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Recommended Plan for a Comprehensive Solution of the Polynuclear Aromatic Hydrocarbon Contamination Problem in the St. Louis Park Area

Volume III
Appendix G

ERT
ENVIRONMENTAL RESEARCH & TECHNOLOGY, INC.
ATLANTA · CHICAGO · CONCORD, MA · FORT COLLINS, CO
HOUSTON · LOS ANGELES · PITTSBURGH · WASHINGTON, DC

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TABLE OF CONTENTS

	Page
FOREWORD	1a
LIST OF APPENDICES	31a
LIST OF TABLES	33a
LIST OF FIGURES	35a
DEFINITION OF TERMS	37a
DEFINITION OF TRACE CONCENTRATION UNITS	41a
ERT PROJECT TEAM	43a
TECHNICAL SUMMARY	49a

Volume I

1.0 PURPOSE	1
2.0 BACKGROUND	3
2.1 Historical Use of the RT&CC Plant Site	7
2.1.1 Plant Site Use Prior to 1905	7
2.1.2 Plant Site Use From 1917 to 1972	8
2.2 Current Characteristics of the Site	14
2.3 Ground-Water Resources and Use in the St. Louis Park Area	16
2.4 Ground-Water Contamination in the St. Louis Park Area	18
2.5 Efforts to Solve the St. Louis Park Area Problem	19
3.0 APPROACH	31
3.1 Objectives and Priorities	31
3.1.1 Safe and Adequate Potable Water Supplies	34
3.1.2 Use of Ground-Water Resources	34
3.1.3 Safe Future Use of the Site Area	37
3.1.4 Priorities	37
3.2 Overall Approach	38
3.2.1 Source Versus End-Use Actions	38
3.2.2 Choosing Among Alternative Actions	42
3.2.3 Arriving at Conclusions and Recommendations	43

TABLE OF CONTENTS (Continued)

	Page
3.3 Technical Approach	44
3.3.1 Data Sources	44
3.3.2 Appropriateness of Techniques	45
3.3.3 Accuracy and Sensitivity	46
4.0 RECOMMENDED CRITERIA FOR PAH IN FINISHED POTABLE WATER	49
4.1 Recommended Criteria	51
4.2 Basis for Recommended Criteria	55
4.2.1 Carcinogenic PAH Criterion	57
4.2.2 Noncarcinogenic PAH Criterion	59
4.2.3 Synergistic Effects	63
4.2.4 Other Possible Criteria	63
4.3 Compliance Monitoring for Proposed Criteria	65
4.3.1 Objectives	65
4.3.2 Selection of Monitoring Pollutants	66
4.3.3 Monitoring Designations and Frequencies	68
4.3.4 Sampling and Preservation Procedures	70
4.3.5 Analytical Procedures	71
4.3.6 Enforcement	71
4.4 Evaluation of St. Louis Park Area Wells by the Recommended Criteria	73
5.0 EVALUATION OF SOURCE CONTROL ALTERNATIVES	85
5.1 Site Controls	85
5.1.1 Objectives	85
5.1.2 Approach	86
5.1.3 Site Characterization	86
5.1.4 Site Area Control Alternatives	96
5.1.5 Recommended Site Area Controls	101
5.2 Plant Site Multi-Aquifer Well Controls	102
5.2.1 Objectives	103
5.2.2 Approach	103
5.2.3 Well W23 Characteristics	104
5.2.4 Well W23 Control Alternatives	109
5.2.5 Recommended Well W23 Controls	111
5.2.6 W105 Recommendations	114

TABLE OF CONTENTS (Continued) Page

5.3 Off-Site Multi-Aquifer Well Controls 114
5.3.1 Objectives 114
5.3.2 Approach 115
5.3.3 Off-Site Multi-Aquifer Well Characteristics 115
5.3.4 Remedial Action Alternatives for Off-Site Multi-Aquifer Wells 121
5.3.5 Recommended Remedial Actions for Off-Site Multi-Aquifer Wells 126
5.4 Gradient Control Well Systems 129
5.4.1 Objectives 129
5.4.2 Approach 130
5.4.3 Applicability of Gradient Control Well Schemes 130
5.4.4 Costs of Gradient Control Well Schemes 134
5.4.5 Recommended Gradient Control Well Schemes 135
6.0 EVALUATION OF END-USE CONTROL ALTERNATIVES 139
6.1 Management of Ground-Water Flow in St. Louis Park Area 140
6.1.1 Ground-Water Modeling Results 140
6.1.2 Contaminant Migration in the Prairie du Chien-Jordan 146
6.1.3 Ground-Water Management Implications of End-Use Controls 149
6.2 Municipal Water Supply Systems in the St. Louis Park Area 150
6.2.1 Supply System Characteristics 151
6.2.2 Supply Shortfalls 157
6.3 Drinking Water Treatment 164
6.3.1 Objectives 164
6.3.2 Approach 165
6.3.3 Drinking Water Treatment Alternatives 165
6.3.4 Drinking Water Treatment System Costs 176

TABLE OF CONTENTS (Continued) Page

6.4 Alternate Drinking Water Supplies 181
6.4.1 Approach 181
6.4.2 Costs of Additional Mt. Simon-Hinckley Wells 182
6.4.3 Costs of Municipal Supply Interconnections 185
6.5 Ground Water Monitoring 187
6.5.1 Drift-Plateville and St. Peter 188
6.5.2 Muncipal Water Supply Aquifers 191
6.5.3 Costs of Ground-Water Monitoring 192
6.6 Recommended End-Use Controls 194
6.6.1 Costs of End-Use Controls 194
6.6.2 Adequacy of Drinking Water Supplies 199
6.6.3 Reliability and Effectiveness Considerations 200
6.6.4 Effects of Recommended Criteria 202
6.6.5 Recommendations 204
7.0 CONCLUSIONS AND RECOMMENDATIONS 207
7.1 Conclusions 207
7.1.1 Sources of Contamination 207
7.1.2 Transport of Contaminants 209
7.1.3 Effects of Contamination 214
7.1.4 Remedy of Contamination 219
7.2 Recommendations 229
7.2.1 Current Remedial Action Recommendations 229
7.2.2 Contingency Action Recommendations 237
7.3 Comments on Proposed Superfund Studies 238
8.0 REFERENCES 245

LIST OF APPENDICES

APPENDICES	TITLE
Volume II	
A	Site History
B	Site Characterization
C	Site Remedial Actions
D	Multi-Aquifer Well Characteristics and Remedial Action
E	Ground-Water Modeling
F	Wastewater Treatment and Disposal Alternatives
Volume III	
G	Evaluation of Drinking Water Treatment Technologies for PAH Removal
Volume IV	
H	Impacts of PAH on Nonpotable Use of Ground Water in the Affected Areas
I	Scientific Basis for Recommended Criteria for PAH and Heterocyclic PAH in Potable Water with Reference to the St. Louis Park, Minnesota Ground-Water Supply
J	Compliance Monitoring Standards for PAH Criteria
K	Ground Water Quality Database
L	Present Value Cost Comparisons

LIST OF TABLES

Table		Page
2-1	Quality of Drainage Ditch Water Leaving RT&CC Plant Site	13
2-2	Summary of Major Ground-Water Pumpage in the Modeling Area	17
2-3	Chronological Listing of Studies Relevant to the St. Louis Park Problem	20
3-1	Possible Effectiveness of Remedial Action Types in Meeting the Three Primary Objectives	39
4-1	List of Unsubstituted Carcinogenic PAH and Heterocyclic PAH Based on Animal Testing Results	52
4-2	List of Alkyl-Substituted Carcinogenic PAH and Heterocyclic PAH Based on Animal Testing Results	53
4-3	Estimate of Total Daily Human Exposure to PAH From Various Media	56
4-4	List of Noncarcinogenic PAH and Heterocyclic PAH Based on Results of Animal Testing	61
4-5	Compliance Monitoring Standard, Primary Compound List	67
4-6	Recommended Municipal Supply Well Groups for a Compliance Monitoring Standard	69
5-1	Estimated Background Concentrations of Phenolics and Benzene Extractable Hydrocarbons	89
5-2	Identification of Site Remedial Actions Previously and Currently Under Consideration	97
5-3	Cost of Site Remedial Actions	100
5-4	Multi-Aquifer Wells Identified By USGS, MDH and MPCA	117
5-5	Other Possible Multi-Aquifer Wells	119
5-6	Estimated Costs for Multi-Aquifer Well Abandonment and Reconstruction	124
5-7	Estimated Costs of Recommended Remedial Actions for Off-Site Multi-Aquifer Wells	127
6-1	Summary Data for the St. Louis Park Municipal Well System	153

LIST OF TABLES (Continued)

Table		Page
6-2	Summary Data for the Edina & Hopkins Municipal Water Supply Systems	155
6-3	Population Projections	158
6-4	Historical and Projected Water Usage	159
6-5	Predicted Municipal Well Closures & Resulting Supply Shortfalls	161
6-6	Summary of Key Results from PAH Removal Studies at St. Louis Park Well SLP 15	168
6-7	Estimated Costs of Drinking Water Treatment Alternatives for a 1200 Gallon Per Minute Capacity Well Operated at 300 Million Gallons Per Year	174
6-8	Predicted Municipal Water Supply Shortfalls in St. Louis Park and Edina to be Met by Treating Contaminated Wells	177
6-9	Estimated Costs for Drinking Water Treatment As An End-Use Control	180
6-10	Predicted Municipal Water Supply Shortfalls in St. Louis Park and Edina to be Met by Providing Alternative Water Supply Sources	183
6-11	Present Value Costs for New Mt. Simon-Hinckley Wells	186
6-12	Estimated Present Value Cost of Ground-Water Monitoring	193
6-13	Present Value Cost of End-Use Control Options, Including Compliance Monitoring Costs	195
6-14	Sensitivity of Present Value Costs for Drinking Water Treatment and New Mt. Simon-Hinckley Wells to Different Effective Interest Rates	198
6-15	Summary of Peak Demand Capacity in the St. Louis Park Water Supply System With and Without End-Use Controls	201
7-1	Summary of Recommended Remedial Actions	230
7-2	Summary of Recommended Contingency Actions	232
7-3	Summary of Comments on Proposed $2.0 Million Superfund Activities	240

LIST OF FIGURES

Figure		Page
2-1	Definition of Subdivisions Within the Overall Area of Investigation	5
2-2	RT&CC's Plant, 1950's	9
2-3	Plant Site Drawing From 1944 Blueprint	10
2-4	Current Aerial Photograph of Site	15
4-1	Enforcement Decision Tree	72
4-2	Chronological Summary of Total Carcinogenic and Noncarcinogenic PAH Concentrations Measured at St. Louis Park Well SLP 4	74
4-3	Chronological Summary of Total Carcinogenic and Noncarcinogenic PAH Concentrations Measured at St. Louis Park Well SLP 5	75
4-4	Chronological Summary of Total Carcinogenic and Noncarcinogenic PAH Concentrations Measured at St. Louis Park Well SLP 7	76
4-5	Chronological Summary of Total Carcinogenic and Noncarcinogenic PAH Concentrations Measured at St. Louis Park Well SLP 9	77
4-6	Chronological Summary of Total Carcinogenic and Noncarcinogenic PAH Concentrations Measured at St. Louis Park Well SLP 10	78
4-7	Chronological Summary of Total Carcinogenic and Noncarcinogenic PAH Concentrations Measured at St. Louis Park Well SLP 15	79
4-8	Chronological Summary of Total Carcinogenic and Noncarcinogenic PAH Concentrations Measured at Hopkins Well H3	80
5-1	Areal Limits of Soil and Surficial Ground Water Contamination	93
5-2	Current Sketch of Well W23	105
6-1	Pattern of Ground Water Flow in the Prairie du Chien Jordan Aquifer Predicted by Computer Model	144
6-2	Location of Supply Wells and Iron Removal Plants in the St. Louis Park Municipal Water Supply System	152

LIST OF FIGURES (Continued)

Figure		Page
6-3	Location of Municipal Supply Wells and Iron Removal Treatment Plants in St. Louis Park and Neighboring Communities	156
6-4	Map of St. Louis Park Showing Area of 1982 Well Survey and the Extent of Contamination in the Drift-Platteville	189

DEFINITION OF TERMS

Bog	The land immediately south and adjacent to the plant site that received runoff and waste water from the plant site. The bog is bounded by Walker Street to the north, on the east by the route of Louisiana Avenue, on the south by Lake Street and on the west by former railroad embankments. The bog is shown in Figure 2-1.
Benzene Extractable Hydrocarbons	The weight of organic material, per unit volume or mass, obtained on extracting a water or soil sample with benzene. Hydrocarbon in this definition is not meant to be restrictive to material containing carbon and hydrogen, but rather is meant to include all organic material so extracted.
Contaminants	PAH and related compounds that are present in soil or ground water at levels that are clearly above expected background levels for an urban area in the affected media.
Contaminated	Soil or ground water that contains concentrations of PAH and related compounds which are clearly above expected background levels of these compounds for an urban area in the affected media.
Heterocyclic PAH	PAH chemicals with one or more aromatic carbon atoms replaced by nitrogen, oxygen, or sulfur atoms. Unless otherwise stated, alkyl substituted heterocylic PAH are also included by this term.
Hetero-Substituted PAH	PAH chemicals with one or more heteroatomic functional substituted groups attached to the aromatic rings. For the purposes of this term, such functional groups include amines, cyanides, mercaptans, thiols, ketones, ethers, carboxylic acids, alkyl groups, etc. but specifically exclude hydroxyl groups (i.e., phenols).

Modeling Area	An area of 22 miles east-west and 16 miles north-south which is approximately centered on the site area and was modeled for ground-water flow hydraulics as part of this study. The modeling area is defined by the border of the upper map in Figure 2-1.
PAH and Related Compounds	PAH (as defined above) plus related aromatic chemicals that are often associated with PAH in coal tar, soot, petroleum distillates and similar materials. These related aromatic chemicals are by definition limited to heterocyclic PAH, heterosubstituted PAH and phenols (defined elsewhere).
Phenolics	Chemicals measured by standard colorimetric tests for phenols, the current standard test being the 4-aminoantipyrene method. Colorimetric tests typically measure one-ring phenols (phenol and ortho-and meta-substituted phenols and possibly certain para-substituted phenols), and possibly two ring or larger phenols.
Phenols	Chemicals consisting of one or more fused aromatic rings containing carbon and hydrogen with one or more hydroxyl (-OH) groups attached to the ring. Unless otherwise stated, alkyl substituted phenolics are also included by this term.
Plant Site	The land that was formerly the site of the Reilly Tar & Chemical Corporation's creosote wood preserving and coal tar refinery plant. The plant site is bounded on the north by West 32nd street, on the east by Gorham Avenue, Second Street Northwest and Republic Avenue, on the south by Walker Street, and on the West by Pennsylvania Avenue and Oak Hill Park. The plant site is shown in Figure 2-1.

Polynuclear Aromatic Hydrocarbons (PAH)	Chemicals consisting of carbon and hydrogen and containing two or more fused aromatic rings, with each ring consisting of five or six carbon atoms. Unless otherwise stated, alkyl-substituted PAH are also included by this term.
Site	The plant site and bog area together.
Site Area	An area extending approximately 8500 feet east-west and 6000 feet north-south in which the site occupies the northwest corner. The site area is defined by the border of the lower map appearing in Figure 2-1.
St. Louis Park Area	Areas of St. Louis Park and neighboring communities that have been affected by ground water contamination by PAH and related compounds.
St. Louis Park Problem	The overall problems in the St. Louis Park Area related to the contamination of soil and ground water by PAH and related compounds, including in particular the presence of contaminated soil and ground water in the former RT&CC plant site and adjacent bog, the presence of contamination in confined bedrock aquifers underlying the St. Louis Park area, and the present water supply shortage faced by the Cities of St. Louis Park and Hopkins as a result of municipal supply well closures.

DEFINITION OF TRACE CONCENTRATION UNITS

This report makes frequent use of units for expressing trace concentrations. The units used in this report are defined in the table below. In order to avoid misunderstandings over real or suspected typographic errors, an effort has been made to write out all of the units used in this report. Abbreviations are therefore presented below for comparison with other data and reports.

Dimensionless Concentration	Concentration in Water	Concentration in Soil or Other Solid
Parts per million (ppm)	Milligrams per liter (mg/l)	Milligrams per kilogram (mg/kg)
Parts per billion (ppb)	Micrograms per liter ug/l	Micrograms per kilogram (ug/kg)
Parts per trillion (ppt)	Nanograms per liter ng/l	Nanograms per kilogram (ng/kg)

In order to provide a better understanding for the magnitude of these trace concentration units, the following table presents equivalent quantities in more familiar measures of volume, length and time.

Fractional Expression	Volume Equivalent	Length Equivalent	Time Equivalent
1 part per million	1 drop in 26.4 gallons	1 inch in 15.8 miles	1 second in 11.6 days
1 part per billion	1 drop in 26,400 gallons (volume of a typical railroad tank car)	1 inch in 15,800 miles (almost two-thirds of the distance around the earth)	1 second in 31.7 years
1 part per trillon	1 drop in 26.4 million gallons (volume of a 10 acre lake that is 8 feet deep)	1 inch in 15.8 million miles (66 times the distance from the earth to the moon)	1 second in 317 centuries (3 times more distant than the last Ice Age)

APPENDIX G

EVALUATION OF DRINKING-WATER TREATMENT TECHNOLOGIES FOR PAH REMOVAL

TABLE OF CONTENTS

	Page
LIST OF FIGURES	
LIST OF TABLES	
LIST OF EXHIBITS	
G1. INTRODUCTION	G-1
G2. DESCRIPTION OF MUNICIPAL WATER SUPPLY SYSTEMS IN THE ST. LOUIS PARK AREA	G-3
G2.1 St. Louis Park Municipal Water Supply Systems	G-3
G2.1.1 Supply Characteristics	G-7
G2.1.2 Treatment of Water Supplies	G-9
G2.1.3 Summary	G-27
G2.2 Neighboring Municipal Water Supply Systems	G-28
G2.3 Supply and Demand Variations	G-30
G2.3.1 Hourly Demand Variations	G-30
G2.3.2 Daily Demand Variations	G-33
G2.3.3 Seasonal Demand Variations	G-36
G3. PAH OCCURRENCE AND REMOVAL IN CONVENTIONAL DRINKING WATER TREATMENT PLANTS	G-41
G3.1 PAH Occurrence in Supply Waters	G-41
G3.2 PAH Removal By Conventional Drinking Water Treatment	G-44
G3.3 Distribution System Effects	G-50
G3.4 Summary	G-50
G4. PAH REMOVAL STUDIES AT ST. LOUIS PARK	G-53
G4.1 Serco Studies	G-53
G4.1.1 Test Description	G-54
G4.1.2 Test Results	G-58
G4.1.3 Summary	G-63

TABLE OF CONTENTS (Cont'd)

	Page
G4.2 Hickok Studies	G-63
G4.2.1 Test Description	G-64
G4.2.2 PAC Test Results	G-66
G4.2.3 GAC Test Results	G-69
G4.2.4 Hydrogen Peroxide Test Results	G-73
G4.2.5 Economic Evaluations	G-73
G4.2.6 Summary	G-77
G4.3 CH2M Hill Studies	G-78
G4.3.1 Sampling and Analysis Procedures	G-79
G4.3.2 Investigation of the Iron Removal Treatment Plant at Well SLP15	G-81
G4.3.3 First Round Bench Testing	G-89
G4.3.4 Second Round Bench Testing	G-100
G4.3.5 Economic Evaluations	G-105
G4.3.6 Summary	G-112
G4.4 ERT's December 1982 Test of the Iron Removal Treatment Plant at Well SLP15	G-115
G4.4.1 Test Objectives	G-117
G4.4.2 Test Descriptions	G-118
G4.4.3 Sampling, Handling and Analysis Methods	G-131
G4.4.4 Results	G-136
G4.4.5 Data Interpretation - Plant Operation	G-142
G4.4.6 Data Interpretation - PAH Removal	G-171
G4.4.7 Summary	G-195
G4.5 ERT's February 1983 Test of the Iron Removal Treatment Plant at Well SLP15	G-197
G4.5.1 Test Objectives	G-197
G4.5.2 Test Descriptions	G-198
G4.5.3 Sampling, Handling and Analysis Methods	G-203
G4.5.4 Test Results	G-203
G4.5.5 Data Interpretation	G-204
G4.5.6 Summary	G-218
G4.6 Summary of PAH Removal Studies at St. Louis Park	G-221
G4.6.1 SERCO Tests	G-221
G4.6.2 Hickok Test	G-224
G4.6.3 CH2M Hill	G-224
G4.6.4 ERT Tests	G-227

TABLE OF CONTENTS (Cont'd)

		Page
G.5	ESTIMATED COSTS OF DRINKING WATER TREATMENT ALTERNATIVES	G-229
	G5.1 Introduction	G-229
	G5.2 Modified Iron Removal Plant Alterntives	G-233
	G5.2.1 Iron Removal Plant Costs	G-234
	G5.2.2 Ozone Injection Costs	G-239
	G5.2.3 PAC Injection Costs	G-247
	G5.3 Granular Activated Carbon Treatment	G-254
	G5.3.1 Design Basis	G-255
	G5.3.2 Cost Estimates	G-261
	G5.4 Plant Performance Monitoring	G-271
	G5.5 Cost Comparisons	G-275
	G5.5.1 Costs for a Single Well	G-276
	G5.5.2 Costs for a Actual & Predicted Well Closures	G-282
	G5.6 Summary	
G6.	CONCLUSIONS AND RECOMMENDATIONS	G-293
G7.	REFERENCES	G-297
G8.	DATA FOR ERT TESTS	G-305

LIST OF FIGURES

Figure		Page
G2-1	Location of Supply Wells and Iron Removal Plants in the St. Louis Park Municipal Water Supply System	G-4
G2-2	Schematic Diagram of the St. Louis Park Station No. 1 Treatment Plant	G-12
G2-3	Layout of St. Louis Park Station No. 1 Treatment Building	G-13
G2-4	Overall Layout of St. Louis Park Station No. 1	G-14
G2-5	Cross Section of the Operator at St. Louis Park Water Treatment Station No. 1	G-15
G2-6	Top View of Sand Filter Units at St. Louis Park Water Treatment Station No. 1	G-17
G2-7	Side View of Sand Filter Unit at St. Louis Park Water Treatment Station No. 1	G-18
G2-8	End View of Sand Filter Unit at St. Louis Park Water Treatment Station No. 1	G-19
G2-9	Cross Section of Sand Filter Unit at St. Louis Park Water Treatment Station No. 1	G-20
G2-10	Location of Municipal Supply Wells & Iron Removal Treatment Plants in St. Louis Park and Surrounding Communities	G-29
G2-11	Frequency Distribution for Daily Demand in the St. Louis Park Water Supply System	G-35

LIST OF FIGURES (Cont'd)

