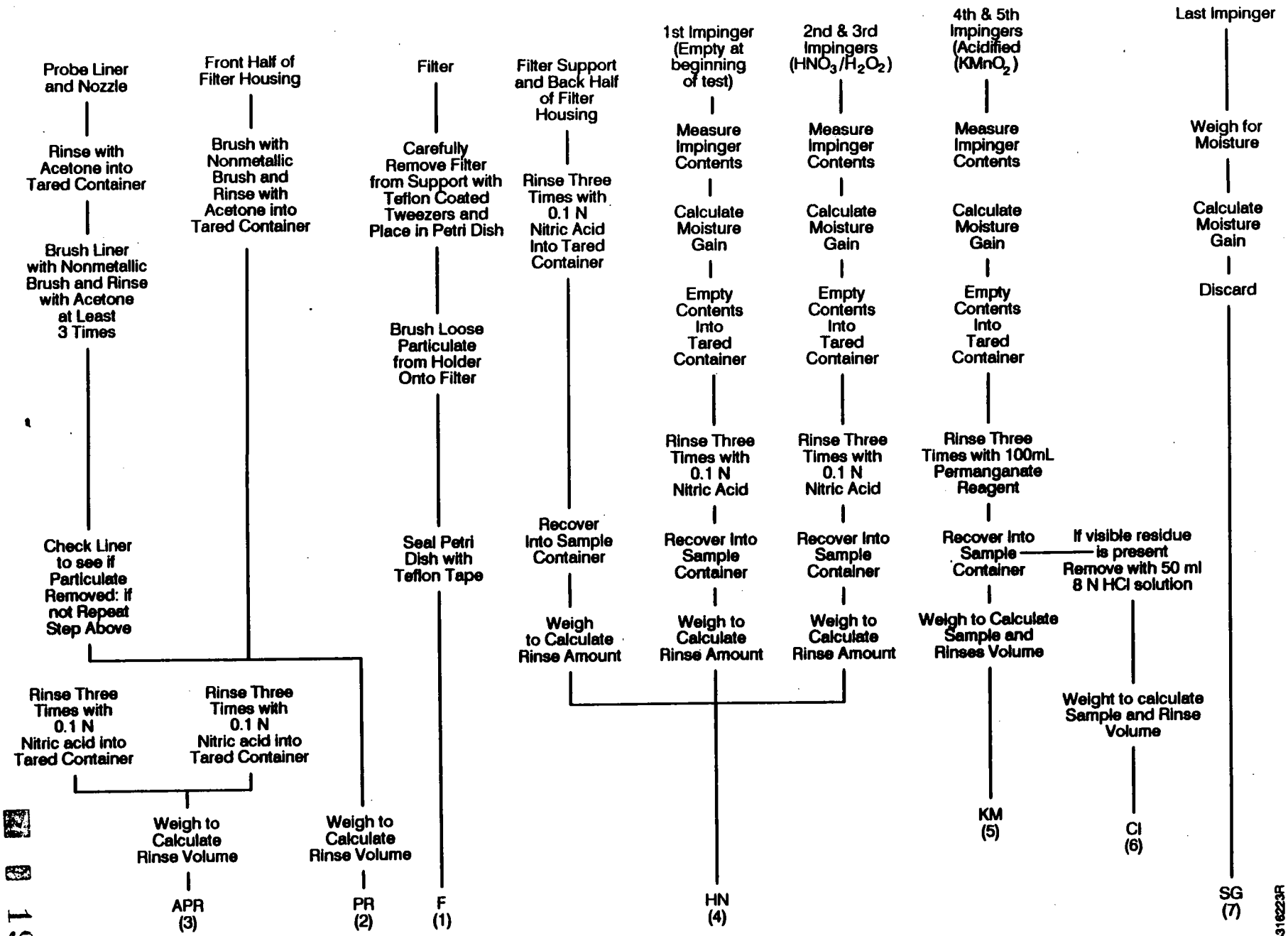

Figure 5-7. Metals Sample Recovery Scheme

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caught in the sample container. This procedure was repeated until no visible particulate remained and was finished with a final acetone rinse of the probe and brush. The front-half of the filter was also rinsed with acetone until all visible particulate was removed. After all front-half acetone washes were collected, the cap was tightened, the liquid level marked, and the bottle weighed to determine the acetone rinse volume. The method specifies a total of 100 ml of acetone may be used for rinsing these components. However, Radian feels that a thorough rinse requires more reagent. An acetone reagent blank of approximately the same volume as the acetone rinses was collected with the samples.

The nozzle/probe liner and front half of the filter holder were rinsed three times with 0.1N HNO_3, and the rinse was collected in a separate amber bottle. The bottle was capped tightly, the weight of the combined rinse was recorded, and the liquid level was marked. The filter was placed in a clean, well-marked glass petri dish and sealed with Teflon® tape.

Prior to recovering the back half impingers, the contents were weighed for moisture control determinations. Any unusual appearance of the filter or impinger contents were noted.

The contents of the knockout impinger (if used) were recovered into a preweighed, prelabeled bottle with the contents from the HNO_3/H_2O_2 impingers. These impingers and connecting glassware were rinsed thoroughly with 0.1N HNO_3, the rinse was captured in the impinger contents bottle, and a final weight was taken. The method specified a total of 100 ml of 0.1N HNO_3 may be used to rinse these components. A HNO_3 reagent blank of approximately the same volume as the rinse volume was collected with the samples.

The impingers that contain the acidified $KMnO_4$ solution were poured together into a preweighed, prelabeled bottle. The impingers and connecting glassware were rinsed with at least 100 ml of the acidified $KMnO_4$ solution (from the same batch used for sampling) a minimum of three times. Rinses were added to the sample recovery bottle. A final 50 ml 8N hydrochloric acid (HCl) rinse was conducted and placed into the sample recovery bottle. A final weight was recorded, and the liquid level was marked on the bottle. The bottle cap was applied loosely to allow venting.

After final weighing, the silica gel from the train was saved in a bag for regeneration. The ground glass fittings on the silica gel impinger were cleaned after sample recovery to ensure a leak-tight fit for the next test.

A reagent blank was recovered in the field for each of the following reagents:

- Acetone blank - 100 ml sample size;
- 0.1N HNO_3 blank - 1,000 ml sample size;
- 5 percent HNO_3/10 percent H_2O_2 blank - 200 ml sample size;
- Acidified $KMnO_4$ blank - 1,000 ml sample size; this blank required a vented cap;
- 8N HCl blank - 50 ml sample size;
- Dilution water; and
- Filter blank - one each.

Each reagent blank was of the same lot used during the sampling program. Each lot number and reagent grade was recorded on the field blank label and recovery logbook.

The liquid level of each sample container was marked on the bottle to determine if any sample loss occurred during shipment. If sample loss had occurred, the sample would be voided or a method would be used to incorporate a correction factor to scale the final results according to the volume of the loss.

5.2.5 Particulate Analysis

The same general gravimetric procedure described in Method 5 (Section 4.3) was followed. Filters and precleaned beakers were weighed to a constant weight before use in the field. The same balance used for taring was used for weighing the samples.

The acetone rinses were evaporated under a clear hood at 20°C (68°F) in a tared beaker. The filter was also desiccated under the same conditions to a constant weight. Weight gain was reported to the nearest 0.1 mg. Each replicate weighing agreed to within 0.5 mg or 1 percent of total weight minus the tare weight, whichever is greater, between two consecutive weighings at least 6 hours apart.

5.2.6 Metals Analytical Procedures

A diagram illustrating the sample preparation and analytical procedure for the target metals is shown in Figure 5-8.

The front half fractions were digested with concentrated HNO_3 and hydrofluoric (HF) acid in a microwave pressure vessel. The microwave digestion took place over a period of approximately 10 to 12 minutes in intervals of 1 to 2 minutes at 600 watts. Both the digested filter and the digested probe rinses were combined to yield the front half sample fraction. The fraction was diluted with water to a specified volume and divided for analysis.

The absorbing solutions from the HNO_3/H_2O_2 impingers were combined. An aliquot was removed for the analysis of Hg by CVAAS, and the remainder was acidified and reduced to near dryness. The sample was then digested in a microwave with 50 percent HNO_3 and 3 percent H_2O_2. After the fraction had cooled, it was filtered and diluted with water to a specified volume.

Each sample fraction was analyzed by ICAPS using EPA Method 200.7. All target metals except Hg, Fe, and Al, were quantified. If Fe and Al were present, the samples were diluted to reduce interference with As and Pb analysis. If As or Pb levels were less than 2 ppm, GFAAS was used to analyze for these elements by EPA Methods 7060 and 7421. The total volume of the absorbing solutions and rinses for the various fractions were measured and recorded in the field notebook.

To prepare for Hg analysis by CVAAS, an aliquot from the $KMnO_4$ impingers, HNO_3/H_2O_2 impingers, filter digestion, and front half rinses were digested with acidic reagents at 95°C in capped BOD bottles for approximately 3 hours. Hydroxylamine hydrochloride solution and stannous chloride were added immediately before analysis. Cold vapor AAS analysis for Hg followed the procedure outlined in EPA Method 7470 or in Standard Methods for Water and Wastewater Analysis, Method 303F.

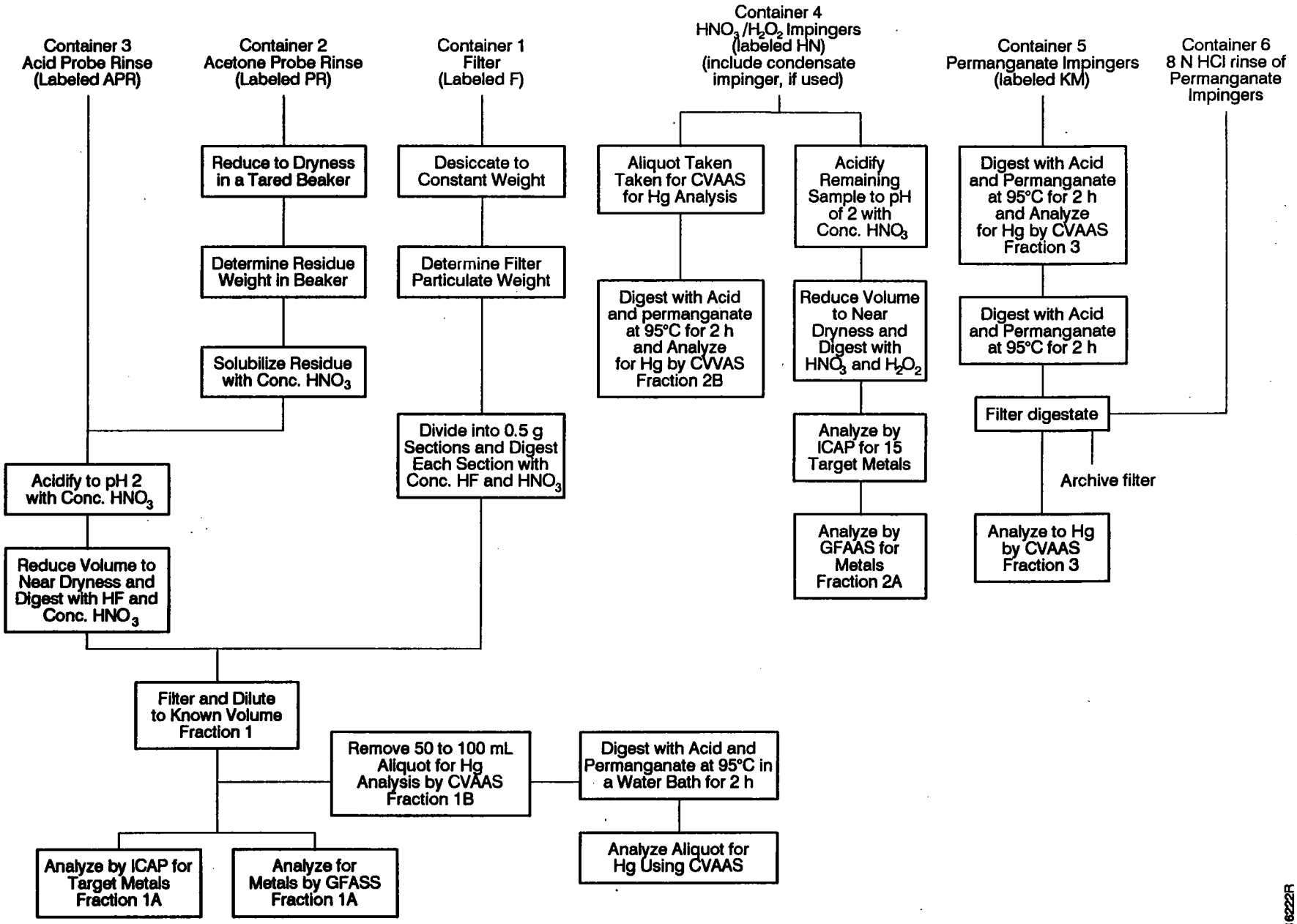

Figure 5-8. Metals Sample Preparation and Analysis Scheme

5.2.7 Quality Control for Metals Analytical Procedures

All quality control procedures specified in the test method were followed. All field reagent blanks were processed, digested, and analyzed as specified in the test method. To ensure optimum sensitivity in measurements, the concentrations of target metals in the solutions were at least 10 times the analytical detection limits.

5.2.7.1 ICAP Standards and Quality Control Samples. The quality control procedures included running two standards for instrument checks (or frequency of 10 percent), two calibration blank runs (or frequency of 10 percent), one interference check sample at the beginning of the analysis (must be within 10 percent or analyze by standard addition), one quality control sample to check the accuracy of the calibration standards (must be within 10 percent of calibration), one duplicate analysis and one standard addition for every 10 samples (must be within 5 percent of average or repeat all analysis).

Standards less than 1 μg/ml for an individual metal were prepared daily; those with concentrations greater than this were made weekly or bi-monthly.

5.2.7.2 Graphite Furnace Standards and Quality Control Samples. Standards used for GFAAS analysis were matrix matched with the samples analyzed and the matrix modifiers that were added. Standards less than 1 μg/ml for an individual metal were prepared daily; those with concentrations greater than this were made weekly or bi-monthly. A minimum of five standards are required to make the standard calibration curve. Quality control samples were prepared from a separate 10 μg/ml standard by diluting it into the range of the samples.

All samples were analyzed in duplicate. A matrix spike on one front half sample and one back half sample for each 10 field samples was analyzed. If recoveries of less than 75 percent or greater than 120 percent were obtained for the matrix spike, each sample was analyzed by the method of additions. One quality control sample was analyzed to check the accuracy of the calibration standards. The results were within 10 percent, or the calibration was repeated.

5.2.7.3 Mercury Standards and Quality Control. An intermediate Hg standard was prepared weekly; working standards were prepared daily. The calibration curve was

made with at least six points. Quality Control samples were prepared from a separate 10 μg/ml standard by diluting it into the range of the samples.

A quality control sample agreed within 10 percent of the calibration, or the calibration was repeated. A matrix spike on one of every 10 samples from the HNO_3/H_2O_2 back half sample fraction was within 20 percent, or the samples were analyzed by the method of standard addition.

5.3 MERCURY EMISSIONS BY METHOD 101A

Mercury emissions testing by Method 101A was performed as specified in 40 CFR Part 61, Appendix B. The method calls for isokinetic extraction of flue gas through a sample train similar to the standard EPA Method 5 train. The sample stream passes through the filter (optional) and bubbles through acidified $KMnO_4$ solution. Not counting blanks, there were two fractions of the sample train, the probe rinse/impinger catch and the filter. Following sample recovery, the $KMnO_4$ and filter solutions were shipped back to the laboratory for analysis. The analytical preparation procedures consisted of filtering the $KMnO_4$ solutions, and analyzing the filtrate by CVAAS. Studies recently conducted by EPA show that after a certain sample hold time, the analytical filtering procedures may remove a certain portion of the collected Hg contained in the MnO_2 precipitate. This may be the case only when visible precipitate is present. For this test program, the analytical filter was archived and analyzed at a later date. A graphical representation was provided for each analysis.

The following sections briefly describe Method 101A testing procedures.

5.3.1 Method 101A Sampling Equipment

The Method 101A sampling train, including the use of the optional heated filter, is shown in Figure 5-9. The front half of this train is similar to an EPA Method 5 train incorporating all isokinetic sampling apparatus. A glass nozzle/probe liner was used to prevent the sample stream from touching any metal surfaces. Four impingers were used with the first 3 containing 50 ml, 100 ml, and 100 ml, respectively, of acidified 4 percent $KMnO_4$. The last impinger was filled with silica gel to remove water prior to the sampling train meter and pump. All reagent preparation followed strict QA/QC guidelines as dictated by the Method 101A protocol.

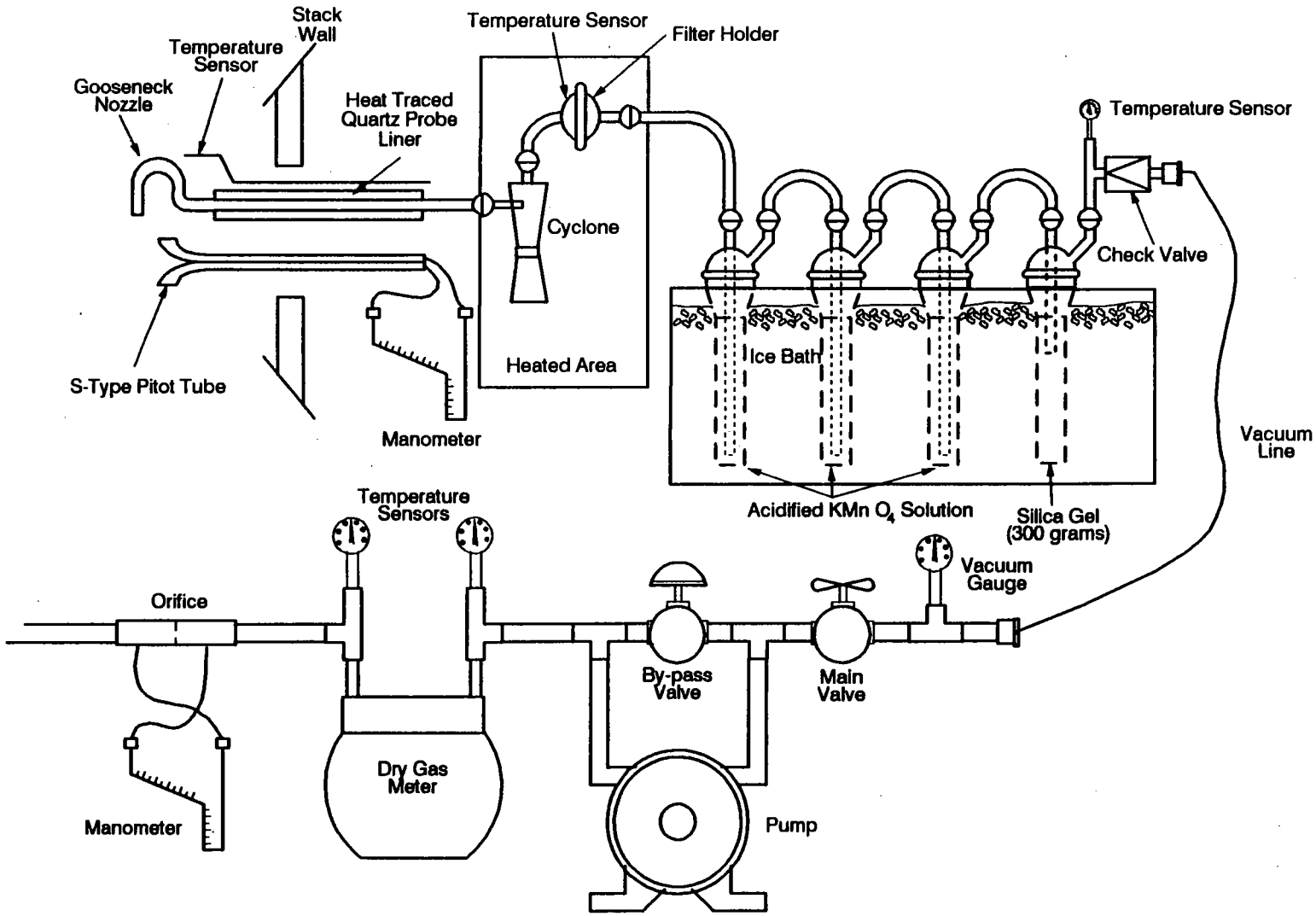

Figure 5-9. EPA Method 101A Sampling Train

5.3.2 Equipment Preparation

All sampling equipment was calibrated accordancing to EPA Method 5 guidelines. This included dry gas meters, pitot tubes, nozzle orifice, and other equipment.

All glassware was cleaned as follows:

- Soaked in 10% HNO_3 acid bath;
- Rinsed 3 times with 50% HNO_3;
- Rinsed 3 times with tap water;
- Rinsed 3 times with 8N HCl;
- Rinsed 3 times with tap water; and
- Rinsed 3 times with deionized/distilled (or equivalent) water.

Glassware was then sealed with Parafilm™, wrapped in bubble wrap, packed, and shipped to the testing facility.

All nozzles and probe liners were cleaned on site by following the above rinsing procedures. Nozzles were then calibrated on site.

5.3.3 Reagent Preparation

The following reagents were used during sampling operations:

- 8N HCl = 67 ml concentrated HCl/100 ml deionized (DI) H_2O;
- 4 percent $KMnO_4$ = see Section 5.2.2.2; and
- 50 percent HNO_3 = (Equal parts acid to DI H_2O must be added very slowly using extreme caution.)

Blank samples of all reagents used were taken to determine if Hg contamination was present.

5.3.4 Sample Operation

The Method 101A sample train was operated similar to an EPA Method 5 train. Care was taken to determine the proper isokinetic sample rate. Sampling rates never exceeded 1.0 cfm. Temperatures of the stack gas, oven (filter skin), silica gel impinger, and inlet and outlet to the gas meter were monitored. Additional recordings of dry gas meter readings, velocity head (ΔH), orifice pressure (Δp), and sample vacuum were taken. The above data were collected at each sample point every 5 minutes. The test

duration was divided by the number of sample points to determine the interval of time spent at each sample point.

Leak checks of the sampling train were performed prior to the test, following train removal from a port (port change), and following completion of the test. The maximum acceptable leak rate was 0.02 cfm or 4 percent of the average sample rate, whichever was less.