Figure		Page
G4-1	Chronological Plot of MDH Anaylsis of Samples Collected During Serco's July 1979 PAC Tests at Well SLP15	G-61
G4-2	Schematic Diagram of PAC and GAC Testing at Well SLP15 by Hickok	G-65
G4-3	Chronological Plot of PAH Concentration in Untreated Water from Well SLP15 During Hickok's 1980 PAC and GAC Treatment Tests	G-72
G4-4	Total PAH Adsorption Isotherms Determined by CH2M Hill	G-93
G4-5	Sample Tap Locations and Numbers for ERT's December 6-8, 1982 Test at St. Louis Park Water Treatment Station No. 1	G-121
G4-6	Chronological Chart of Operating Conditions and Sample Collection During ERT's December 1982 Test at St. Louis Park Water Treatment Station No. 1	G-122
G4-7	Schematic Diagram of Air Sampling Apparatus Used During ERT's December 6-8, 1982 Test at St. Louis Park Water Treatment Station No. 1	G-135
G4-8	Results of Time-Series Measurements of Dissolved Oxygen in the Outlet of Various Filter Unit Cells, December 7, 1982	G-168
G4-9	Sketch of Sampling Cock for the Sand Filter Cells at St. Louis Park Water Treatment Station No. 1	G-170
G4-10	Results of Time-Series Sampling for PAH in Well SLP15, December 6-8, 1982	G-176

LIST OF FIGURES (Cont'd)

Figure		Page
G4-11	Sample Tap Locations and Numbers for ERT's February 1-2, 1983 Test at St. Louis Park Water Treatment Station No. 1	G-202
G5-1	Capital Costs for Pressure Sand Filter Iron Removal Plants	G-236
G5-2	Operating and Maintenance Costs for Pressure Sand Filter Iron Removal Plants	G-240
G5-3	Construction Costs for Ozone Injection Equipment	G-244
G5-4	Operating and Maintenance Costs for Ozone Injection Systems	G-246
G5-5	Capital Costs for Powdered Activated Carbon Injection Systems	G-250
G5-6	Operating and Maintenance Costs for Powdered Activated Carbon Injection Systems	G-253
G5-7	Granular Activated Carbon Column Bed Size as a Function of Plant Capacity and Contact Time	G-257
G5-8	Nomograph for Determining Equilibrium Capacity Breakthrough Time	G-260
G5-9	Capital Costs for Granular Activated Carbon Treatment	G-265
G5-10	Operating and Maintenance Costs for Granular Activated Carbon Treatment for a One-Year Breakthrough Time	G-269

LIST OF FIGURES (Cont'd)

Figure		Page
G5-11	Operating and Maintenance Costs for Granular Activated Carbon Treatment for Equilibrium Breakthrough Times	G-270
G5-12	Present Value Costs for Iron Removal Treatment Plants	G-277
G5-13	Present Value Costs for Powdered Activated Carbon Treatment at Wells with Existing Iron Removal Treatment Plants	G-278
G5-14	Present Value Costs for Ozone Injection Treatment at Wells with Existing Iron Removal Treatment	G-279
G5-15	Present Value Costs for Granular Activated Carbon Treatment at Equilibrium Breakthrough Time	G-280
G5-16	Present Value Costs for Granular Activated Carbon Treatment at One-Year Breakthrough Time	G-281
G5-17	Sensitivity Analysis of Present Value Costs at Different Effective Interest Rates	G-283
G8-1	PAH SIM Chromatograms for Water Samples Collected During ERT's December 6-8, 1982 Test at St. Louis Park Station No. 1	G-345
G8-2	PAH SIM Chromatograms for Sand and Slime Samples Collected During ERT's December 6-8, 1982 Test at St. Louis Park Station No. 1	G-366
G8-3	PAH SIM Chromatograms for Air Sample XAD Resin Extracts Collected During ERT's December 6-8, 1982 Test at St. Louis Park Station No. 1	G-369

LIST OF FIGURES (Cont'd)

Figure		Page
G8-4	PAH SIM Chromatograms for Splicing Standards and Method Blanks Corresponding to Samples Collected During ERT's December 6-8, 1982 Test at St. Louis Park Station No. 1	G-370
G8-5	Volatile Organics Analysis Chromatograms for Samples Collected During ERT's December 6-8, 1982 Test at St. Louis Park Station No. 1	G-376
G8-6	Recording Chart for St. Louis Park Well SLP15 Flowrate During ERT's December 6-8, 1982 Test	G-384
G8-7	Recording Chart for St. Louis Park Well SLP3 Flowrate During ERT's December 6-8, 1982 Test	G-385
G8-8	Recording Chart for Backwash Controller During ERT's December 6-8, 1982 Test	G-386
G8-9	Recording Chart for St. Louis Park Well SLP15 Flowrate During ERT's February 1-2, 1983 Test	G-387
G8-10	Recording Chart for Backwash Controller During ERT's February 1-2, 1983 Test	G-388

LIST OF TABLES

Table		Page
G2-1	Summary Data for the St. Louis Park Municipal Well System	G-5
G2-2	Capacity and Historical Pumping Rate Data for St. Louis Park Municipal Wells	G-8
G2-3	Typical Water Quality Data for St. Louis Park Municipal Supply Wells	G-10
G2-4	Historical Data on Iron Removal Plant Performance in St. Louis Park	G-22
G2-5	Summary Data for the Edina and Hopkins Municipal Water Supply Systems	G-31
G2-6	Summary Data for Iron Removal Plants in Edina and Hopkins	G-32
G2-7	Peak Demand Pumping Rates of St. Louis Park Municipal Supply Wells	G-34
G2-8	Summer Pumpage Rates for St. Louis Park Municipal Supply Wells in 1976 and 1978	G-38
G2-9	Total Monthly Municipal Well Pumpage in Edina in 1982	G-39
G3-1	Summary of Selected Studies of PAH Concentrations in Ground and Surface Water Supplies	G-42
G3-2	Summary of Basu and Saxena (1978) Data on PAH Occurrence and Treatment in Drinking Water Supply Systems	G-46
G3-3	Summary of Sorrell, et. al., (1980) Data on PAH Occurrence and Removal in Drinking Water Supply Systems with Conventional Treatment	G-47
G3-4	PAH Concentrations at Various Stages of a Water Treatment Works	G-49
G3-5	PAH Concentrations in Distributed Water in Drinking Water Supply Systems with Asphalt or Coal Tar Linings	G-51
G4-1	Summary Listing of Samples Collected During Serco's July 1979 PAC Tests at Well SLP15	G-56
G4-2	List of PAH Compounds Analyzed During Serco's PAC Tests at Well SLP15	G-57
G4-3	Summary of PAH Analysis Results from Serco's July 1979 PAC Tests at Well SLP15	G-59
G4-4	List of PAH Compounds Analyzed During Hickok's Tests of PAC and GAC Treatment at Well SLP15	G-67

LIST OF TABLES (Cont'd)

Table		Page
G4-5	Results of Hickok's PAC Tests at Wells SLP11 and SLP15	G-68
G4-6	Results of Hickok's GAC Tests at Well SLP15	G-70
G4-7	Summary of Hickok's 1981 Economic Evaluation of Treating St. Louis Park Wells SLP4, SLP10, and SLP15	G-76
G4-8	List of PAH and Hetrocyclic PAH Compounds Analyzed by CH2M Hill	G-80
G4-9	List of Compounds Analyzed by CH2M Hill and MRC During September 1982 Testing of the Iron Removal Plant at Well SLP15	G-83
G4-10	Summary of PAH Analysis Results by CH2M Hill and MRC During September 1982 Testing of the Iron Removal Plant at Well SLP15	G-85
G4-11	Summary of PAH Analyses for Compounds Measured in Common by CH2M Hill and MRC During September 1982 Testing of the Iron Removal Plant at Well SLP15	G-86
G4-12	Summary of CH2M Hill's First-Round Bench Testing Results for Pulverized Carbon Adsorption Treatment of Water from Well SLP15	G-95
G4-13	Summary of CH2M Hill's First-Round Bench Testing Results for Oxidative Treatment of Water from Well SLP15	G-96
G4-14	Summary of CH2M Hill's First-Round Bench Testing Results of Iron Removal Plant Unit Operations for Water from Well SLP15	G-98
G4-15	Summary of CH2M Hill's Second-Round Bench Testing Results for Granular Activated Carbon Columns and Water from Well SLP15	G-102
G4-16	Summary of CH2M Hill's Second-Round Bench Testing Results for Hydrogen Peroxide Treatment of Water from Well SLP15	G-103
G4-17	Summary of CH2M Hill's Second-Round Bench Testing Results for Ozone Treatment of Water from Well SLP15	G-104
G4-18	Summary of CH2M Hill's Cost Estimates for Various Treatment Alternatives at Well SLP15	G-107
G4-19	List of all Samples Collected During ERT's December 6-8, 1982 Test at St. Louis Park Station No. 1	G-123
G4-20	Summary of Specific Test Objectives During ERT's December 6-8, 1982 Test at St. Louis Park Station No. 1	G-128

LIST OF TABLES (Cont'd)

Table		Page
G4-21	Summary Descriptions of Analytical Methods Used for Samples Collected During ERT's December 6-8, 1982 Test at St. Louis Park Station No. 1	G-137
G4-22	Inorganic Constituent Concentrations at Various Points in the Iron Removal Plant During the Collection of Composite Samples Under Normal Operating Conditions on Decmeber 7, 1982	G-143
G4-23	Field Measurements of Individual Filter Cell Sample Taps on December 6, 1982	G-144
G4-24	Effects of Different Aeration and Prechlorination Rates on Inorganic Constitutents During ERT's December 6-8,1982 Test	G-146
G4-25	Results of Field Measurements During Operational Adjustments Made on December 6, 1982	G-148
G4-26	Inorganic Constituent Concentrations in Filter Outlet Water with No Aeration or Prechlorination During Testing on December 7, 1982	G-150
G4-27	Gross Characterization Analytical Results for Sand and Slime Samples Collected during ERT's December 6-8, 1982 Test at St. Louis Park Station No. 1	G-159
G4-28	Inorganic Constituent Concentrations in Backwash Feed and Wastewater Samples Collected During ERT's December 6-8, 1982 Test	G-162
G4-29	PAH Concentrations in Composite Samples Collected at Various Points from the Iron Removal Plant at St. Louis Park Station No.1 on December 7, 1982	G-173
G4-30	Effects of Different Aeration and Prechlorination Rates on PAH Removal During ERT's December 6-8, 1982 Test	G-178
G4-31	PAH Concentrations in Filter Outlet Samples With no Aeration or Prechlorination Collected During Testing on December 7, 1982	G-182
G4-32	Results of Filtering Various Samples Collected During ERT's December 6-8, 1982 Test at St. Louis Park Station No. 1	G-184
G4-33	Statistical Summary of Results from Filtering Samples Collected During ERT's December 6-8, 1982 Test at St. Louis Park Station No. 1	G-185
G4-34	PAH Concentrations in Backwash Feed and Wastewater Samples Collected During ERT's December 6-8, 1982 Test	G-188
G4-35	Summary Results of Split Samples from ERT's Test on December 7, 1982 Analyzed by CH2M Hill	G-192

LIST OF TABLES (Cont'd)

Table		Page
G4-36	Comparison of CH2M Hill and Monsanto Research Results for PAH Analyzed in Common by Both Labs for Split Samples	G-194
G4-37	Chronological Summary of ERT's February 1-2, 1983 Test at St. Louis Park Station No. 1	G-199
G4-38	Summary of Operating Conditions During ERT's February 1-2, 1983 Test at St. Louis Park Station No. 1	G-205
G4-39	Summary of Inorganic Constituent Analyses During Composite Sampling Period on February 2, 1983	G-206
G4-40	Summary of PAH Concentrations in Composite Samples Collected During ERT's February 1983 Test at St. Louis Park Water Treatment Station No. 1	G-208
G4-41	Simplified Statistical Analysis of PAH Data Obtained During February 1983 Test at St. Louis Park Treatment Station No. 1	G-210
G4-42	Average Compound Class PAH Concentrations in Composite Samples Collected on February 2, 1983	G-211
G4-43	Summary of Inorganic Constituent Analyses During Backwashing on February 2, 1983	G-213
G4-44	PAH Concentrations in Backwash Water Samples Collected on February 2, 1983	G-214
G4-45	Summary of PAH Concentrations in Sand Sample Collected During ERT's February 1-2, 1983 Test at St. Louis Park Station No. 1	G-216
G4-46	Calculated Correspondence Between Changes in Filter Bed Sand PAH Concentrations and Filter Inlet Water and Backwash Wastewater PAH Concentrations	G-219
G4-47	Summary of Key Results from PAH Removal Studies at St. Louis Park Well SLP15	G-222
G5-1	Engineering News Record Construction Cost Indices	G-232
G5-2	Construction Costs for the Iron Removal Plants in St. Louis Park, Minnesota	G-235
G5-3	1982 Operating Costs for Iron Removal Plants in St. Louis Park	G-237
G5-4	Estimated Operating Costs for Pressure Sand Filter Iron Removal Plants	G-238
G5-5	Estimated Capital Costs for Ozone Generation Equipment	G-243
G5-6	Estimated Operating & Maintenance Costs for Ozone Generation Systems	G-245

LIST OF TABLES (Cont'd)

Table		Page
G5-7	Estimated Capital Cost for Powdered Activated Carbon Feed Systems	G-249
G5-8	Estimated Operating & Maintenance Costs for Powdered Activated Carbon Injection	G-251
G5-9	Estimated Capital Cost for Granulated Activited Carbon Treatment	G-262
G5-10	Estimated Capital Cost for Backwash Wastewater Surge Basins for GAC Treatment Without Iron Removal Treatment Plants	G-264
G5-11	Estimated Operating & Maintenance Costs for Granular Carbon Treatment, Excluding Carbon Costs	G-266
G5-12	Carbon Replacement Costs for Granular Activated Carbon Treatment	G-268
G5-13	Present Value Cost of Treating all Contaminated Municipal Supply Wells	G-285
G5-14	Alternative Well Management Scenarios for Meeting Municipal Water Supply Shortfalls	G-287
G5-15	Present Value Cost of Treating Selected Municipal Supply Wells	G-289
G5-16	Potential Cost Savings in Combined Treatment of Wells SLP4 and SLP6	G-290
G8-1A to K	Results of SIM Analyses for PNA's for December 1982 CW#15 Treatment System Study	G-307
G8-2A to D	Inorganic Analyses for December 1982 CW#15 Water Treatment Study	G-318
G8-3A to C	Field Measurement Made on December 6, 1982 During ERT's Test at St. Louis Park Station No. 1	G-322
G8-4	Retention Times for SIM PAH Analyses by MRC on Samples Collected During ERT's December 6-8, 1982 Test at St. Louis Park Station No. 1	G-328
G8-5A to C	Results of SIM Analyses for PNA's for the February 1983 CW#15 Treatment System Study	G-329
G8-6A & B	Results of SIM Analysis for PNA's for Sand Samples from the February 1983 CW#15 Treatment System Study	G-332
G8-7A to C	Inorganic Analses for the February 1983 Test at St. Louis Park Station No. 1	G-334

LIST OF TABLES (Cont'd)

Table		Page
G8-8	Results of Field Measurements Made on February 2, 1983 During ERT's Test at St. Louis Park Station No. 1	G-338
G8-9A to C	Results of SIM Analyses for PNA's for City Well #15 Treatment System	G-341
G8-10	Results of SIM Analyses for PNA's for City Well #15 Treatment System	G-344

LIST OF EXHIBITS

Exhibit		Page
G2-1	Front View of the Aerator for Wells 11 and 15 at St. Louis Park Water Treatment Station No. 1	G-23
G2-2	Side View of the Aerator for Wells 11 and 15	G-23
G2-3	View Towards the Aerator Between the Two Filter Units for Wells 11 and 15 at St. Louis Park Water Treatment Station No. 1	G-24
G2-4	High Service Pumps and Control Panel at St. Louis Park Water Treatment Station No. 1	G-24
G2-5	Pumphouse for Wells 11 and 15 at St. Louis Park Water Treatment Station No. 1	G-25
G2-6	Pump for St. Louis Park Well 7	G-25
G2-7	St. Louis Park Water Treatment Station No. 8	G-26
G2-8	View Between the Two Filter Units at St. Louis Park Water Treatment Station No. 8	G-26
G4-1	Backwash Wastewater Being Discharged to the Storm Sewer During the First Backwash	G-133
G4-2	Sample Bottles and Cartons in Position for Composite Sampling on December 7, 1982	G-133
G4-3	Surface of the Filter Bed in Cell E Before the First Backwash	G-152
G4-4	Surface of the Filter Bed in All E After the First Backwash	G-152
G4-5	Surface of the Filter Bed in Cell E Before the Second Backwash	G-153
G4-6	Surface of the Filter Bed in Cell E After the Second Backwash	G-153
G4-7	Surface of the Filter Bed in Cell A Before the Second Backwash	G-154
G4-8	Distributor Pipe in Cell E After the First Backwash	G-154
G4-9	Scanning Electron Microscope Photographs of Slime Sample Collected From Cell E Before the First Backwash (12/6/82) at 1500 X and 5000X Magnification	G-156
G4-10	Scanning Electron Microscope Photographs of Slime Sample Collected From Cell A Before the Second Backwash (12/8/82) at 1500X and 5000X Maginfication	G-157

G1. INTRODUCTION

Drinking water treatment has been studied since 1979 by a number of investigators as a potential solution to the contamination of St. Louis Park municipal supply wells by PAH. This Appendix summarizes the results of these various studies, including those conducted independently by ERT. It provides necessary background information for evaluating the application of drinking water treatment remedies to the St. Louis Park problem; and also presents ERT's cost estimates for applying various types of drinking water treatment alternatives to contaminated St. Louis Park wells.

Section G2 presents background information on the operation of the St. Louis Park municipal water supply system, including supply and demand characteristics and treatment plant operations. Similar information is also provided for the Edina and Hopkins municipal water supply systems, which have been, or in the future may be, affected by PAH contaminants in the Prairie du Chien-Jordan aquifer. The information in section G2 is necessary to understand the PAH removal drinking water treatment studies performed to date at St. Louis Park and to evaluate the costs of alternatives for satisfying the water supply shortfall created by current or predicted closures of certain municipal supply wells.

Section G3 contains a summary discussion of data from the scientific literature on the occurrence and removal of PAH in existing drinking water supply systems. This information is important in establishing a context for the PAH contamination problems in St. Louis Park, including the selection of potentially applicable drinking water treatment technologies.

Section G4 summarizes the results of the drinking water treatment studies performed to date for removing PAH from contaminated St. Louis Park municipal supply wells. The results of early studies by Serco Laboratories and Eugene A. Hickok and Associates and of on-going

studies by CH2M Hill, all conducted at St. Louis Park well SLP15, are summarized. Economic evaluations of drinking water treatment alternatives made by Hickok and CH2M Hill are also summarized. Section G4 also presents complete results of ERT's two tests of PAH removal at the existing iron removal treatment plant at well SLP15. ERT's results are presented in detail since they have not been reported elsewhere. A separate section (G8) at the end of this appendix presents complete analytical results from ERT's texts.

Section G5 presents ERT's cost estimates for various drinking water treatment alternatives. These estimates are based on the results of the treatment tests summarized in section G4. The estimates are developed parametrically for a variety of design bases in order 1) to account for uncertainties in the appropriate design bases and 2) to allow costs to be readily estimated for treating different wells. Section G5 also presents cost estimates for treating specific combinations of wells as required by the different ground-water contamination and treatment scenarios presented in Chapter 6.

G2. DESCRIPTION OF MUNICIPAL WATER SUPPLY SYSTEMS IN THE ST. LOUIS PARK AREA

The purpose of this section is to provide summary descriptions of the major features of municipal water supply systems in St. Louis Park and neighboring communities. The material in this section represents important background information in understanding possible applications of drinking-water treatment technologies for removing PAH and related compounds from potable water supplies. The first half of this section describes the St. Louis Park municipal water supply system. The second half describes the municipal water supply systems in neighboring communities, particularly Hopkins and Edina.

G2.1 St. Louis Park Municipal Water Supply System

The municipal water supply system in St. Louis Park serves a population of some 47,000 people through about 14,000 service connections (MDH 1981). The system provides an average of 6.2 million gallons of water per day, with highest daily production being 11.6 million gallons (ibid). Average daily per capita demand has been fairly constant at about 120 to 130 gallons per capita per day since the late 1960's (Orr, Schelen, Mayeron 1976; MDH 1975, 1977, 1979, 1980, 1981).

All of the water for the St. Louis Park water supply system is obtained from wells. The City has fourteen wells available, with six wells currently not in use due to PAH contamination. Ten of the supply wells draw from the Prairie du Chien-Jordan aquifer, three from the Mt. Simon-Hinckley and one from the Platteville-St. Peter. The wells are dispersed throughout the City, as shown in Figure G2-1, with multiple wells occurring at some locations. Water from all of the wells is treated by chlorination and fluoridation. In addition, water from ten of the wells is treated for iron removal. Table G2-1 summarizes historical production volumes for each of the wells and indicates the aquifer(s) utilized and the treatment applied at each well. Further details on supply and treatment aspects of the St. Louis Park municipal water supply system are provided in the following subsections.

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NON-RESPONSIVE

TABLE G2-1

SUMMARY DATA FOR THE ST. LOUIS PARK MUNICIPAL WELL SYSTEM

Well Station	Iron Removal Plant[e]	Well Numbers	Aquifer	Average Annual Production[a] 1972 - 1977 Millions of Gallons per Year	Operating Rate, Percent of Capacity[d]	Well Status
1	Yes	3	Platteville-St. Peter	57	9.0	
		10	Prairie du Chien-Jordan	46	8.8	Closed 11/78.
		11	Mt. Simon-Hinckley	305	48.4	
		15	Prairie du Chien-Jordan	242	38.4	Closed 11/78.
4	No	4	Jordan	41	6.5	Closed 12/79.
5	No	5	Prairie du Chien-Jordan	91	14.4	Closed 8/81.
		17	Mt. Simon-Hinckley	NA		Construction begun 10/81.
6	Yes	6	Jordan	273	43.3	
		12	Mt. Simon-Hinckley	171	21.7	
7	No	7	Prairie du Chien-Jordan	26	4.1	Closed 11/78.
		9	Prairie du Chien-Jordan	26	4.1	Closed 11/78.
8	Yes	8	Prairie du Chien-Jordan	321	58.2	
10	Yes	13	Hinckley	243	30.8	
		14	Jordan	94	22.4	Closed 9/81. Reopened 12/81.
16	Yes	16	Jordan	225 [b]	69.9	
			TOTAL	2161 [c]		
Total for wells which are presently closed			472 (22%)	Total for wells with iron removal plants	1977 (91%)	

Notes:

(a) Averages calculated from data in Table G2-2.
(b) Average pumpage for well 16 is from 1972 to 1977 even though this well was started up in late 1974.
(c) Total is of individual well averages shown. The actual average total pumpage from 1972 to 1977 was 2166 million gallons per year.
(d) Average annual production for 1972-1977 divided by design capacity given in Table G2-2.
(e) All wells have chlorination and fluorination treatment, with or without iron removal treatment.