5.3.5 Sample Recovery

The Method 101A flue gas samples were recovered as shown in Figure 5-10. The first step, after completion of the post-test leak check, was to dismantle and seal the train into the following components:

- Probe nozzle and liner,
- Filter holder, and
- Impinger train.

These components were transported back to the laboratory trailer for recovery operations. The impingers were weighed to determine flue gas moisture levels. Two sample bottles were collected from each flue gas sample.

The contents of the $KMnO_4$ impingers were poured into a 950-ml sample bottle. The nozzle and probe were then brushed/rinsed three times with fresh 4 percent $KMnO_4$ and deionized water and added to the 950-ml bottle. The front half filter holder was also rinsed into the same sample bottle. If any visible deposits were left on these pieces of glassware, a small amount (approximately 50 ml) of 8N HCl was used to rinse them, and the rinse was added to a separate sample bottle.

A second sample bottle (third if an HCl rinse was performed) was collected. The filter was carefully placed in a 150 ml sample jar, and 20 to 40 ml of fresh 4 percent $KMnO_4$ was added. Any residual filter pieces left on the filter holder were carefully removed using a sharpened edge blade and/or nylon bristle brush so as not to lose any material and added to this container. A filter and reagent blank were also collected.

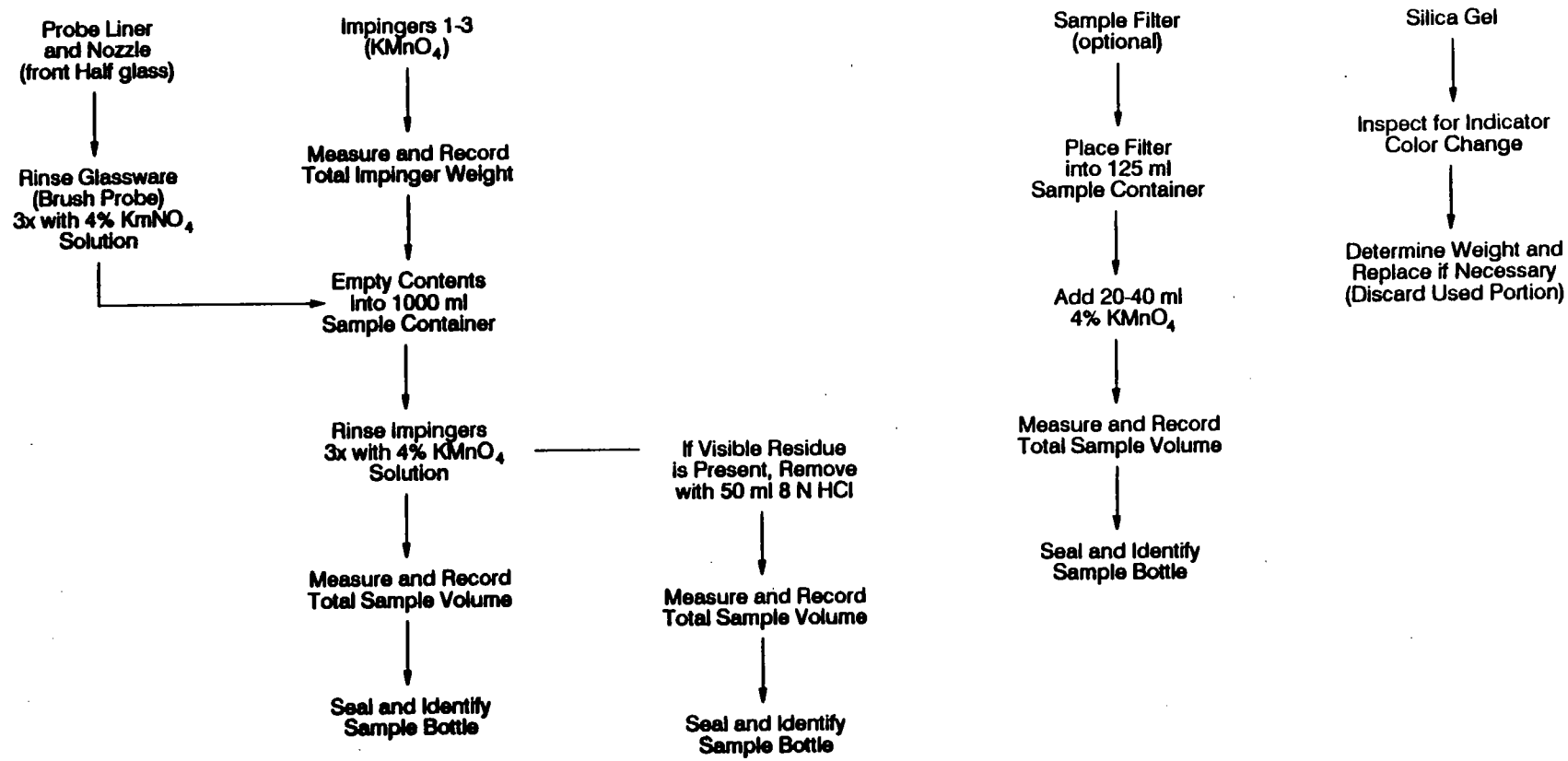

Figure 5-10. Method 101A Sample Recovery Scheme

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Following recovery operations, the samples were fully labeled and logged in the sample log book, and chain of custody forms were filled out.

5.3.6 Analytical Preparation

A simplified diagram of the sample preparation and analysis scheme for the 101A Hg analysis is shown in Figure 5-11. After the samples were recovered by the laboratory, the chain of custody forms were signed and fluid levels checked to determine if any sample loss occurred during transport. As stated in the previous section, there were two sample containers: one for the front half rinse/impinger contents, and one for the filter/$KMnO_4$ digestion. However, all sample fractions were combined and analyzed together.

Prior to analysis, the front half rinse/impinger sample was filtered. The filter was washed, and the rinsings were combined with the filtrate for analysis. At this point the filter is normally discarded. However, recent concern has arisen regarding this procedure. It seems that if visible precipitate in the $KMnO_4$ is present, a portion of the sampled Hg contained in the precipitate may be lost if the filter is discarded. For this test program, all analytical filters were archived pending a decision on analytical procedure. If sample hold time is kept to a minimum (i.e., < 7 days), the precipitate has typically not formed and this matter is not as critical. If, however, precipitate has formed and is visible on the filter, a digestion of the filter in 8N HCl may be warranted. If this procedure is completed, the digestion solution is again filtered with the filtrate added to the original $KMnO_4$ filtrate.

The sample from the sample filter/$KMnO_4$ was transferred to a beaker and placed in a steam bath and evaporated until most of the liquid has disappeared (not dryness). Twenty ml of concentrated HNO_3 was then added to the sample; it was placed on a hot plate (with watch glass cover) and heated for 2 hours at 70°C. This solution was allowed to cool and was then filtered. The filtrate was combined with the front half rinse/impinger sample filtrate prior to analysis.

5.3.7 Analysis

The final combined $KMnO_4$ sample was increased to a fixed volume using DI water. A 5 ml aliquot was removed and placed in 25 ml of DI water in an aeration bottle. Then 5 ml of 15 percent HNO_3 was added, followed by 5 ml of 5 percent

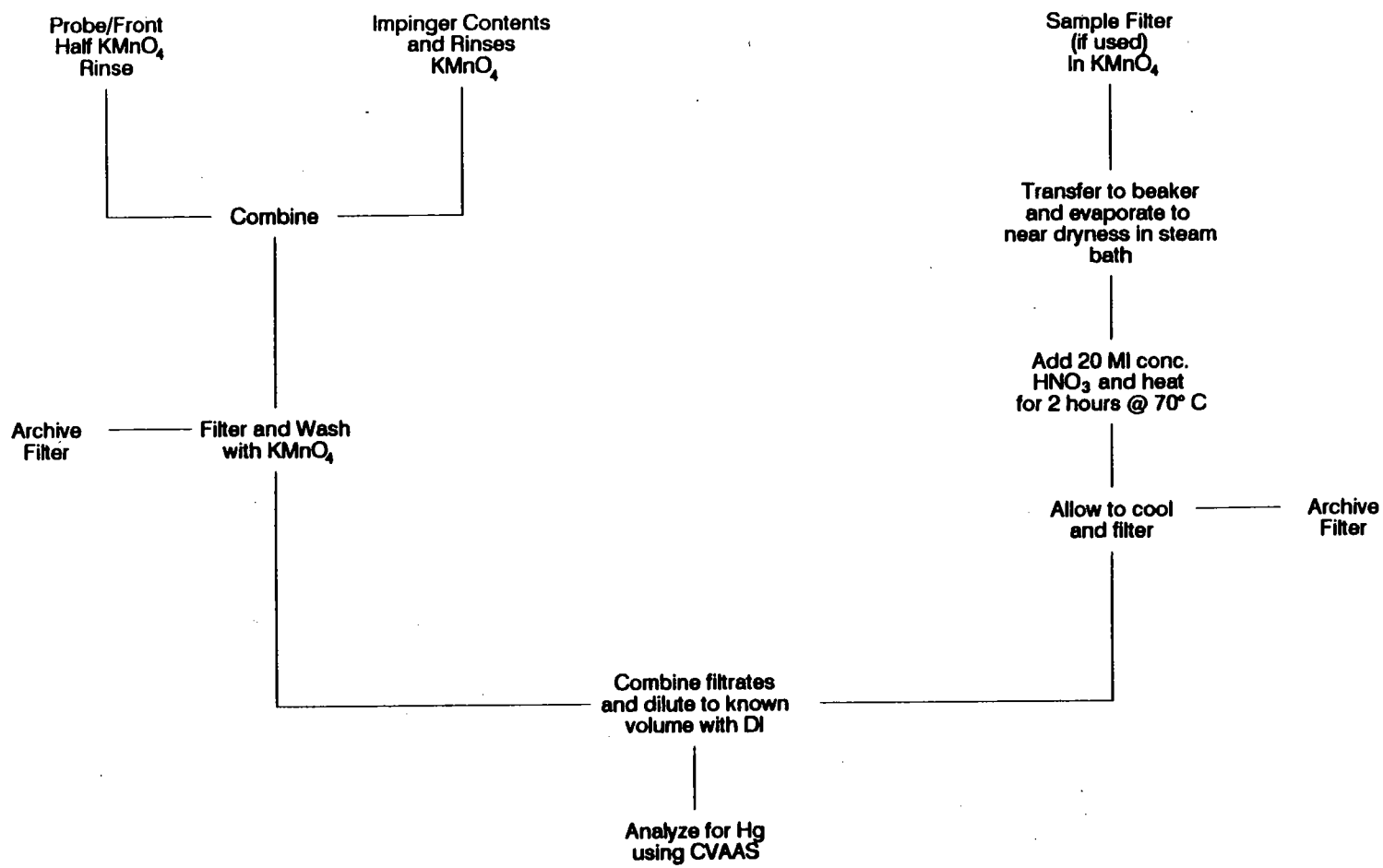

Figure 5-11. Method 101 A
Sampling Preparation and Analysis Scheme

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$KMnO_4$. The solution was mixed thoroughly with the exit arm stopcock closed. The reducing agents, sodium chloride, hydroxylamine and tin (II), were then added as specified in the method, and aeration was initiated. Absorbance was then read at 253.7 nm.

5.4 HYDROGEN CHLORIDE/HYDROGEN BROMIDE/HYDROGEN FLUORIDE EMISSIONS TESTING BY EPA METHOD 26

Hydrogen chloride, HBr, and HF sampling was accomplished using a single sampling train. The procedure follows the EPA Method 26 draft protocol entitled "The Determination of HCl Emissions from Municipal and Hazardous Waste Incinerators." In this method, an integrated gas sample was extracted from the stack and passed through acidified water. In acidified water, HCl becomes soluble and forms Cl^- ions. Ion chromatography was used to detect the Cl^- ions present in the sample. For this test program, the presence of Br^- and F^- ions were also be detected by IC. The method is included in Appendix K.

5.4.1 HCl/HBr/HF Sampling Equipment

A diagram of the HCl/HBr/HF sampling train is shown in Figure 5-12. The sampling train consisted of a quartz probe with a pallflex Teflon/glass filter to remove PM, a series of chilled midget impingers, and a DGM system. A small amount of quartz glass wool was placed in the front half of the filter holder to help remove excessive PM in this gas stream. Because the high temperatures in the stack and the short sampling probe kept the sample gas in the probe above the acid dewpoint, the probe was not heated. The train consisted of an optional knockout impinger followed by two impingers containing 0.1 N H_2SO_4 to collect HCl, HBr, and HF; two impingers containing 0.1 N NaOH to capture any pollutants present in the flue gas that might cause DGM damage; and one impinger containing silica gel.

5.4.2 HCl/HBr/HF Sampling Preparation

5.4.2.1 Equipment Preparation. Sampling preparation included calibration and leak checking of all train equipment including meterboxes, thermocouples, and umbilicals. Referenced calibration procedures were followed when available, and the results properly documented and retained. If a referenced calibration technique for a

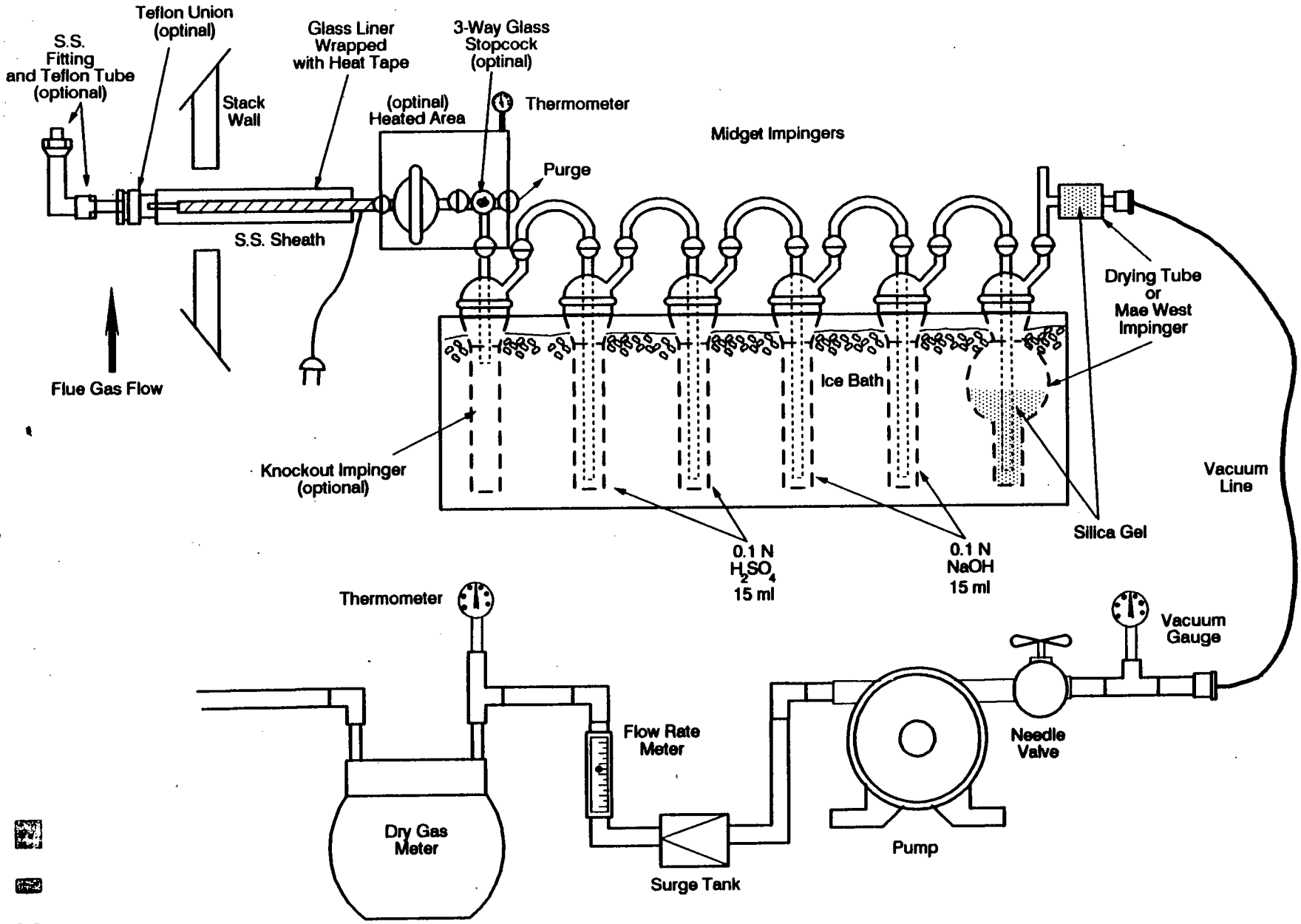


Figure 5-12. HCl Sample Train Configuration

particular piece of apparatus was not available, then a state-of-the-art technique was used.

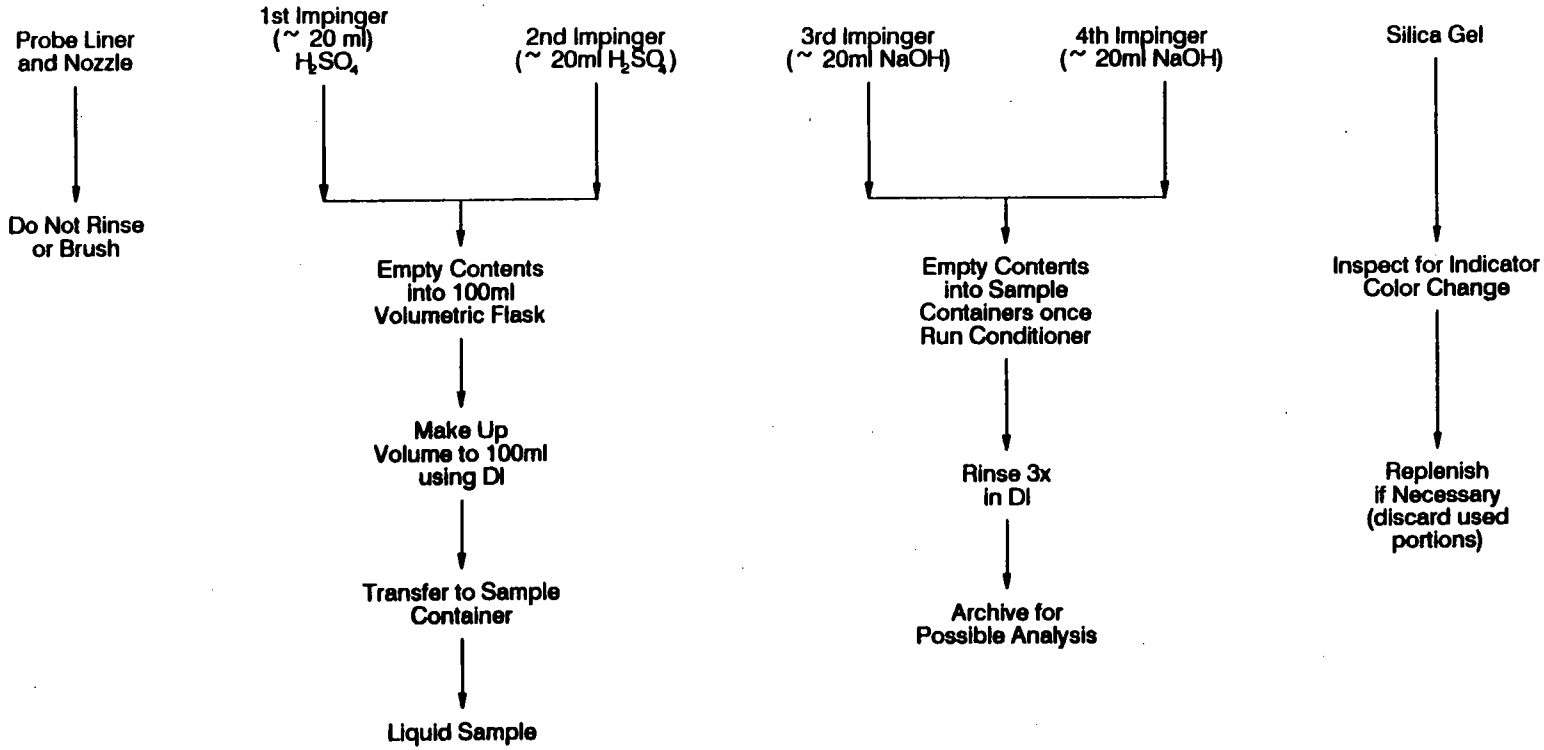
5.4.2.2 Assembling the Train. Assembly of the sampling train was done both in the recovery trailer and at the stack location. First, the empty, clean impingers were assembled and laid out in the proper order. The optional knockout impinger was not used for testing at this facility. The first two impingers each contained 15 to 20 ml 0.1 N H_2SO_4. The following two impingers were filled with 15 to 20 ml each of 0.1 N NaOH, and the final impinger contained 20 to 30 grams of silica gel. When the impingers were loaded, they were wrapped with Teflon® tape to secure the two sections of the impinger. The impingers were connected using U-tube connectors and arranged in the impinger bucket. All the impingers were approximately the same height to easily obtain a leak-free seal. The open ends of the train were sealed with aluminum foil.

5.4.3 HCl/HBr/HF Sampling Operations

Prior to sampling, the HCl/HBr/HF train was leak checked as required by Method 26 protocol. The leak checking procedure was the same as that discussed in Section 5.1. The leak rate, sampling start and stop times, and any other significant events that occurred during sampling were recorded on the sampling log. Upon completion of a sampling run, the leak-check procedure was repeated. Sampling train data were recorded every five minutes, and included readings of the DGM, DGM temperature, flow rate meter, and vacuum gauge.

5.4.4 HCl/HBr/HF Sample Recovery

The impingers were disconnected from the probe and filter and moved to the recovery trailer. Once in the trailer, the contents of the two acidified impingers were quantitatively recovered with deionized distilled water and placed into a clean sample bottle. The sample bottle was sealed, mixed and labeled, and the fluid level marked. The contents of the second set of impingers (containing the 0.1 N NaOH) were discarded, except for one set from every triplicate series (i.e., 3 test runs). These were archived for possible future analyses. The sample recovery scheme is shown in Figure 5-13.



Figrue 5-13. HCl/HBr/HF Sample Recovery Scheme

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5.4.5 HCl/HBr/HF Analytical Procedures

Before analysis, the samples were checked against the chain-of-custody forms and then given an analytical laboratory sample number. Then, each sample was examined to determine if any leakage occurred, and any discoloration or other particulars of the samples were noted.