Notes to Table G2-1:

(a) Averages calculated from data in Table G2-2.
(b) Average pumpage for well 16 is from 1972 to 1977 even though this well was started up in late 1974.
(c) Total is of individual well averages shown. The actual average total pumpage from 1972 to 1977 was 2166 million gallons per year.
(d) Average annual production for 1972-1977 divided by design capacity given in Table G2-2.
(e) All wells have chlorination and fluorination treatment, with or without iron removal treatment.
(f) Well closure dates from Englund (1982).

G2.1.1 Supply Characteristics

Table G2-2 shows annual pumpage rates for each of the St. Louis Park municipal supply wells from 1972 to 1982. The data in Table G2-1 indicate that pumpage rates for a single well may change dramatically from year to year even though total system pumpage remains relatively constant. The data in Table G2-2 also indicate that certain wells are pumped much more intensively than others. These variations in well pumpage reflect changes in operation to meet seasonal and yearly changes in demand. Certain wells are pumped regularly throughout the year to meet base-load demand while other wells are only pumped to meet peak seasonal (summer) demand. In addition, all wells are affected by daily demand variations. This is illustrated more clearly by Table G2-1, which shows average production as a percentage of full capacity operation for the period 1972 to 1977. Even the most intensively pumped wells are only operated at from 40 to 70 percent of capacity, which largely reflects decreased demand at night.* Section G2.3 provides further discussion of demand variations and their effects on well pumpage.

Table G2-1 shows that in the period from 1972 to 1977, only half of the St. Louis Park municipal supply wells were pumped at over 100 million gallons per year on average, yet these seven wells supplied 82 percent of the total production during this period. In recent years, however, as wells have been taken out of service due to contamination by PAH (starting in October 1978) the production load has been distributed somewhat more evenly among the remaining wells. In 1981, for example, all nine of the wells which were not closed throughout the year pumped over 100 million gallons. The production load was still skewed, however, in that the five wells that pumped over 200 million gallons provided 71 percent of the supply.

*Expressing production rates as a percentage of design pumping capacity is a legitimate means of evaluating the amount of time that a well is actually pumped. This is because the well pumps in St. Louis Park usually run at or near full capacity when they are operated (Tollefsrud 1982a).

TABLE G2-2

CAPACITY AND HISTORICAL PUMPING RATE DATA
FOR ST. LOUIS PARK MUNICIPAL WELLS

Well No.	Aquifer[a]	Year Installed	Design Capacity, Gallons per Minute[b]	Volume Pumped, Millions of Gallons[c] 1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982[g]
3	Platteville-St. Peter	1939	1200	30.9	58.2	52.7	28.7	125.9	44.1	84.6	88.3	188.7	170.1	117.8
4	Jordan	1946	1200	27.7	9.6	37.6	28.6	91.7	49.2	120.9	116.2[f]	6.5[f]	0[f]	0.2[f]
5	Prairie du Chien-Jordan	1947	1200	100.2	124.9	111.3	43.7	151.5	14.1	38.7	20.7	132.2	159.9[f]	0[f]
6	Jordan	1948	1200	268.6	150.1	288.0	228.8	349.6	354.5	467.6	451.3	275.3	143.2	141.7
7[e]	Prairie du Chien-Jordan	1952	1200	48.4	32.3	34.6	15.5	21.9	1.9	18.3[f]	0[f]	11.4[f]	0[f]	0.3[f]
8	Prairie du Chien-Jordan	1955	1050	312.7	377.3	342.6	134.8	375.3	386.1	341.9	378.9	377.9	257.1	321.9
9[e]	Prairie du Chien-Jordan	1955	1200	48.4	32.3	34.6	15.5	21.9	1.9	18.3[f]	0[f]	11.4[f]	0[f]	0.3[f]
10	Prairie du Chien-Jordan	1955	1000	32.8	42.1	71.5	30.3	86.1	14.7	49.3[f]	0[f]	0[f]	0[f]	0[f]
11	Mount Simon-Hinckley	1961	1200	282.5	341.8	318.6	306.5	315.8	266.6	190.3	313.7	295.8	342.3	279.3
12	Mount Simon-Hinckley	1963	1500	288.0	133.8	200.6	178.7	108.4	117.8	129.8	73.7	225.9	297.3	254.2
13	Hinckley	1964	1500	186.6	473.2	355.2	294.6	101.8	49.2	63.2	92.2	260.9	256.8	315.0
14	Jordan	1965	800	129.3	142.2	74.0	63.2	102.4	55.5	22.2	18.5	107.6	124.3[f]	72.9
15	Prairie du Chien-Jordan	1969	1200	258.5	291.9	237.4	254.5	232.6	179.7	118.0[f]	10.4[f]	3.0[f]	3.2[f]	4.9[f]
16	Jordan	1973	1100	0	0	6.9	416.4	442.3	485.9	422.5	388.6	270.3	320.2	324.7
			16,550	2024[d]	2214[d]	2167[d]	2040	2527	2021	2086	1952	2167	2074	1833

(a) From MDH (1981).
(b) From Orr, Schelen, Mayeron (1976).
(c) Data for 1972-1975 from Orr, Schelen, Mayeron (1976). Data for 1976-1982 from Tollefsrud (1982).
(d) Includes production from wells 1 & 2, which were abandoned in 1974 & 1972, respectively. Total production from these wells was 8.9 million gallons in 1972, 3.9 million gallons in 1973 & 1.0 million gallons in 1974. (Orr, Schelen, Mayeron 1976).
(e) Pumpage for wells 7 & 9 is metered together, not separately.
(f) Wells closed down throughout or for a portion of the year shown due to PAH contamination. See Table G2-1.
(g) Through September 30.

Table G2-3 summarizes water quality data for major inorganic constituents in untreated water from the various St. Louis Park supply wells (MDH 1975). The data show that the wells generally provide high quality water with respect to trace metal and inorganic contituents. The supply water would be classified as hard to very hard (EPA 1976), with total hardness (as calcium carbonate) ranging from about 200 to 400 milligrams per liter. Water from Mount Simon-Hinckley wells is softer than water from Prairie du Chien-Jordan wells by about 100 milligrams per liter total hardness.

Water from all of the aquifers used contains high levels of iron, ranging from about 0.6 milligrams per liter to over 1.0 milligrams per liter. These iron concentrations exceed the recommended criterion for iron in domestic water supplies of 0.3 milligrams per liter, which is based on preventing objectionable tastes or staining of laundry or plumbing fixtures (EPA 1976). Similarly, water from many of the wells exceeds the recommended criteria for manganese of 0.05 milligrams per liter, which is also based on preventing objectionable tastes or staining (ibid). Most of the water supply in St. Louis Park is treated to remove iron (see Table G2-1), and this treatment can also somewhat reduce manganese levels. A description of the iron removal treatment employed in St. Louis Park is provided in the next subsection.

G2.1.2 Treatment of Water Supplies

There are five iron removal treatment plants in St. Louis Park, as shown in Figure G2-1 and Table G2-1. These plants treat water from ten of the fourteen wells in the City. Over 90 percent of the total water supply is treated for iron removal (see Tables G2-1 and G2-2). Water from all of the supply wells is treated with chlorine and fluoride, whether or not iron removal treatment is provided. Chlorine treatment is used to provide a level of residual chlorine in the distribution system for disinfection purposes, with a target residual chlorine level of at least 1.0 milligrams per liter (MDH 1981). The addition of fluoride at specified dosages is required by law in Minnesota to aid in the prevention of dental caries.

TABLE G2-3

TYPICAL WATER QUALITY DATA FOR
ST. LOUIS PARK MUNICIPAL SUPPLY WELLS[a]

Parameter	Concentrations in Milligrams per Liter, Unless Otherwise Noted		
	Platteville-St. Peter Well[b]	Prairie du Chien-Jordan Wells[c]	Mount Simon-Hinckley Wells[d]
pH Value	7.6	7.4 - 7.8	7.7 - 7.8
Specific Conductance, μmhos/cm	680	500 - 600	420 - 500
Coliform, M.P.N.[g] per 100 ml	<2.2	<2.2	<2.2
Total Solids	460	310 - 410	240 - 300
Total Hardness as $CaCO_3$	390	280 - 360	170 - 220
Alkalinity as $CaCO_3$	330	280 - 320	180 - 220
Iron	0.83	0.59 - 3.0[e]	0.54 - 0.67
Manganese	0.10	0.04 - 0.11	<0.10 - 0.18
Chloride	34	<1 - 25	2 - 27
Sulphate	64	7 - 64	10 - 46
Fluoride	0.15	0.14 - 0.29	0.33 - 0.51
Total Phosphorus	0.06	0.05 - 0.15[e]	0.002 - 0.01
Nitrite Nitrogen	0.03	<0.01 - 0.56	0.01 - 0.25
Nitrate Nitrogen	<1	<1	<1
Calcium as $CaCO_3$	240	140 - 220	100 - 130
Magnesium	NA[f]	120 - 140	NA
Sodium	14	6 - 17	27 - 37
Potassium	2.8	1.7 - 3.0	8.0 - 9.8
Ammonia	<0.05	0.20 - 0.49	0.32 - 0.36
Total Organic Carbon	<5	<5	<5
Phenolics	0.016	<0.002 - 0.013	<0.002
Methylene Blue Active Substances as ABS	<0.1	<0.1	<0.1
Trace Metals, micrograms per liter:			
Cadmium	<10	<10	<10
Copper	16	<10 - 11	<10
Lead	NA	<10	<10
Nickel	<10	<10	<10
Zinc	14	<10 - 17	<10

Notes:

(a) All data from MDH 1975.
(b) Data for SLP well 3.
(c) Range represents data from SLP wells 4 to 10, 15 and 16.
(d) Range represents data from SLP wells 11, 12 and 13.
(e) Excluding unusually high values for SLP well 10.
(f) NA indicates data not available.
(g) M.P.N. = most probable number.

The iron removal plants in St. Louis Park are all based on high pressure sand filtration. In simple terms, they operate by first oxidizing bivalent, ferrous iron (Fe^{+2}) - which is the predominant form of iron in the raw water - to trivalent, ferric iron (Fe^{+3}). Ferric iron is very insoluble in water at neutral pH valves and tends to form insoluble ferric salts. Insoluble ferric compounds are then removed by filtration in sand filter beds. This treatment technique is very common for ground water supplies in the Minneapolis area (Goplin 1982) and for many water supplies throughout the United States (AWWA 1969).

Figure G2-2 shows a schematic diagram of the iron removal treatment plant at St. Louis Park Water Treatment Station No. 1. Water from wells 3, 10, 11 and 15 is treated at this station. The design and operation of this treatment plant is very similar to that of the other four iron removal plants in St. Louis Park. Figure G2-3 shows the physical layout of the treatment plant and Figure G2-4 shows the overall plan at St. Louis Park Station No. 1.

As shown in Figures G2-2 and G2-3, water from wells 3 and 10 is combined for treatment in one bank of filters and water from wells 11 and 15 is combined for treatment in a second bank. Water from each pair of wells is aerated in an in-line aerator as it first enters the treatment building. Aeration is intended to add oxygen to the water to oxidize ferrous iron to the ferric state. The aeration rate is normally set to add 2.6 milligrams per liter of oxygen.* Figure G2-5 shows a schematic diagram of the aerator.

Immediately after aeration, chlorine solution is injected at a dose of about 1.2 milligrams per liter.** This prechlorination step is intended to prevent iron bacteria from growing on the sand filters.*** Iron bacteria are naturally present in many ground water supplies in the Minneapolis area (Goplin 1982). Iron bacteria

*Based on air at 20 percent of full-scale (6.07 standard cubic feet per minute) for each well operating at 1000 gallons per minute (Senander 1982).
**Based on 15 pounds per day chlorine dose for each well operating at 1000 gallons per minute (Senander 1982).
*** As noted in section G4.4.5, prechlorination also oxidizes ferrous iron.

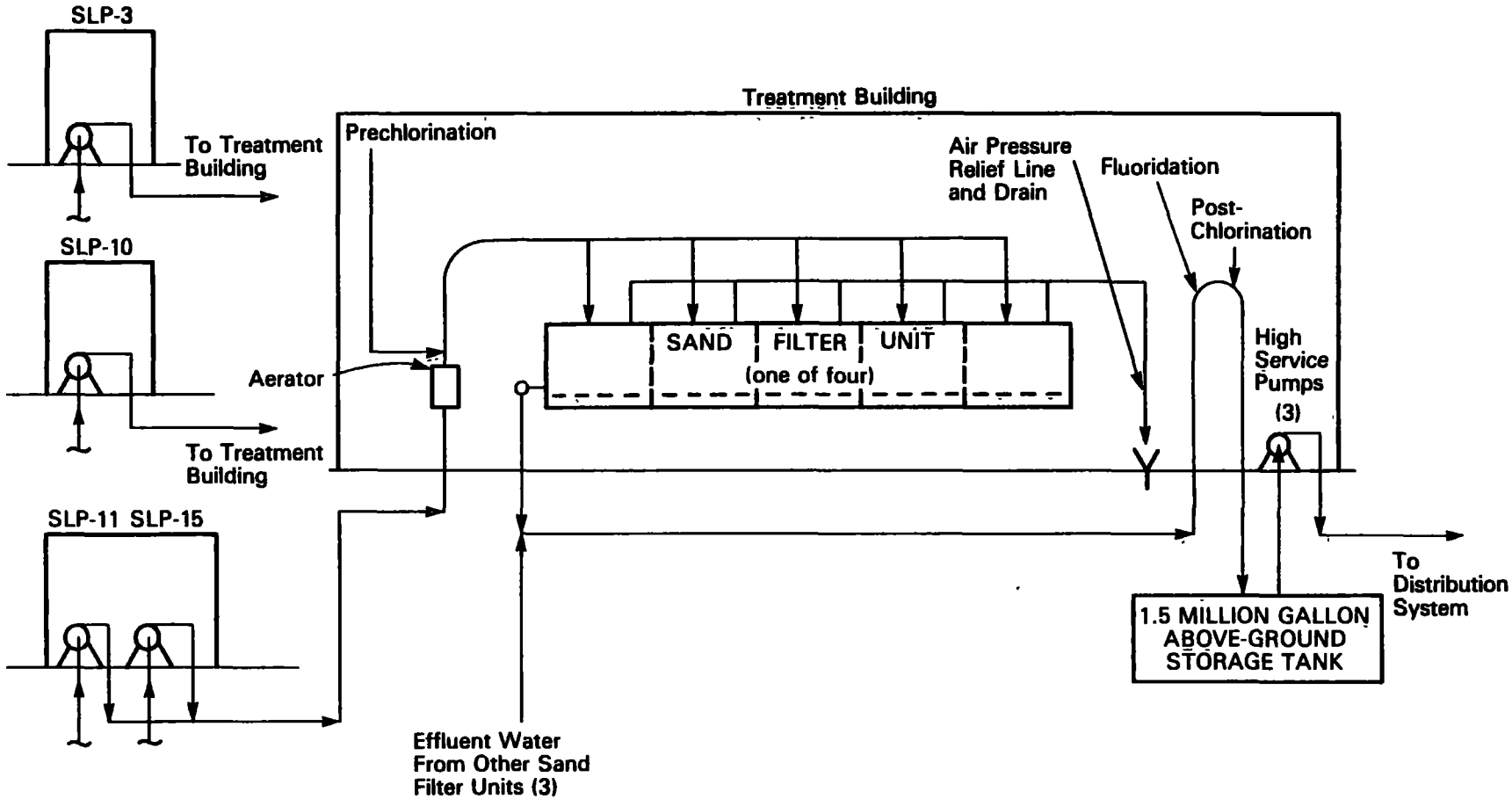

Figure G2-2 Schematic Diagram of the St. Louis Park Station No. 1 Treatment Plant

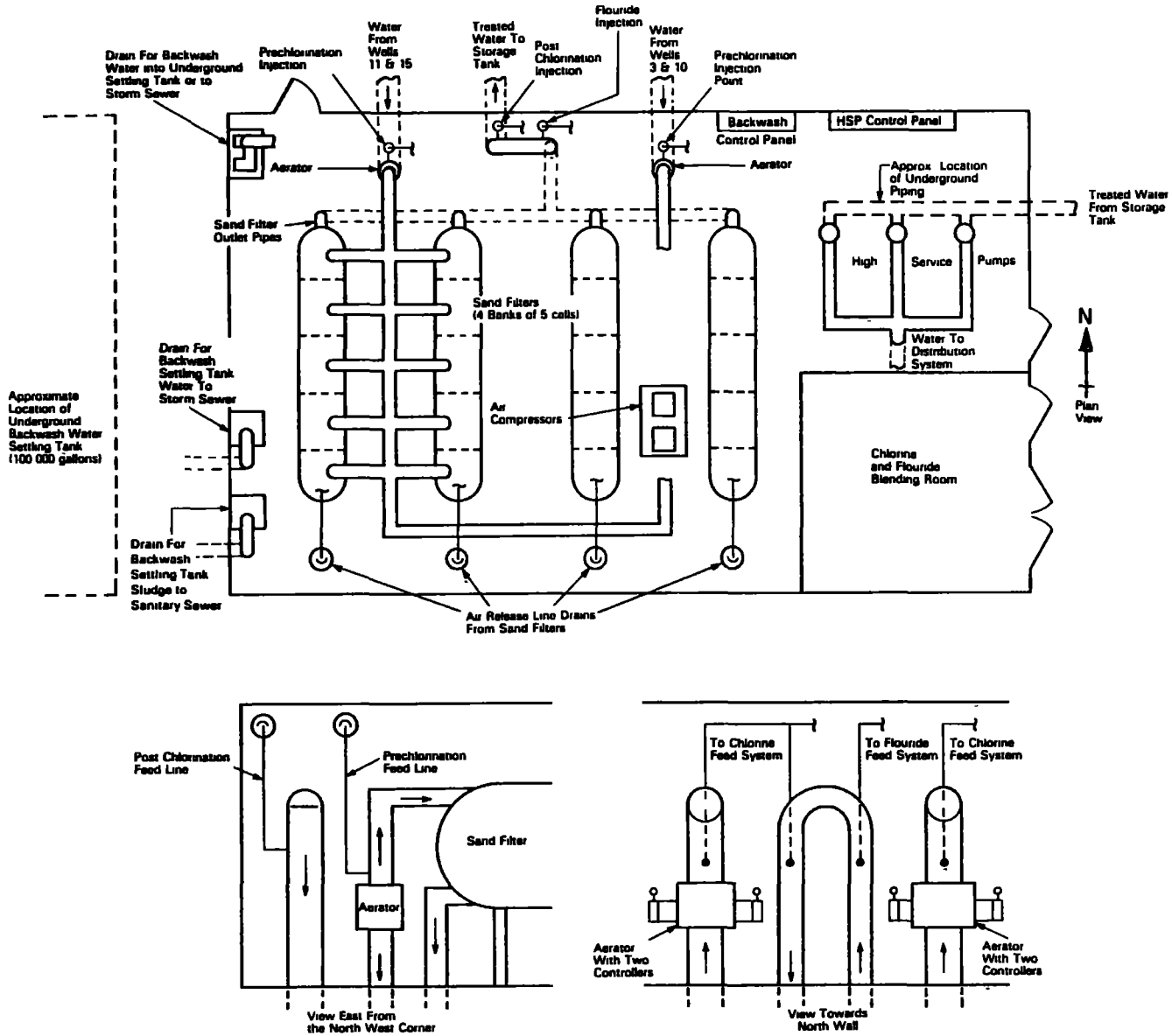

Figure G2-3 Layout of St. Louis Park Station No. 1 Treatment Building (Not to Scale)

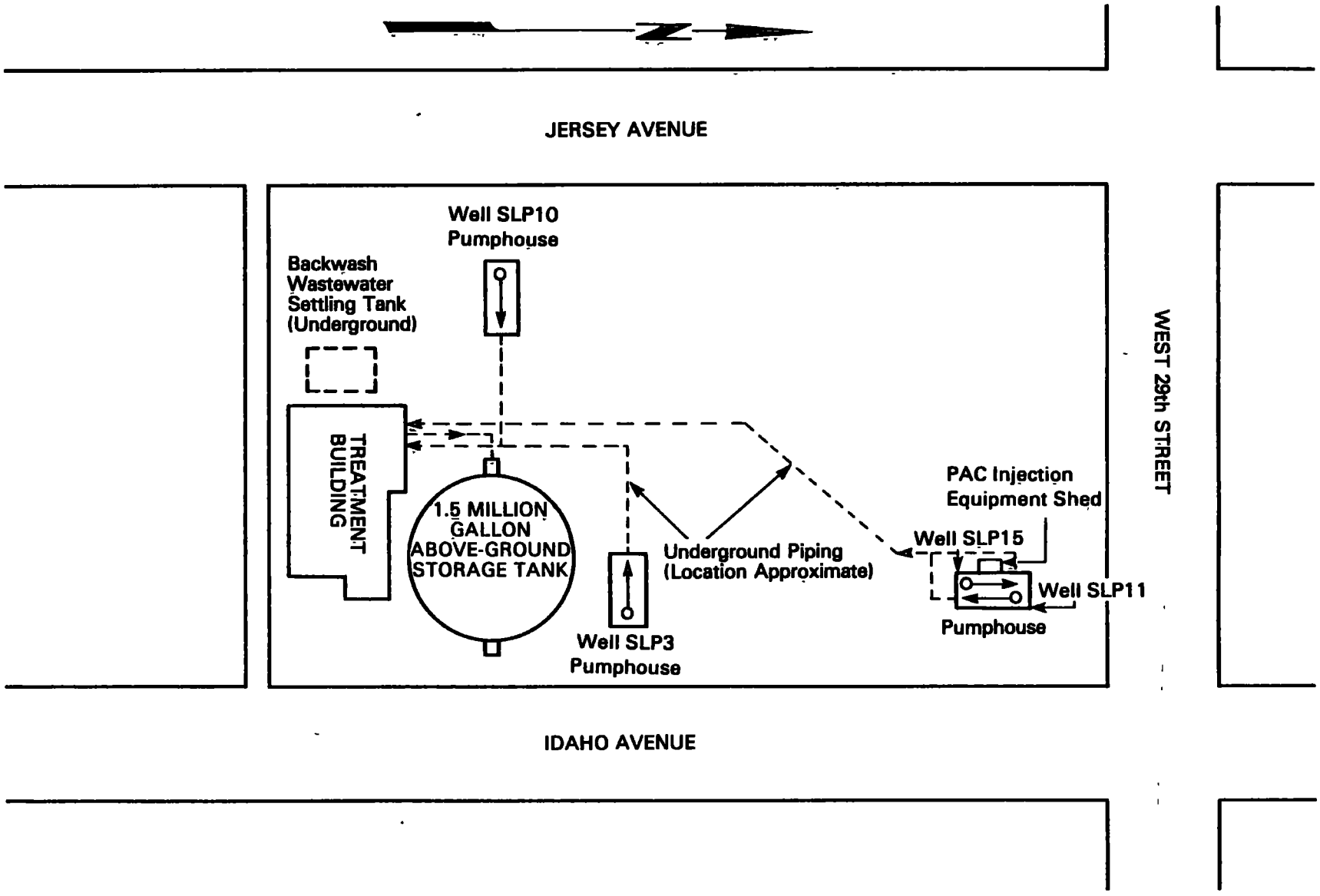

Figure G2-4 Overall Layout of St. Louis Park Station No. 1 (Not to Scale)

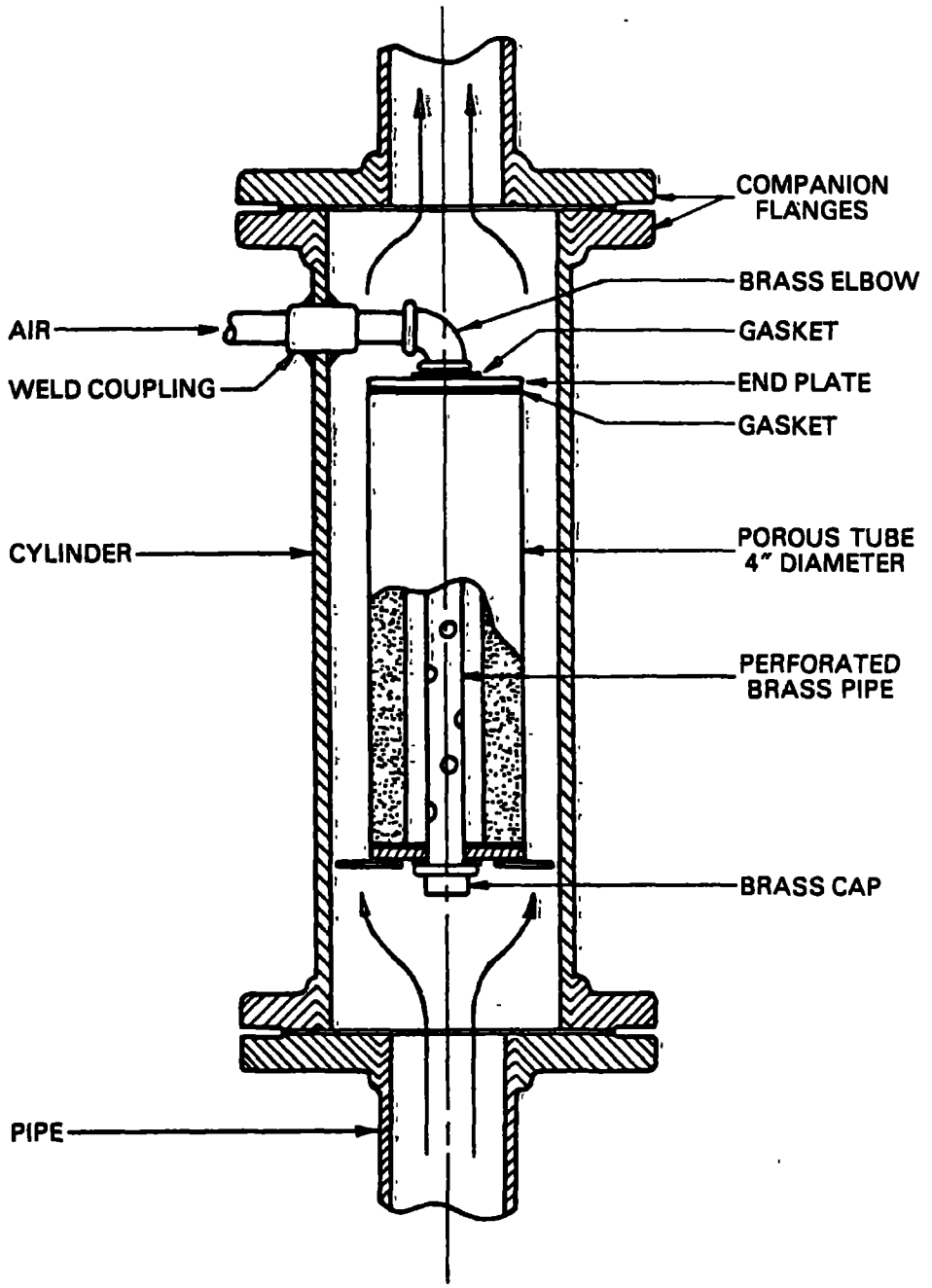

Figure G2-5 Cross-Section of the Aerator at St. Louis Park Water Treatment Station No. 1 (Reproduced from General Filter Company 1969)

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(the major species being sphaerotilus and gallionella) derive their energy by oxidizing ferrous iron and can build up to form bacterial slimes (Kemmer 1979; Stanier, Doudoroff and Adelberg 1963).

Water from the aerator is then passed through high pressure sand filters. At St. Louis Park Station No. 1 there are two filter units for each pair of wells. Each filter unit has five individual cells with a common underdrain (twenty cells in all). Filtered water from each filter unit is combined in a common header (located below grade) and then treated with fluoride and a post-filtration dose of chlorine. The treated water is then sent to a 1.5 million gallon above-ground storage tank. Three high service pumps deliver water from the storage tank into the distribution system. Not all of the other treatment stations in St. Louis Park have associated storage tanks.

The design filtration rate at St. Louis Park Station No.1 is 2.44 gallons per minute per square foot of filter area, based on four units each with 512 square feet of filtering area and a design flow rate of 5000 gallons per minute (General Filter Company 1969). Design filtering rates at the other iron removal plants in St. Louis Park range from 2.38 to 2.5 gallons per minute per square foot, with a range of from 420 to 1200 square feet of total filter area per plant (Goplin 1983b). Figures G2-6 through G2-9 show top, side, end and cross-sectional views of the filter units at St. Louis Park Station No.1 (General Filter Company 1969). The filter units at the other St. Louis Park iron removal plants are similar in design (all were provided by General Filter Company), and consist of two filter units with either 4 or 5 cells per unit (Goplin 1983b). The treatment plant at Station No. 1 operates at well pump discharge pressure (about 15 pounds per square inch gauge), although some of the other plants in St. Louis Park operate at distribution system pressure (about 60 to 70 pounds per square inch gauge).

The sand filters are backwashed at regular intervals to remove the iron precipitate which accumulates in the filter beds. During backwashing, the flow of water through the filter beds is reversed

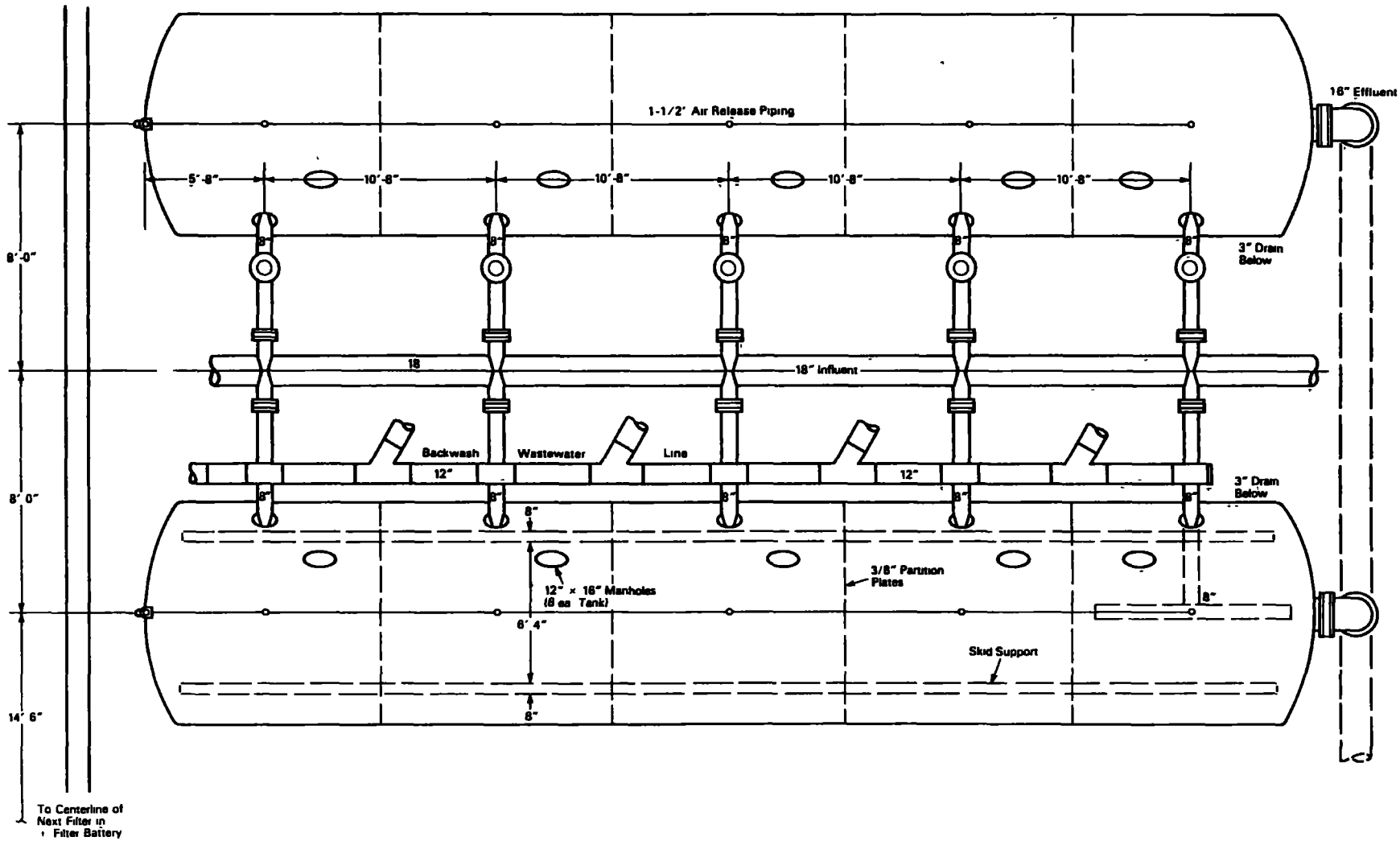
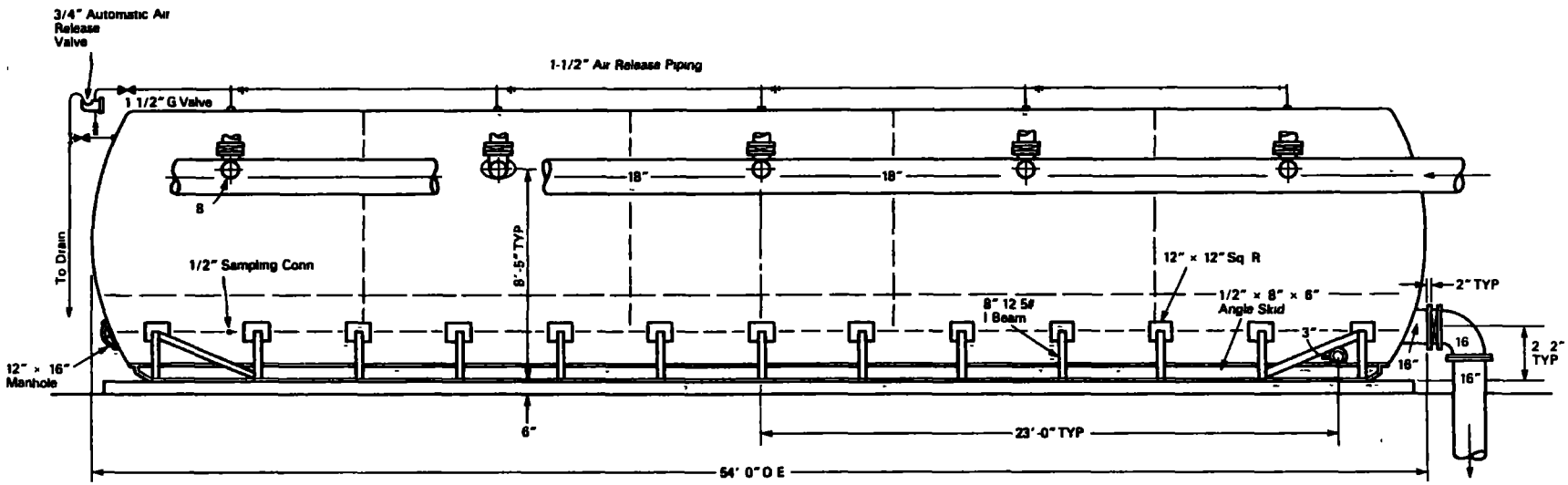


Figure G2-6 Top View of Sand Filter Units at St. Louis Park Water Treatment Station No. 1 (Reproduced from General Filter Company 1969, Drawing D-16035-F)



ELEVATION

Figure G2-7 Side View of Sand Filter Unit at St. Louis Park Water Treatment Station No. 1 (Reproduced from General Filter Company 1969, Drawing D-16035-F)

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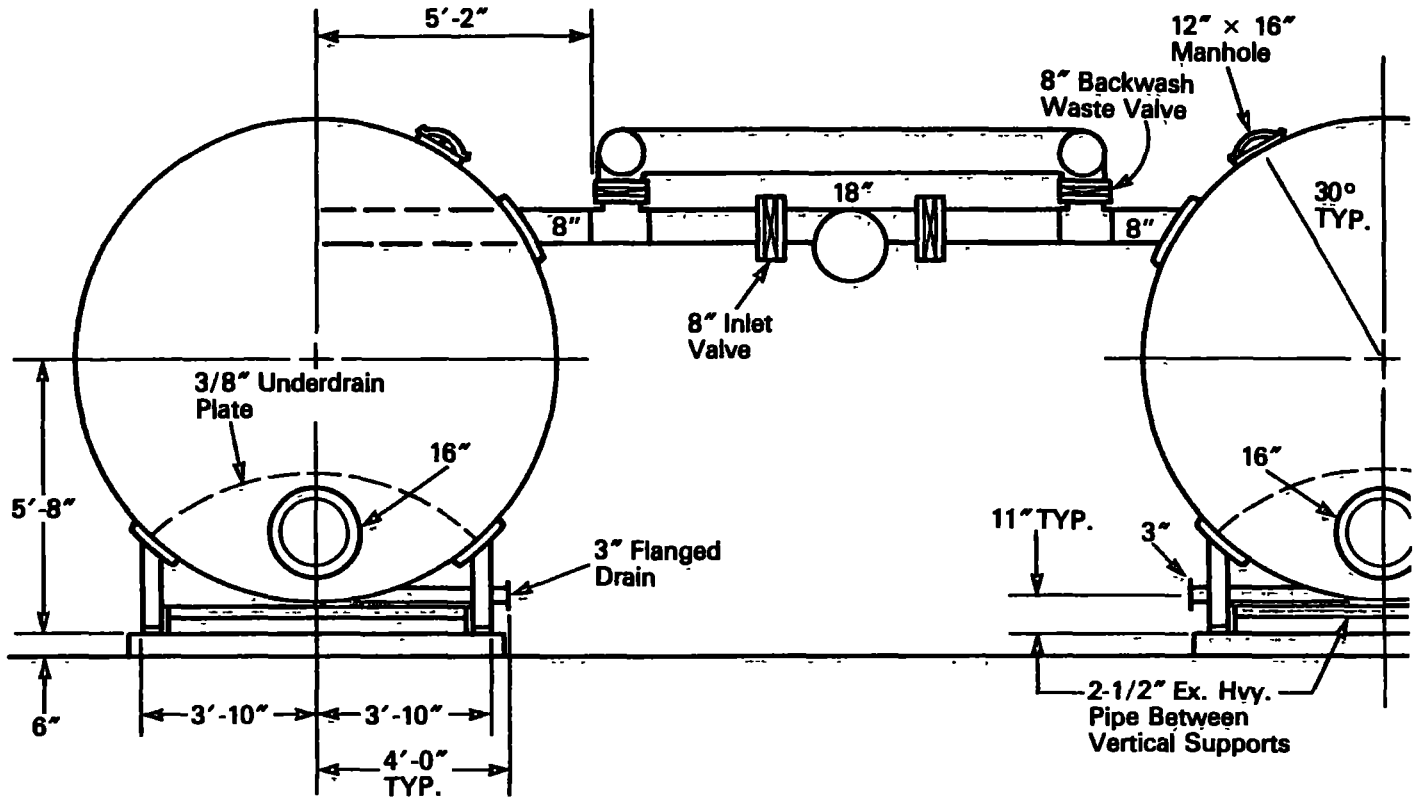

END VIEW

Figure G2-8 End View of Sand Filter Units at St. Louis Park Water Treatment Station No. 1 (Reproduced from General Filter Company 1969, Drawing D-16035-F)

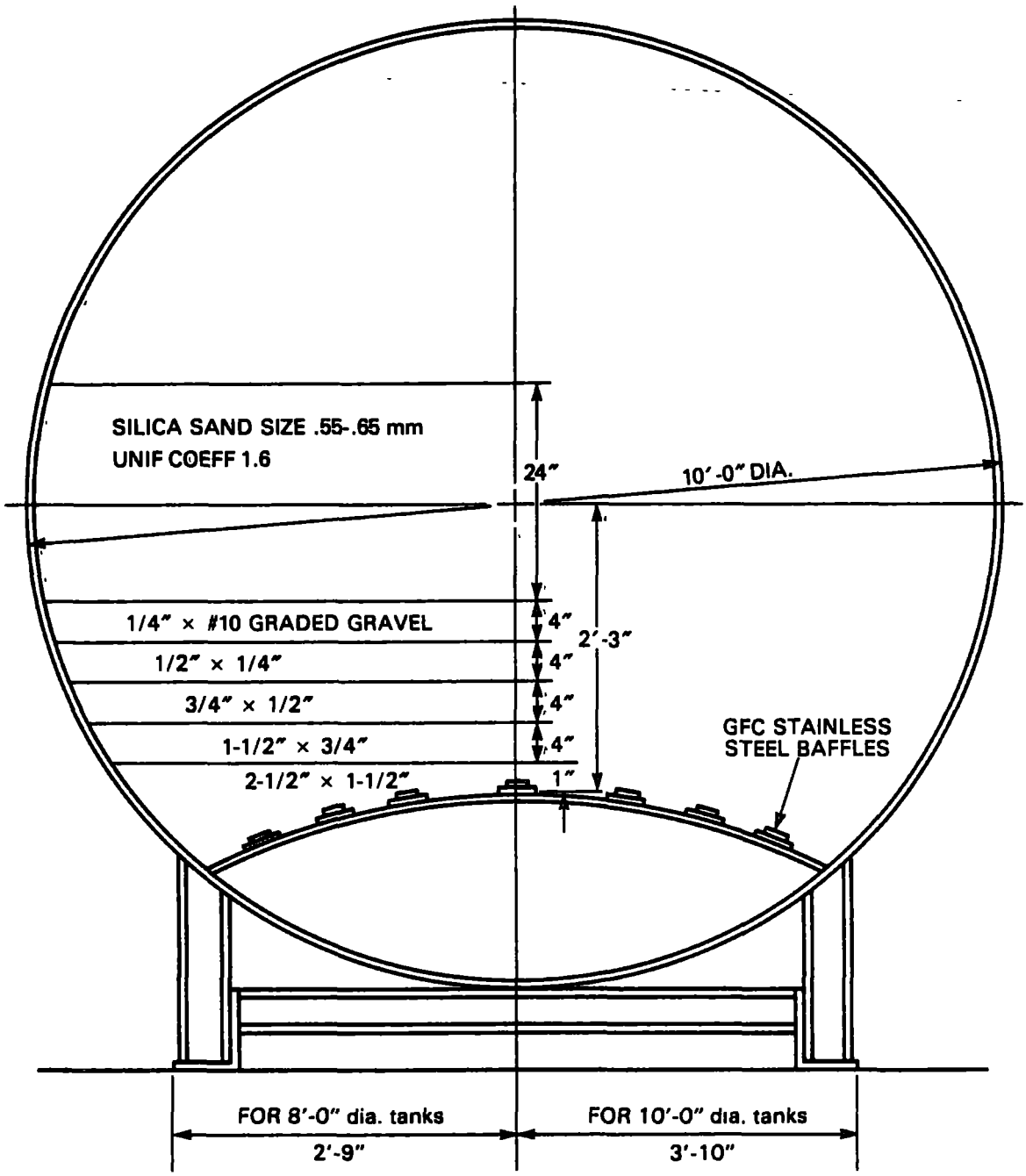

Figure G2-9 Cross-Section of Sand Filter Unit at St. Louis Park Water Treatment Station No. 1 (Reproduced from General Filter Company 1969)

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(i.e., water flows from the underdrain up through the filter cell) and the rate is increased to expand the bed and obtain "scrubbing" action. The backwash wastewater is routed to a separate piping system with a series of automatically controlled butterfly valves (see Figures G2-6, 7 and 8) and is discharged to an underground settling tank located just outside the treatment building (see Figure G2-3). Settled iron precipitate is pumped from the settling tank to the sanitary sewer and clarified water is pumped to the storm sewer.

The backwashing process is automatically controlled using a flow rate controller and timer to achieve the desired backwash rate and duration. Each cell is backwashed individually in sequence and takes about 15 minutes. The design backwash rate is 15 gallons per minute per square foot (General Filter Company 1969). Backwashing is initiated every 10 days or when the pressure drop across the filter beds reaches 6 pounds per square inch, whichever comes first (Tollefsrud 1982a).

When properly operated, the iron removal plants in St. Louis Park are capable of producing treated water containing less than 0.05 milligrams per liter of iron. However, iron levels in treated waters greater than 0.3 milligrams per liter have been measured at some of the treatment stations on the occasion of some Minnesota Department of Health (MDH) surveys. Table G2-4 summarizes the available MDH survey data on iron removal plant efficiencies in St. Louis Park from 1973 to 1981. The data show that all of the plants except Station No. 6 have experienced operating difficulties at one time or another, as evidenced by treated water (effluent) iron concentrations above 0.3 milligrams per liter.

Exhibits G2-1 through G2-8 show photographs of various parts of the St. Louis Park municipal water supply system* to help illustrate some of the features described above. Exhibits G2-1 through G2-5 are

*All of the photographs in Exhibits G2-1 through G2-8 were taken on November 1, 1982.