The IC conditions are described by the type of analytical column and whether suppressed or nonsuppressed IC was used. Prior to sample analysis, a stable baseline was established, and water samples were injected until no Cl^-, Br^-, or F^- appeared in the chromatogram. Then, the IC was calibrated using standards spanning the appropriate concentration range, starting with the lowest concentration standard. Next, a QC check sample was injected in duplicate, followed by a water blank and the field samples. The calibration standards were re-injected at the end of the analysis to compensate for any drift in the instrument response during analysis of the field samples. The Cl^-, Br^-, and F^- sample concentrations were calculated from either the respective ion peak area or peak height and the calibration curve.

5.4.6 HCl/HBr/HF Analytical Quality Control

The IC was calibrated with a minimum of three concentrations, not including zero. A correlation coefficient of greater than or equal to 0.995 was required for acceptable calibration. At least 10 percent of the total number of samples were analyzed in duplicate. Ion concentrations in the duplicates must agree to within ±20 percent.

5.5 EPA METHODS 1-4

5.5.1 Traverse Point Location By EPA Method 1

The number and location of sampling traverse points necessary for isokinetic and flow sampling was dictated by EPA Method 1 protocol. These parameters were based upon how much duct distance separated the sampling ports from the closest downstream and upstream flow disturbances. The minimum number of traverse points for a circular duct less than 24 inches in diameter is 4 (8 total sample points). Several sets of perpendicular sampling ports were established at each sampling location. Traverse point locations were determined for each port depending on the distances to duct disturbances (see Section 4).

5.5.2 Volumetric Flow Rate Determination by EPA Method 2

Volumetric flow rate was measured according to EPA Method 2. A Type K thermocouple and S-type pitot tube were used to measure flue gas temperature and velocity, respectively. All of the isokinetically sampled methods that were used (CDD/CDF, PM/metals, Mercury 101A) incorporate Method 2.

5.5.2.1 Sampling and Equipment Preparation. For EPA Method 2, the pitot tubes were calibrated before use following the directions in the method. Also, the pitot tubes were leak checked before and after each run.

5.5.2.2 Sampling Operations. The parameters that were measured include the pressure drop across the pitot tubes, stack temperature, and stack static and ambient pressure. These parameters were measured at each traverse point, as applicable. A computer program was used to calculate the average velocity during the sampling period.

5.5.3 O_2 and CO_2 Concentrations by EPA Method 3A

The O_2 and CO_2 concentrations were determined by CEMs following EPA Method 3A. Flue gas was extracted from the duct and delivered to the CEM system through heated Teflon® tubing. The sample stream was then conditioned (PM and moisture removed) and was directed to the analyzers. The O_2 and CO_2 concentrations were, therefore, determined on a dry basis. Average concentrations were calculated to coincide with each respective sampling time period. More information on the CEM system is given in Section 5.6.

5.5.4 Average Moisture Determination by EPA Method 4

The average flue gas moisture content was determined according to EPA Method 4. Before sampling, the initial weight of the impingers was recorded. When sampling was completed, the final weights of the impingers were recorded, and the weight gain was calculated. The weight gain and the volume of gas sampled were used to calculate the average moisture content (percent) of the flue gas. The calculations were performed by computer. Method 4 was incorporated in the techniques used for all of the manual sampling methods that were used during the test.

5.6 CONTINUOUS EMISSIONS MONITORING (CEM) METHODS

EPA Methods 3A, 7E, 6C, and 10 are continuous monitoring methods for measuring CO_2, O_2, NO_x, SO_2, and CO concentrations. Total hydrocarbons were analyzed by EPA Method 25A. Flue gas HCl concentrations were also monitored using CEMs with state-of-the-art equipment and procedures. A diagram of the CEM system is shown in Figure 5-14.

Two extractive systems were used to obtain flue gas samples for the CEM systems. One system was for HCl monitoring, and the other system was for all other CEMs. For the main CEM extraction system, samples were withdrawn continuously from a single point in the incinerator outlet duct and transferred to the CEM trailer through heat-traced Teflon® line. The flue gas was conditioned (temperature lowered and moisture removed) before the flue gas stream was divided using a manifold and sent to the various analyzers. Hydrocarbon measurements were made on a wet basis; therefore, its sample stream bypassed the gas conditioner.

5.6.1 CEM Sampling Equipment

5.6.1.1 Sample Probes. The main CEM probe consisted of a black iron pipe mounted to a Swagelok® reducing union which was attached directly to the heat trace tubing. The probe was placed approximately at a point of average velocity in the stack determined by a velocity traverse.

5.6.1.2 Heated Lines. Heated sample lines were used to transfer the flue gas samples to the instrument trailer for O_2, CO_2, NO_x, SO_2, CO, and THC analyses. These lines were heated to prevent condensation. (Condensate could clog sample lines or provide a medium for the flue gas sample to react and change composition.)

All heat trace lines contained three 3/8-inch Teflon® tubes. One tube carried the sample, one tube was used for calibration and QC gases, and the other was available as a backup. With this system, calibration gases were directed to the sampling probe and through the entire sampling/conditioning system during calibration procedures.

5.6.1.3 Gas Conditioning. Special gas conditioners are used to reduce the moisture content of the flue gas. A Radian-designed gas conditioning system uses a chiller (antifreeze liquid) system to cool a series of glass cyclones. The hot flue gas is chilled by convecting cooling through the glass wall causing the moisture to condense

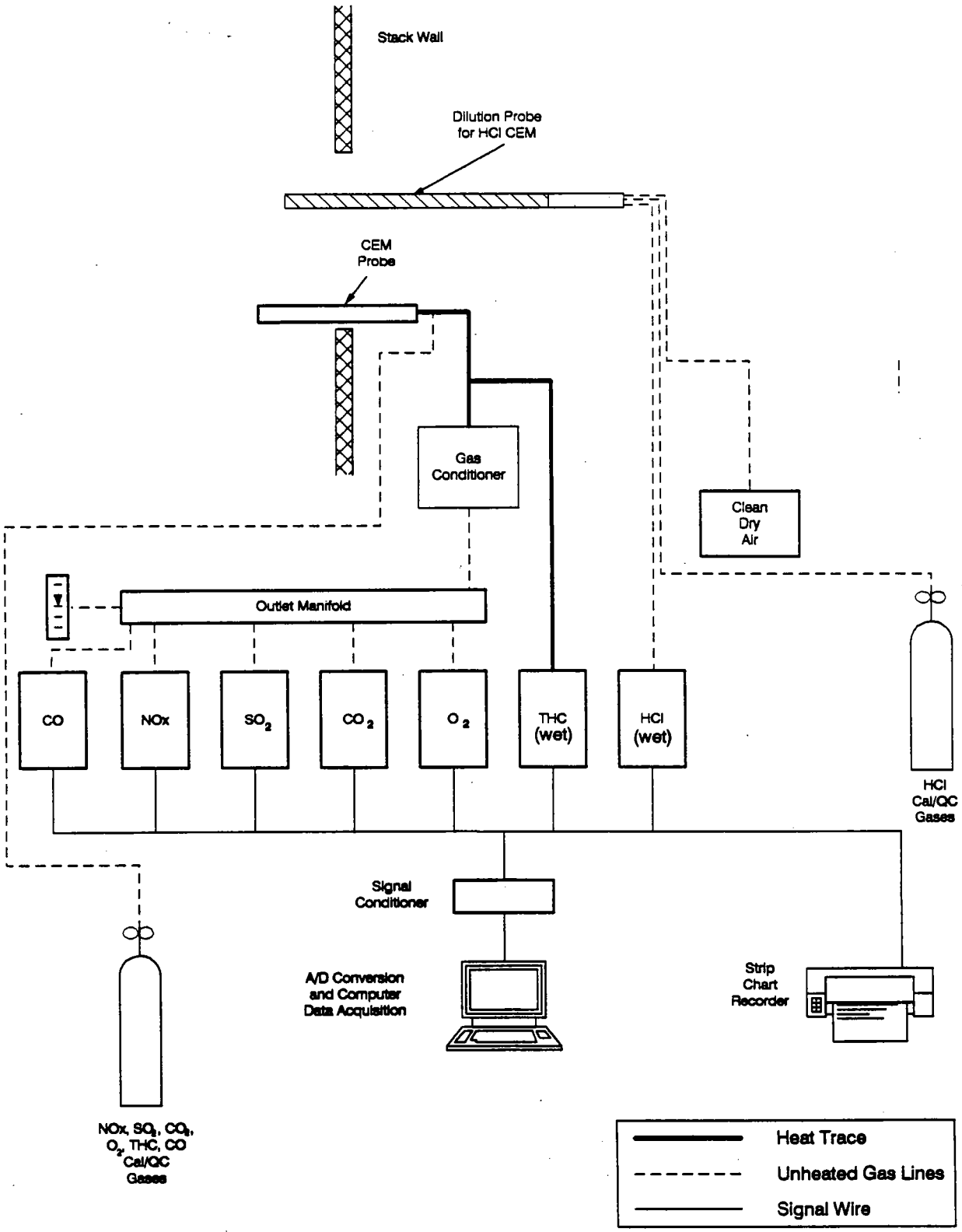

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Figure 5-14. Schematic of CEM System
(2 CEM systems will be used)

into droplets. The droplets and any particulate are flung outward toward the glass walls by centrifugal force, impact the glass walls and fall to the bottom of the cyclone, where they are drained from the system. In this manner, both moisture and PM are effectively removed from the flue gas sample stream. This system operates under positive pressure, eliminating the possibility of a leak. The gas conditioner is located in the CEM trailer.

5.6.1.4 HCl CEM Sample System. The HCl flue gas concentrations were monitored using a CEM analyzer as well as by manual test runs (EPA Method 26). The HCl CEM sampling system used a GMD Model 797 dilution probe. A nominal dilution ratio of 200:1 was used.

5.6.2 CEM Principles of Operation

5.6.2.1 SO_2 Analysis. The Western 721A SO_2 analyzer is essentially a continuous spectrophotometer in the ultraviolet (UV) range. The SO_2 selectively absorbs UV light at a wavelength of 202.5 nm. To take advantage of this property of SO_2, the analyzer emits UV light at 202.5 nm and measures the absorbance (A) of the radiation through the sample cell by the decrease in intensity. Beer's law, $A = abc$, was used to convert the absorbance into SO_2 concentration (A = absorbance, a = absorbitivity, b = path length, c = concentration). The SO_2 measurements were performed in accordance with EPA Method 6C.

5.6.2.2 NO_x Analysis. The principle of operation of this instrument is a chemiluminescent reaction in which ozone (O_3) reacts with nitric oxide (NO) to form oxygen (O_2) and nitrogen dioxide (NO_2). During this reaction, a photon is emitted and is detected by a photomultiplier tube. The instrument is capable of analyzing total oxides of nitrogen ($NO + NO_2$) by thermally converting NO_2 to NO in a separate reaction chamber prior to the photomultiplier tube, if desired. The NO_x measurements were performed specified by EPA Method 7E.

5.6.2.3 O_2 Analysis. Oxygen measurements were performed using EPA Method 3A. Oxygen analysis was completed using the Thermox WDG III analyzer. This instrument measures O_2 using an electrochemical cell. Porous platinum electrodes, which are attached to the inside and outside of the cell, provide the instrument voltage response. Zirconium oxide contained in the cell conducts electrons when it is hot due to the mobility of O_2 ions in its crystal structure. A difference in O_2 concentration between the sample side of the cell and the reference (outside) side of the cell produces a voltage. This response voltage is proportional to the logarithm of the O_2 concentration ratio. A linearizer circuit board is used to make the response linear. Reference gas is ambient air at 20.9 percent O_2 by volume.

5.6.2.4 CO_2 Analysis. Non-dispersive infrared (NDIR) CO_2 analyzers emit a specific wavelength of infrared (IR) radiation which is selectively absorbed by CO_2 molecules through the sample cell. The intensity of radiation that reaches the end of the sample cell is compared to the intensity of radiation through a CO_2-free reference cell. A reference cell is used to determine background absorbance, which is subtracted from the sample absorbance. The detector uses two chambers filled with CO_2 connected by a deflective metallic diaphragm. One side receives radiation from the sample cell, and the other side receives radiation from the reference cell. Since more radiation is absorbed in the sample cell than in the reference cell, less radiation reaches the sample side of the detector. This causes a deflection of the diaphragm due to increased heat from radiation absorption on the reference side. Deflection of the diaphragm creates an electrical potential which is proportional to absorbance. Absorbance is directly proportional to CO_2 concentration in the gas. Carbon dioxide measurements were performed by EPA Method 3A.

5.6.2.5 CO Analysis. A Thermo Electron Corporation (TECO) 48 analyzer was used to monitor CO emissions. TECO analyzers measure CO using the same principle of operation as CO_2 analysis. The instruments are identical except that a different wavelength of infrared radiation is used; 5 nm is selective for CO. Carbon monoxide measurements were performed by EPA Method 10.

5.6.2.6 Total Hydrocarbon Analysis. A Ratfisch RS55 was used to monitor THC emissions. By allowing the THC sample stream to bypass the gas conditioners,

concentrations were determined on a wet basis. This analyzer employs Flame Ionization Detectors (FID). As the flue gas enters the detector, the hydrocarbons are combusted in a hydrogen flame. The ions and electrons formed in the flame enter an electrode gap, decrease the gas resistance, and permit a current flow in an external circuit. The resulting current is proportional to the instantaneous concentration of the total hydrocarbons. This method is not selective between species. EPA Method 25A applies to the continuous measurement of total gaseous organic concentrations of primarily alkanes, alkenes, and/or arenes (aromatic hydrocarbons). The results were reported on a methane basis, and methane was used as the calibration gas.

5.6.2.7 HCl CEM Analysis. HCl flue gas concentrations were continuously monitored using an NDIR/GFC instrument manufactured by TECO. HCl is detected by alternately passing an IR beam between reference HCl gas and reference HCl free gas contained in the filter wheel. The "chopped" beam passes through the sample cell to the detector. The difference in IR beam strength caused by the absorption of the IR beam is proportional to the HCl concentration.

5.6.3 CEM Calibration

All the CEM instruments were calibrated once during the test program (and linearized, if necessary) using a minimum of three certified calibration gases (zero and two upscale points). Radian performed the multipoint calibrations with four general categories of certified gases: zero gas (generally N_2), a low scale gas concentration, a midrange concentration, and a high scale concentration (span gas). The criterion for acceptable linearity is a correlation coefficient (R^2) of greater than or equal to 0.998, where the independent variable is cylinder gas concentration and the dependent variable is instrument response. If an instrument did not meet these requirements, it was linearized by adjusting potentiometers on the linerarity card within the instrument or by other adjustments, if necessary.

The CEM analyzers were calibrated before and after each test run (test day) on a two point basis: zero gas (generally N_2), and a high-range span gas. These calibrations were used to calculate response factors used for sample gas concentration determinations. Instrument drift, as a percent of span, was also determined using these calibrations for each test run.

After each initial calibration, midrange gases for all instruments were analyzed, with no adjustment permitted, as a QC check. If the QC midrange gas concentration observed was within ±2 percent of full scale, the calibration was accepted and the operator began sampling. If the QC check did not fulfill this requirement, another calibration was performed and linearization was performed if necessary. Calibration procedures are further detailed in the daily operating procedure (Section 5.6.5).

Table 5-8 lists the concentration of all calibration and QC gases used on this test program.

5.6.4 Data Acquisition

The data acquisition system consists of a Dianachart PC Acquisitor data logger, a signal conditioner and a 386 Desktop computer. All instrument outputs were connected in parallel to stripchart recorders and the data acquisition system. The stripchart recorders were used to backup the data logger. The PC Acquisitor scanned the instrument output and logged digitized voltages. A Radian computer program translated the digitized voltages into relevant concentrations in engineering units (ppmv, %V, etc.). The computer program has several modes of operation: calibration, data acquisition, data reduction, data view, data edit, and data import. The import function is used to combine other data files for comparison and correlation.

5.6.5 Daily Operating Procedure

The following is a detailed standard operating procedure for calibrating and operating the CEMS:

1. Turn on computer and printer, put printer on-line, and load the CEM.EXE program. Be sure that the CEM instruments have been on for at least 20 hours.

2. Synchronize DAS clock with sample location leaders and the test leader.

3. Turn on strip chart recorders (SCR) and make appropriate notes on charts and in logbook (write down all procedures and observations in logbook and on SCR's as the day progresses).

4. Turn on the gas conditioners and blow back compressor. Blow back the system.

5. Open all calibration gas cylinders so that they may be introduced to the instruments via control panel valves.

6. Perform daily pre-test leak check on CEM's by introducing ultra high purity nitrogen to the system. Zero all instruments except the Thermox O_2 analyzers. Make adjustments to the zero potentiometers as required to zero the instruments. Be sure to check and maintain all flows throughout calibration and operation.

7. Record the zero values in the computer calibration routine.

8. Introduce 2.0 percent O_2 to set the low scale response for the Thermox O_2 analyzers and repeat Step 7 for these instruments.

9. Introduce the mixed span gases for O_2, CO_2, and CO. Make adjustments as required to these instruments.

10. Enter these values in the computer calibration routine.

11. Introduce the NO_x span gas.

12. Make adjustments to the NO_x instruments as required and enter the value into the computer calibration routine.

13. Introduce the SO_2 span gas for the SO_2 analyzer and repeat Step 12 for the SO_2 analyzer. (Note that all calibration gases are passed through the entire sampling system.)

14. Switch the Western SO_2 analyzer range to 0-500 ppm introduce the span gas for this range and repeat Step 12 for this instrument.

15. Check the calibration table on the computer, and make a hardcopy. Put the computer in the standby mode.

16. Introduce QC gases to instruments in the same sequence as the calibration gases. Record three minutes of data for each once the responses have stabilized. If the QC gas response is not within ±2 percent of the instrument range, the operator should recalibrate the instrument, or perform other corrective actions.

17. Begin sampling routine with the computer on standby.

18. Start the data acquisition system when signaled by radio that system is in stack.

19. Carefully check all flows and pressures during the operation of the instruments and watch for apparent problems in any of the instruments, such as unusual readings or unreasonable fluctuations. Check the gas conditioning system periodically and drain the traps.

TABLE 5-8. CEM OPERATING RANGES AND CALIBRATION GASES

Analyte	Gas Concentration
CO_2	
Instrument	Beckman 865
Range	0-20%
Span Gas Value	18%
Zero Gas	N_2
Midrange QC Gas Value	10%
Low Range QC Gas Value	5%
CO - dry	
Instrument	TECO 48H
Range	0-50,000 ppm
Span Gas Value	1000, 9000 or 19,000 ppm[a]
Zero Gas	N_2
Midrange QC Gas Value	1000 or 9000 ppm
Low Range QC Gas Value	2100 ppm
CO - wet	
Instrument	TECO 48
Range	0-100, 0-200, 0-5000 ppm
Span Gas Value	1000, 180 or 90 ppm[a]
Zero Gas	N_2
Midrange QC Gas Value	180 ppm
Low Range QC Gas Value	90 ppm
O_2	
Instrument	Thermox WDG III
Range	0-25%
Span Gas Value	20%
Zero Gas	0.2% O_2
Midrange QC Gas Value	10%
Low Range QC Gas Value	5%

TABLE 5-8. CEM OPERATING RANGES AND CALIBRATION GASES, continued

Analyte	Gas Concentration
SO_2	
Instrument	Western 721A
Range	0-500 or 0-5000 ppm
Span Gas Value	200 or 50 ppm
Zero Gas	N_2
Midrange QC Gas	100 ppm
Low Range QC Gas	30 ppm
NO_x	
Instrument	TECO 10AR
Range	0-250 ppm
Span Gas Value	200 ppm
Zero Gas	N_2
Midrange QC Gas Value	100 ppm
Low Range QC Gas Value	50 ppm
THC	
Instrument	Beckman 402
Range	0-10, 0-50, 0-100 ppm
Span Gas Value	100 ppm as methane
Zero Gas	N_2
Midrange QC Gas Value	45 ppm as methane
Low Range QC Gas Value	25 ppm as methane
HCl	
Instrument	TECO Model 15
Range	0-2000 ppm
Span Gas Value	1800 ppm
Zero Gas	N_2
Midrange QC Gas Value	900 ppm
Low Range QC Gas Value	100 ppm

[a] Several sets of calibration/QC gases were acquired in order to closely approximate stack gas concentrations.

20. Stop the data acquisition system at the end of the test when signaled.

21. Perform final leak check of system.

22. Perform the final calibration (Repeat steps 6-16) except make no adjustments to the system.

23. Check for drift on each channel.

6. QUALITY ASSURANCE/QUALITY CONTROL

Specific QA/QC procedures were strictly followed during this test program to ensure the production of useful and valid data. A detailed presentation of QC procedures for all manual flue gas sampling, process sample collection, and CEM operations can be found in the Borgess Test Plan. This section will report the test program QA parameters so that the degree of data quality may be ascertained.

Ten days of testing were conducted at Borgess Medical Center. During the first day of testing, a miscue resulted in nonuniform sampling times between the APCS inlet and outlet locations. Since one of the goals of this project was to run all testing simultaneously for comparison purposes, the data from the first testing day were not considered useful. During the second day, the ID fan flow rates drifted to unusually high values during most of the sampling period. After the run (Run 1) was completed, it was decided to archive the data and repeat the run at a more representative condition.

Eight runs were completed successfully at three different operating conditions. The incinerator and APCS operating conditions were identical for all the runs except for varying carbon injection rates. The first three runs (Runs 2, 3, and 4) were conducted with no carbon injection (baseline). The last three runs (Runs 7, 8, and 9) were performed at a carbon injection rate of 2.5 lb/hr. The remaining 2 runs (Runs 5 and 6) were executed at a carbon injection rate of 1 lb/hr. Due to time and budgetary restraints it was decided that a third run at this rate would not be performed.

In summary, a high degree of data quality was maintained throughout the project. Post-test leak checks for all sampling trains were within acceptable limits except for one instance. All post-test calibration checks of the dry gas meters were within acceptable limits. Manual isokinetic sampling trains at the inlet and outlet met the isokinetic criterion of 100 ±10 percent for all but 4 of the test runs. The deviation from this criterion was so low that the runs were not repeated. Dioxin field blanks for all three sample locations showed slight detection of the target CDD/CDF compounds. Most recovery percentages met the acceptable criterion. An unusually high number of isomers exhibited recovery percentages outside QA parameters for CDD/CDF Run 2 at the baghouse inlet location, however. This analytical result was accepted as valid by

Triangle Laboratory's QA officer after an assessment of additional analytical QA parameters (i.e., signal to noise ratio, etc.).