TABLE G2-4

HISTORICAL DATA ON IRON REMOVAL PLANT PERFORMANCE IN ST. LOUIS PARK [i]

Date of Sample	Iron Concentrations, Milligrams per Liter										MDH Sanitation Safety Rating
	Station No. 1		Station No. 6		Station No. 8		Station No. 10		Station No. 16		
	Influent	Effluent	Influent[c]	Effluent	Influent[d]	Effluent	Influent[e]	Effluent	Influent[f]	Effluent	
September, 1973	0.41-0.84[a]	0.05	1.2/0.59	0.02	1.0	0.50	0.91/1.4	0.07	NO[h]	NO	NA
August, 1975	0.59-0.83[a]	0.15	0.60/0.54	NA[g]	0.71	NA	0.56/NA	0.69	0.67	0.86	96
October, 1977	0.27-1.7[a]	0.25	0.55/0.20	0.17	0.65	0.42	0.68/0.64	0.05	0.60	0.14	94.5
March, 1979	4.1/0.71[b]	0.05	0.69/0.34	0.05	0.76	2.5	0.87/0.83	0.05	0.80	0.54	96
May, 1980	4.0/0.67[b]	1.9/0.13[b]	4.8/0.48	0.05	0.77	0.14	0.65/1.5	0.05	0.78	1.4	97
September, 1981	4.6/0.63[b]	0.36	3.2/0.59	0.05	0.65	0.36	0.63/NO	0.05	0.84	0.15	97.5

Notes:

(a) Range of data for wells 3, 10, 11 and 15.
(b) Data for well 3/well 11 (wells 10 and 15 out of service).
(c) Data for well 6/well 12.
(d) Data for well 8.
(e) Data for well 13/well 14.
(f) Data for well 16.
(g) NA = not available.
(h) NO = not operating.
(i) Data from MDH (1973, 1975, 1977, 1979, 1980, 1981).

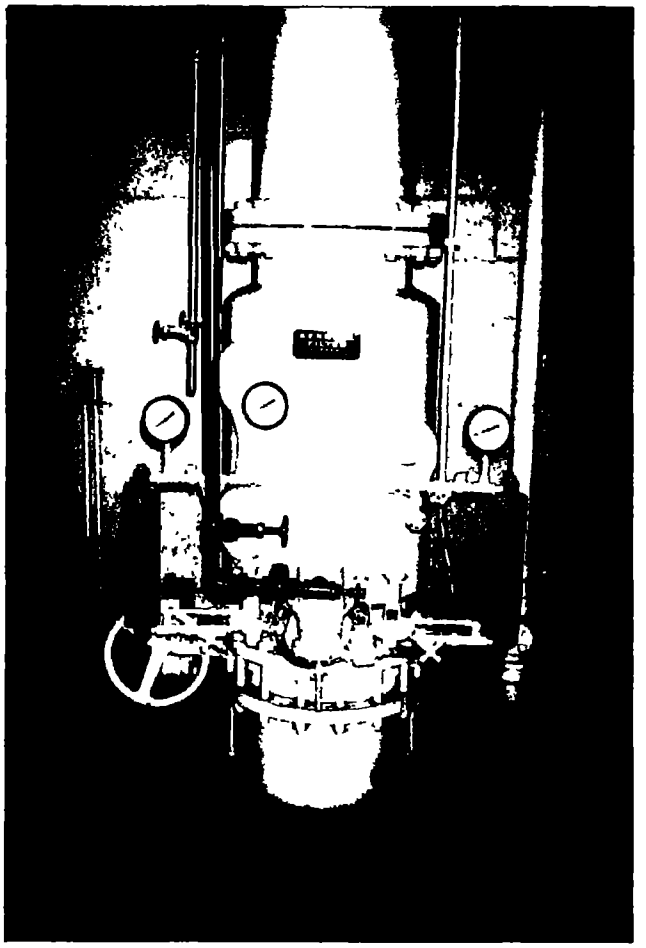

Exhibit G2-1 Front View of the Aerator for Wells 11 and 15 at St. Louis Park Water Treatment Station No. 1

Exhibit G2-2 Side View of the Aerator for Wells 11 and 15

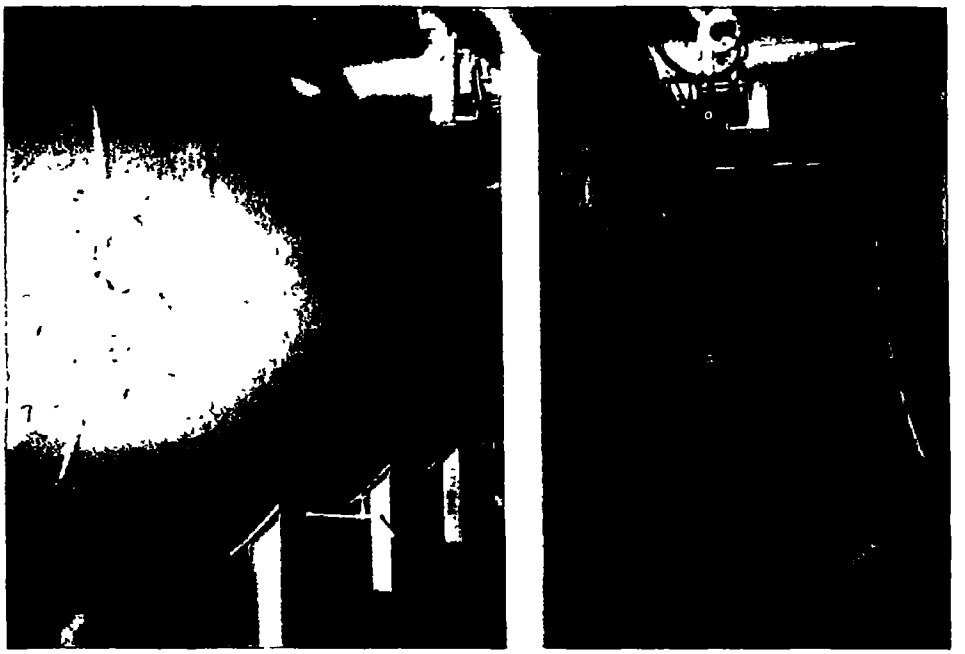

Exhibit G2-3 View Towards the Aerator Between the Two Filter Units for Wells 11 and 15 at St. Louis Park Water Treatment Station No. 1

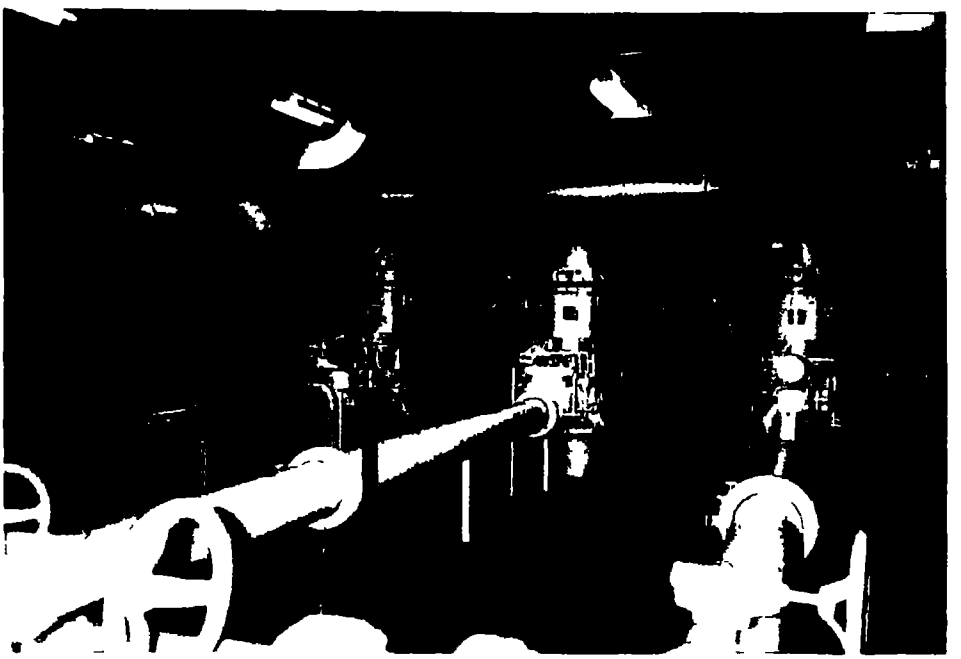

Exhibit G2-4 High Service Pumps and Control Panel at St. Louis Park Water Treatment Station No. 1

Exhibit G2-5 Pumphouse for Wells 11 and 15 at St. Louis Park Water Treatment Station No. 1 (Temporary Shed for Mixing Powdered Activated Carbon Slurry on the Left Side of the Pumphouse)

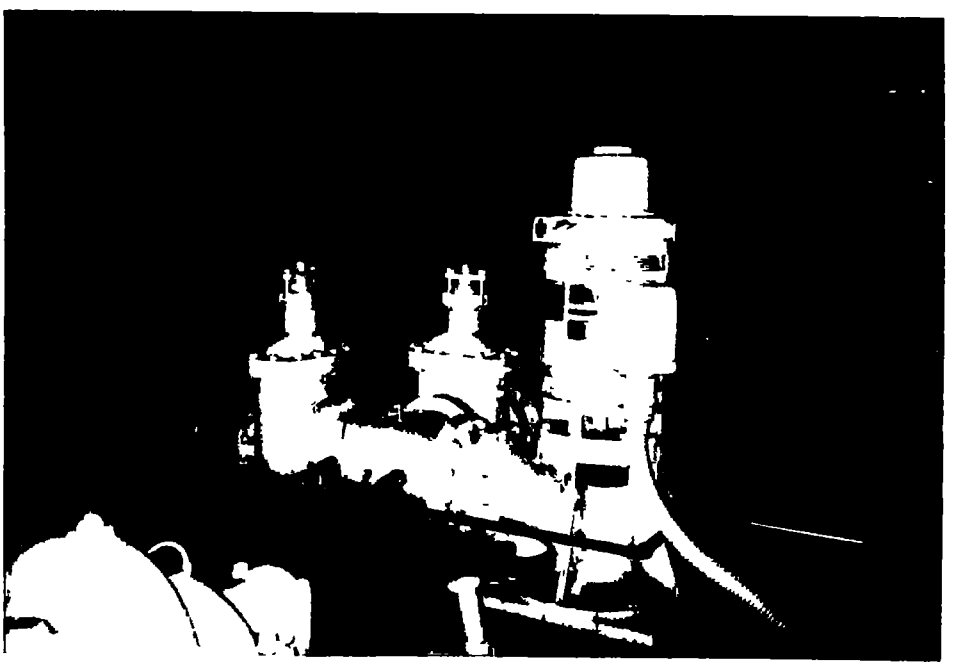

Exhibit G2-6 Pump for St. Louis Park Well 7 (Chlorine and Fluoride Injection Lines Enter at the Pipe Tee)

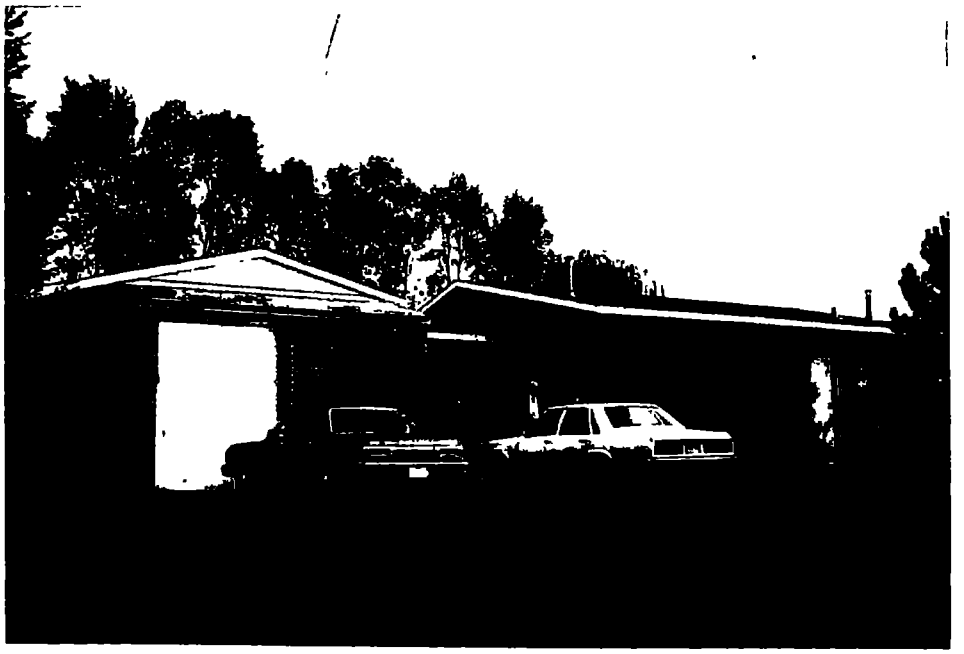

Exhibit G2-7 St. Louis Park Water Treatment Station No. 8

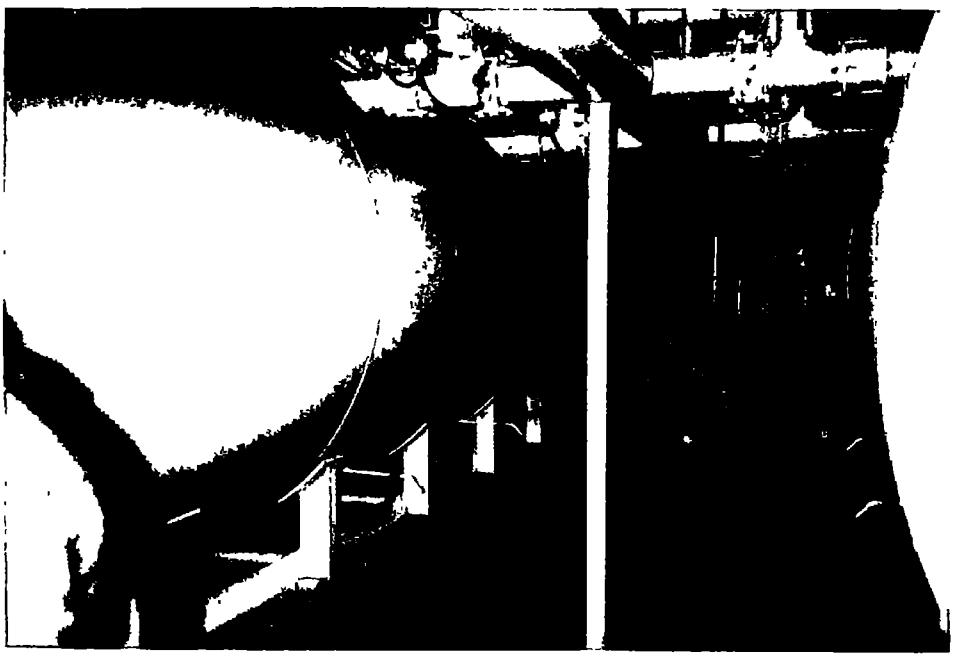

Exhibit G2-8 View Between the Two Filter Units at St. Louis Park Water Treatment Station No. 8 (Air Compressor on the Floor Between the Two Filter Units)

all photographs taken at St. Louis Park Station No. 1. Exhibits G2-1 and 2 show front and side views of the in-line aerator for wells 11 and 15. The front view photograph shows the separate aerator controls for each well. Exhibit G2-3 shows the two filter units for wells 11 and 15, with the aerator at the far end. Note the backwash piping and valving arrangements on the influent line between the two filter units (compare Figures G2-6, 7 and 8). Exhibit G2-4 shows the three high service pumps at Station No. 1, with the pump control panel located along the wall. Exhibit G2-5 shows the pumphouse for wells 11 and 15.

Exhibit G2-6 shows the vertical turbine pump at well 7. This pump is typical of those used at the other St. Louis Park wells. The two small curved pipes entering the well discharge pipe at the tee are chlorine and fluoride injection lines.

Exhibits G2-7 and 8 are photographs taken at St. Louis Park Station No. 8. Exhibit G2-7 shows the station building, which is typical of the other water supply system buildings in St. Louis Park. The pump for well 8 is located in the smaller wing on the left and the high pressure sand filters are located in the larger wing on the right. Exhibit G2-8 is a view between the two filter units at Station No. 8. Some of the backwash piping and valving is visible at the top of the photograph. The air compressor which supplies air for the aerator is visible on the floor between the two filter units. The discharge line for backwash wastewater is visible against the far wall.

G2.1.3 Summary

ERT personnel have had numerous discussions with the St. Louis Park Water Department Superintendent (Vern Tollefsrud) and selected Water Department personnel (particularly Bob Burke and Don Senander). ERT personnel have also tested and inspected various aspects of the system's performance, especially with respect to iron removal treatment. In the course of four separate visits, ERT personnel have inspected each of the system stations in St. Louis Park at least once, with the exception of Station Numbers 4 and 5. ERT has also reviewed MDH reports on investigating the St. Louis Park municipal water supply system from 1975 to 1981. The MDH investigations have generally

resulted in Sanitation Safety Rating scores of 96 or more out of a total score of 100 points (see Table G2-4). In ERT's opinions these visits, tests, conversations and data reviews indicate that the St. Louis Park municipal water supply system appears in general to be operated well for a system of its size and to generally produce finished water of acceptable quality. However, thorough documentation and understanding of the performance of the iron removal plants in the system has not always been apparent. This latter opinion is based in part on the results of ERT's testing efforts at Station No. 1, which are described in Sections G4.4. and G4.5

G2.2 Neighboring Municipal Water Supply Systems

Most of the communities surrounding St. Louis Park also obtain their municipal water supplies from ground-water sources, with the exception of Minneapolis and Golden Valley - to the east and north of St. Louis Park, respectively - which obtain their water from the Mississippi River. Golden Valley obtains its water by connection to the Minneapolis supply system (Orr, Schelen, Mayeron 1976). The adjacent communities to the northwest, west and south (Plymouth, Minnetonka, Hopkins, and Edina) and other communities further removed from St. Louis Park (Robinsdale, Richfield and Bloomington) all obtain their water supply from ground-water sources.

Figure G2-10 shows the location of municipal supply wells in St. Louis Park and surrounding communities. The figure shows that most municipal supply wells in the St. Louis Park area draw from the Prairie du Chien-Jordan aquifer, with some occasional Mount Simon-Hinckley wells. Figure G2-10 also shows that iron removal treatment plants are common in the area, with all of the water supplies for Plymouth, Hopkins, Richfield and Bloomington and many of the wells in Edina receiving such treatment.

Further information on the municipal water supply systems in Hopkins and Edina was collected for this study because these communities are located immediately downgradient from the area of PAH contamination in the Prairie du Chien-Jordan aquifer in St. Louis Park

NON-RESPONSIVE

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Figure G2-10 Location of Municipal Supply Wells and Iron Removal Treatment Plants in St. Louis Park and Surrounding Communities

(see Appendix E). Table G2-5 shows 1976 and 1982 pumpage data for municipal supply wells in Edina and Hopkins and indicates which wells have iron removal treatment. The pumpage data show that all of the water in Hopkins and about two-thirds of the total supply in Edina is treated for iron removal.

Table G2-6 summarizes design and operating data for the iron removal plants in Hopkins and Edina. The Edina plants use pressure sand filters similar to those in St. Louis Park. The Hopkins plants use gravity filters. Design filtration rates for the plants in both communities are similar to those for St. Louis Park plants, ranging from 2.1 to 3.0 gallons per minute per square foot.

G2.3 Supply and Demand Variations

As noted in section G2.1.1, municipal supply wells in St. Louis Park are not pumped continuously at constant rates. Instead, well pumpage rates are affected by daily and seasonal demand variations. These demand variations are largely satisfied by changing the number of wells in operation and by storage of pumped water. Demand variations are met to a lesser extent by changing the pumping rates at a given well, since the wells are usually pumped near capacity rates when they are operated instead of being throttled back significantly (Tollefsrud 1982a).

This section provides a brief description of drinking water demand variations in St. Louis Park and neighboring communities, since the closure of municipal supply wells as a result of PAH contamination affects the ability to satisfy both long-term average and peak demands. For purposes of this discussion, demand variations are considered for three different time-frames: hourly, daily, and seasonal variations.

G2.3.1 Hourly Demand Variations

Drinking water demand varies from hour to hour during any given day. Demand is generally highest during the day and drops off at

TABLE G2-5
SUMMARY DATA FOR THE EDINA AND HOPKINS MUNICIPAL WATER SUPPLY SYSTEMS

Well Number	Aquifer[a]	Iron Removal Treatment[b]	Well Capacity Gallons Per Minute[c]	Annual Production,[a,c] Millions of Gallons per Year 1976	1982
EDINA WELLS					
E2	Jordan	Plant No. 1	800	426.5	(417.0)
E3	Prairie du Chien-Jordan		500	39.1	(21.9)
E4	Prairie du Chien-Jordan	Plant No. 2	650	167.7	(29.1)
E5	Prairie du Chien-Jordan		600	86.8	(56.8)
E6	Prairie du Chien-Jordan	Plant No. 2	1200	348.2	(413.4)
E7	Prairie du Chien-Jordan		900	72.6	(72.7)
E8	Jordan		900	64.2	(64.9)
E9	Mount Simon-Hinckley		1000	74.0	(45.3)
E10	Mount Simon-Hinckley	Plant No. 3	2000	256.5	(220.4)
E11	Jordan	Plant No. 3	2000	397.3	(356.4)
E12	Hinckley	Plant No. 4	2000	57.6	(387.5)
E13	Jordan	Plant No. 4	2000	385.6	(40.8)
E14	Prairie du Chien-Jordan		1000	46.4	(30.6)
E15	Prairie du Chien		1000	169.4	(51.4)
E16	Prairie du Chien-Jordan		1000	306.4	(265.2)
E17	Jordan		1200	117.5	(56.9)
E18	Jordan		1200	49.8	(18.8)
				3066	(2549.1)
HOPKINS WELLS					
H1	Prairie du Chien-Jordan	Plant No. 1	269.0		
H3	Prairie du Chien-Jordan	Plant No. 3	71.3		
H4	Prairie du Chien-Jordan	Plant No. 4			
H5	Prairie du Chien-Jordan	Plant No. 4	573.9		
H6	Prairie du Chien-Jordan	Plant No. 4	0		
			914		

Notes:

(a) Aquifer and pumpage data from Hult and Schoenberg (1981).
(b) Treatment plant location data from Libby (1983) and Strojan (1983).
(c) 1982 pumpage data from Libby (1983).

TABLE G2-6

SUMMARY DATA FOR IRON REMOVAL PLANTS
IN EDINA AND HOPKINS

Plant Number	Design Capacity, Gallons per Minute	Design Filtration Rate, Gallons per Minute per Square Foot	Chlorination Dose, Milligrams per Liter	
			Prefiltration	Postfiltrati
EDINA PLANTS[a]				
E1	1,000	2.50	2.7[c]	
E2	2,100	2.32	3.0	
E3	2,100	2.32	2.7	
E4	2,100	2.32	3.0	
HOPKINS PLANTS[b]				
H1	900	3.0	2.6	None
H3	1,250	2.1	2.0	None
H4	2,800	2.4	0.9	0.6

Notes:

(a) Data from Libby (1983). All plants use pressure sand filter cylinders with two filter units per plant with 3 or 4 cells per unit. All cylinders are 10 feet in diameter with 24 inches of sand supported by 15 inches of graded gravel. All plants operate from 65 to 100 pounds per square inch gauge pressure.

(b) Data from Strojan (1983). All plants use gravity filtration through sand-gravel media.