Metals blank results showed some contamination; these results are discussed in Section 6.4.1. Method spike recovery values for the metals analyzed were all within acceptable limits except for Ag in the ash analysis, which is also discussed in section 6.4.1. The manual halogen gas tests met acceptable reagent blank and field blank levels, as well as acceptable method spike results.

The CEM results showed good calibration drift values and QC gas responses. All CEM QC procedures and objectives were followed as described in the Borgess Test Plan.

Section 6.1 presents the QA/QC definitions and data quality objectives. Section 6.2 presents manual flue gas sampling and recovery QA parameters. Section 6.3 discusses the QC procedures for ash sampling, and Section 6.4 presents method-specific analytical QA parameters. Section 6.5 discusses the CEM QA parameters. Section 6.6 presents a discussion on data variability.

6.1 QA/QC DEFINITIONS AND OBJECTIVES

The overall QA/QC objective is to ensure precision, accuracy, completeness, comparability, and representativeness for each major measurement parameter called for in this test program. For this test program, quality control and quality assurance can be defined as follows:

- Quality Control: The overall system of activities whose purpose is to provide a quality product or service. QC procedures are routinely followed to ensure high data quality.

- Quality Assurance: A system of activities whose purpose is to provide assurance that the overall quality control is being done effectively. Assessments can be made from QA parameters on what degree of data quality was achieved.

- Data Quality: The characteristics of a product (measurement data) that bear on its ability to satisfy a given purpose. These characteristics are defined as follows:

  - Precision - A measure of mutual agreement among individual measurements of the same property, usually under prescribed similar conditions. Precision is best expressed in terms of the standard deviation and in this report will be expressed as the relative standard deviation or coefficient of variation.

- Accuracy - The degree of agreement of a measurement (or an average of measurements of the same thing), X, with an accepted reference or true value, T, can be expressed as the difference between two values, X-T, the ratio X/T, or the difference as a percentage of the reference or true value, 100 (X-T)/T.

- Completeness - A measure of the amount of valid data obtained from a measurement system compared with the amount that was expected to be obtained under prescribed test conditions.

- Comparability - A measure of the confidence with which one data set can be compared to another.

- Representativeness - The degree to which data accurately and precisely represent a characteristic of a population, variations of a parameter at a sampling point, or an environmental condition.

A summary of the estimated precision, accuracy, and completeness objectives is presented in Table 6-1.

6.2 MANUAL FLUE GAS SAMPLING AND RECOVERY PARAMETERS

The following section will report method-specific sampling QA parameters so that insight can be gained into the quality of the emissions test data produced from manual tests during the test program.

6.2.1 Dioxin/Furan Sampling Quality Assurance

Table 6-2 lists both the pre-test and post-test leak checks completed on the CDD/CDF sampling trains. The acceptance criterion is that all post-test leak checks must be less than 0.02 cfm or 4 percent of the average sampling rate (whichever is less). All of the leak rates were lower than 0.02 cfm; therefore, sample volume corrections were not performed.

Table 6-3 presents the isokinetic sampling rates for CDD/CDF, PM/metals, and Hg sampling trains. The acceptance criterion is that the average sampling rate must be within 10 percent of 100 percent isokinetic. Isokinetic rates for the CDD/CDF trains were within the 10 percent criterion for all of the test runs.

All dry gas meters were fully calibrated within the last six months against an EPA approved intermediate standard. The full calibration factor or meter Y was used to correct actual metered sample to true sample volume. To verify the full calibration, a post-test calibration was performed. The full and post-test calibration coefficients must

Table 6-1

Summary of Precision, Accuracy, and Completeness Objectives[a]

Parameter	Precision (RSD)	Accuracy[b] (%)	Completeness[c] (%)
Dioxins/Furans Emissions	±40[d]	±50	100
Metals Emissions	±15[d]	±30	100
Particulate Matter Emissions	±12	±10	100
HCl/HBr/HF Concentrations	±10[d]	±15	95
CEM Concentrations	±20	±15	95
Velocity/Volumetric Flow Rate	±6	±10	95
Molecular Weight	±0.3%V	±0.5%V	100
Flue Gas Moisture	±20	±10	95
Flue Gas Temperature	±2°F	±5°F	100

RSD = Relative Standard Deviation. Uses worst case assumption that variation amongst run results is not due to process variation.

[a] Precision and accuracy estimated based on results of EPA collaborative tests. All values stated represent worst case values. All values are absolute percentages unless otherwise indicated.

[b] Relative error (%) derived from audit analyses, where:

$$\text{Percent Relative Error} = \frac{\text{Measured Value - Actual Value}}{\text{Actual Value}} \times 100$$

[c] Minimum valid data as a percentage of total tests conducted.

[d] Analytical phase only. Percent difference for duplicate analyses, where:

$$\text{Percent Relative Error} = \frac{\text{First Value - Second Value}}{0.5\ (\text{First + Second Values})} \times 100$$

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TABLE 6-2. LEAK CHECK RESULTS FOR CDD/CDF SAMPLE TRAINS
BORGESS MEDICAL CENTER (1991)

Date	Run Number	Maximum Vacuum	Port	Avg. Sample Rate (acfm)	Measured Leak Rate	Vacuum (in. Hg)	Leak Corrected (Y or N)
9/07/91	2 BOI Inlet	5	A	0.511	0.008	15	N
		5	B	0.464	0.009	9	N
9/07/91	2 BH Inlet	3	A	0.360	0.015	15	N
		4	B	0.383	0.006	5	N
9/07/91	2 BH Outlet	5	A	0.366	0.018	15	N
		4	B	0.355	0.018	6	N
9/09/91	3 BOI Inlet	4.5	A	0.363	0.008	8	N
		4	B	0.364	0.008	15	N
9/09/91	3 BH Inlet	7	A	0.452	0.014	15	N
		8	B	0.456	0.008	7	N
9/09/91	3 BH Outlet	3.8	A	0.345	0.014	15	N
		3	B	0.398	0.004	5	N
9/10/91	4 BOI Inlet	2.1	A	0.353	0.008	6	N
		2.9	B	0.325	0.007	15	N
9/10/91	4 BH Inlet	6.8	A	0.445	0.008	15	N
		7	B	0.425	0.007	8	N
9/10/91	4 BH Outlet	2	A	0.350	0.018	15	N
		2	B	0.334	0.016	4	N
9/11/91	5 BOI Inlet	5	A	0.330	0.012	15	N
		6.2	B	0.315	0.004	5	N
9/11/91	5 BH Inlet	3.6	A	0.522	0.010	15	N
		4.4	B	0.460	0.008	15	N
9/11/91	5 BH Outlet	4	A	0.399	0.014	15	N
		3	B	0.322	0.012	5	N
9/12/91	6 BOI Inlet	3.5	A	0.385	0.014	17	N
		3.5	B	0.331	0.006	10	N
9/12/91	6 BH Inlet	3.0	A	0.436	0.008	15	N
		3.8	B	0.442	0.004	5	N
9/12/91	6 BH Outlet	2	A	0.360	0.016	15	N
		2	B	0.285	0.014	5	N
9/13/91	7 BOI Inlet	4	A	0.684	0.008	17	N
		7	B	0.606	0.012	9	N
9/13/91	7 BH Inlet	4	A	0.441	0.014	15	N
		3.6	B	0.439	0.008	5	N
9/13/91	7 BH Outlet	4	A	0.379	0.018	15	N
		3	B	0.357	0.012	5	N
9/14/91	8 BOI Inlet	4.2	A	0.649	0.008	15	N
		9	B	0.681	0.008	5	N
9/14/91	8 BH Inlet	3.8	A	0.422	0.014	16	N
		3.4	B	0.426	0.006	5	N
9/14/91	8 BH Outlet	2	A	0.366	0.018	15	N
		2	B	0.333	0.019	5	N
9/16/91	9 BOI Inlet	8.0	A	0.701	0.014	15	N
		9	B	0.725	0.008	15	N
9/16/91	9 BH Inlet	4.2	A	0.411	0.016	15	N
		5	B	0.423	0.004	7	N
9/16/91	9 BH Outlet	3	A	0.346	0.016	15	N
		2	B	0.328	0.010	5	N

TABLE 6-3. ISOKINETIC SAMPLING RATES FOR MANUAL SAMPLING TEST RUNS
BORGESS MEDICAL CENTER (1991)

Date	Run Number	Location	CDD/CDF Isokinetic Sample Rate (%)	Toxic Metals Isokinetic Sample Rate (%)	Mercury Isokinetic Sample Rate (%)	PM Isokinetic Sample Rate (%)
9/07/91	2	BOI Inlet	109.60	a	a	95.62
		BH Inlet	104.62	95.34	93.31	b
		BH Outlet	103.15	103.26	100.37	b
9/09/91	3	BOI Inlet	109.93	a	a	103.29
		BH Inlet	102.74	97.30	95.09	b
		BH Outlet	101.93	106.28	101.01	b
9/10/91	4	BOI Inlet	98.89	a	a	109.49
		BH Inlet	102.53	95.81	97.32	b
		BH Outlet	97.22	102.15	101.46	b
9/11/91	5	BOI Inlet	94.57	a	a	104.39
		BH Inlet	106.25	97.43	99.28	b
		BH Outlet	99.94	103.28	101.87	b
9/12/91	6	BOI Inlet	98.63	a	a	89.69
		BH Inlet	102.66	96.23	103.80	b
		BH Outlet	100.82	110.17	108.72	b
9/13/91	7	BOI Inlet	92.91	a	a	107.97
		BH Inlet	101.53	100.57	102.81	b
		BH Outlet	98.49	104.36	104.63	b
9/14/91	8	BOI Inlet	94.00	a	a	109.62
		BH Inlet	101.23	95.63	103.92	b
		BH Outlet	99.59	110.23	104.56	b
9/16/91	9	BOI Inlet	98.76	a	a	113.99
		BH Inlet	104.42	101.27	105.61	b
		BH Outlet	101.35	106.38	105.35	b

a No test at this location.
b PM testing was performed with the toxic metals train at the baghouse inlet and outlet locations.

be within 5 percent to meet Radian's internal QA/QC acceptance criterion. As can be seen from Table 6-4, the post-test calibration factor for all meter boxes used for CDD/CDF, PM/metals, and Hg were well within the 5 percent criterion of the full calibration factor. Field blanks were collected at the boiler inlet, baghouse inlet, and baghouse outlet to verify the absence of any sample contamination. The CDD/CDF sampling train was fully prepared, taken to the sample location, leak checked, and then recovered. Table 6-5 compares the CDD/CDF analytical results for the MM5 field blanks and reagent blanks versus average MM5 samples for the test runs. No 2378 TCDD was detected in any of the field blanks. A small amount of 2378 TCDF was found in all of the field blanks, but only at levels less than six times the detection limit. The heavier CDD/CDF isomers were detected in the MM5 field blanks, with most contamination found at the boiler inlet and baghouse outlet at levels much lower than detected in the actual runs. However, field blank corrections were not made on the emissions results. Analytical blank results are further discussed in Section 6.4.1.

6.2.2 PM/Metals Sampling Quality Assurance

Table 6-6 presents the leak check results for the PM/metals. All runs met the leak rate criterion of 0.02 cfm. Leak check results for the Method 5 train at the boiler inlet are shown in Table 6-7. None of the leak checks were above 0.02 cfm, therefore, a leak correction of the PM results was not made. The isokinetic sampling rates for the PM/metals trains are listed in Table 6-3. All isokinetic values were within 10 percent of 100 percent except Run 6 and Run 8 at the baghouse outlet which had isokinetic sampling rates of 110.17 and 110.23, respectively.

The post-test dry gas meter calibration checks for boxes used for PM/metals sampling are shown in Table 6-4. The results were well within the 5 percent acceptance criterion.

6.2.3 Mercury 101A Sampling Quality Assurance

Table 6-8 presents the leak check results for the Hg trains. Only the leak check for Run 2 did not meet the leak rate criterion. However, the exceedance was so small that no leak correction was applied to the data.

Mercury isokinetic results are shown in Table 6-3. All of the test runs met the isokinetic criterion of 100 ± 10 percent.

TABLE 6-4. DRY GAS METER POST-TEST CALIBRATION RESULTS
BORGESS MEDICAL CENTER (1991)

Meter Box ID	Sample Trains	Full Calibration Factor	Post-Test Calibration Factor	Post-Test Deviation (%)[1]
A-36	CDD/CDF-BOI	0.9968	1.0060	0.91
N-33	CDD/CDF-BHI	0.9875	0.9788	-0.89
R-4	CDD/CDF-BHO	0.9912	0.9929	0.17
N-34	Metals-BHI	1.0032	1.0147	1.13
N-31	Metals-BHO	1.0108	0.9937	-1.72
N-32	Mercury-BHI	1.0006	0.9897	-1.10
N-30	Mercury-BHO	0.9998	1.0218	2.15
A-35	Method 5-BOI	1.0010	0.9972	-0.38

[1] [(Post-Test)-(Full)]/(Full)*100

TABLE 6-5. CDD/CDF FIELD BLANK AND REAGENT BLANK RESULTS COMPARED TO AVERAGE RUN RESULTS
BORGESS MEDICAL CENTER (1991)

COGENER	MM5 REAGENT BLANK (total ng)	BOILER INLET				BAGHOUSE INLET				BAGHOUSE OUTLET			
		MM5 FIELD BLANK (total ng)	MM5 COND. 1 AVG. (total ng)	MM5 COND. 2 AVG. (total ng)	MM5 COND. 3 AVG. (total ng)	MM5 FIELD BLANK (total ng)	MM5 COND. 1 AVG. (total ng)	MM5 COND. 2 AVG. (total ng)	MM5 COND. 3 AVG. (total ng)	MM5 FIELD BLANK (total ng)	MM5 COND. 1 AVG. (total ng)	MM5 COND. 2 AVG. (total ng)	MM5 COND. 3 AVG. (total ng)
DIOXINS													
2378 TCDD	[0.008]	[0.010]	0.057	0.045	0.060	[0.020]	0.143	0.405	0.370	[0.020]	0.037	[0.025]	[0.0233]
TOTAL TCDD	[0.008]	[0.010]	0.577	2.965	1.967	[0.020]	1.273	3.900	3.233	[0.020]	0.397	0.030	0.030
12378 PCDD	[0.010]	[0.020]	0.193	0.165	0.370	[0.030]	0.423	0.965	0.863	[0.030]	0.147	[0.070]	[0.050]
TOTAL PCDD	[0.010]	(0.150)	0.957	1.235	3.233	[0.030]	2.367	5.800	5.667	(1.000)	0.953	0.090	0.050
123478 HxCDD	[0.010]	0.010	0.133	0.115	0.423	[0.030]	0.493	1.290	1.167	[0.030]	0.263	[0.085]	[0.053]
123678 HxCDD	[0.008]	0.030	0.170	0.145	0.630	[0.020]	0.730	1.365	1.367	(0.020)	0.307	0.120	0.030
123789 HxCDD	[0.010]	0.040	0.300	0.270	1.303	[0.030]	1.367	2.400	2.633	[0.030]	0.513	0.200	[0.047]
TOTAL HxCDD	[0.008]	0.170	1.557	1.600	6.633	[0.030]	6.733	13.050	13.867	(0.090)	3.100	0.565	0.113
1234678-HpCDD	0.040	0.500	1.653	1.550	8.067	0.080	11.067	19.600	19.533	0.270	4.033	0.895	0.343
TOTAL Hepta-CDD	0.060	0.900	3.100	3.000	15.633	0.080	19.867	37.700	38.500	0.540	7.967	1.850	0.607
Octa-CDD	(0.022)	1.500	5.433	6.400	25.367	0.390	37.800	65.950	64.367	0.900	8.900	2.250	1.300
FURANS													
2378 TCDF	(0.008)	(0.030)	6.033	2.900	2.400	(0.020)	2.387	2.600	15.633	0.020	0.317	0.060	0.033
TOTAL TCDF	(0.008)	0.050	10.867	10.700	24.967	(0.020)	16.767	41.050	32.300	0.240	8.867	0.850	0.447
12378 PCDF	[0.010]	(0.050)	1.200	0.895	1.967	[0.020]	1.800	3.750	3.333	(0.030)	0.693	0.100	0.050
23478 PCDF	[0.010]	(0.070)	1.350	1.155	3.133	[0.020]	2.933	6.650	5.867	(0.040)	1.400	0.140	0.063
TOTAL PCDF	[0.010]	0.260	13.467	11.350	29.533	[0.020]	28.700	67.200	61.867	0.260	12.633	0.790	0.153
123478 HxCDF	[0.010]	0.330	3.733	3.100	12.333	[0.020]	15.767	25.950	24.633	0.210	5.700	0.595	0.190
123678 HxCDF	[0.008]	0.160	1.470	1.280	4.533	[0.020]	4.833	9.300	8.800	0.070	1.867	0.200	0.067
234678 HxCDF	(0.010)	0.390	2.633	2.750	11.433	0.030	16.300	26.700	24.367	0.210	6.667	0.660	0.230
123789 HxCDF	[0.010]	0.030	0.177	0.150	0.653	[0.020]	0.913	0.955	1.007	[0.030]	0.197	[0.060]	[0.043]
TOTAL HxCDF	(0.010)	1.200	14.933	13.050	48.900	0.030	64.633	111.850	99.700	0.540	21.867	1.845	0.540
1234678-HpCDF	[0.008]	1.300	7.133	6.650	29.467	0.100	33.600	48.600	56.967	0.640	12.433	1.450	0.590
1234789-HpCDF	[0.010]	0.440	1.730	1.400	7.033	[0.030]	10.500	11.950	11.967	(0.170)	2.907	0.230	0.140
TOTAL Hepta-CDF	[0.010]	3.300	16.500	14.650	64.300	0.130	83.933	111.500	120.333	1.100	28.700	2.850	1.100
Octa-CDF	[0.020]	3.500	14.167	12.750	59.567	0.200	43.967	120.500	114.333	1.500	20.367	1.650	1.333

[] = Detection limit
() = Estimated maximum possible concentration

TABLE 6-6. LEAK CHECK RESULTS FOR TOXIC METALS SAMPLE TRAINS
BORGESS MEDICAL CENTER (1991)

Date	Run Number	Maximum Vacuum	Port	Avg. Sample Rate (acfm)	Measured Leak Rate	Vacuum (in. Hg)	Leak Corrected (Y or N)
9/07/91	2 BH Inlet	2.5	A	0.529	0.012	15	N
		3.2	B	0.536	0.004	3.5	N
9/07/91	2 BH Outlet	1	A	0.408	0.014	17	N
		1	B	0.356	0.014	5	N
9/09/91	3 BH Inlet	2.5	A	0.571	0.014	15	N
		3.3	B	0.600	0.006	3.5	N
9/09/91	3 BH Outlet	1	A	0.413	0.007	15	N
		1	B	0.391	0.003	4	N
9/10/91	4 BH Inlet	2.2	A	0.563	0.010	15	N
		3.1	B	0.589	0.006	3.5	N
9/10/91	4 BH Outlet	1	A	0.411	0.008	15	N
		1	B	0.399	0.006	5	N
9/11/91	5 BH Inlet	2.3	A	0.562	0.008	16	N
		3.3	B	0.581	0.004	4	N
9/11/91	5 BH Outlet	1	A	0.428	0.010	15	N
		1	B	0.410	0.012	5	N
9/12/91	6 BH Inlet	2.8	A	0.577	0.016	15	N
		3.8	B	0.588	0.004	4	N
9/12/91	6 BH Outlet	1	A	0.397	0.014	15	N
		1	B	0.362	0.012	5	N
9/13/91	7 BH Inlet	2	A	0.573	0.016	15	N
		3	B	0.597	0.004	6	N
9/13/91	7 BH Outlet	1	A	0.419	0.016	15	N
		1	B	0.382	0.006	5	N
9/14/91	8 BH Inlet	2	A	0.550	0.008	15	N
		2	B	0.556	0.004	5	N
9/14/91	8 BH Outlet	1	A	0.419	0.018	15	N
		1	B	0.383	0.005	5	N
9/16/91	9 BH Inlet	2	A	0.560	0.010	15	N
		2	B	0.555	0.005	7	N
9/16/91	9 BH Outlet	1	A	0.405	0.006	15	N
		1	B	0.379	0.005	5	N

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TABLE 6-7. LEAK CHECK RESULTS FOR METHOD 5 SAMPLE TRAINS
BORGESS MEDICAL CENTER (1991)

Date	Run Number	Maximum Vacuum	Port	Avg. Sample Rate (acfm)	Measured Leak Rate	Vacuum (in. Hg)	Leak Corrected (Y or N)
9/07/91	2 BOI Inlet	9	A	0.684	0.019	16	N
		3	B	0.694	0.014	6	N
9/09/91	3 BOI Inlet	1	A	0.374	0.017	15	N
		1	B	0.355	0.010	15	N
9/10/91	4 BOI Inlet	1	A	0.374	0.010	15	N
		1	B	0.329	0.016	5	N
9/11/91	5 BOI Inlet	1	A	0.344	0.016	15	N
		1	B	0.358	0.020	5	N
9/12/91	6 BOI Inlet	1	A	0.278	0.012	15	N
		1	B	0.320	0.018	10	N
9/13/91	7 BOI Inlet	1	A	0.296	0.014	12	N
		1	B	0.270	0.008	5	N
9/14/91	8 BOI Inlet	1	A	0.263	0.010	15	N
		1	B	0.305	0.010	5	N
9/16/91	9 BOI Inlet	1	A	0.312	0.018	15	N
		1	B	0.275	0.018	12	N

TABLE 6-8. LEAK CHECK RESULTS FOR MERCURY SAMPLE TRAINS
BORGESS MEDICAL CENTER (1991)

Date	Run Number	Maximum Vacuum	Port	Avg. Sample Rate (acfm)	Measured Leak Rate	Vacuum (in. Hg)	Leak Corrected (Y or N)
9/07/91	2 BH Inlet	3	A	0.499	0.010	15	N
		3.6	B	0.521	0.010	4	N
9/07/91	2 BH Outlet	1	A	0.403	0.014	17	N
		1	B	0.354	0.015	5	N
9/09/91	3 BH Inlet	2.4	A	0.537	0.008	15	N
		2.8	B	0.566	0.006	6	N
9/09/91	3 BH Outlet	1	A	0.411	0.006	15	N
		1	B	0.380	0.008	4.5	N
9/10/91	4 BH Inlet	2.5	A	0.535	0.014	15	N
		3.1	B	0.566	0.005	3.5	N
9/10/91	4 BH Outlet	1	A	0.416	0.010	15	N
		1	B	0.401	0.003	5	N
9/11/91	5 BH Inlet	2.2	A	0.538	0.010	15	N
		3	B	0.562	0.008	4	N
9/11/91	5 BH Outlet	1	A	0.437	0.014	15	N
		1	B	0.407	0.006	5	N
9/12/91	6 BH Inlet	2.7	A	0.552	0.002	15	N
		3.5	B	0.568	0.008	4	N
9/12/91	6 BH Outlet	1	A	0.399	0.012	15	N
		1	B	0.360	0.004	5	N
9/13/91	7 BH Inlet	2	A	0.554	0.008	15	N
		2	B	0.576	0.009	7	N
9/13/91	7 BH Outlet	1	A	0.426	0.010	15	N
		1	B	0.384	0.004	5	N
9/14/91	8 BH Inlet	2	A	0.541	0.016	15	N
		2	B	0.547	0.010	6	N
9/14/91	8 BH Outlet	1	A	0.426	0.012	15	N
		1	B	0.385	0.005	5	N
9/16/91	9 BH Inlet	2	A	0.557	0.008	15	N
		2	B	0.541	0.006	5	N
9/16/91	9 BH Outlet	1	A	0.398	0.010	15	N
		1	B	0.384	0.004	5	N

The Hg field blank results are presented in Table 6-9. The amount of Hg detected in the field blanks was negligible compared to amounts detected in the run samples.