(c) Combined dose for pre- and post-chlorination.

night. On many occasions, demand during certain periods of the day will exceed supply capacity. This shortfall is typically satisfied by stored water that was produced during off-peak hours. A recent analysis of the St. Louis Park water supply system by Orr, Schelen, Mayeron & Associates (1976) indicates that St. Louis Park has sufficient storage capacity (6.1 million gallons usable and 9.1 million gallons total) to meet the difference between peak hourly demand and supply capacity, based on the maximum supply capacity of all fourteen municipal supply wells (20 million gallons per day - see Table G2-7). However, closure of wells SLP4, SLP5, SLP7, SLP9, SLP10, and SLP15 has reduced the maximum supply capacity to about 12 million gallons per day. It appears that this has resulted in accumulated maximum daily demand exceeding storage capacity plus supply capacity (based on Figure XII in Orr, Schelen, Mayerson & Associates 1976). The two scenarios presented in Chapter 6 for satisfying St. Louis Park water requirements will result in a maximum daily supply capacity of from 16 to 18 million gallons per day (see Table G2-7). This should be sufficient capacity to meet peak hourly demands in conjunction with existing storage capacity, based on the analysis presented by Orr, Schelen, Mayeron & Associates, which indicates that St. Louis Park has from 2 to 3 million gallons of extra storage capacity beyond that required to meet accumulated maximum daily demand.

G2.3.2 Daily Demand Variations

Drinking water demand varies from day to day, in part from seasonal effects and in part from shorter term effects (e.g. weekend versus weekday demand). Figure G2-11 (from Orr, Schelon, Mayeron & Associates 1976) shows the frequency distribution of daily demand in St. Louis Park for 1975 and for the projected ultimate daily usage in the system. The current peak daily demand capacity of the St. Louis Park municipal supply wells is shown in Table G2-7. The peak demand capacity prior to closure of contaminated supply wells was 19.7 million gallons per day. This capacity is based on pumping rates on June 8, 1976, which was one of the highest demand days in St. Louis Park (Orr, Schelen, Mayerson & Associates 1976). Figure G2-11 shows that this peak daily demand capacity was sufficient to meet daily

TABLE G2-7

PEAK DEMAND PUMPING RATES OF

ST. LOUIS PARK MUNICIPAL SUPPLY WELLS

Well Number	Peak Demand Rate, June 8, 1976[a] Gallons per Minute	Millions of Gallons per Day
Existing Wells:		
SLP 3	850	1.2
SLP 4	750	1.1
SLP 5	1450	2.1
SLP 6	1250	1.8
SLP 7	1125	1.6
SLP 8	1000	1.4
SLP 9	1125	1.6
SLP 10	500	0.7
SLP 11	1000	1.4
SLP 12	1250	1.8
SLP 13	950	1.4
SLP 14	800	1.2
SLP 15	520	0.7
SLP 16	1100[b]	1.6
New Wells:		
SLP 17	800[b]	1.2
SLP 18	1000[c]	1.4
Totals:		
All Existing Wells	13,670	19.7
Existing Wells Less Currently Closed Wells [d]	8,200	11.8
Drinking Water Treatment at Wells SLP 6, 10 and 15[e]	12,270	17.7
New Mt. Simon-Hinckley Wells[f]	11,000	15.8

Notes:

(a) Data from Orr, Schelen, Mayeron & Associates 1976.
(b) Well capacity.
(c) Assumed capacity.
(d) Wells SLP4, SLP5, SLP7, SLP9, SLP10 and SLP15 are currently closed.
(e) Wells SLP4 and SLP5 abandoned. Wells SLP6, SLP7, SLP9, SLP10, SLP15 and SLP17 in use. See Chapter 6.
(f) Wells SLP4, SLP5, SLP6, SLP10 and 15 abandoned. Wells SLP7, SLP9, SLP17 and SLP18 in use. See Chapter 6.

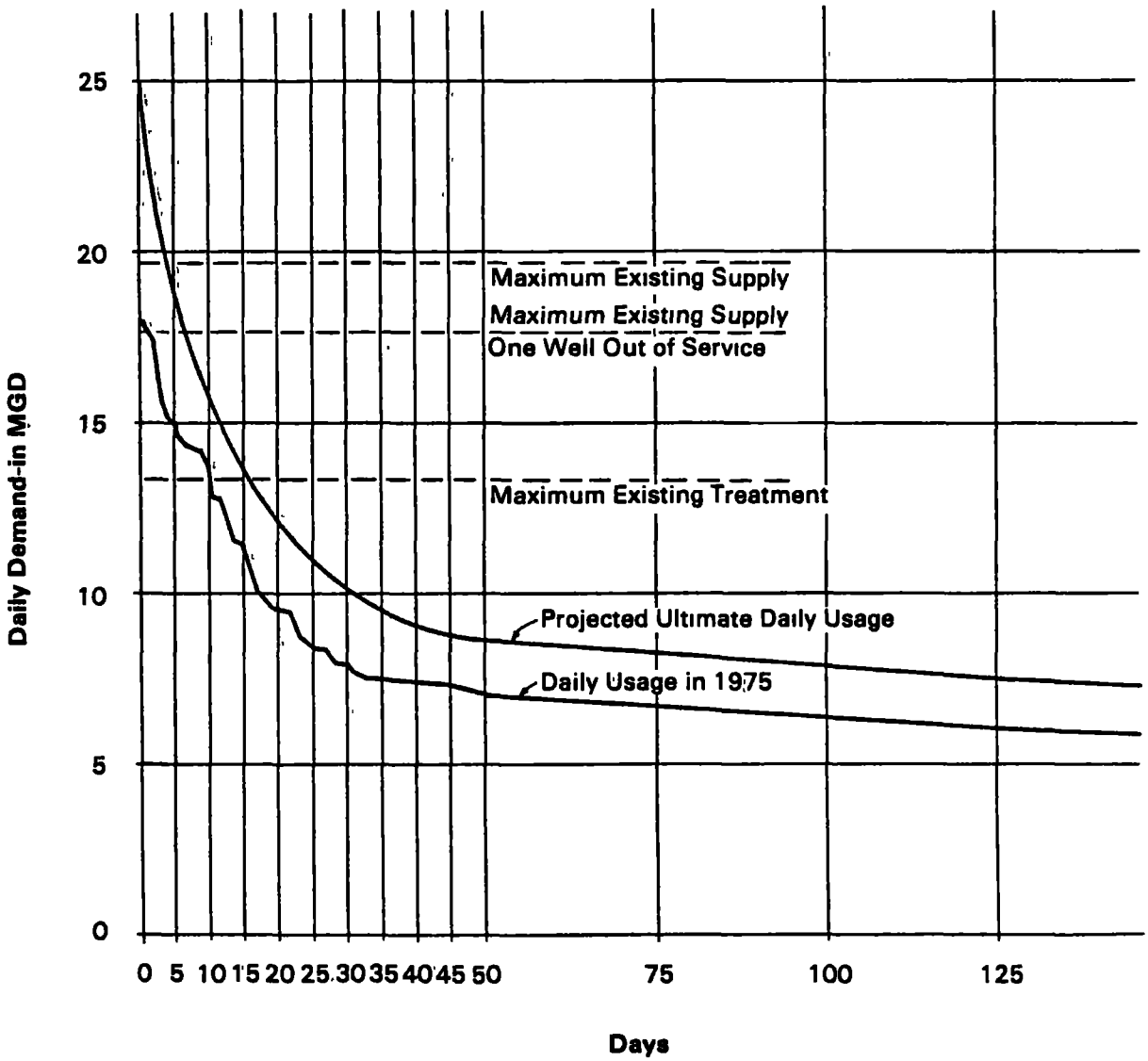

Figure G2-11 Frequency Distribution for Daily Demand in the St. Louis Park Water Supply System (Reproduced from Orr, Schelen, Mayeron & Associates 1976)

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usage in 1975, but would result in demand exceeding supply for about 4 days per year at projected ultimate daily usage. However, it is unclear if projected ultimate daily usage will be as high as shown in Figure G2-11, given projected declines in population and water usage in St. Louis Park (see Tables 6-3 and 6-4 in Chapter 6).

As shown in Table G2-7, the closure of wells SLP4, SLP5, SLP7, SLP9, SLP10 and SLP15 has reduced the peak daily supply capacity in St. Louis Park to 11.8 million gallons per day. Figure G2-11 indicates that this has caused daily demand to exceed supply from 13 to 21 days per year, based on 1975 daily usage and projected ultimate daily usage, respectively. The two options for satisfying water supply requirements discussed in Chapter 6 will add from 4 to 6 million gallons per day of peak supply capacity, resulting in a loss of from 2 to 4 millions gallons per day compared to the peak supply capacity prior to any well closures (Table G2-7). Figure G2-11 indicates that daily demand will exceed the resulting peak supply capacity from 1 to 10 days per year, based on 1975 daily usage and projected ultimate daily usage, respectively. As noted above, however, it seems doubtful that the ultimate daily usage projected by Orr, Schelen, Mayeron & Associates (1976) will ever occur. To the extent that daily demand shortfalls do occur, Orr, Schelen, Mayeron & Associates (1976) indicate that the supply capacities of existing wells can be increased by adding more stages to existing pumps during preventative maintenance operations, at an estimated cost of $18,000 per well (1976 dollars).

G2.3.3 Seasonal Demand Variations

Potable water demand exhibits marked seasonal variations. Demand is highest in summer months as a result of lawn watering, air conditioning, and other seasonal uses. Seasonal demand variations in St. Louis Park and neighboring communities are primarily satisfied by using more wells during the summer months and fewer wells during the winter.

Tables G2-8 and G2-9 present data that indicate the extent of seasonal demand variations in St. Louis Park and Edina, respectively. The pumpage data shown indicate that demand during June, July, and August can range from 32 to 43 percent of total annual demand, and can be more than twice as high on a monthly basis than demand in other months. The data in these tables also shows how the operation of individual wells changes in response to seasonal demand variations. In Edina, for example, all of the wells are operated during the summer months, but less than half are operated year-round. Similarly, in St. Louis Park, wells SLP4, SLP5, SLP7 and SLP9 are primarily operated to meet summer demand. These are the only St. Louis Park wells without iron removal treatment plants, and all four are currently closed as a result of PAH contamination. Satisfying St. Louis Park water supply requirements by either of the options presented in Chapter 6 should satisfy summer demand requirements, since these options should satisfy peak daily demand usages (see preceding subsection), which occur during summer months.

TABLE G2-8

SUMMER PUMPAGE RATES FOR ST. LOUIS PARK

MUNICIPAL SUPPLY WELLS IN 1976 and 1978

	June-August 1976		June-August 1978	
Well	Millions of Gallons Pumped[a]	Percent of Total Annual Pumpage[b]	Millions of Gallons Pumped[a]	Percent of Total Annu Pumpage[b]
SLP3	68.7	54.6	9.6	11.4
SLP4	56.9	62.0	94.4	78.1
SLP5	107.4	70.9	28.5	73.6
SLP6	106.4	30.4	117.1	25.0
SLP7	17.7	80.8	9.4	51.4
SLP8	129.9	34.6	124.3	36.4
SLP9	17.7	80.8	9.4	51.4
SLP10	46.8	54.4	3.8	7.7
SLP11	95.7	30.3	63.2	33.2
SLP12	68.3	63.0	38.6	29.7
SLP13	39.9	39.2	8.4	13.3
SLP14	40.4	39.4	8.5	38.3
SLP15	58.6	25.2	59.8	50.7
SLP16	112.3	25.4	102.2	24.2
	966.6	38.2	677.2	32.5

Notes:

(a) Data from St. Louis Park City Manager (1980).
(b) Based on pumpage data given in Table G2-2.

TABLE G2-9

TOTAL MONTHLY MUNICIPAL WELL PUMPAGE IN EDINA IN 1982[1]

Month	Number of Wells Operating[b]	Pumpage, Millions of Gallons
January	7	169
February	7	145
March	6	159
April	7	162
May	16	170
June	17	312
July	17	426
August	16	390
September	12	200
October	8	169
November	6	147
December	7	155
Total		2604

Notes:

(a) Data from Libby 1983.
(b) A total of 17 wells are available.

G3. PAH OCCURRENCE AND REMOVAL IN CONVENTIONAL DRINKING WATER TREATMENT SYSTEMS

PAH occur ubiquitously in raw water supplies (Sorrell, et al 1980; see also Appendix I). Because of this, and the fact that certain PAH are carcinogenic, a number of studies have been made on the occurrence of PAH in raw and finished drinking water supplies and the effects of various drinking water treatment techniques on removing PAH. These studies date back about twenty years, starting primarily with studies in Europe. Studies in the United States have also been performed over the last few years, primarily under the auspices of the U.S. EPA. A recent paper by Sorrell, Brass and Reding of the U.S. EPA's Cincinnati laboratory provides an excellent review of recent work in the U.S. (Sorrell, et al 1980).

This section provides a summary of the recent literature on the occurrence of PAH in drinking water supply systems and the effects of conventional drinking water treatment technologies on removing PAH. The purpose of this summary is to provide background and perspective on drinking water treatment techniques that could be applicable for treating contaminated municipal supply wells in St. Louis Park.

G3.1 PAH Occurrence in Supply Waters

Table G3-1 summarizes some of the reported data on PAH concentrations in ground and surface waters. These data are obtained from the summary by Sorrell, et al (1980) of work by other investigators. Additional data are also available in the literature, much of which is summarized in Appendix I.

The data in Table G3-1 indicate that up to low microgram per liter levels of total PAH may be present in surface waters used for drinking water supply. Ground water may contain up to hundreds of nanograms per liter of total PAH. Such high values in ground water are supported by data cited by Harrison, et al (1975) and Andelman and Snodgrass (1974). Significantly, concentrations of carcinogenic PAH in surface waters typically exceed the 28 nanogram per liter ambient

TABLE G3-1

SUMMARY OF SELECTED STUDIES OF PAH CONCENTRATIONS

IN GROUND AND SURFACE WATER SUPPLIES

(Concentrations in nanograms per liter)

Water Supply	Number of Samples	Reported Range of Concentrations		Concentrations of Corresponding Compounds in Well SLP15(e)	
		Total PAH	Carcinogenic PAH	Total PAH	Carcinogenic PAH
German Ground Waters	3	31-381(b)	3-108(a)	1000	15
German Surface Waters	7	57-1239(b)	36-979(a)	1000	15
Thames River(b)	3	600-1760	530-1230	1014	29
Severn River(c)	5	25-160	10-42	550	ND
Trent River and Its Tributaries(c)	10	46-2596	29-1653	550	ND
U.S. Surface Waters(d)	4	58-1586	34-830	550	ND

Notes:

(a) Data of Borneff and Kunte 1964 as reported by Sorrell, et al 1980. Carcinogenic PAH analyzed were benz(a)anthracene, benzo(b,j&k) fluoranthenes, benzo(ghi)perylene, benzo(a)pyrene and indeno(1,2,3-cd)pyrene. Noncarcogenic PAH analyzed were fluoranthene and pyrene.

(b) Data of Acheson, et al 1976 as reported by Sorrel, et al 1980. Carcinogenic PAH analyzed were same as in note(a) plus chrysene. Noncarcinogenic PAH analyzed were fluoranthene, perylene and pyrene.

(c) Data of Lewis, 1975 as reported by Sorrel, et al 1980. Carcinogenic PAH analyzed were benzo(h)fluoranthene, benzo(ghi)perylene, benzo(a)pyrene, and indeno(1,2,3-cd)pyrene. Noncarcinogenic PAH analyzed was fluoranthene.

(d) Data of Saxena, et al 1977 as reported by Sorrell, et al 1980. Carcinogenic PAH analyzed were same as in note (c) plus benzo(j) fluoranthene. Noncarcinogenic PAH analyzed was fluoranthene.

(e) Average of CH2M Hill results for wellhead and drum samples from well SLP15 during first and second round bench testing (seven samples in all - CH2M Hill 1982e). These results were selected for comparison because they gave among the highest concentrations measured by GCMS at SLP15.

water quality criterion for carcinogenic PAH established by the U.S. EPA (1980) (based on an excess lifetime cancer risk of one chance in 100,000), which has also been used by the MDH in evaluating St. Louis Park wells for possible closure (Englund 1982) and is also recommended by this study for application to finished drinking water supplies (see Appendix I and Chapter 4). Table G3-1 indicates that untreated drinking water supplies may commonly exceed a criterion of 28 nanograms per liter for carcinogenic PAH by a factor of ten or more. Conventional drinking water treatment should significantly reduce noncarcinogenic and carcinogenic PAH concentrations, however, as discussed below.

It is important to note that the studies summarized in Table G3-1 analyzed for many fewer PAH than have typically been analyzed for in St. Louis Park well samples. In order to compare results from St. Louis Park municipal supply wells on an equivalent basis with those from the studies summarized in Table G3-1, selected results from analyses of well SLP15 by CH2M Hill (see section G4.3) have been included in Table G3-1, where CH2M Hill results have only been included for the specific compounds analyzed by the various studies (see the notes to Table G3-1). It is important to compare St. Louis Park results with other studies for specific compounds analyzed in common because St. Louis Park samples have generally been analyzed for many more low molecular weight, two and three-ring PAH and because St. Louis Park well samples generally do not contain detectable concentrations of high molecular weight, five and six-ring carcinogenic PAH, which are usually the compounds predominantly analyzed by studies reported in the scientific literature.

Comparing PAH concentrations in St. Louis Park well SLP15 with concentrations of the same compounds analyzed in other surface and ground water supplies (Table G3-1) shows that total PAH concentrations are similar, but concentrations of carcinogenic PAH in well SLP15 are much lower than those typically measured in surface water supplies. The total PAH concentrations reported in Table G3-1 for well SLP15

primarily represent concentrations of pyrene and fluoranthene, which are both noncarcinogenic. The carcinogenic PAH concentrations reported in Table G3-1 for well SLP15 represent only benz(a)anthracene and chrysene, since none of the carcinogenic five and six-ring PAH, which predominate in the reported carcinogenic PAH values by other studies, have been detected by CH2M Hill in water from well SLP15. It appears, then, that water from well SLP15 contains total PAH concentrations comparable with, and carcinogenic PAH concentrations significantly less than, those in water used by many other drinking water supply and systems, for a specific set of four to six-ring PAH.

There is an important difference between ground and surface waters with respect to PAH concentrations. PAH in surface waters are largely associated with suspended solids (Andelman and Snodgrass 1974, Sorrell, et al 1980), while this does not appear to be the case with ground waters. For example, ten water samples from the River Trent and its tributaries indicated that from 77 to 99 percent (93 percent average) of the total PAH was associated with suspended solids, with the suspended solids portion generally increasing as total concentrations increased (Lewis 1975 as reported by Sorrell, et al 1980). These data are for five different four-to six-ring compounds. It is expected that the association of two-and three-ring PAH with suspended solids would be less than that of higher molecular weight PAH, based on the adsorption tendencies of different size PAH (see Appendix E). PAH in contaminated St. Louis Park municipal wells, on the other hand, are only slightly associated with suspended particulates (see ERT data in section G.4 and CH2M Hill 1982d).

G3.2 PAH Removal by Conventional Drinking Water Treatment

Various studies have indicated that conventional drinking water treatment is generally effective at reducing PAH concentrations. The treatment steps investigated have included particulate removal techniques, use of chlorine and other oxidants, and activated carbon treatment. This summary focuses on investigations at full-scale drinking water treatment plants, as opposed to laboratory testing

results, because the latter typically involve PAH concentrations much higher than those encountered in drinking water supplies. A review of some of the laboratory testing literature has been provided by CH2M Hill (1982b). However, investigations at operating drinking water treatment plants have often looked only at the effects of the entire treatment plant, as opposed to individual treatment steps.

Tables G3-2 and G3-3 summarize the results of recent studies by Basu and Saxena (1978) and Sorrell, et al (1980), respectively, of PAH removal at a total of 22 drinking water treatment plants in the United States. The data indicates that conventional treatment is generally effective in removing PAH, particularly for cases where the untreated water contains higher concentrations of PAH. Conventional treatment in this context refers to steps for removing particulate matter, chlorination, and other treatment steps other than activated carbon treatment. Some of the treatment plants studied by Basu and Saxena (1978) also used activated carbon treatment (powdered or granular), and these plants were also effective in removing PAH.

Tables G3-2 and G3-3 show that PAH concentrations in finished water supplies are generally about 10 nanograms per liter for noncarcinogenic PAH and about 4 nanograms per liter for carcinogenic PAH. These values compare with untreated water concentrations of up to 100 nanograms per liter or more of both carcinogenic and noncarcinogenic PAH. These concentrations can not be directly compared to those measured in St. Louis Park municipal wells because many more individual PAH compounds have been analyzed for in St. Louis Park samples, particularly for lower molecular weight PAH. It is noteworthy that Basu and Saxena's data (Table G3-2) indicate that finished water from one of the treatment plants (Wheeling, WV) exceeded the U.S. EPA criterion for carcinogenic PAH of 28 nanograms per liter. However, the data of Sorrell, et al (Table G3-3) show much lower concentrations for this treatment plant and, on average, for the other plants studied, when compared to Basu and Saxena's results. The cause of this apparent discrepancy is unknown, but may be related to sampling variations or differences in analytical procedures.

TABLE G3-2

SUMMARY OF BASU AND SAXENA (1978) DATA ON PAH

OCCURRENCE AND TREATMENT IN DRINKING WATER SUPPLY SYSTEMS

(Concentrations in nanograms per liter)

Location	Water Source	Treatment Provided[a]	Raw Water[b]	Finished Water[b]
Appleton, WI[g]	NA	AC, other	ND/7.0	ND/6.1
Buffalo, NY	Lake Erie	C/F,CL,FL	ND[c]/4.7	ND/0.9
Champaign, IL[g]	NA	conventional (no AC)	ND/6.9	ND/2.8
Endicott, NY	Ground Water	CL,FL	NA[d]	4.3/4.0
Hammandsport, NY	Keuka Lake	CL	NA	ND/3.5
Huntington, WV	Ohio River	L,C/F,AC,CL,FL	24/34	2.4/4.7
Lake George, NY	Lake George	CL	NA	ND/4.2
New Orleans, LA	Mississippi River	C/F,A,CL	NA	ND/4.4
New York, NY[c]	NA	NA	NA	ND/6.4
Philadelphia, PA	Delaware River	L,C/F,AC[f],CL,FL,A	114/237	8.9/6.0
Pittsburgh, PA	Monongahela River	L,C/F,AC,CL,FL	408/192	ND/2.8
Syracuse, NY	Lake Skaneateles	C/F,CL,FL	NA	ND/1.1
Wheeling, WV[e]	NA	NA	756/830	94/44

Notes:

(a) C/F = Coagulation/flocculation (including additon of copper sulfate, ferric sulfate, ferric chloride, or other coagulants), CL = chlorination, FL = fluoridation, L = lime addition, A = ammonia addition, AC = activated carbon addition or filtration. Treatment steps not necessarily listed in proper order, and any filtration steps are not listed.