6.2.4 Halogen Flue Gas Sampling Quality Assurance

Halogen flue gas concentration tests by EPA Method 26 did not require isokinetic sampling. A constant flow of flue gas was extracted from the stack through a heated 3 foot quartz probe. The sample stream was bubbled through a series of impinger collection solutions and sent to the laboratory for analysis of Cl^-, F^-, and Br^-. A slight modification to the method (EPA Method 26) was incorporated into the test scheme by placing a small amount of quartz wool into the upstream side of the HCl filter housing.

Leak checks were completed before and after each halogen test run. They were conducted by establishing approximately 10 inches of vacuum on the train, plugging the end of the probe, turning off the flow, and checking for any detectable vacuum loss over a 30-second period. If a leak was observed in the system, the run was invalidated. There was no quantitation of leak rate. All halogen tests met the post-test leak check criterion.

Halogen field blank results are shown in Table 6-10. No Cl-, Br^- or F^- was detected in either the baghouse inlet or outlet field blanks. Neither were any of the halogen ions detected in any of the three method blanks.

6.3 QC PROCEDURES FOR ASH SAMPLING

Daily samples of both incinerator bottom ash and baghouse ash were collected. Incinerator ash was collected before each test day (from the previous test run), and baghouse ash was collected on the afternoon of its respective test run. The ash was analyzed for metals, CDD/CDF, carbon, loss on ignition, and moisture content. All ash was removed from the incinerator bed every morning and placed in a large 55-gallon drum. Three 1000-gram samples were taken and placed in pre-cleaned, amber glass bottles. This same procedure was used to collect baghouse ash. All material used for sampling, sample compositing, and sample aliquoting was cleaned to prevent sample contamination.

Table 6-9

Mercury Method 101A Blank Results

Blank Type	Results (total μg)	Percent Recovery (%)
Baghouse Inlet Field Blank	3.08	NA
Baghouse Outlet Field Blank	12.5	NA
Method Blank	[0.299]	NA
Matrix Spike (Outlet Run 6)	NA	97.8
Matrix Spike Duplicate (Outlet Run 6)	NA	92.7

NA = Not Applicable

[ ] = Minimum Detection Limit

TABLE 6-10. HALOGEN FIELD BLANK AND METHOD BLANK RESULTS; BORGESS MEDICAL CENTER (1991) a

ANALYTE	INLET FIELD BLANK (total mg)	OUTLET FIELD BLANK (total mg)	METHOD BLANK 1 (total mg)	METHOD BLANK 2 (total mg)	METHOD BLANK 3 (total mg)
Cl	[0.00342]	[0.00405]	[0.595]	[0.488]	[0.00484]
F	[0.012]	[0.0142]	[0.180]	[0.111]	[0.0170]
Br	[0.00381]	[0.00451]	[0.444]	[0.253]	[0.00539]

a Values are reported as respective anions.
[] = Detection limit.

6.4 ANALYTICAL QUALITY ASSURANCE

The following section reports QA parameters for the CDD/CDF, metals, halogen, and Hg analytical results.

6.4.1 CDD/CDF Analytical Quality Assurance

6.4.1.1 Flue Gas (MM5) Analytical Procedure. The full screen analyses were conducted using a DB-5 GC column which separates each class of chlorination (i.e., tetra, penta, etc.) and fully resolves 2378 TCDD from the other TCDD isomers. The confirmation analysis, performed on a DB-225 GC column, is needed to fully resolve the 2378 TCDF from the other TCDF isomers. The 2378 TCDD and total TCDD isomers are also reported on the confirmation analysis. The final results for 2378 TCDF and other TCDF concentrations were taken from the confirmation analysis. All other CDD/CDF results were taken from the full screen analysis unless directed otherwise by the analytical "case narratives," which are shown in Appendix E.1.

A component of the CDD/CDF analytical laboratory's QA/QC program is adding isotopically labeled standards to each sample during various stages of analysis to determine recovery efficiencies and to aid in the quantitation of "native" CDD/CDF on the XAD absorbent trap prior to the sampling session. (Toluene surrogates are added to species. Four different type standards are added. Surrogate standards are usually spiked in the sample prior to extraction.) Recovery of these compounds allows for the evaluation of overall sample collection efficiency and analytical matrix effects. Internal standards are spiked after the sampling session but prior to extraction. Alternate standards are also spiked at this stage. Recovery percentage of internal standards are used in quantifying the flue gas native CDD/CDF isomers. Recovery of alternate standards allows for extraction/fractionation efficiencies to be determined. Finally, recovery standards are added after fractionation, just prior to the HRGC/HRMS analysis. Internal standards recovery are determined relative to recovery standards recovery. Recovery standards recovery efficiencies are not typically reported with the analytical results.

Poor recovery percentage of the various standards can reveal poor data quality. In some cases, if an analysis with a poor recovery is also accompanied by a suitable QA/QC "flag", the sample result can be validated. A full discussion of the analytical

QA/QC program cannot be presented in this summary report, but can be found in Triangle's CDD/CDF Data User Manual.

6.4.1.2 CDD/CDF MM5 Blank Results. The method blank and the field blank were analyzed for CDD/CDF isomers. Small quantities of several isomers were detected in the method blanks. Levels were all less than one third the "theoretical method quantitation limit" and were, therefore, within analytical QA guidelines. As discussed in Section 6.2.1, some of the heavier CDD/CDF isomers were detected in the field blanks at minute levels. These results are shown in Table 6-5. No correction was made for the field blank contamination.

6.4.1.3 CDD/CDF Standard Recoveries. Tables 6-11, 6-12, and 6-13, present the standard recovery values for the MM5 flue gas samples, respectively. Both full screen and confirmation values are presented. Confirmation analyses were only completed when positive detections of 2378 TCDD or 2378 TCDF were found in the full screen (DB-5) analysis. The analytical acceptance criterion for internal standard recoveries is 40 percent to 130 percent for tetra- through hexa-chlorinated compounds, while the range is 25 percent to 130 percent for hepta- and octa-chlorinated compounds. Recoveries outside of these limits may still be acceptable if other identification criteria are met.

The majority of the CDD/CDF internal standard recoveries for the boiler inlet, baghouse inlet, and baghouse outlet met the acceptable criteria. A few isomers exceeded the acceptance criterion for some test runs at each location. However, because the majority of the standards recoveries are within acceptable QC limits, the quality of the outlet CDD/CDF data appears reasonable.

All CDD/CDF data was inspected and released as valid by the Triangle Laboratory QA officer.

Table 6-14 presents the recovery standards for the incinerator and baghouse ash samples. For the flue gas, a few isomers exceeded the standard recoveries acceptance

TABLE 6-11. STANDARDS RECOVERIES FOR THE CDD/CDF MODIFIED METHOD 5 BOILER INLET ANALYSE BORGESS MEDICAL CENTER (1991)

	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Field Blank	TLI
Full Screen Analyses										
Surrogate Standards Recovery (%)										
37Cl-TCDD	97.4	95.1	90.2	99.6	94.2	96.4	87.7	91.7	94.5	94.4
13Cl2-PeCDF 234	89.5	101.0	101.0	98.7	106.0	96.3	90.4	66.8	91.0	93.8
13Cl2-HxCDF 478	104.0	100.0	111.0	109.0	98.8	107.0	101.0	104.0	95.4	114.0
13Cl2-HxCDD 478	84.8	88.9	81.3	86.8	85.7	75.8	93.7	78.5	75.7	82.4
13Cl2-HpCDF 789	94.2	95.4	105.0	105.0	94.4	92.7	97.0	81.9	95.8	110.0
Alternate Standards Recovery (%)										
13Cl2-HxCDF 789	88.2	93.6	104.0	93.1	90.2	96.5	98.3	71.9	96.8	88.9
13Cl2-HxCDF 234	103.0	104.0	122.0	107.0	122.0	123.0	125.0	82.8	129.0	97.7
Internal Standards Recovery (%)										
13Cl2-2378-TCDF	82.0	73.5	78.2	81.8	82.1	85.2	80.3	116.0	89.5	86.7
13Cl2-2378-TCDD	73.8	69.9	76.9	73.0	81.0	78.3	74.7	76.0	84.3	83.9
13Cl2-PeCDF 123	83.2	72.7	93.3	83.0	94.7	95.2	85.7	112.0	92.1	90.7
13Cl2-PeCDD 123	91.3	85.0	121.0	101.0	126.0	134.0	93.6	120.0	133.0	140.0
13Cl2-HxCDF 678	96.7	100.0	87.3	91.0	85.6	90.7	95.6	68.4	89.7	65.2
13Cl2-HxCDD 678	117.0	110.0	135.0	119.0	128.0	146.0	115.0	97.5	148.0	113.0
13Cl2-HpCDF 678	92.4	94.9	105.0	94.8	96.9	110.0	110.0	87.9	103.0	90.8
13Cl2-HpCDD 678	77.6	84.0	105.0	89.1	95.4	99.8	96.8	72.7	104.0	107.0
13Cl2-OCDD	72.5	66.4	92.0	74.6	86.5	79.6	90.0	73.3	95.3	90.4
Confirmation Data										
Surrogate Standards Recovery (%)										
37Cl-TCDD	86.4	89.2	90.8	93.7	90.8	89.9	84.8	85.3	86.1	86.2
Internal Standards Recovery (%)										
13Cl2-2378-TCDF	80.2	61.5	57.6	54.6	71.6	51.3	75.6	76.6	45.1	63.0
13Cl2-2378-TCDD	61.3	57.7	53.3	50.2	65.9	48.7	66.6	76.4	45.5	64.9

TABLE 6-12. STANDARDS RECOVERIES FOR THE CDD/CDF MODIFIED METHOD 5 BAGHOUSE INLET ANALYSES
BORGESS MEDICAL CENTER (1991)

	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Field Blank	TLI
Full Screen Analyses										
Surrogate Standards Recovery (%)										
37Cl-TCDD	94.8	102.0	105.0	102.0	106.0	101.0	42.0	106.0	104.0	101.0
13Cl2-PeCDF 234	78.9	101.0	94.1	96.6	111.0	102.0	38.5	94.3	103.0	99.3
13Cl2-HxCDF 478	134.0	115.0	118.0	114.0	113.0	107.0	48.1	113.0	97.2	107.0
13Cl2-HxCDD 478	82.0	81.5	70.5	81.9	113.0	87.9	46.4	106.0	115.0	86.0
13Cl2-HpCDF 789	185.0	96.9	98.4	112.0	76.1	85.8	40.8	85.5	101.0	119.0
Alternate Standards Recovery (%)										
13Cl2-HxCDF 789	63.8	94.7	87.7	70.7	103.0	94.5	94.3	114.0	99.4	88.1
13Cl2-HxCDF 234	40.2	108.0	114.0	86.2	167.0	133.0	143.0	117.0	131.0	108.0
Internal Standards Recovery (%)										
13Cl2-2378-TCDF	69.5	92.2	94.2	70.0	106.0	88.9	89.5	102.0	81.7	71.7
13Cl2-2378-TCDD	75.0	81.5	75.9	61.3	92.0	77.9	75.6	80.6	79.3	68.4
13Cl2-PeCDF 123	37.9	65.9	77.7	68.5	98.1	91.2	83.5	90.4	76.3	78.0
13Cl2-PeCDD 123	44.1	103.0	102.0	107.0	124.0	119.0	97.0	87.0	90.1	126.0
13Cl2-HxCDF 678	14.5	92.1	76.6	62.0	98.4	96.5	80.4	89.4	91.9	74.6
13Cl2-HxCDD 678	41.8	126.0	142.0	93.3	135.0	117.0	98.7	99.9	99.1	107.0
13Cl2-HpCDF 678	17.5	90.0	89.8	74.5	134.0	110.0	91.5	96.0	85.4	86.2
13Cl2-HpCDD 678	43.1	82.6	83.6	80.0	101.0	88.8	77.7	74.0	85.2	97.5
13Cl2-OCDD	59.1	55.4	69.1	75.1	97.6	79.1	68.6	67.1	79.0	78.2
Confirmation Data										
Surrogate Standards Recovery (%)										
37Cl-TCDD	100.0	103.0	99.5	100.0	101.0	99.2	41.6	101.0	94.6	92.7
Internal Standards Recovery (%)										
13Cl2-2378-TCDF	95.7	88.3	92.8	66.0	107.0	91.7	92.8	82.1	65.4	106.0
13Cl2-2378-TCDD	87.2	82.3	92.8	62.0	87.5	78.3	78.4	85.7	66.5	116.0

TABLE 6-13. STANDARDS RECOVERIES FOR THE CDD/CDF MODIFIED METHOD 5 BAGHOUSE OUTLET ANALYSES
BORGESS MEDICAL CENTER (1991)

	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Field Blank	TLI
Full Screen Analyses										
Surrogate Standards Recovery (%)										
37Cl-TCDD	97.7	97.3	102.0	99.8	103.0	99.3	98.8	99.6	102.0	101.0
13Cl2-PeCDF 234	109.0	99.1	97.8	97.8	101.0	97.5	109.0	109.0	92.8	99.3
13Cl2-HxCDF 478	107.0	102.0	111.0	107.0	120.0	105.0	109.0	111.0	99.1	107.0
13Cl2-HxCDD 478	95.8	115.0	112.0	130.0	110.0	96.1	114.0	108.0	71.3	86.0
13Cl2-HpCDF 789	108.0	99.8	102.0	108.0	101.0	84.1	109.0	113.0	86.3	119.0
Alternate Standards Recovery (%)										
13Cl2-HxCDF 789	99.7	79.1	95.7	104.0	97.2	89.7	97.2	88.1	93.5	88.6
13Cl2-HxCDF 234	126.0	135.0	133.0	132.0	121.0	158.0	141.0	141.0	116.0	139.0
Internal Standards Recovery (%)										
13Cl2-2378-TCDF	102.0	89.9	87.4	88.6	90.9	94.1	89.9	87.0	86.5	86.6
13Cl2-2378-TCDD	96.1	83.8	76.6	82.9	81.0	86.0	86.4	83.6	79.6	83.2
13Cl2-PeCDF 123	93.3	70.6	72.3	75.0	78.1	81.4	87.5	71.6	75.8	71.3
13Cl2-PeCDD 123	115.0	79.5	76.1	67.8	72.4	90.3	99.6	79.1	102.0	76.6
13Cl2-HxCDF 678	84.9	71.1	93.7	94.1	72.9	102.0	80.2	71.9	91.4	61.3
13Cl2-HxCDD 678	111.0	92.9	116.0	93.4	96.4	149.0	105.0	106.0	141.0	91.8
13Cl2-HpCDF 678	85.6	63.5	88.4	84.7	77.2	88.2	79.3	71.0	82.3	74.0
13Cl2-HpCDD 678	86.1	63.5	80.0	81.7	73.8	80.1	78.7	72.5	83.0	73.8
13Cl2-OCDD	81.8	56.5	51.8	70.7	60.5	46.0	70.8	56.8	60.8	62.9
Confirmation Data										
Surrogate Standards Recovery (%)										
37Cl-TCDD	93.8	95.2	93.7	95.0	96.2	95.2	95.3	95.8	95.6	92.7
Internal Standards Recovery (%)										
13Cl2-2378-TCDF	81.1	84.1	76.4	78.7	59.2	71.3	78.4	81.6	101.0	106.0
13Cl2-2378-TCDD	77.1	78.8	69.6	77.3	58.1	68.9	78.0	82.5	110.0	116.0

TABLE 6-14. STANDARDS RECOVERIES FOR THE BAGHOUSE ASH AND INCINERATOR ASH CDD/CDF ANALYSES
BORGESS MEDICAL CENTER (1991)

	Run 2		Run 3		Run 4		Run 5		Run 6		Run 7		Run 8		Run 9		TLI
	BAG H.	INCIN.	BAG H.	INCIN.	BAG H.	INCIN.	BAG H.	INCIN.	BAG H.	INCIN.	BAG H.	INCIN.	BAG H.	INCIN.	BAG H.	INCIN.	
Full Screen Analyses																	
Surrogate Standards Recovery (%)																	
37Cl-TCDD	69.5	58.3	50.9	70.8	52.3	77.9	65.1	76.1	63.0	66.5	71.8	76.4	54.5	59.1	70.4	70.2	39.1
13Cl2-PeCDF 234	84.1	98.6	67.2	101.0	70.8	85.0	77.9	82.0	75.8	84.1	119.0	129.0	74.4	78.5	91.9	75.0	88.7
13Cl2-HxCDF 478	97.1	135.0	105.0	101.0	110.0	103.0	121.0	97.5	128.0	88.1	104.0	127.0	100.0	88.2	95.1	119.0	45.2
13Cl2-HxCDD 478	110.0	114.0	114.0	106.0	114.0	103.0	118.0	104.0	113.0	100.0	106.0	117.0	108.0	96.1	138.0	113.0	55.9
13Cl2-HpCDF 789	72.6	75.1	69.9	84.1	75.2	54.8	73.7	64.7	70.8	61.3	93.4	71.1	77.1	73.5	75.3	71.3	52.2
Alternate Standards Recovery (%)																	
13Cl2-HxCDF 789	106.0	88.0	95.5	86.0	89.6	86.5	94.2	79.4	93.8	77.6	91.9	90.4	78.8	79.3	85.5	93.5	51.9
13Cl2-HxCDF 234	146.0	190.0	120.0	95.8	130.0	92.0	146.0	163.0	128.0	138.0	103.0	151.0	91.4	83.7	97.9	98.6	77.0
Internal Standards Recovery (%)																	
13Cl2-2378-TCDF	61.1	64.9	46.3	66.3	47.8	79.0	70.0	82.9	63.0	66.9	71.4	83.4	51.0	54.9	64.0	74.1	36.4
13Cl2-2378-TCDD	74.2	63.3	55.7	78.2	56.9	89.5	74.4	84.7	67.9	69.3	82.4	81.0	58.4	65.0	69.6	82.7	41.8
13Cl2-PeCDF 123	76.9	103.0	59.3	97.5	64.3	90.5	88.0	84.7	75.3	82.2	105.0	126.0	68.4	79.3	88.8	85.5	75.0
13Cl2-PeCDD 123	97.9	111.0	78.6	104.0	81.6	94.9	94.9	126.0	90.2	90.2	116.0	172.0	77.1	80.8	99.3	79.2	110.0
13Cl2-HxCDF 678	100.0	116.0	128.0	92.9	142.0	94.4	198.0	124.0	132.0	90.6	92.8	126.0	80.5	78.9	78.0	105.0	51.8
13Cl2-HxCDD 678	115.0	114.0	115.0	91.4	116.0	86.2	115.0	149.0	110.0	97.0	93.0	125.0	82.5	82.4	88.5	95.1	61.2
13Cl2-HpCDF 678	89.9	135.0	87.5	85.4	97.8	81.8	110.0	83.8	107.0	74.4	99.8	128.0	64.8	71.5	70.5	85.8	49.9
13Cl2-HpCDD 678	85.5	109.0	84.2	99.5	90.8	70.1	89.2	83.0	85.3	77.7	108.0	104.0	67.7	84.7	80.1	83.6	51.4
13Cl2-OCDD	74.7	98.2	70.6	110.0	81.6	44.8	75.4	71.6	66.6	62.3	135.0	102.0	62.5	94.7	88.2	87.6	49.0
Confirmation Data																	
Surrogate Standards Recovery (%)																	
37Cl-TCDD	70.2	63.5	60.5	75.6	59.3	94.0	76.8	79.7	77.8	74.1	85.2	72.3	47.0	66.3	60.8	90.2	NA
Internal Standards Recovery (%)																	
13Cl2-2378-TCDF	74.8	74.3	60.5	86.8	58.9	94.7	89.9	93.3	77.3	76.5	93.6	76.8	47.3	75.2	63.8	103.0	NA
13Cl2-2378-TCDD	68.5	69.4	57.8	76.8	60.5	102.0	83.2	87.5	80.0	75.6	88.7	74.0	52.4	65.3	64.3	94.8	NA

criterion. This is not expected to affect the quality of the data. More information on standards recoveries can be found in Appendix E.

6.4.2 Metals Analytical Quality Assurance

The analytical methods used for the flue gas samples, the ash samples, and the metals samples are fully discussed in Section 5. The following paragraph will briefly report metals analytical QA parameters.

Table 6-15 presents the metals method blank results for the ash and flue gas samples. No metals were detected in the ash blank. Aluminum, Ba, and Pb were detected in the flue gas method blank at low levels. Table 6-16 presents the field blank metal results with the field blank for the flue gas samples. There was a noticeable contamination in the field blanks. The front half samples were contaminated with Al, Sb, Cr, and Ni. The back half samples were contaminated with Al, As, Cr, Cu, Hg, and Ni. The samples were not blank corrected, but it should be noted that the contamination is present.

Table 6-17 presents the method and matrix spike results for the metals analysis. All spiked recoveries were within the QA allowance of ±20 percent of 100 percent. Silver, in the matrix spike for the ash sample, had low recoveries probably due to the presence of anions precipitating the Ag out of solution. No matrix corrections were applied.

6.4.3 Mercury 101A Analytical Quality Assurance

Table 6-9 presents the method blank Hg 101A analysis. No Hg was detected in the blank. Table 6-9 presents the matrix spike results. All spike recoveries were within ±10 percent of 100 percent acceptance.

6.4.4 Halogen Analytical Quality Assessment

The analysis for Cl^-, F^-, and Br^- incorporate stringent QA/QC guidelines. Table 6-10 presented the method blank results for the IC analysis. None of the target halogen ions were detected in any of the method blanks or the reagent blank. The field blank revealed very low amounts of HCl, which represented a small percentage of the sample run amounts.

The matrix spike recoveries are shown in Table 6-18. Results for all 3 ions were within the 20 percent criteria.

Table 6-15

METALS ASH AND FLUE GAS METHOD BLANK RESULTS - BORGESS MEDICAL CENTER (1991)

Metal	Ash Method Blank (mg/kg)	Flue Gas Method Blank		
		Front Half (total ug)	Impingers 1,2,3 (total ug)	Impingers 4,5,6 (total ug)
Aluminum	[3.00]	5.81	8.04	
Antimony	[0.600]	[1.50]	[0.109]	
Arsenic	[0.800]	[0.400]	[0.436]	
Barium	[3.00]	0.130	[0.109]	
Beryllium	[0.200]	[0.100]	[0.109]	
Cadmium	[0.200]	[0.200]	[0.218]	
Chromium	[0.400]	[0.600]	[0.654]	
Copper	[1.20]	[0.400]	[0.436]	
Lead	[1.20]	0.471	[0.327]	
Mercury	[1.96]	[2.45]	[6.91]	[7.53]
Nickel	[0.600]	[0.300]	[0.327]	
Silver	[0.600]	[0.600]	[0.646]	
Thallium	[1.20]	[10.0]	[10.9]	

NOTE: Impingers 4,5 and 6 sample fractions analyzed for Mercury content only.

[ ] = Minimum Detection Limit.

Table 6-16
METALS AMOUNT IN FIELD BLANK FLUE GAS BY SAMPLE FRACTION - BORGESS MEDICAL CENTER (1991)

METALS	INLET				OUTLET			
	Front Half (total ug)	Impinger 1,2,3 (total ug)	Impinger 4,5,6 (total ug)	Total ug	Front Half (total ug)	Impinger 1,2,3 (total ug)	Impinger 4,5,6 (total ug)	Total ug
Aluminum	468	22.0		490	152	23.2		175
Antimony	30.0	[1.85]		30.0	10.2	[1.71]		10.2
Arsenic	[1.00]	0.655		0.655	[0.400]	[0.457]		[0.857]
Barium	15.8	1.03		16.8	3.79	0.503		4.29
Beryllium	[0.250]	[0.124]		[0.374]	[0.100]	[0.114]		[0.214]
Cadmium	8.93	[0.247]		8.93	0.490	0.263		0.753
Chromium	47.5	4.21		51.7	4.90	6.63		11.5
Copper	46.5	9.65		56.2	16.2	79.8		96.0
Lead	27.3	0.538		27.8	2.62	1.04		3.66
Mercury	[2.45]	20.0	30.6	50.6	[0.980]	18.5	[0.529]	18.5
Nickel	59.5	3.49		63.0	94.3	6.48		101
Silver	[1.50]	[1.85]		[3.35]	4.72	0.800		5.52
Thallium	[25.0]	[12.4]		[37.4]	[10.0]	[11.4]		[21.4]

[ ] = Minimum Detection Limit

NOTE: Analyzed impingers 4,5 and 6 for mercury only

Table 6-17

METALS METHOD AND MATRIX SPIKE RESULTS - BORGESS MEDICAL CENTER (1991)

Metal	Method Spike (% rec)			Method Spike Duplicate (% rec)			Ash Samples (% rec)	
	Front Half	Impingers 1,2,3	Impingers 4,5,6	Front Half	Impingers 1,2,3	Impingers 4,5,6	Matrix Spike	Matrix Spike Dup
Aluminum	106%	107%		106%	109%		85.4%	109%
Antimony	101%	103%		102%	103%		87.9%	91.2%
Arsenic	107%	103%		105%	93.8%		97.9%	97.9%
Barium	95.0%	93.7%		94.2%	94.4%		87.4%	90.2%
Beryllium	95.6%	97.2%		95.6%	98.0%		83.1%	85.7%
Cadmium	101%	102%		101%	103%		83.0%	85.2%
Chromium	102%	103%		103%	103%		85.3%	87.4%
Copper	99.6%	95.8%		99.3%	97.0%		81.6%	86.2%
Lead	96.2%	97.0%		93.2%	101%		85.6%	88.6%
Mercury	97.8%	97.6%	97.6%	103%	103%	96.8%	100%	105%
Nickel	100%	102%		101%	102%		82.2%	84.4%
Silver	86.2%	92.7%		104%	95.7%		8.00%	35.2%
Thallium	97.7%	102%		106%	99.0%		85.9%	86.1%

NOTE: Impingers 4,5 and 6 sample fractions analyzed for Mercury content only.

TABLE 6-18. HALOGEN MATRIX SPIKE AND MATRIX SPIKE DUPLICATES RECOVERY VALUES; BORGESS MEDICAL CENTER (1991)

ANALYTE	RUN 4A		RUN 5B		RUN 6C		RUN 7C		RUN 8C	
	MATRIX SPIKE RECOVERY (%)	MATRIX SPIKE DUPLICATE RECOVERY (%)	MATRIX SPIKE RECOVERY (%)	MATRIX SPIKE DUPLICATE RECOVERY (%)	MATRIX SPIKE RECOVERY (%)	MATRIX SPIKE DUPLICATE RECOVERY (%)	MATRIX SPIKE RECOVERY (%)	MATRIX SPIKE DUPLICATE RECOVERY (%)	MATRIX SPIKE RECOVERY (%)	MATRIX SPIKE DUPLICATE RECOVERY (%)
Cl	118.0%	118.0%	101.0%	101.0%	160.0%	119.0%	94.5%	97.3%	107.0%	105.0%
F	91.2%	91.7%	81.4%	81.1%	94.4%	112.0%	91.7%	93.6%	96.0%	94.1%
Br	119.0%	119.0%	101.0%	103.0%	114.0%	109.0%	101.0%	105.0%	127.0%	118.0%

6.5 CEM QUALITY ASSURANCES

Flue gas was analyzed for O_2, CO_2, CO, SO_2, NO_x, and THC, using EPA Methods 10, 3A, 6C, 7E, and 25A, respectively. An additional CEM analyzer was also employed for real time HCl gas concentrations. The following section will report the CEM QA parameters specific for each of those methods and analyzers.

6.5.1 CEM Data Overview

Daily QA/QC procedures were performed on the CEM sampling system and instruments. These included calibration drift checks and corrections (if necessary) , QC gas challenges, sample system bias checks, response time checks, leak checks, sample systems blow back, probe maintenance, filter replacement, conditioner inspection and maintenance, and others. The aim was to ensure that quality data were produced. Details of the CEM QC procedures and objectives are fully outlined in the Borgess Test Plan. The following sections will report QA parameters specific to the previously mentioned QA/QC procedures and also data variation.

Table 6-19 presents the CEM internal QA/QC checks along with their respective acceptance criteria which were conducted at the Borgess MWI tests.

6.5.2 Calibration Drift Checks

All CEM analyzers were calibrated daily with a zero gas (generally nitrogen), and a high-range span gas. Calibrations were performed prior to and at the completion of each test run. By comparing the post-test calibration to the pre-test calibration, the calibration drift was determined (zero drift and span drift).

Daily drift criteria between calibrations for both zero and span was ±5 percent of full scale. Although Method 10 for CO allows ±10 percent of full scale drift, the CO drift requirements were ±5 percent for this test program to ensure the high quality of data produced. The HCl drift criteria was set at ±10 percent of full scale. This was because the calibration routines using the HCl dilution probe necessitate a constant sample gas temperature. While testing a fluctuating process like MWIs, this can be difficult to achieve. Pre-test calibrations are typically conducted after the incinerator has reached full operating temperature. The gas temperature during the post-test calibrations may have differed enough to produce false calibration drift estimates.

TABLE 6-19. CEM INTERNAL QA/QC CHECKS

Check	Frequency	Criteria
Multipoint Linearity Check (Calibration Error)	Every 3rd Day 3 point for O_2, CO_2, NO_x, SO_2, HCl 4 point for CO, THC	±2% Span
Sample System Bias	Once/Site	< 5% Span
Response Time	Once/Site	85% of time for stable SO_2 measurements
NO_x Convertor	Once/Site	> 90% conversion efficiency
Initial Leak Check	Once/Site	< 4% of Total flow while under vacuum
Daily Leak Checks	Before Each Test Run	< 0.5% O_2 with 0.2% O_2 gas
Stratification Test	Once/Site	Within 10% of average
Calibration Drift	Daily	< ±3% Span zero and upscale gas (can use ±10 ppm limit for HCl if less restrictive)

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However, the constant temperature problem was minimized during this test program by the use of a CEM probe heater, which minimizes probe gas temperature fluctuations.

The zero and span calibration drift results for each CEM analyzer on each test day are listed in Appendix D.3. All analyzers met the drift criteria throughout the program (over 100 drift checks), except the outlet CO monitor for Run 3. The outlet CO drifts for this day were 6.76 and -3.24 percent of full scale, respectively. These data were drift corrected assuming linear drift between calibrations.

6.5.3 Daily QC Gas Challenges

After initial calibration, mid-range QC gases for all instruments were analyzed with no adjustment as a quality control check of daily calibrations. The calibration was considered acceptable if the difference between the measured response and the certified concentration was within ±2 percent of full scale of the analyzer full range. Post test QC gases were analyzed after the test run (with no adjustment) as well.

The results of the daily QC gas challenges are shown in Appendix D.4. The QC responses were not quantitated in terms of percent of full scale deviation; however, if a QC gas challenge did show any calibration problems in the field, these would have been noted and rectified.

6.5.4 Multipoint Linearity Check

Multipoint linearity can be determined for each CEM analyzer based on the response of the calibration and QC gases. A linearity calibration is important because flue gas concentrations are determined from a two point linear regression analysis (zero calibration and span calibration gas) bracketing the expected flue gas concentrations. Multipoint calibrations can be performed with either three or four certified gases depending on the instrument: a zero gas, a low scale gas concentration, a mid-range concentration, and a high scale concentration (span gas). The QC criterion for acceptable linearity was a correlation coefficient (R^2) of greater than or equal to .998, where the independent variable is the cylinder gas concentration and the dependent variable is the instrument response.

CEM linearity was calculated for the inlet and outlet instruments from calibration and pre-test QC gas data from September 7, 1991; these calculations are listed in Appendix D.5. All linearity checks met the acceptance criteria except the outlet HCl

CEM, which had an R^2 value of 0.997. No corrective action was taken for this occurrence. The inlet HCl linearity for that day was R^2 = 0.9999. Linearity can be calculated for any test day by using the calibration and QC data included in Appendix D.4.

6.5.5 Sample Bias

Sample bias can be described as any CEM inaccuracies caused by the CEM sampling system. Normal calibrations are performed by directing calibration gas straight to the analyzers. Sample bias is determined by directing QC gases to the probe and pulling them through the entire sampling system (heat trace, conditioner/pump, manifold, etc.). Any deviation that the "through-the-system" response showed from the QC response of a direct QC gas challenge would be defined as sample bias.

All HCl calibrations were performed through the sampling system which would correct for any bias which may have occurred. Sample bias on the other instruments was checked on September 15 and 16, 1991. September 15 bias checks were completed on the SO_2 analyzers during the response time check. Bias checks were completed on all analyzers on September 16, 1991 as each QC gas was directed to the probe and back through the entire sampling system. The sample bias criterion for the Borgess test program was that bias response deviation was to be no greater than ±5 percent of span. The sample bias data is listed in Appendices D.4 and D.5. The data have not been quantitatively assessed in terms of percent of full scale but (as with the QC gas challenges), if any sample bias was detected in the field, it would have been noted and rectified.

6.5.6 Response Time

CEM response time was determined on September 15, 1991, and the results are shown in Appendix D.5. Response time for the Borgess test program was defined as the amount of time taken for the SO_2 analyzer to reach 85 percent of a QC gas value when the gas was directed through the entire sampling system. Both inlet and outlet extractive systems had response times of approximately 2 minutes.

6.5.7 Stratification Checks

Because the size of the ducts sampled in the Borgess Test Program were so small (inlet diameter = 15.5 inches, outlet diameter = 26.5 inches), stratification of CEM gases in the ducts was assumed to be negligible.

6.6 DATA VARIABILITY

6.6.1 Overview

Coefficients of variation (CV) were calculated for all the final stack gas pollutant concentrations. The CV or relative standard deviation (RSD) is calculated by dividing the standard deviation by the mean and expressing it as a percentage. Coefficient of variations from several distinct groups of data can be combined into a "Pooled CV". The pooled CV is calculated as follows:

$$CV = \frac{S}{M} \times 100$$

where:

CV = Coefficient of variation

S = Standard deviation (calculated using LOTUS 123™ which uses n and not n-1 where n = number of data points.)

M = mean

$$CV_p = \sqrt{\frac{\Sigma (CV_i)^2 n_i}{\Sigma n_i}}$$

CV_p = Pooled coefficient of variation

CV_i = Coefficient of variation for a simple sample set i.

n_i = Number of data points in that sample set.

The CV values expressed in the following tables are not intended to represent sampling/analytical precision. They reflect the variability of the data as a whole, including process-caused emission variability.

6.6.2 CDD/CDF Data Variation

Tables 6-20, 6-21, and 6-22 present the CVs for the CDD/CDF flue gas concentrations. Values are listed for each congener for each triplicate run, as well as a pooled CV for the entire eight runs. Pooled CVs are also compiled for all of the congeners at each location and for the entire test program (overall). The overall pooled CVs for the CDD/CDF flue gas concentrations was 16.67 percent at the boiler inlet, 19.07 percent at the baghouse inlet, and 26.03 percent baghouse outlet.

6.6.3 Metals and Mercury 101A Data Variation

Table 6-23 presents the CVs for the metal flue gas concentrations for the three test conditions. Table 6-24 presents the CVs for the Hg 101A results for the three test conditions.

6.6.4 Halogen Data Variation

The halogen gas test CVs are listed in Table 6-25. Values were calculated for each run, which consisted of three "sub-runs" during the course of the day's test run. The CVs were calculated for HCl, HF, and HBr for the runs at the baghouse inlet and outlet. The overall pooled CVs for the halogen gas results ranged from 38.32 percent to 67.93 percent.

6.6.5 CEM Data Variation

The variability of the CEM data has been quantified in this section by calculating CV for each analyzer on each day. The CV's were calculated by dividing the standard deviation by the mean for each set of daily data and expressing it as a percentage. It is important to note that the variability expressed by these values is not an indicator of the precision of the test method. These values are mostly a reflection of the variability of the process itself with respect to emissions of specific compounds. In addition to CV values for data from one compound for one day, pooled CV values were also calculated for various combined data sets. Pooled CVs are calculated by taking the square root of the sum of the squares of the individual CV values. Pooled CVs were calculated for all the data sets from each sample location per day, for each analyzer data set for the entire test program (i.e., inlet CO), and for the entire CEM data set.

TABLE 6-20. COEFFICIENTS OF VARIATION FOR CDD/CDF FLUE GAS EMISSIONS; BORGESS MEDICAL CENTER (1991)

BOILER INLET

	Coefficients of Variation (CV)			
CONGENER	RUNS 2,3,4	RUNS 5,6	RUNS 7,8,9	Pooled CV
DIOXINS				
2378 TCDD	7.530	31.451	58.633	39.468
Other TCDD	21.181	89.308	11.169	47.000
12378 PCDD	14.879	43.770	2.630	23.761
Other PCDD	15.087	53.660	33.692	35.084
123478 HxCDD	17.077	37.335	17.488	23.928
123678 HxCDD	9.857	29.122	8.978	16.694
123789 HxCDD	16.310	20.214	22.275	19.697
Other HxCDD	22.138	30.820	32.640	28.649
1234678-HpCDD	14.643	7.590	23.981	17.620
Other Hepta-CDD	16.555	1.347	23.592	17.662
Octa-CDD	6.088	25.415	51.876	34.417
Total CDD	10.634	14.395	33.375	22.626
FURANS				
2378 TCDF	47.102	26.131	40.156	40.092
Other TCDF	25.376	40.310	16.314	27.340
12378 PCDF	9.426	43.563	11.979	23.697
23478 PCDF	11.719	36.723	15.114	21.779
Other PCDF	25.291	35.815	16.231	25.677
123478 HxCDF	15.018	17.323	9.702	13.961
123678 HxCDF	11.558	30.923	5.133	17.293
234678 HxCDF	18.986	28.995	8.177	19.246
123789 HxCDF	6.430	31.451	5.636	16.574
Other HxCDF	33.391	31.568	22.869	29.383
1234678-HpCDF	21.356	7.688	18.033	17.543
1234789-HpCDF	17.635	5.048	8.813	12.334
Other Hepta-CDF	26.856	2.103	5.067	16.769
Octa-CDF	19.975	21.233	27.530	23.378
TOTAL CDF	19.228	13.691	13.424	15.908
TOTAL CDD+CDF	17.907	13.823	17.110	16.667

TABLE 6-21. COEFFICIENTS OF VARIATION FOR CDD/CDF FLUE GAS EMISSIONS; BORGESS MEDICAL CENTER (1991)

BAGHOUSE INLET

	Coefficients of Variation (CV)			
CONGENER	RUNS 2,3,4	RUNS 5,6	RUNS 7,8,9	Pooled CV
DIOXINS				
2378 TCDD	33.843	51.888	21.124	35.636
Other TCDD	54.570	55.426	31.094	47.405
12378 PCDD	25.796	46.440	23.674	31.605
Other PCDD	20.962	66.434	15.167	36.803
123478 HxCDD	27.963	48.614	11.871	30.609
123678 HxCDD	29.062	40.643	19.165	29.452
123789 HxCDD	5.787	38.972	8.851	20.534
Other HxCDD	26.458	40.291	13.303	27.106
1234678-HpCDD	29.697	26.609	10.546	23.440
Other Hepta-CDD	71.019	29.209	12.831	46.545
Octa-CDD	24.041	0.738	5.338	15.085
Total CDD	30.685	17.577	9.031	21.469
FURANS				
2378 TCDF	43.315	1.737	46.535	38.941
Other TCDF	47.702	50.725	23.886	41.358
12378 PCDF	26.727	53.246	11.102	31.982
23478 PCDF	29.598	48.694	20.554	32.859
Other PCDF	35.450	48.512	5.089	32.701
123478 HxCDF	9.380	36.380	9.888	20.013
123678 HxCDF	20.540	44.405	10.383	26.298
234678 HxCDF	18.085	41.881	15.357	25.487
123789 HxCDF	35.919	27.257	6.008	26.136
Other HxCDF	25.401	38.368	9.279	25.343
1234678-HpCDF	17.634	13.834	7.447	13.611
1234789-HpCDF	2.663	6.235	6.575	5.347
Other Hepta-CDF	15.801	4.763	8.962	11.376
Octa-CDF	70.997	6.283	10.709	44.081
TOTAL CDF	23.422	24.936	8.098	19.641
TOTAL CDD+CDF	24.019	23.333	8.249	19.441

TABLE 6-22. COEFFICIENTS OF VARIATION FOR CDD/CDF FLUE GAS EMISSIONS; BORGESS MEDICAL CENTER (1991)

BAGHOUSE OUTLET

	Coefficients of Variation (CV)			
CONGENER	RUNS 2,3,4	RUNS 5,6	RUNS 7,8,9	Pooled CV
DIOXINS				
2378 TCDD	24.840	19.101	53.457	37.340
Other TCDD	22.634	0.448	46.242	31.528
12378 PCDD	34.208	14.625	57.370	41.552
Other PCDD	33.881	22.648	45.305	36.447
123478 HxCDD	21.777	18.272	49.761	34.494
123678 HxCDD	27.968	49.650	37.330	37.844
123789 HxCDD	25.688	59.867	51.726	46.333
Other HxCDD	18.776	57.291	4.891	31.012
1234678-HpCDD	60.244	34.474	8.395	41.043
Other Hepta-CDD	54.440	46.947	7.570	41.035
Octa-CDD	64.310	11.554	9.731	40.247
Total CDD	51.861	30.228	2.641	35.208
FURANS				
2378 TCDF	23.693	33.731	29.059	28.489
Other TCDF	9.606	54.745	35.032	35.271
12378 PCDF	24.440	53.448	38.729	38.738
23478 PCDF	18.837	35.902	15.700	23.404
Other PCDF	12.770	61.354	70.881	53.724
123478 HxCDF	10.155	29.821	16.606	19.089
123678 HxCDF	19.613	40.376	31.789	30.508
234678 HxCDF	33.019	30.777	23.759	29.280
123789 HxCDF	41.717	16.279	62.852	46.907
Other HxCDF	9.930	75.997	76.802	60.768
1234678-HpCDF	40.995	24.560	19.067	30.288
1234789-HpCDF	51.545	3.857	6.296	31.858
Other Hepta-CDF	39.639	7.423	25.695	29.165
Octa-CDF	62.088	26.857	16.135	41.516
TOTAL CDF	32.453	22.948	14.603	24.629
TOTAL CDD+CDF	36.017	25.596	8.524	26.029

Table 6-23

COEFFICEINTS OF VARIATION OF THE FLUE GAS METALS CONCENTRATIONS AT THE INLET AND OUTLET BORGESS MEDICAL CANTER (1991)