(b) Total concentrations of noncarcinogenic/carcinogenic PAH. Fluoranthene was the only noncarcinogenic PAH analyzed. Carcinogenic PAH analyzed were benzo(j)fluoranthene, benzo(k)fluoranthene, benzo(ghi)perylene, benzo(a)pyrene, and indeno(1,2,3-cd)pyrene.

(c) ND = not detected, with a detection limit ranging from 0.1 to 4.6 nanograms per liter.

(d) NA = not analyzed or not available.

(e) Data from Saxena, et al 1977 as reported by Sorrell, et al 1980.

(f) Sorrell, et al (1980) indicate that activated carbon is not used at the Philadelphia treatment plant.

(g) Data from Basu, et al 1978 as reported by Sorrell, et al 1980.

TABLE G3-3

SUMMARY OF SORRELL, ET AL (1980) DATA ON PAH OCCURRENCE AND REMOVAL IN DRINKING WATER SUPPLY SYSTEMS WITH CONVENTIONAL TREATMENT

(Concentrations in nanograms per liter)

Location	Raw Water[a]	Finished Water[a]
Cape Girardeau, MO[d]	35/23	6/ND[c]
Cincinnati, OH	14/25	10/ND
Columbus, OH	NA[b]	4/ND
Jefferson Parish, LA[d]	77/48	24/ND
Miami, FL	6/ND	14/2
New Orleans, LA	NA	14/ND
Portland, OR	18/ND	NA
Seattle, WA	10/ND	12/2
Tucson, AZ[d]	10/ND	NA
Wheeling, WV[d]	44/63	10/ND

Notes:

(a) Total concentrations of noncarcinogenic/carcinogenic PAH. Noncarcinogenic PAH analyzed were benzo(e)pyrene, fluoranthene, 1-methylphenanthrene, perylene, phenanthrene, and pyrene. Carcinogenic PAH analyzed were benz(a)anthracene, benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(ghi)perylene, benzo(a)pyrene, chrysene, dibenzo(a,h)anthracene, and indeno(1,2,3-cd)pyrene.

(b) NA = not analyzed.

(c) ND = not detected. Detection limit was generally 1 nanogram per liter for each compound.

(d) Anthracene also analyzed.

As noted by Sorrell, et al (1980, p. 20) "the traditional perception has been that only activated carbon can significantly reduce PAH concentrations in water". However, conventional water treatment practices for particulate removal can be very effective in removing PAH because of the significant association of PAH with suspended solids in surface waters. For example, Table G3-4 indicates 41 percent removal of noncarcinogenic PAH and 58 percent removal of carcinogenic PAH by filtration of water from a surface source (based on comparison with water in the reservoir). Similarly, Sorrell, et al (1980) note the comparable PAH removals observed in drinking water treatment plants in Philadelphia and Pittsburgh, where both use conventional treatment, with Pittsburgh also including two stages of activated carbon treatment (Table G3-2). Andelman and Snodgrass (1974) and Shabad (1979) also cite studies indicating that particulate removal treatment, such as floculation and filtration, can be very effective in removing PAH. While activated carbon treatment has been shown to be very effective in removing PAH (Sorrell, et al 1980, Harrison, et al 1975), it is not the only means for achieving significant PAH removal. Moreover, activated carbon treatment "appears to have limited applicability ... for the removal of PAH present at very low concentrations" (Sorrell, et al 1980, p. 21). As an example, conventional treatment and treatment including activated carbon gave similar PAH removals for untreated water containing only 7 nanograms per liter of carcinogenic PAH (Champaign, IL and Appleton, WI, respectively, see Table G3-2).

Chlorination and other oxidizing agents for removing PAH have been studied by a number of different investigators. In general, these studies have shown that chlorine, chlorine dioxide, and ozone can achieve significant destruction of PAH, although the amount removed depends on the specific PAH tested, the initial concentrations, and the reaction conditions (Sorrell, et al 1980; Harrison, et al 1975; Andelman and Snodgrass 1974). The widespread use of oxidizing agents in drinking water treatment has led to some concern that PAH-related reaction by-products may be formed that are toxic or even carcinogenic. However, Shabad (1979) has reported that tests by

TABLE G3-4

PAH CONCENTRATIONS AT VARIOUS STAGES

OF A WATER TREATMENT WORKS[a]

(Concentrations in nanograms per liter)

Treatment Step	Noncarcinogenic PAH[b]	Carcinogenic PAH[c]
River Intake	250	378
After Reservoir	215	384
After Filtration	126	162
After Chlorination	63	60

Notes:

(a) Data from Harrison, et al 1976 as reported by Sorrell, et al 1980.

(b) Fluoranthene and pyrene.

(c) Benz(a)anthracene, benzo(b,j&k)fluoranthene (sum of isomers), benzo(a&e)pyrene (sum of isomers), benzo(ghi)perylene, chrysene, and indeno(1,2,3-cd)pyrene.

G3.3 Distribution System Effects

A number of studies have demonstrated that finished water can become contaminated by PAH in the distribution system during storage in tanks or transit in pipes lined with coal tar or coal-tar-based materials, such as pitches or enamels (Alben 1980; Sorrel, et al 1980). This also appears to be true for asphaltic-base linings (Sorrel, et al 1980). Coal tar and asphaltic linings are still used in many drinking water supply systems, and the use of these materials is still approved by the American Water Works Association (AWWA 1978). These linings are used to increase the service life of water distribution tanks and pipes.

The magnitude and duration of PAH leaching from coal tar and asphaltic linings is probably determined by many factors, including the age of the lining material and the application technique used. The data base for determining the importance of the different variables likely to be involved in leaching of coal tar and asphaltic-based lining materials is poor. Some of the available data for both types of linings are summarized in Table G3-5. No consistent trend is observed from these data regarding the degree of contamination or the effects of type of lining, which is consistent with results of other studies (Sorrell, et al 1980). It is noteworthy, however, that distributed water in Portland, OR contains PAH at concentrations similar to those observed at St. Louis Park well SLP15.

G3.4 Summary

PAH appear to be ubiquitous in ground and surface waters used for drinking water supply. Total PAH concentrations in many water supplies are comparable to those in contaminated St. Louis Park municipal supply wells, at least for the limited number of four to

TABLE G3-5

PAH CONCENTRATIONS IN DISTRIBUTED WATER IN

DRINKING WATER SUPPLY SYSTEMS WITH ASPHALT OR COAL TAR LININGS[a]

(Concentrations in nanograms per liter)

Location	Finished Water(b)	Distributed Water(b)
Asphalt Linings:		
Columbus, OH	4/ND[d]	38/16
Ludlow, MA[c]	4/1	5/1
Standish, ME[c]	8/ND	72/ND
Coal Tar Linings:		
Colorado Springs, CO[c]	5/ND	35/ND
Portland, OR	18/ND	4280/31
Seattle, WA[c]	7/ND	42/ND

Notes:

(a) Data from Sorrell, et al 1980.
(b) Total concentrations of noncarcinogenic PAH/carcinogenic PAH. Compounds analyzed same as those listed in note(a) of Table G3-3.
(c) Anthracene also analyzed.
(d) Not detected. Detection limit was generally 1 nanogram per liter for each compound

six-ring PAH compounds analyzed in other water supplies. In fact, concentrations of carcinogenic PAH in many water supplies are much higher --by up to a factor of ten or more-- than those observed in contaminated St. Louis Park wells. This is because St. Louis Park municipal supply wells generally do not contain detectable concentrations of five and six-ring carcinogenic PAH, which are found in many surface and ground-water supplies, often at levels that greatly exceed the U.S. EPA ambient water quality criterion of 28 nanograms per liter for carcinogenic PAH.

Conventional drinking water treatment particulate removal techniques are generally very effective at removing PAH from surface water supplies, where the majority of the PAH are associated with suspended solids. Activated carbon treatment is also very effective at removing PAH, although not at very low nanogram per liter concentrations. Chorination and ozonation can also effect significant removal of PAH. While there is concern over the possible adverse health effects of potential reaction by-products from oxidizing PAH, there are studies indicating that the by-products are not carcinogenic.

Finished drinking water can become significantly recontaminated by PAH in distribution systems that use coal tar or asphaltic linings in storage tanks and pipes. Such linings are commonly used in the United States.

G4. PAH REMOVAL STUDIES AT ST. LOUIS PARK

A number of technical studies have occurred over the last four years related to the specific problem of drinking water treatment techniques for removing PAH from contaminated municipal supply wells in St. Louis Park. This section summarizes the results of these studies, in particular:

- July and October 1979 studies of powdered activated carbon (PAC) treatment conducted by Serco Laboratories;
- September 1980 to April 1981 studies of PAC and granular activated carbon (GAC) treatment conducted by Eugene A. Hickok and Associates (hereafter referred to as Hickok);
- August 1982 to present studies of PAC, GAC, various oxidation techniques and iron removal treatment by CH2M Hill; and
- December 1982 to February 1983 studies of the effects of iron removal treatment on PAH removal by ERT.

All of these studies were performed at well SLP15.

The major aspects of Serco's, Hickok's and CH2M Hill's studies are discussed in Sections G4.1, G4.2 and G4.3, respectively. ERT's tests of the iron removal plant at SLP15 in December 1982 and February 1983 are discussed in Sections G4.4 and G4.5, respectively. ERT's test results are presented and discussed in detail, as they have not been published elsewhere. Section G4.6 presents a summary of the various studies conducted at SLP15.

G4.1 Serco Studies

Serco Laboratories was hired by the City of St. Louis Park to test the feasibility of using PAC to remove PAH from contaminated municipal supply wells. The study cost about $15,000, including equipment purchases by the City of about $7,000 (Elwell 1979, 1980).

The results of the study are reported in a Serco report by D.A. Thingvold (1980), which is the primary reference for the material presented in this section.

G4.1.1 Test Description

Two small-scale pilot tests of PAC injection were performed at well SLP15, one in July 1979 and one in October 1979. The tests were jointly designed by Serco, the Minnesota Department of Health (MDH), and the City of St. Louis Park. The tests were conducted by St. Louis Park Water Department personnel, including sample collection. Sample analyses were performed by Serco and the MDH.

Prior to actual testing, the City of St. Louis Park purchased and installed PAC slurry preparation and injection equipment at the head of well SLP15. A temporary shed was built adjacent to the well SLP15 pumphouse to house the PAC slurry equipment (see Figure G2-4). The equipment consisted of a tank for mixing a slurry of PAC and a pump for metering the slurry into the pipe at the wellheads. During testing, the injected PAC traveled with the water through several hundred feet of pipe into the iron removal plant treatment building, where the PAC was filtered from the water by the sand filter beds (see Figures G2-3 and G2-4). Samples of untreated water were collected at the wellhead and samples of treated water were collected at the outlet of the sand filter bed. Well SLP15 was operated at 1000 gallons per minute during testing.*

In the July test, two different injection doses of PAC were studied, nominally 1 and 10 milligrams per liter. Actual dosages were determined by suspended solids analyses made by Serco. During the first phase, measured dosages were generally 1 milligram per liter (5 analyses), with the single measurements also showing 2 and 4

*Thingvold (1980) does not say whether or not well SLP11, whose water flows in the same pipe to the iron removal plant as SLP15 (see Figure G2-4), was also operating during the test. It is assumed that SLP11 was shut down during the test so that only water from SLP15 was treated.

milligrams per liter suspended solids. PAC injection at the low dose began at 9:00 P.M. on July 16 and continued through late in the evening of July 18 or early in the morning of July 19 (the Serco report does not give a specific time). After a brief period of operation without any PAC, when the sand filters were presumably backwashed*, injection was restarted early in the morning of July 19, at a nominal dose of 10 milligrams per liter, and continued through the morning of July 20. Two suspended solids measurements during this second phase yielded results of 9 and 12 milligrams per liter.

The MDH was responsible for analyzing samples from the July test, with some samples split with Serco. Table G4-1 shows a chronological listing of all of the samples collected during the July test. A total of 23 samples were analyzed by the MDH, including 3 duplicate samples. Nine split samples were analyzed by Serco. Both the MDH and Serco used high performance liquid chromatography (HPLC) for analyzing samples. Table G4-2 lists the individual PAH compounds analyzed by each lab and indicates whether or not the compounds are carcinogenic, based on the definition and listing of carcinogenic PAH in Appendix I. Serco analyzed for 12 compounds and the MDH analyzed for 14, with 9 compounds analyzed in common by both laboratories.

In October 1979, a second limited test was performed to check the results of the July test, due to concern that they might have been affected by problems with the slurry pump operation in July. It is reported that "the PAC level was set for 10.87 milligrams per liter concentration" (Thingvold 1980, p. 6), implying that the metering rate was set or that the amount of slurry used was measured to determine the actual PAC dose. It is unclear, however, how the stated dose was

*There is some indication from Thingvold (1980) that the sand filters were backwashed between the two phases of testing, but this is unclear and is not directly stated one way or another in his report. However, memos in the Appendix of Thingold's report indicate that the test plan called for the sand filters to be backwashed between the two phases of testing.

TABLE G4-1

SUMMARY LISTING OF SAMPLES COLLECTED

DURING SERCO'S JULY 1979 PAC TESTS AT WELL SLP15

Date	Time	Sample Description[a,b]	Analyses By Serco	Analyses By MDH
July 16, 1979	11 am	Untreated water	X	X
	11 pm	Untreated water[d]		X
	11 pm	Sand filtration only	X	X
July 17	5 am	2 milligrams per liter PAC [e]		X
	11 am	1 milligrams per liter PAC	X	X(c)
	5 pm	1 milligrams per liter PAC	X	X
	11 am	1 milligrams per liter PAC		X(c)
July 18	5 am	1 milligram per liter PAC	X	X
	11 am	Untreated water		X
	11 am	1-2 milligrams per liter PAC		X
	5 pm	4 milligrams per liter PAC		X
	9 pm	1 milligrams per liter PAC		X
July 19	3 am	Sand filtration only [f]	X	X(c)
	4 am	Untreated water	x	
	5 am	Untreated water		X
	5 am	9 milligrams per liter PAC	X	X
	11 am	9-12 milligrams per liter PAC		X
	5 pm	9-12 milligrams per liter PAC		X
	11 pm	9-12 milligrams per liter PAC		X
July 20	4 am	Untreated water	X	
	5 am	Untreated water		X
	5 am	12 milligrams per liter PAC		X

Notes:

(a) "Untreated water" refers to wellhead samples. All other samples were collected downstream of the sand filter bed. "Sand filtration only" refers to samples collected downstream of the filter bed when no PAC was being injected at the wellhead.

(b) Where single values are reported for the PAC injection dose, they are the suspended solids values reported in Table 2 by Thingvold (1980). Where a range is reported, no suspended solids measurements were made and the reported range is based on Table 1 of Thingvold (1980).

(c) Duplicate samples and analyses.

(d) This sample is not reported in Tables 1 or 2 of Thingvold (1980). However, the MDH lab sheets in the Appendix to Thingvold (1980) list sample no. 55075 as "well #15 before sand filter (11:00 pm)" being collected on July 16 or 17. The July 17 date would not make sense, so the July 16 date has been used. This sample (no. 55075) corresponds to the sample listed as "Post Sand-Filter Untreated 7/16 11:05 am" in Thingvold's Table 1, which appears to represent an incorrect description.

TABLE G4-2

LIST OF PAH COMPOUNDS ANALYZED

DURING SERCO'S PAC TESTS AT WELL SLP15

Compound	Carcinogenic[a]	Serco	MDH
Acenaphthene		X[e]	X[g]
Anthracene		X	X
Benz(a)anthracene[i]	X	X[f]	X
Benzo(ghi)perylene	X	X	
Benzo(a)pyrene	X	X	X
Biphenyl			X[g]
Chrysene	X	X[f]	X
Dibenz(a,h)anthracene[c]	X	X	X
Fluoranthene		X	X
Fluorene		X[e]	
Indeno(1,2,3-cd)pyrene[d]	X		X
2-Methylnaphthalene			X
Naphthalene		X	
Perylene			X
Phenanthrene		X	X[h]
Pyrene		X	X[h]
Triphenylene[b]			X

Notes:

(a) Per definition and listing of carcinogenic PAH in Appendix I.

(b) MDH listed as 9,10-benzphenanthrene, which is synonymous with triphenylene (see Appendix K).

(c) MDH listed as 1,2-5,6-dibenzanthracene, which is synonymous with dibenz(a,h)anthracene (see Appendix K).

(d) MDH listed as o-phenylenepyrene, which is synonymous with indeno (1,2,3-cd)pyrene (see Appendix K.).

(e) Acenaphthene and fluorene co-eluted in some analyses.

(f) Benz(a)anthracene and chrysene co-eluted in some analyses.

(g) Acenaphthene and biphenyl co-eluted in most analyses.

(h) Phenanthrene and pyrene co-eluted in most analyses.

(i) MDH listed as 1,2-benzanthracene, which is synonymous with benz(a)anthracene (see Appendix K).

measured. All of the samples from the October test (eight samples total) were analyzed by Serco for the same list of compounds given in Table G4-2, with no splits with the MDH.

G4.1.2 Test Results

Table G4-3 summarizes the PAH analysis results by the MDH and Serco for the July 1979 test. Three major conclusions are clear from the data in Table G4-3. First, carcinogenic PAH were rarely detected in any of the 32 samples, with noncarcinogenic PAH predominating instead. Second, the agreement between Serco and MDH results is generally very poor. Third, injection of PAC resulted in significant removal of PAH, with greater removal occurring at the higher PAC dose. Each of these points are discussed in more detail below.

Table G4-3 shows that carcinogenic PAH were only detected in 2 of the 32 samples analyzed by Serco and the MDH. Both of these were untreated wellhead water samples analyzed by Serco. In both cases, the concentrations of noncarcinogenic PAH are much lower than for carcinogenic PAH, which is the opposite of the trend seen in almost all other analyses of well SLP15 (see Appendix K). Serco's results for noncarcinogenic PAH are sporadic, ranging from nondetected to over 800 nanograms per liter, and varying in the number and identity of individual compounds detected. MDH results, on the other hand, are more consistent, both in concentrations and in the number and identity of compounds detected. Acenaphthene, biphenyl, fluoranthene, phenanthrene and pyrene (all noncarcinogenic PAH) were detected in every sample analyzed by the MDH, with few exceptions. None of the other compounds measured by the MDH were ever detected, with few exceptions.

Table G4-3 indicates that MDH results for noncarcinogenic PAH are from 7 times to over 1000 times greater than Serco results. A more precise statistical measure of the comparability of results between the two labs can not be made because there are few instances where both labs reported results for a single compound. This is in part

TABLE G4-3
SUMMARY OF PAH ANALYSIS RESULTS FROM
SERCO'S JULY 1979 PAC TESTS AT WELL SLP15
(All concentrations in nanograms per liter)

Date	Time	Carcinogenic PAH[a] Serco[b]	Carcinogenic PAH[a] MDH[c]	Noncarcinogenic PAH[a] Serco[b]	Noncarcinogenic PAH[a] MDH[c]
UNTREATED WATER SAMPLES					
July 16	11 am	ND	ND	817	5410
	11 pm	--	ND	--	10
July 18	11 am	--	ND	--	4640
July 19	4 am	29	--	1	--
	5 am	--	ND	--	5080
July 20	4 am	8	--	2	--
	5 am	--	ND	2	2100
				Average	4310 ± 1500[f]
SAND FILTRATION ONLY					
July 16	11 pm	--	ND	--	4484
July 19	3 am	ND	ND/ND[d]	ND	6220/5220[d,e]
1-2 MILLIGRAMS PER LITER PAC					
July 17	5 am	--	ND	--	2131
	11 am	ND	ND/ND[d]	54	1429/1641[d]
	5 pm	ND	ND	ND	1662
	11 pm	--	ND/ND[d]	--	739/2920[d]
July 18	5 am	ND	ND	ND	1708
	11 am	--	ND	--	2851
	5 pm	--	ND	--	797
	9 pm	--	ND	--	925
				Average	1680 ± 780[g]
9-12 MILLIGRAMS PER LITER PAC					
July 19	5 am	ND	ND	135	914
	11 am	--	ND	--	87
	5 pm	--	ND	--	37
	11 pm	--	ND	--	11
July 20	5 am	ND	ND	ND	5

Notes:

(a) Per listing in Table G4-2.
(b) From Table 2 in Thingvold (1980).
(c) From MDH lab sheets in Appendix to Thingvold (1980).
(d) Results of analyzing duplicate samples.
(e) Thingvold (1980) Table 1 reports 32 nanograms per liter for fluoranthene while the MDH lab sheets in Thingvold's Appendix report 320 nanograms per liter. The latter result is used here.
(f) Mean ± standard deviation, excluding July 16, 11 pm analysis.
(g) Mean ± standard deviation, ignoring any effects of improved PAH removal as the test progressed.

because most of the compounds detected by the two labs co-eluted (see notes to Table G4-2). For the one compound that was regularly detected by both labs (fluoranthene), MDH results were up to several hundred times higher than Serco results. Furthermore, Serco's detection limits were generally much lower than those of the MDH. Serco's detection limits for individual compounds were generally tenths of nanograms per liter, while MDH detection limits were generally in the tens of nanograms per liter range.

The cause of the large discrepancy between Serco and MDH results is unknown. It is apparent, however, that the MDH results are more closely comparable with other analyses of well SLP15 by other laboratories, which generally show noncarcinogenic PAH concentrations in the low microgram per liter (thousands of nanograms per liter) range (see subsequent discussions of Hickok, CH2M Hill and ERT testing at SLP15, and also data in Appendix K).

Figure G4-1 shows the MDH data for noncarcinogenic PAH from Table G4-3 plotted chronologically for the two different PAC doses. Three key points are indicated by this figure. First, PAC injection at either dose resulted in significant removal of PAH, based on an average untreated water concentration of 4300 ± 1500 nanograms per liter (mean ± standard deviation).* Second, PAC injection at the higher dose (9 to 12 milligrams per liter) gave greater removal than at the lower dose. Third, PAH removal appears to have increased as testing progressed for both PAC dosages.

The fact that PAH removals increased as the testing progressed probably resulted from 1) build up of PAC on the sand filter bed and/or 2) the contact time required to achieve equilibrium adsorption, which are related factors. The length of pipe from the wellhead of

*The average untreated water concentration is 4700 ± 1300 nanograms per liter if the samples from sand filtration are also included. Including these samples in the average is based on the fact that sand filtration alone did not effect significant PAH removal (see Table G4-3). This is consistent with the results of ERT's testing of the sand filter beds at well SLP15 (see Sections G4.4 and G4.5).