Condition Run	Without Carbon Injection		Carbon Injection @ 1 lb/hr		Carbon Injecton @ 2.5 lb/hr	
	Inlet 2 thru 4 CV (%)	Outlet 2 thru 4 CV (%)	Inlet 5 & 6 CV (%)	Outlet 5 & 6 CV (%)	Inlet 7 thru 9 CV (%)	Outlet 7 thru 9 CV (%)
Aluminum	24.3%	3.63%	22.8%	3.54%	22.8%	16.4%
Antimony	47.6%	13.1%	27.9%	2.52%	61.3%	5.24%
Arsenic	17.9%	71%	1.62%	70.7%	56.2%	NA
Barium	46.0%	13.5%	20.1%	12.6%	73.8%	11.9%
Beryllium	NA	NA	NA	NA	NA	NA
Cadmium	2.51%	39.4%	117%	1.36%	65.6%	147%
Chromium	42.7%	52.8%	46.0%	42.1%	39.2%	11.3%
Copper	31.3%	81.9%	30.3%	1.87%	66.9%	63.8%
Lead	47.1%	51.3%	30.1%	39.9%	62.3%	63.6%
Mercury	46.7%	46.6%	23.5%	12.7%	43.1%	84.5%
Nickel	24.3%	38.7%	39.4%	24.8%	22.2%	23.9%
Silver	101%	73.9%	9.52%	70%	44.8%	70.8%
Thallium	NA	NA	NA	NA	NA	NA

NA = Not Applicable

Table 6-24

COEFFICEINTS OF VARIATION OF THE MERCURY 101A CONCENTRATIONS AT THE INLET AND OUTLET - BORGESS MEDICAL CENTER (1991)

Condition Run	Without Carbon Injection Inlet 2 thru 4 CV (%)	 Outlet 2 thru 4 CV (%)
Mercury	41.6%	41.6%
Condition Run	**Carbon Injection @ 1 lb/hr Inlet 5 & 6 CV (%)**	** Outlet 5 & 6 CV (%)**
Mercury	25.6%	15.4%
Condition Run	**Carbon Injecton @ 2.5 lb/hr Inlet 7 thru 9 CV (%)**	** Outlet 7 thru 9 CV (%)**
Mercury	39.4%	63.3%

TABLE 6-25. COEFFICIENTS OF VARIATION FOR HALOGEN
MANUAL FLUE GAS CONCENTRATIONS
BORGESS MEDICAL CENTER (1991)

TEST RUN NUMBER	HYDROGEN CHLORIDE		HYDROGEN FLOURIDE		HYDROGEN BROMIDE	
	B.H. INLET CV,(%)	B.H. OUTLET CV,(%)	B.H. INLET CV,(%)	B.H. OUTLET CV,(%)	B.H. INLET CV,(%)	B.H. OUTLET CV,(%)
AVERAGE 1-3	30.57%	72.36%	58.19%	5.49%	11.14%	65.61%
AVERAGE 4-6	27.29%	81.65%	52.80%	6.01%	54.76%	70.95%
AVERAGE 7-9	54.43%	49.36%	28.27%	4.14%	16.75%	5.18%
AVERAGE 10-12	35.61%	78.89%	34.59%	51.43%	39.55%	14.36%
AVERAGE 13-15	11.87%	59.40%	11.50%	17.25%	36.59%	18.60%
AVERAGE 16-18	56.55%	56.54%	26.92%	13.14%	89.17%	13.27%
AVERAGE 19-21	33.91%	71.53%	44.78%	10.60%	13.74%	10.35%
AVERAGE 22-24	31.11%	53.71%	30.87%	0.30%	6.47%	1.00%
TOTAL POOLED HALOGEN	37.69%	66.42%	38.71%	20.34%	42.56%	35.71%

The CEM CVs are listed in Table 6-26. The overall pooled CV value was 126 percent. Individual analyzer pooled CVs ranged from 4.7 percent for the outlet O_2 values to 303 percent for the outlet SO_2 values. Outlet CVs were generally higher than the corresponding inlet values.

TABLE 6-26. COEFFICIENTS OF VARIATION FOR THE CONTINUOUS EMISSIONS MONITORING DATA. BORGESS MEDICAL CENTER (1991)

DATE	RUN NO.	O2 CV (%)		CO2 CV (%)		CO CV (%)		NOx CV (%)		SO2 CV (%)		THC CV (%)		HCl CV (%)		Inlet Pooled by Day (%)	Outlet Pooled by Day (%)	Total Pooled by Day (%)
		Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet			
9/7	2	5.7	4.7	13.1	13.0	7.9	112.7	29.3	28.1	77.4	118.1	10.7	87.0	25.3	114.7	33.5	83.1	63.4
9/9	3	4.8	4.3	12.5	13.4	40.2	111.6	21.2	22.8	111.8	97.7	32.8	NR	29.4	114.9	48.8	77.4	63.6
9/10	4	4.0	3.6	11.9	12.7	13.3	118.4	21.5	21.9	467.5	507.0	15.3	NR	41.6	135.9	177.8	219.9	198.4
9/11	5	4.9	4.7	15.3	16.9	17.5	353.3	29.8	29.7	205.1	169.5	24.4	NR	43.8	124.0	81.1	168.4	129.0
9/12	6	6.5	4.6	43.4	14.2	10.1	88.3	31.0	52.0	212.8	24.8	17.7	NR	26.1	45.1	83.9	47.2	69.4
9/13	7	5.3	4.9	23.2	14.3	10.0	66.5	27.4	38.0	57.8	42.3	30.3	NR	21.6	62.1	29.6	44.2	37.1
9/14	8	8.0	4.7	22.6	13.6	38.4	381.7	25.2	NR	148.3	83.6	13.3	NR	30.7	33.4	60.7	175.5	122.4
9/16	9	10.4	5.9	20.8	13.5	35.7	640.9	26.0	NR	60.2	49.2	16.4	NR	28.3	67.4	32.0	289.1	188.2
POOLED		6.5	4.7	22.6	14.0	25.3	302.6	26.6	33.7	210.2	200.3	21.5	87.0	31.7	94.7			

OVERALL
POOLED 121.6

NC = Data not compiled yet.
NR = Not recorded (instrument was inoperative for these test runs).

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A-88-03

United States
Environmental Protection
Agency

Office of Air Quality
Planning and Standards
Research Triangle Park NC 27711

EPA-453/D-93-016
October 1992

Air

EPA

Ethylene Oxide Emissions from Commercial Sterilization/Fumigation Operations

DRAFT EIS

Background Information for Proposed Standards

NESHAP

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ETHYLENE OXIDE EMISSIONS FROM COMMERCIAL STERILIZATION/FUMIGATION OPERATIONS --

BACKGROUND INFORMATION FOR PROPOSED STANDARDS

Final

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ETHYLENE OXIDE EMISSIONS FROM COMMERCIAL STERILIZATION/FUMIGATION OPERATIONS -- BACKGROUND INFORMATION FOR PROPOSED STANDARDS

Emission Standards Division

U. S. ENVIRONMENTAL PROTECTION AGENCY
Office of Air and Radiation
Office of Air Quality Planning and Standards
Research Triangle Park, North Carolina 27711

March 1993

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INFORMATION COLLECTION REQUEST FOR ENHANCED MONITORING PROGRAM PURSUANT TO SECTION 114(a)(3) OF THE CLEAN AIR ACT

Prepared by

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January 27, 1993

001

1. IDENTIFICATION OF THE INFORMATION COLLECTION

1(a) TITLE OF THE INFORMATION COLLECTION

The title of this Information Collection Request (ICR) is "Enhanced Monitoring Program monitoring, reporting, and recordkeeping requirements."

1(b) SHORT CHARACTERIZATION (ABSTRACT)

The Enhanced Monitoring Program will require permit applications, monitoring, periodic reporting, and recordkeeping information collections. Such information will be collected by owners and operators of emission units that are subject to the operating permit program [57 Fed. Reg. 32250-32312] (1992) (to be codified at 40 C.F.R. Part 70) and that emit hazardous air pollutants and major amounts of other regulated air pollutants. Owners or operators will include in their permit applications descriptions of enhanced monitoring protocols and demonstrations that the data obtained from such protocols are sufficient to determine compliance with applicable emissions limitations or standards.

Upon approval by the permitting authority of the enhanced monitoring protocols, owners or operators will collect the data generated via the protocols to determine compliance with emissions limitations or standards. This data will provide the basis on which owners or operators can annually certify, in accordance with the requirements of the operating permit program, the compliance of their emissions units with the applicable emissions limitations or standards. In addition, this data will provide the basis on which owners or operators submit quarterly enhanced monitoring reports. Consistent with the recordkeeping period established in the operating permit program, all information will be stored and maintained for at least five years by owners and operators of affected emissions units.

The Environmental Protection Agency (EPA) and State or local air pollution regulatory agency will use the data in enforcement proceedings. Data summaries submitted by owners or operators can be used by environmental groups or citizens to determine compliance status of specific emissions units or categories of emissions units.

[redacted] monitoring [redacted] [redacted]. The cost includes the purchase of instrumental equipment as well as the development of enhanced monitoring protocols.

2. NEED FOR AND USE OF THE COLLECTION

2(a) NEED/AUTHORITY FOR THE COLLECTION

EPA decisions in both the operating permit and enhanced monitoring programs require this information. The operating permit program requires owners or operators of sources units that emit air pollutants to submit annual compliance certifications, to submit monitoring results at least semiannually, and to report deviations promptly, but no implementation guidance is provided with the operating permit program.

EPA formed a workgroup consisting of EPA, State, and local officials to develop the enhanced monitoring program, as well as to help implement the operating permit program. The workgroup determined that:

1) The compliance certifications required in the operating permit program should be based upon data obtained from enhanced monitoring to the extent practicable;

2) Enhanced monitoring need only apply to emissions units that would have the most impact on air quality;

3) The enhanced monitoring program should establish procedures to select monitoring systems, instead of prescribing monitoring systems;

4) Cost-effective instrumental, parameter, recordkeeping, or fugitive monitoring systems exist or could be innovated;

5) Owners or operators, in preconstruction or operating permit applications, should propose enhanced monitoring protocols and supply demonstrations that the proposed protocols provide data that can be used to determine compliance with emissions limitations or standards;

6) In many cases, existing monitoring requirements could serve as the basis for enhanced monitoring protocols;

7) The enhanced monitoring program could not increase the stringency of any existing emissions limitation or standard;

8) The enhanced monitoring program could not eliminate any compliance exemption or emissions excursion, as provided in existing rules;

9) The enhanced monitoring program could not change the emissions averaging times provided in existing rules;

10) Permitting authorities would accept, modify, or reject such protocols;

11) Upon acceptance of the protocols, owners or operators would implement their protocols by collecting data and performing associated quality assurance procedures;

12) Owners or operators would submit to the permitting authority quarterly enhanced monitoring reports detailing periods of noncompliance or indeterminate compliance;

13) Enhanced monitoring reports would detail deviations from emission limitations or standards;

14) Owners or operators who report periods of noncompliance or indeterminate compliance could only certify intermittent compliance under the operating permit program requirement;

15) All information should be kept by owners or operators of affected emissions units; and

16) Since the enhanced monitoring program helps implement part of the operating permit program, all enhanced monitoring information should be retained consistent with retention of operating permit program information.

Agency goals aided by the collection of this information include:

1) Providing cost-effective means of achieving air pollution emission reductions;

2) Enabling voluntary compliance and self-certification by owners or operators;

3) Using monitoring data for direct enforcement of emissions limitations and standards; and

4) Holding owners or operators accountable for regulated air pollutants emitted by units.

The Clean Air Act (Act) Amendments of 1990, Public Law 101-549, enacted on November 15, 1990, establish the legal authority for this information collection. Section 702(b) directs EPA to promulgate regulations that will require certain stationary sources of air pollution to install and operate enhanced monitoring systems and to submit compliance certifications.

This section amends section 114(a) of the Act by adding a new paragraph (3) that provides, in part,

> "(t)he Administrator shall in the case of any person which is the owner or operator of a major stationary source, and may, in the case of any other person, require enhanced monitoring and submission of compliance certifications. Compliance certifications shall include (A) identification of the applicable requirement that is the basis of certification, (B) the method used for determining the compliance status of the source, (C) the compliance status, (D) whether compliance is continuous or intermittent, (E) such other facts as the Administrator may require..."

In addition, related provisions under Title V of the Act specify that operating permits must include requirements on monitoring and compliance certification. Section 503(b)(2) states that permitted sources must certify compliance "no less frequently than annually." Section 504(c) requires that each permit must set forth "monitoring, compliance certification, and reporting requirements to assure compliance with the permit terms and conditions." Finally, section 504(b) permits the Administrator to promulgate appropriate test methods and monitoring requirements --

> "The Administrator may by rule prescribe procedures and methods for determining compliance and for monitoring and analysis of pollutants regulated under this Act, but continuous emissions monitoring need not be required if alternative methods are available that provide sufficiently reliable and timely information for determining compliance..."

2(b) USE/USERS OF THE DATA

Owners or operators of affected emissions units will use the information collected as the basis for the compliance certification required by the operating permit program, and as the basis for enhanced monitoring reports. Owners or operators could use the information collected to determine or maintain the efficiency of process or emissions control devices. Permitting authorities will use the information collected and submitted in permit applications in determining acceptability of proposed enhanced monitoring protocols. Permitting authorities will use the information collected in reports to other agencies and as evidence in enforcement proceedings. Permitting authorities will use the information collected from owners or operators that report deviations to ensure that the operating permit program compliance certification does not omit any period of noncompliance based on an interpretation made solely by owners or operators and to ensure that proper action is taken to minimize excess emissions.

Citizens will be able to use the information collected to determine the compliance status of each affected emissions unit.

Permitting authorities will collect summaries of the information and will review the information as part of their permitting responsibilities and ongoing compliance activities. The information may be entered into local, regional, or national databases for review and action by local, regional, or national air pollution control agencies. Other Federal bodies, such as the Department of Energy, may request and use the information collected to fulfill specific mission objectives. Citizens may request the information collected in order to determine the compliance status of any emissions unit or particular group of emissions units.

3. THE RESPONDENTS AND THE INFORMATION REQUESTED

3(a) RESPONDENTS/SIC CODES

The enhanced monitoring program applies to most Standard Industrial Classification (SIC) code groups. The enhanced monitoring program also applies to certain service industries regulated under the Act.

3(b) INFORMATION REQUESTED

(i) Data items

Reporting Requirements	Regulation Reference
Base compliance certifications on data collected from enhanced monitoring protocols	64.5(a)
Submit no less frequently than quarterly an enhanced monitoring report for each enhanced monitoring protocol required	64.5(b)
Submit reports which contain:	
Company name and mailing address, the facility name and street location, if different, and the EPA identification code	64.5(c)(1)
The name, daytime telephone number and facsimile number (if available) of the responsible official submitting the report	64.5(c)(2)
The emissions unit and regulated air pollutant	65.5(c)(3)

Specific identification of the applicable regulation and permit condition, and the emission limitation or standard	64.5(c)(4)
A description of the enhanced monitoring protocol	64.5(c)(5)
The calendar period covered by the report	64.5(c)(6)
The number of hours the emission unit operated during the reporting period	64.5(c)(7)
A summary of the number and duration of deviations classified by reason and, if applicable, the number and duration of periods of indeterminate compliance	64.5(c)(8)
Identification of the data availability achieved during the reporting period, including a summary of the number of and total duration of incidents that the enhanced monitoring protocol failed to operate in accordance with the design of the protocol or produced data that did not meet the minimum data accuracy and precision requirements, classified by reason	64.5(c)(9)
If the total duration of deviations exceeds a fixed percentage, a copy of the information recorded pursuant to 64.6(a)(3)(i)-(iv) shall be included	64.5(c)(10)
If the data availability for an enhanced monitoring protocol is less than a fixed percentage, a copy of the information recorded pursuant to 64.6(a)(3)(i)-(vi) shall be included	64.5(c)(11)
A summary of the results of any other required activity	64.5(c)(12)
Submit reports signed by the responsible official, who must certify that, based on information and belief formed after reasonable inquiry, the statements and information in the document are true, accurate, and complete	64.5(d)
Submit reports within thirty days following the last day of the reporting period	64.5(e)

Perform the procedures in subpart B of part 2 of chapter 40 if protection from public disclosure of reported information (other than emissions data) is desired	64.5(f)

Recordkeeping Requirements	Regulation Reference
Maintain enhanced monitoring records for a minimum of five years from the date of any monitoring, testing, certification, reporting or other activity required. These records shall include:	
All documentation relating to the design, installation and testing of all elements of the enhanced monitoring protocol and all required compliance plan activities	64.6(a)(1)
All maintenance logs, calibration checks, and other required quality assurance activities, and all records of corrective and preventive action	64.6(a)(2)
All documentation supporting required enhanced monitoring reports and those elements of a compliance certification submitted pursuant to title V of the Act that are based on data from an enhanced monitoring protocol, including documentation of:	
Each period that the enhanced monitoring protocol identified deviations, including:	
The date and time that each period of deviation began and ended	64.6(a)(3)(i)(A)
The magnitude of each deviation	64.6(a)(3)(i)(B)
The reason for each deviation	64.6(a)(3)(i)(C)
A description of the action taken to correct the deviation, including action taken to minimize each deviation and action taken to prevent recurrence	64.6(a)(3)(i)(D)

Each period that the enhanced monitoring protocol identified periods of indeterminate compliance, including:	
The date and time that each period of indeterminate compliance	64.6(c)(3)(ii)(A)
The parameter value during each period of indeterminate compliance that is nearest to the estimated correlation level established in accordance with the procedures in Appendix D	64.6(a)(3)(ii)(B)
The reason for each such period	64.6(a)(3)(ii)(C)
A description of any corrective action that was taken during any such period, including action taken to minimize the duration of each period and action taken to prevent a recurrence	64.6(a)(3)(ii)(D)
The date and time of the beginning and end of each period that the emissions unit was not in operation	64.6(a)(3)(iii)
Each period that any element of the enhanced monitoring protocol was not operating in accordance with its design, and each period that the enhanced monitoring protocol was in operation but producing unacceptable data, including:	
The date and time that each period began and ended	64.6(a)(3)(iv)(A)
An indication for each period of whether the monitoring protocol was not in operation or was producing unacceptable data	64.6(a)(3)(iv)(B)
The reason for inoperation or unacceptable data	64.6(a)(3)(iv)(C)
A description of the corrective action that was taken for each incident, including action taken to prevent a recurrence	64.6(a)(3)(iv)(D)
All calibrations and other quality assurance activities performed on any element of the enhanced monitoring protocol	64.6(a)(3)(v)
All calculation factors and equations	64.6(a)(3)(vi)

All measurements and calculations	64.6(a)(3)(vii)
All other data collected or recorded as part of the enhanced monitoring protocol	64.6(a)(3)(viii)
Maintain the records so that they may be inspected by the permitting authority or the Administrator and so that they may be submitted expeditiously to the permitting authority or the Administrator	64.6(b)

(ii) Respondent Activities

The following are the activities that the owner or operator of a unit that emits volatile organic compounds (VOC) will have to perform to meet the recordkeeping and reporting requirements of the rule:

1. Review requirements
2. Process, compile, and review data
3. Conduct data reduction and reduction and reporting
4. Conduct work practice reporting
5. Conduct mass balance reporting
6. Assess enhanced monitoring (EM) data prior to certifying compliance (CC)
7. Maintain records

An owner or operator of a unit that emits total suspended particulate (TSP), sulfur dioxide (SO_2), carbon monoxide (CO), or nitrogen oxides (NO_x) will have to perform the following tasks:

1. Review requirements
2. Process, compile, and review data
3. Conduct data reduction
4. Assess EM data prior to CC
5. Maintain records

4. THE INFORMATION COLLECTED--AGENCY ACTIVITIES, COLLECTION METHODOLOGY, AND INFORMATION MANAGEMENT

4(a) AGENCY ACTIVITIES

The State and local agencies shall perform the following activities:

1. Develop guidelines
2. Conduct audits
3. Review data
4. Review compliance submissions

The EPA shall perform the following activity:

1. Provide oversight and guidance to State and Local agencies.

4(b) COLLECTION METHODOLOGY AND MANAGEMENT

The EPA has developed sample forms which are available upon request. Use of these formats is not mandatory, rather the forms provide a suggested format for permitting authorities and owners or operators of affected emissions units.

4(c) SMALL ENTITY FLEXIBILITY

The operating permit program defines small entities as sources which emit less than one hundred tons per year of a regulated air pollutant, and the operating permit program was determined to have little or no impact on small entities. The enhanced monitoring program is also expected to have little or no impact on small entities because the definition of small entity provided in the enhanced monitoring program is consistent with the definition of small entity provided in the operating permit program. Furthermore, the enhanced monitoring program excludes emissions units at sources subject to the operating permits program which emit less than one hundred tons per year of a regulated air pollutant from its applicability.

4(d) COLLECTION SCHEDULE

Owners or operators of affected emissions units will be required to submit their enhanced monitoring protocols in their permit applications. Upon acceptance of the enhanced monitoring protocols, owners or operators will be required to collect the information specified in the protocols in accordance with the collection frequency specified in the protocols. Information will be required to be maintained for at least five years. Owners or operators will be required to submit quarterly enhanced monitoring reports.

5. NONDUPLICATION, CONSULTATIONS, AND OTHER COLLECTION CRITERIA

5(a) NONDUPLICATION

The information required to be collected in part 64 is not duplicative because this is a new program or rulemaking. Enhanced

Monitoring data has never been collected. Previously, owners or operators of sources have never been required to ascertain and declare their compliance status based on enhanced monitoring data.

The information contained in the Enhanced Monitoring protocol and in the demonstration of the protocol establishes that the proposed monitoring system provides data which can be correlated to an emission standard or limitation. Data collected under an approved protocol provides the basis for the compliance certifications required under the operating permit program. None of this information is required elsewhere, so the collection is non-duplicative.

5(b) CONSULTATIONS

The workgroup has received extensive public participation concerning the development of the Enhanced Monitoring Program Regulation. A public meeting to determine the scope and impact of an enhanced monitoring program was held on 22 August 1991, and environmental and industry groups have discussed, made suggestions, and participated in individual meetings on the enhanced monitoring program. Representatives of State and local air pollution regulatory agencies have participated as informational members of the rulemaking workgroup. A public review and comment period will occur upon proposal of the regulations in the *Federal Register*. A public hearing is scheduled on the proposed regulations.

5(c) EFFECTS ON LESS FREQUENT COLLECTION

As part of the permit application required under the operating permit program, an owner or operator must submit a proposed enhanced monitoring protocol for each affected emissions unit and a demonstration that each protocol is sufficient to provide compliance status information. Without such proposals or demonstrations, permitting authorities will be unable to issue permits and owners or operators will be unable to certify compliance with emissions limitations or standards. Quarterly reports are required because the information is necessary for timely enforcement. Without timely enforcement, emissions of regulated air pollutants would rise.

5(d) GENERAL GUIDELINES

The recordkeeping and reporting requirements contained in the proposed enhanced monitoring program regulations do not exceed any of the Paperwork Reduction Act guidelines contained in 5 CFR 1320.6, except for the guideline which limits retention of records by respondents to three years. The enhanced monitoring program and the operating permit program require both sources and State or

local agencies to retain records for a period of five years. The justification for this exception is found in 28 U.S.C. 2462, which specifies five years as the general statute of limitations for Federal claims in response to violations by regulated entities. The decision in U.S. v. Conoco, Inc., No. 83-1916-E (W.D. Okla., January 23, 1984) found that the five year general statute of limitations applied to the Clean Air Act.

5(e) CONFIDENTIALITY AND SENSITIVE QUESTIONS

(i) Confidentiality

Information received and identified by owners or operators as confidential business information (CBI) and approved as CBI by EPA, in accordance with Title 40, Chapter 1, Part 2, Subpart B, shall be maintained appropriately (see 40 CFR 2; 41 FR 36902, September 1, 1976; amended by 43 FR 39999, September 8, 1978; 43 FR 42251, September 28, 1978; 44 FR 17674, March 23, 1979).

(ii) Sensitive Questions

This section is not applicable. This ICR does not contain any sensitive questions relating to sexual behavior or attitudes, religious beliefs, or other matters usually considered private.

6. ESTIMATING THE BURDEN AND COST OF THE COLLECTION

6(a) ESTIMATING RESPONDENT BURDEN

This section presents estimates of the burden hours expected to be incurred by respondent workers at emission units affected by enhanced monitoring (EM). The estimates are contained in seven tables, Tables 6(a).1 to 6(a).7, and summarize burden impacts by pollutant, size, and activity. These tables correspond to the following categories:

- VOC emissions units, reported for small and large emissions units.
- TSP emissions units, reported for small and large emissions units.
- SO_2 emissions units, reported for large emissions units.
- CO emissions units, reported for large emissions units.
- NO_x emissions units, reported for large emissions units.

Estimates of burden hours and costs for emissions units affected by the enhanced monitoring and compliance certification

rule are derived from two types of data. First, selected burden items are based on a top-down methodology in which burden costs are determined as a fixed allocation of total costs incurred by sources that have previously been subject to other monitoring regulations. The allocation factors (weights) are obtained from the 1991 *Program Users Manual for Estimates of CEMS and Annual O&M Costs for New and Existing Combustion Facilities*, which was prepared by Entropy Environmentalists for the Emissions Measurement Branch of the EPA under contract number 68D90055. Given burden costs, burden hour estimates are derived through division of costs by a wage per hour, taking into consideration the labor category most likely to perform the burden task. Discussion of wage rates is provided in Section 6(b) below.

While the allocation approach provides a good estimate of total burden costs as a fraction of total respondent costs, the Entropy (1991) data do not indicate the further allocation of burden costs among burden categories. In order to maintain consistency with the Regulatory Impact Analysis (RIA), it is assumed in the ICR that processing, compilation and review activities will account for 57 percent of total burden; data reduction and reporting account for 33 percent of total burden; and record maintenance constitutes the remaining 10 percent of total burden. These burden allocations may differ according to the actual response taken by an affected point, but aggregate estimates should be reasonable, based on the Entropy (1991) findings.

The second way in which burden hour estimates are identified is through reliance on the expert judgment of EPA staff. These estimates are especially useful in circumstances where the enhanced monitoring program will require only incremental adjustments in source activities. These estimates occur for VOC emissions units that must conduct work practice or mass balance calculations.

The set of respondent tables presented in this section identify burden information in terms of the different pollutants potentially affected. This manner of presentation is necessary since different pollutants will generally require different responses to the proposed rule. In fact, the costing methodology also allows affected emissions units of the same pollutant type to meet the rule requirements in different ways. The selection of a particular response is conditioned by baseline characteristics and the potential to emit. This flexibility is evident in the worksheet column which reports the number of respondents. For VOC and TSP, the number of respondents can change by task required.

The information contained in the respondent tables is consistent with the RIA. In accord with the proposed rule, the burden estimates assume quarterly reporting. This frequency is

reflected directly in the hours estimates. It should also be noted that the burden estimates represent impacts that will occur in the third year after rule implementation. This gives the greatest estimate of burden impact because enhanced monitoring requirements will be introduced on a staggered basis as owners and operators are required to comply with the operating permit rules.

Note that the RIA reports costs in the fifth year after implementation. That approach ignores one-time, up-front costs incurred to review rule requirements. For purposes of ICR preparation, an estimate of these costs has been made and reported as an annualized value. The annualizing period is fifteen years; a ten percent real discount rate is assumed.

To address concerns of the Regulatory Flexibility Act, separate burden estimates are provided for "small" emissions units. For this ICR, small emissions units are defined to be those emissions units which emit less than one hundred tons per year of the regulated pollutant. Given the rule design, these emissions units include selected VOC and TSP emissions units that are located in non-attainment areas for the respective pollutant.

6(b) ESTIMATING RESPONDENT COSTS

This section discusses the conversion of burden hour estimates into the corresponding burden cost values. As mentioned in Section 6(a), the RIA methodology relies on a top-down methodology to develop burden costs directly. Total costs, including capital costs, O&M costs, and burden costs, are disaggregated on the basis of allocation weights that have been determined from available data (Entropy, 1991). Thus, the methodology starts with cost measures and assumes labor rates to derive consistent hour estimates. For this study, two labor categories are identified. Rule evaluation tasks are assumed to be conducted by management level staff with loaded hourly wages of $50/hour (1990 dollars). This estimate is 18 percent higher than the average value of $41.00 used for industry wage in the operating permit program ICR and is consistent with the RIA. For reporting and recordkeeping tasks, it is assumed that these functions can be performed by technical staff only. The wage for technical staff is assumed to be $33.75 (1990 dollars) which is approximately 18 percent below the average wage for all industry workers, as used in the operating permit program ICR. This rate is also consistent with the RIA.

Because an affected emissions unit of a given pollutant type may perform different sets of burden activities, it is not appropriate to simply sum burden hours across tasks to obtain an estimate of individual respondent burden. The problem is that activities may have different counts of respondents.

To overcome this problem, columns have been added to the respondent tables in Section 6(a) which identify total cost and burden by activity rather than by individual. These total estimates are then divided by the maximum respondent count for that pollutant to provide an approximate measure of average cost and burden per respondent. Average reporting and recordkeeping burden estimates are derived in a similar manner. That is, as total burden divided by the maximum respondent count for that pollutant.

Note that the average burden cost estimates include measures of the capital and O&M costs associated with the collection request. Because of the top-down methodology, no separate estimate of burden hours for these categories is derived. All capital costs are annualized over a fifteen year time horizon and discounted at a ten percent real rate of discount. This annualizing procedure is consistent with the RIA.

6(c) ESTIMATING AGENCY BURDEN AND COST

Burden costs for State and Local Agencies as well as the Federal EPA are shown in Tables 6(c).1 and 6(c).2. The methodology used to derive State and Local Agency burden hours and costs parallels the procedure described in Section 3 of the RIA Technical Support Document. The approach is statistical and relies on data available in EPA's *Survey of State and Local Air Pollution Agencies' Activities and Costs* (EPA-450/2-90-006), published in February 1990. Separate regressions are estimated for three Agency compliance activities to predict work-hours associated with the number of points affected by the enhanced monitoring regulation. Observations in the regressions correspond to activities of a specific State Agency. The regressions are specified in non-linear form to permit economies of scale to be identified. Given the burden hour regressions, Agency work hours are predicted on a state-by-state basis. Agency costs are determined on the basis of state-specific wage data reported by the Agencies in the *Survey*.

The operating permits program allows compliance activity costs to be paid for through permitting fees. Therefore, the burden cost of the enhanced monitoring program on State and local agencies will be able to be shifted to the respondents.

Burden estimates for Federal activities focus on the provision of guidance and oversight to State and Local Agencies. For the ICR, it is assumed that ten percent of affected emissions units may be associated with burden activity by Federal staff. For this subset of emissions units, four hours of burden annually were assumed. The wage rate for this activity is set at $30.45, which has been used for costing purposes by the EPA Office responsible for the enhanced monitoring rule.

6(d) BOTTOM LINE BURDEN HOURS AND COSTS / BURDEN TABLES

This section of the ICR presents aggregated measures of respondent and Agency burden hour and cost estimates. These results are presented as Master Tables.

i) Table 6(d).1 provides an estimate of respondent burden hours and costs across all pollutants. This table follows the format of the prototype table described in the ICR Instruction Manual and shows total annual burden and total annual cost by pollutant type. Total measures across pollutants are also reported.

ii) An Agency master table is shown in Table 6(d).2. This table is presented in the same format as the individual tables for State and Local burden and Federal EPA burden.

6(e) REASONS FOR CHANGE IN BURDEN

This is an initial request for clearance for the information collection required of the enhanced monitoring program and therefore contains no changes from a previously existing request.

6(f) BURDEN STATEMENT

Public reporting burden for this collection of information is estimated to average 96 hours per response, and to require 18.9 hours recordkeeping. This includes time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden to Chief, Information Policy Branch, PM-223Y, U.S. Environmental Protection Agency, 401 M St., S.W., Washington, D.C. 20460; and to the Office of Information and Regulatory Affairs, Office of Management and Budget, Washington, D.C. 20503.

TABLE 6(a)1 - SOURCE BURDEN COSTS FOR VOC EMISSION UNITS < 100 TONS PER YEAR

TASK	BURDEN HOURS PER RESPONSE		COST PER RESPONSE	RESPONDENTS	TOTAL COST	TOTAL BURDEN HOURS
	MANAGEMENT	TECHNICAL				
1. Review requirements (Annualized)	24	0	$158	2236	$352,841	53,664
2. Process, compile, and review data	0	261.1	$8,812	46	$405,358	12,011
3. Conduct data reduction	0	204.4	$6,899	46	$317,331	9,402
4. Conduct work practice reporting	0	19.4	$655	463	$303,149	8,982
5. Conduct mass balance reporting	0	109.3	$3,689	1472	$5,430,024	160,890
6 Assess EM data prior to CC	30	0	$1,500	2236	$3,354,000	67,080
7. Maintain records	0	46.1	$1,556	46	$71,570	2,121
8. EM capital costs (Annualized)					$1,424,000	
9. Annual EM operation					$19,933,000	

TOTAL BURDEN (SUM OVER TASKS)	314,149
AVERAGE BURDEN (TOTAL/MAXIMUM RESPONDENTS)	140.5
TOTAL COST (SUM OVER TASKS)	$31,591,273
AVG COST TOTAL (MAXIMUM RESPONDENTS)	$14,128
AVG REPORT HOURS (SUM OF 3,4,5/MAX RESPONDENTS	80.2
AVG REPORT COSTS (SUM OF 3,4,5/MAX RESPONDENTS)	$2,706
AVG RECORDKEEPING (TASK 7/MAX RESPONDENTS)	0.9
AVG RECORDKEEPING (TASK 7/MAX RESPONDENTS)	$32

BASIS:

MANAGEMENT COSTS PER HOUR

$50.00	(ANNUAL)
$6.58	(ANNUALIZED)

TECHNICAL COSTS PER HOUR

$33.75	(ANNUAL)
$4.44	(ANNUALIZED)

TABLE 6(a)2 - SOURCE BURDEN COSTS FOR VOC EMISSION UNITS ≥ 100 TONS PER YEAR

TASK	BURDEN HOURS PER RESPONSE		COST PER RESPONSE	RESPONDENTS	TOTAL COST	TOTAL BURDEN HOURS
	MANAGEMENT	TECHNICAL				
1. Review requirements (Annualized)	24	0	$158	905	$142,809	21,720
2. Process, compile, and review data	0	261.1	$8,812	18	$158,618	4,700
3. Conduct data reduction	0	204.4	$6,899	18	$124,173	3,679
4. Conduct work practice reporting	0	19.4	$655	187	$122,438	3,628
5. Conduct mass balance reporting	0	109.3	$3,689	595	$2,194,881	65,034
6 Assess EM data prior to CC	30	0	$1,500	905	$1,357,500	27,150
7. Maintain records	0	46.1	$1,556	18	$28,006	830
8. EM capital costs (Annualized)					$576,000	
9. Annual EM operation and maintenance costs					$8,067,000	

TOTAL BURDEN (SUM OVER TASKS)	126,740
AVERAGE BURDEN (TOTAL/MAXIMUM RESPONDENTS)	140.0
TOTAL COST (SUM OVER TASKS)	$12,771,425
AVERAGE COST (TOTAL/MAXIMUM RESPONDENTS)	$14,112
AVG REPORT HOURS (SUM OF 3,4,5/MAX RESPONDENTS)	79.9
AVG REPORT COSTS (SUM OF 3,4,5/MAX RESPONDENTS)	$2,698
AVG RECORDKEEP HOURS (TASK 7/MAX RESPONDENTS)	0.9
AVG RECORDKEEP COSTS (TASK 7/MAX RESPONDENTS)	$31

BASIS:

MANAGEMENT COSTS PER HOUR

$50.00	(ANNUAL)
$6.58	(ANNUALIZED)

TECHNICAL COSTS PER HOUR

$33.75	(ANNUAL)
$4.44	(ANNUALIZED)

TABLE 6(a)3 - SOURCE BURDEN COSTS FOR TSP EMISSION UNITS < 100 TONS PER YEAR

TASK	BURDEN HOURS PER RESPONSE		COST PER RESPONSE	RESPONDENTS	TOTAL COST	TOTAL BURDEN HOURS
	MANAGEMENT	TECHNICAL				
1. Review requirements (Annualized)	24	0	$158	211	$33,296	5,064
2. Process, compile, and review data	0	46	$1,553	171	$265,478	7,866
3. Conduct data reduction and reporting	0	36.1	$1,218	211	$257,077	7,617
4. Assess EM data prior to CC	30	0	$1,500	211	$316,500	6,330
5. Maintain records	0	8.1	$273	171	$46,747	1,385
6. EM capital costs (Annualized)	0	0			$848,241	
7. Annual EM operation and maintenance costs	0	0			$1,229,950	

TOTAL BURDEN (SUM OVER TASKS)		28,262
AVERAGE BURDEN (TOTAL/MAXIMUM RESPONDENTS)		133.9
TOTAL COST (SUM OVER TASKS)		$2,997,289
AVERAGE COST (TOTAL/MAXIMUM RESPONDENTS)		$14,205
AVERAGE REPORT HOURS	(TASK 3/MAX RESPONDENTS)	36.1
AVERAGE REPORT COSTS	(TASK 3/MAX RESPONDENTS)	$1,218
AVG RECORDKEEP HOURS	(TASK 5/MAX RESPONDENTS)	6.6
AVG RECORDKEEP COSTS	(TASK 5/MAX RESPONDENTS)	$222

BASIS:

MANAGEMENT COSTS PER HOUR

$50.00	(ANNUAL)
$6.58	(ANNUALIZED)

TECHNICAL COSTS PER HOUR

$33.75	(ANNUAL)
$4.44	(ANNUALIZED)

TABLE 6(a)4 - SOURCE BURDEN COSTS FOR TSP EMISSION UNITS > 100 TONS PER YEAR

TASK	BURDEN HOURS PER RESPONSE		COST PER RESPONSE	RESPONDENTS	TOTAL COST	TOTAL BURDEN HOURS
	MANAGEMENT	TECHNICAL				
1. Review requirements (Annualized)	24	0	$158	4764	$751,759	114,336
2. Process, compile, and review data	0	46	$1,553	3864	$5,998,860	177,744
3. Conduct data reduction and reporting	0	36.1	$1,218	4764	$5,804,339	171,980
4. Assess EM data prior to CC	30	0	$1,500	4764	$7,146,000	142,920
5. Maintain records	0	8.1	$273	3864	$1,056,321	31,298
6. EM capital costs (Annualized)					$19,151,759	
7. Annual EM operation and maintenance costs					$27,770,050	

TOTAL BURDEN (SUM OVER TASKS)	638,279
AVERAGE BURDEN TOTAL/MAXIMUM RESPONDENTS)	134.0
TOTAL COST (SUM OVER TASKS)	$67,679,088
AVERAGE COST (TOTAL/MAXIMUM RESPONDENTS)	$14,206
AVERAGE REPORT HOURS (TASK 3/MAX RESPONDENTS)	36.1
AVERAGE REPORT COSTS (TASK 3/MAX RESPONDENTS)	$1,218
AVG RECORDKEEP HOURS (TASK 5/MAX RESPONDENTS)	6.6
AVG RECORDKEEP COSTS (TASK 5/MAX RESPONDENTS)	$222

BASIS:

MANAGEMENT COSTS PER HOUR

$50.00	(ANNUAL)
$6.58	(ANNUALIZED)

TECHNICAL COSTS PER HOUR

$33.75	(ANNUAL)
$4.44	(ANNUALIZED)

TABLE 6(a)5 - SOURCE BURDEN COSTS FOR SO2 EMISSION UNITS

TASK	BURDEN HOURS PER RESPONSE		COST PER RESPONSE	RESPONDENTS	TOTAL COST	TOTAL BURDEN HOURS
	MANAGEMENT	TECHNICAL				
1. Review requirements (Annualized)	24	0	$158	2872	$453,202	68,928
2. Process, compile, and review data	0	261.1	$8,812	2872	$25,308,423	749,879
3. Conduct data reduction and reporting	0	204.4	$6,899	2872	$19,812,492	587,037
4. Assess EM data prior to CC	30	0	$1,500	2872	$4,308,000	86,160
5. Maintain records	0	46.1	$1,556	2872	$4,468,473	132,399
6. EM capital costs (Annualized)					$74,000,000	
7. Annual EM operation and maintenance costs					$154,000,000	

TOTAL BURDEN (SUM OVER TASKS)	1,624,403
AVERAGE BURDEN (TOTAL/MAXIMUM RESPONDENTS)	565.6
TOTAL COST (SUM OVER TASKS)	$282,350,590
AVERAGE COST (TOTAL/MAXIMUM RESPONDENTS)	$98,311
AVG REPORT HOURS (TASK 3/MAX RESPONDENTS)	204.4
AVG REPORT COSTS (TASK 3/MAX RESPONDENTS)	$6,899
AVG RECORDKEEP HOURS (TASK 5/MAX RESPONDENTS)	46.1
AVG RECORDKEEP COSTS (TASK 5/MAX RESPONDENTS)	$1,556

BASIS:

MANAGEMENT COSTS PER HOUR

$50.00	(ANNUAL)
$6.58	(ANNUALIZED)

TECHNICAL COSTS PER HOUR

$33.75	(ANNUAL)
$4.44	(ANNUALIZED)

TABLE 6(a)6 - SOURCE BURDEN COSTS FOR CARBON MONOXIDE EMISSION UNITS

TASK	BURDEN HOURS PER RESPONSE		COST PER RESPONSE	RESPONDENTS	TOTAL COST	TOTAL BURDEN HOURS
	MANAGEMENT	TECHNICAL				
1. Review requirements (Annualized)	24	0	$158	303	$47,813	7,272
2. Process, compile, and review data	0	48.3	$1,630	303	$493,928	14,635
3. Conduct data reduction and reporting	0	37.8	$1,276	303	$386,552	11,453
4. Assess EM data prior to CC	30	0	$1,500	303	$454,500	9,090
5. Maintain records	0	8.5	$287	303	$86,923	2,576
6. EM capital costs (Annualized)					$1,000,000	
7. Annual EM operation and maintenance costs					$3,000,000	

TOTAL BURDEN (SUM OVER TASKS)	45,026
AVERAGE BURDEN (TOTAL/MAXIMUM RESPONDENTS)	148.6
TOTAL COST (SUM OVER TASKS)	$5,469,717
AVERAGE COST (TOTAL/MAXIMUM RESPONDENTS)	$18,052
AVERAGE REPORT HOURS (TASK 3/MAX RESPONDENTS)	37.8
AVG REPORT COSTS (TASK 3/MAX RESPONDENTS)	$1,276
AVG RECORDKEEP HOURS (TASK 5/MAX RESPONDENTS)	8.5
AVG RECORDKEEP COSTS (TASK 5/MAX RESPONDENTS)	$287

BASIS:

MANAGEMENT COSTS PER HOUR

$50.00	(ANNUAL)
$6.58	(ANNUALIZED)

TECHNICAL COSTS PER HOUR

$33.75	(ANNUAL)
$4.44	(ANNUALIZED)

TABLE 6(a)7 - SOURCE BURDEN COSTS FOR NOx EMISSION UNITS

TASK	BURDEN HOURS PER RESPONSE		COST PER RESPONSE	RESPONDENTS	TOTAL COST	TOTAL BURDEN HOURS
	MANAGEMENT	TECHNICAL				
1. Review requirements (Annualized)	24	0	$158	2188	$345,266	52,512
2. Process, compile, and review data	0	248.7	$8,394	2188	$18,365,252	544,156
3. Conduct data reduction and reporting	0	194.8	$6,575	2188	$14,385,006	426,222
4. Assess EM data prior to CC	30	0	$1,500	2188	$3,282,000	65,640
5. Maintain records	0	43.9	$1,482	2188	$3,241,796	96,053
6. EM capital costs (Annualized)					$37,000,000	
7. Annual EM operation and maintenance costs					$66,000,000	

TOTAL BURDEN (SUM OVER TASKS)	1,184,583
AVERAGE BURDEN (TOTAL/MAXIMUM RESPONDENTS)	541.4
TOTAL COST (SUM OVER TASKS)	$142,619,319
AVERAGE COST (TOTAL/MAXIMUM RESPONDENTS)	$65,183
AVERAGE REPORT HOURS (TASK 3/MAX RESPONDENTS)	194.8
AVERAGE REPORT COSTS (TASK 3/MAX RESPONDENTS)	$6,575
AVG RECORDKEEP HOURS (TASK 5/MAX RESPONDENTS)	43.9
AVG RECORDKEEP COSTS (TASK 5/MAX RESPONDENTS)	$1,482

BASIS:

MANAGEMENT COSTS PER HOUR

$50.00	(ANNUAL)
$6.58	(ANNUALIZED)

TECHNICAL COSTS PER HOUR

$33.75	(ANNUAL)
$4.44	(ANNUALIZED)