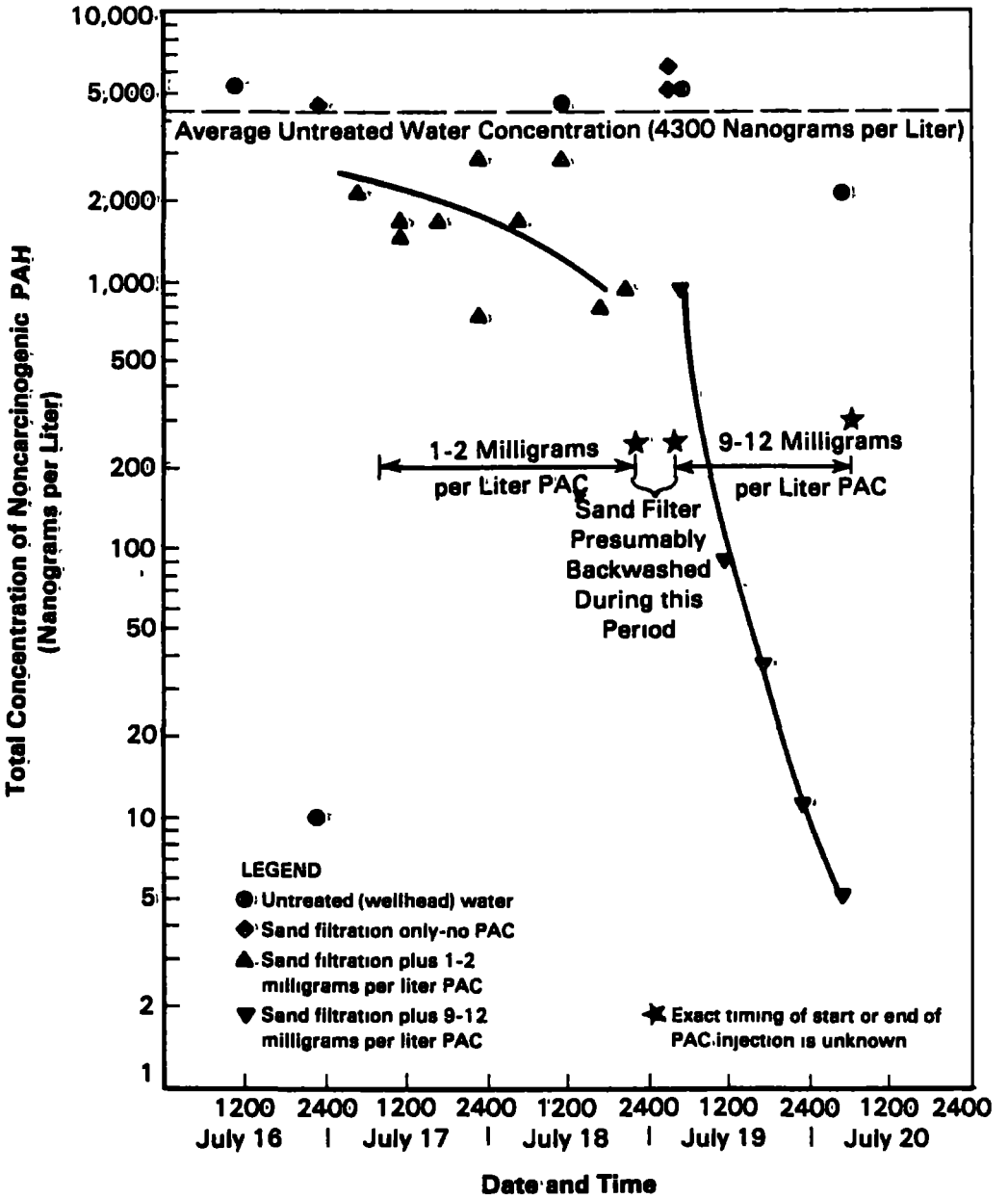

Figure G4-1 Chronological Plot of MDH Analyses of Samples Collected During Serco's July 1979 PAC Tests at Well SLP15

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SLP15 to the sand filter beds is about 300 to 400 feet, with a probable diameter of 12 or 18 inches. Well SLP15 pumping at 1000 gallons per minute would therefore yield a residence time of from 2 to 5 minutes. This is much shorter than a likely contact time of up to 1 to 2 hours for 90 percent of equilibrium adsorption capacity to be achieved with PAC (Dobbs and Cohen 1980). However, as PAC was trapped and built up on the surface of the sand filter, the PAC would remain in contact with water throughout the duration of the test, and water would be in contact with PAC, whether freshly injected or built-up residue on the filter beds, for longer periods. Thirty-six hours of testing at 1 to 2 milligrams per liter PAC injection would have built up 8 to 16 kilograms of PAC on the sand beds, with 24 hours testing at 9 to 12 milligrams per liter PAC adding another 49 to 65 kilograms. The effect of the more rapid build-up of PAC on the sand filters at the higher dose is clearly seen in Figure G4-1.

The average removal of noncarcinogenic PAH at the lower PAC dose was 61 $\pm$ 19 percent (mean $\pm$ 90 percent confidence interval), based on the average concentrations shown in Table G4-3. This average does not account for increased removal rates which may have occurred as the test progressed. An average removal can not be reasonably calculated for the higher PAC dose because of the significant increase in removal that occurred during the test. Removal at the higher PAC dose increased from 98 percent after about 6 hours, to 99.9 percent after about 24 hours.

The results of the October 1979 test were largely inclusive. This test involved added 11 milligrams per liter of PAC over a period of about 2 1/2 days. One untreated water sample and seven treated water samples were analyzed by Serco using HPLC. No PAH were detected in any of the samples, including the untreated water sample.* However, the HPLC "chromatograms suggest that the treated water sample results show the effect of PAC on PAH removal" (Thingvold 1980, p.7).

*The single exception being 386 nanograms per liter of benzo(a)pyrene plus fluoranthene in one of the treated water samples, which is clearly an anomolous result.

G4.1.3 Summary

Testing of PAC injection at well SLP15 by Serco, the MDH and the City of St. Louis Park in July 1979 showed that PAC effected significant removal of PAH. A dose of 1 to 2 milligrams per liter PAC achieved roughly 60 percent removal and a dose of about 10 milligrams per liter PAC achieved over 98 percent removal. The removal of PAH increased during the testing of a given carbon dose, especially for the higher dose. This indicates that build-up of PAC on the sand filter beds downstream of the PAC injection point improved the efficiency of PAH removal. Separate analytical results by Serco and the MDH on duplicate samples showed very poor agreement, with MDH results being much higher and in much better agreement with other tests of SLP15 by other investigators. While the accuracy of the analytical results may be questionable, the MDH results are sufficiently consistent internally to conclude that PAC treatment was indeed effective in removing PAH. A second test in October 1979 at a PAC dose of 11 milligrams per liter gave inconclusive results, although qualitative confirmation that PAC was effective in removing PAH was obtained.

G4.2 Hickok Studies

As a result of the encouraging results from Serco's studies of PAC treatment, and with the support of the MDH (Elwell 1980), the City of St. Louis Park hired Eugene A. Hickok and Associates (Hickok) "to provide the necessary technical and economic information necessary to design and implement a carbon treatment process for one or more of the contaminated City wells" (Hickok 1981, p.4). Hickok's study involved further pilot testing of PAC and GAC, limited testing of hydrogen peroxide, and economic evaluations of alternatives for meeting the municipal water supply shortfall. The study cost $25,000 and is summarized in an April 1981 report by Hickok, which is the primary reference for the material presented in this section. This summary of Hickok's work focuses on the pilot testing studies, with some discussion of Hickok's economic evaluation work.

G4.2.1 Test Description

Hickok performed four separate 24-hour tests of both PAC and GAC treatment at well SLP15 in September and October 1980. Both techniques were tested simultaneously. This was done by withdrawing a slipstream of water from the SLP15 wellhead for treatment in small GAC columns. PAC was then injected, using the existing equipment from Serco's testing, immediately downstream of the slipstream withdrawal point. The injected PAC was then removed by the sand filter beds in the iron removal plant. Figure G4-2 shows a schematic diagram of the PAC and GAC testing systems. Wells SLP11 and SLP15 were both operated at close to 1000 gallons per minute each during the testing. Therefore, PAC was treating water from both wells, while GAC only treated water from SLP15.

PAC treatment was tested at four different injection dosages: 5.5, 8, 11 and 15 milligrams per liter. It is unclear from Hickok's report how these concentrations were measured and whether these concentrations refer to water from SLP15 alone or to water from both wells. It is assumed that they are reported on the basis of treating water from well SLP15 alone, so that the PAC concentration in the combined water from both wells was half of the reported value. PAH concentrations in the combined water from both wells would also have been half of those in SLP15 alone, assuming no detectable PAH in SLP11, which is reasonable (see Appendix K). The weight ratio of PAC to PAH remains constant, irrespective of dilution by SLP11. The PAC concentration is important, however, in that PAH removal (on either a relative or absolute basis) could be affected by both PAH and PAC concentrations. For example, PAH removal by injecting 10 milligrams per liter of PAC into water containing 4 micrograms per liter total PAH would not necessarily be the same removal obtained by injecting 5 milligrams per liter of PAC into water containing 2 micrograms per liter total PAH, even though the mass ratios are the same (2.5 milligrams PAC per microgram PAH).

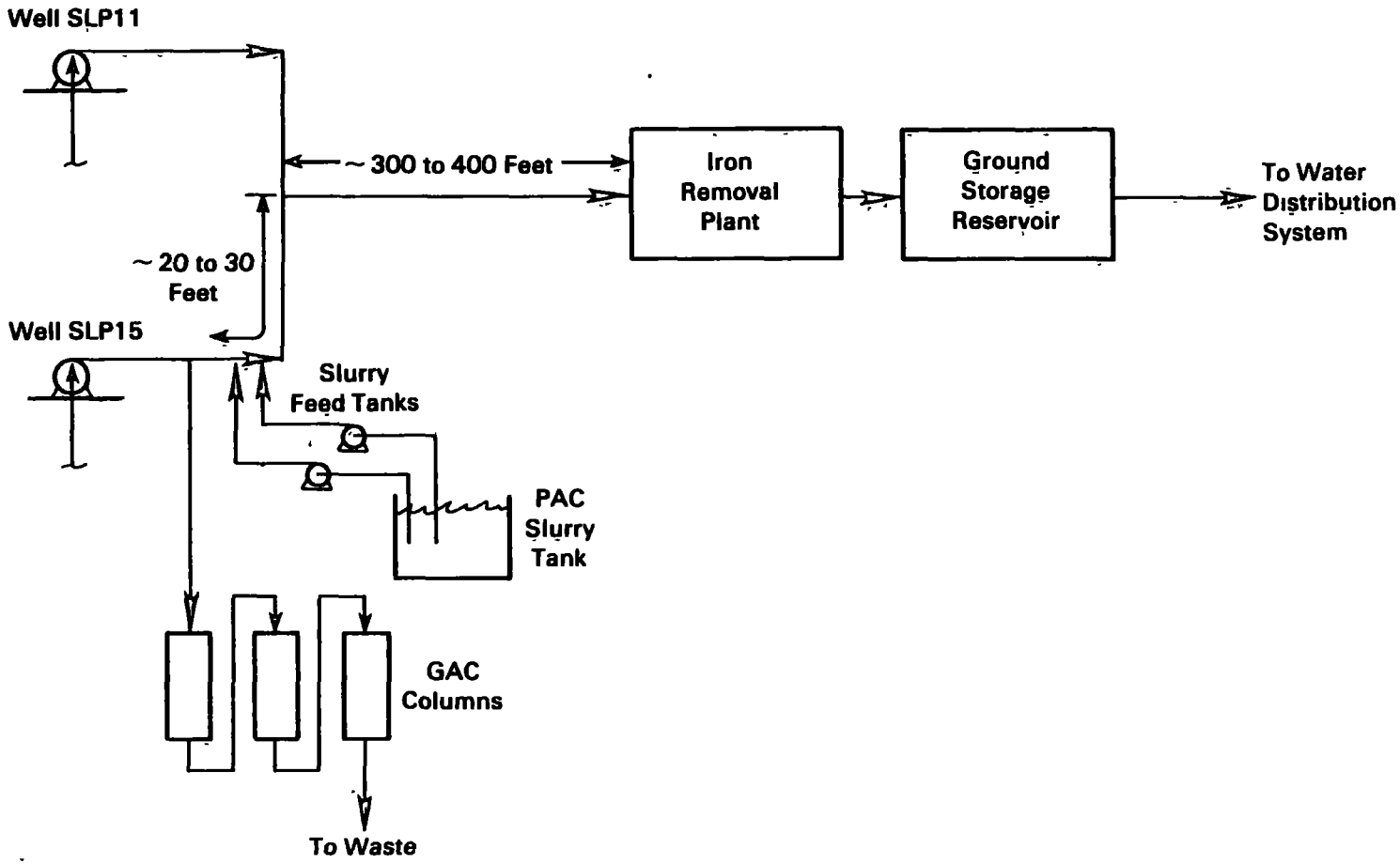

Figure G4-2 Schematic Diagram of PAC and GAC Testing at Well SLP15 by Hickok

GAC treatment was tested in three small carbon columns arranged in series. Each column was 20 inches in diameter, with 48 inches of Westvaco Nuchar WV-G carbon on top of 12 inches of sand and 12 inches of gravel. The flow rate was adjusted during the four tests to yield hydraulic loadings of 4, 8, 12 and 16 gallons per minute per square foot of filter area. These correspond to empty bed contact times (carbon volume only) of 22.5, 11.2, 7.5 and 5.6 minutes, respectively.

Hickok performed a single 24-hour test of hydrogen peroxide injection with ultraviolet (UV) light in February 1981, based on a suggestion made by ERT during a meeting in October 1980. Hydrogen peroxide was injected at the SLP15 wellhead at 6 milligrams per liter and a slipstream of SLP15 water was then withdrawn just upstream of the sand filters and passed through a UV radiation unit. The exposure time in the UV unit was twenty seconds, at a power of 53 UV watts at 253.7 nanometers.

Hickok collected samples of untreated and treated water at regular intervals, generally at 2, 6, 12 and 24 hours, during each test. All PAH analyses were performed by Serco Laboratories using HPLC with UV and fluorescence detectors. Table G4-4 lists the PAH compounds analyzed by Serco and indicates those that are carcinogenic per Appendix I. No results were reported by Hickok for duplicate, field blank or method blank samples, or for water quality constituents other than PAH.

G4.2.2 PAC Test Results

Table G4-5 summarizes the results of Hickok's four PAC tests at wells SLP11 and SLP15. All concentrations are reported for the combined water from the two wells, although some of the untreated water samples were collected only from SLP15. Results from these samples have been divided by two to reflect dilution by SLP11, which should have contained no detectable PAH. No analyses of SLP11 alone were reported by Hickok, but this Mt. Simon-Hinckley well has shown no evidence of PAH contamination (see Appendix K).

TABLE G4-4

LIST OF PAH COMPOUNDS ANALYZED
DURING HICKOK'S TESTS OF PAC AND GAC
TREATMENT AT WELL SLP15

Compound	Carcinogenic[a]
Acenaphthene	
Acenaphthylene	
Anthracene	
Benz(a)anthracene	X
Benzo(k)fluoranthene	X
Benzo(ghi)perylene	X
Benzo(a)pyrene	X
Chrysene	X
Dibenzo(a,h)anthracene	
Fluoranthene	
Fluorene	
Naphthalene	
Phenanthrene	
Pyrene	

Notes:

(a) Based on definition and listing of carcinogenic PAH in Appendix I.

TABLE G4-5

RESULTS OF HICKOK'S PAC TESTS AT WELLS SLP11 AND SLP15

(All concentrations in nanograms per liter)

Time From Start of Test, Hours	Untreated Water[a] Carcinogenic PAH	Untreated Water[a] Noncarcinogenic PAH	Treated Water[b] Carcinogenic PAH	Treated Water[b] Noncarcinogenic PAH
15 MILLIGRAMS PER LITER PAC[j]				
0[c]	10[i]	2720[g]	--	--
2	--	--	ND[e]	ND
6[c]	3[i]	1136	ND	ND
12[c]	6[i]	964	ND	ND
24	--	--	ND	14[h]
11 MILLIGRAMS PER LITER PAC				
0	ND	23[h]	--	--
0	ND	126	--	--
6	--	--	ND	5[h]
12[c]	ND	1490	ND	ND
24[c]	ND	310[h]	ND	ND
8 MILLIGRAMS PER LITER PAC				
2	29	800	ND	6[h]
6	--	--	ND	5[h]
12	2[i]	210[h]	ND	5[h]
24	8[i]	260[h]	38[i]	9[h]
5.5 MILLIGRAMS PER LITER PAC				
2[c,d]	ND	1[h]	--	--
6	--	--	ND	ND
12	82[f]	350[h]	ND	2[h]
24	19[f]	460[h]	ND	ND

Notes:

(a) All untreated water samples represent combined water from wells SLP 11 and SLP15 unless otherwise noted.
(b) All treated water samples represent treatment of combined water from wells SLP11 and SLP15 (combined in approximately equal proportions).
(c) Sample of untreated water from SLP15 alone. Results originally reported by Hickok (1981) are divided by two to approximately represent combined untreated water from SLP11 and SLP15 (i.e., it is assumed that no detectable PAH were present in water from well SLP11).
(d) Table 5 in Hickok (1981) indicates sample collected after 6 hours, while the raw data sheets in the Appendix to Hickok (1981) indicate 2 hours.
(e) ND indicates not detected. Dash indicates no sample or not analyzed.
(f) See note e in Table G4-6.
(g) See note f in Table G4-6.
(h) Only compound detected was fluoranthene.
(i) Only compound detected was benz(a)anthracene.
(j) It is assumed that the PAC concentration is as injected at the SLP15 wellhead, not for water from wells SLP11 and SLP15 combined. Hickok's report (1981) does not say which case applies.

The data in Table G4-5 show that PAC injection was very effective in removing both carcinogenic and noncarcinogenic PAH. Precise quantitative measures of removal efficiencies are difficult to make because of the variability in untreated water concentrations (discussed further in the next subsection) and the large number of nondetected values. In many cases, noncarcinogenic PAH were removed to below detectable levels, where the sum of the detection limits for the corresponding noncarcinogenic PAH detected in untreated samples ranged from 1 to 80 nanograms per liter, depending on the samples. Removal efficiencies for noncarcinogenic PAH, based on average results for treated and untreated samples during each test and treating "not detected" results as zero*, were 99.8 percent for 5.5 and 15 milligrams per liter PAC doses**, 99.7 percent for 11 milligrams per liter PAC***, and 98.5 percent for 8 milligrams per liter PAC. Removal efficiencies calculated by pairwise comparisons of untreated and treated samples both collected at the same time give similar results.

G4.2.3 GAC Test Results

Table G4-6 summarizes the results of Hickok's four GAC tests. All concentrations are reported on the basis of well SLP15 alone, since water from only this well was treated. However, some of the untreated water samples represent combined water from SLP11 and SLP15, in which case, the results have been doubled to represent SLP15 alone, based on the assumed absence of detectable PAH in water from SLP11. The untreated water samples in Tables G4-5 and G4-6 therefore correspond directly to one another, except that they differ by a factor of two.

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*Hickok's report treated "not detected" results for data analysis purposes by dividing detection limits by two and using the resulting values in calculating average removal efficiencies. This is an arbitrary approach with no true physical meaning and has not been done here.

**Excluding the 2 hour untreated sample for 5.5 milligrams per liter PAC.

***Excluding the 0 hour untreated sample.

TABLE G4-6

RESULTS OF HICKOK'S GAC TESTS AT WELL SLP15

(All concentrations in nanograms per liter)

Time From Start of Test, Hours	Untreated Water[a]		Treated Water[b]	
	Carcinogenic PAH	Noncarcinogenic PAH	Carcinogenic PAH	Noncarcinogenic PAH
22.5 MINUTES CONTACT TIME				
0	20[g]	5440[f]	--	--
2	--	--	ND[c]	ND
6	6[g]	2273	6[g]	19[h]
12	13[g]	1929	ND	4[h]
24	--	--	15[g]	56[h]
11.2 MINUTES CONTACT TIME				
0[d]	ND	46[h]	--	--
0	ND	253	--	--
6	--	--	36	14[h]
12	ND	2980	3[g]	4[h]
24	ND	620[h]	ND	ND
7.5 MINUTES CONTACT TIME				
2[d]	58	1600	--	--
6	--	--	ND	6[h]
12[d]	4[g]	420[h]	ND	2[h]
24[d]	16[g]	520[h]	ND	ND
5.6 MINUTES CONTACT TIME				
2	ND	1[h]	--	--
6	--	--	ND	2[h]
12[d]	164[e]	700[h]	ND	1[h]
24[d]	38[e]	920[h]	ND	3[h]

Notes:

(a) All untreated water samples are for well SLP 15 only, unless otherwise noted.
(b) All treated water samples are for treatment of well SLP15 only.
(c) ND indicates not detected. Dash indicates not analyzed or no sample.
(d) Untreated water sample represents water from both wells SLP11 and SLP15 in approximately equal proportions. Results originally reported by Hickok (1981) are doubled to approximately represent untreated water from SLP15 alone (i.e., it is assumed that no detectable PAH were present in water from well SLP11).
(e) Table 5 in Hickok (1981) says that dibenzo(a,h) anthracene was below detection limits in these two samples while Table 10 says it was detected. Results reported here are averages from treating the data both ways.
(f) Table 2 in Hickok (1981) reports 500 nanograms per liter of fluoranthene in this sample while Table 7 reports 1500 nanograms per liter. Result reported here is based on average of these two reported values.
(g) Only compound detected was benz(a)anthracene.
(h) Only compound detected was fluoranthene.

The data in Table G4-6 show that GAC columns were also very effective in removing PAH. Average removal efficiencies for noncarcinogenic PAH, calculated in the same manner as for the PAC tests, ranged from 99.4 percent at 22.5 minutes contact time to 99.8 percent at 5.6 minutes contact time. Carcinogenic PAH were generally reduced to below detectable levels, with the major exception being the 11 minute contact time test, when no carcinogenic PAH were detected in the untreated water but were detected in 2 of the 3 treated samples.

The PAH concentrations in untreated water from well SLP15 show wide variations for both carcinogenic and noncarcinogenic PAH, spanning about two orders of magnitude for each type of PAH. It is unclear to what extent these variations reflect real changes in the quality of the water or simply analytical variability. Neither possibility can be quantitatively assessed without a measure of analytical precision and reproducibility, which can not be obtained from Hickok's reported results because of the absence of duplicate and blank samples. As a qualitative indication of analytical accuracy, however, it is noteworthy that results for simultaneous samples of water from SLP15 alone and SLP11 and SLP15 together at 0 hours on September 29 differed by a factor of eleven for noncarcinogenic PAH, when they only should have differed by a factor of two (see Tables G4-5 and G4-6). It is also noteworthy that carcinogenic PAH were detected in some treated samples at significantly higher concentrations than in untreated samples, which also probably reflects analytical variability.

As a qualitative indication of whether or not changes in PAH concentrations in SLP15 really occurred, Figure G4-3 shows a chronological plot of carcinogenic and noncarcinogenic PAH concentrations during the four test periods. There is no consistent pattern of concentrations as a function of pumping time during an individual 24-hour test. In some cases, concentrations increased as the test progressed and in others they declined. However, total PAH concentrations appear to have declined from the first test to the last test one month later. It is unknown whether or not this decline is real or reflects analytical variability, such as changing instrument conditions over an extended period. If the decline was real, its cause is unknown.

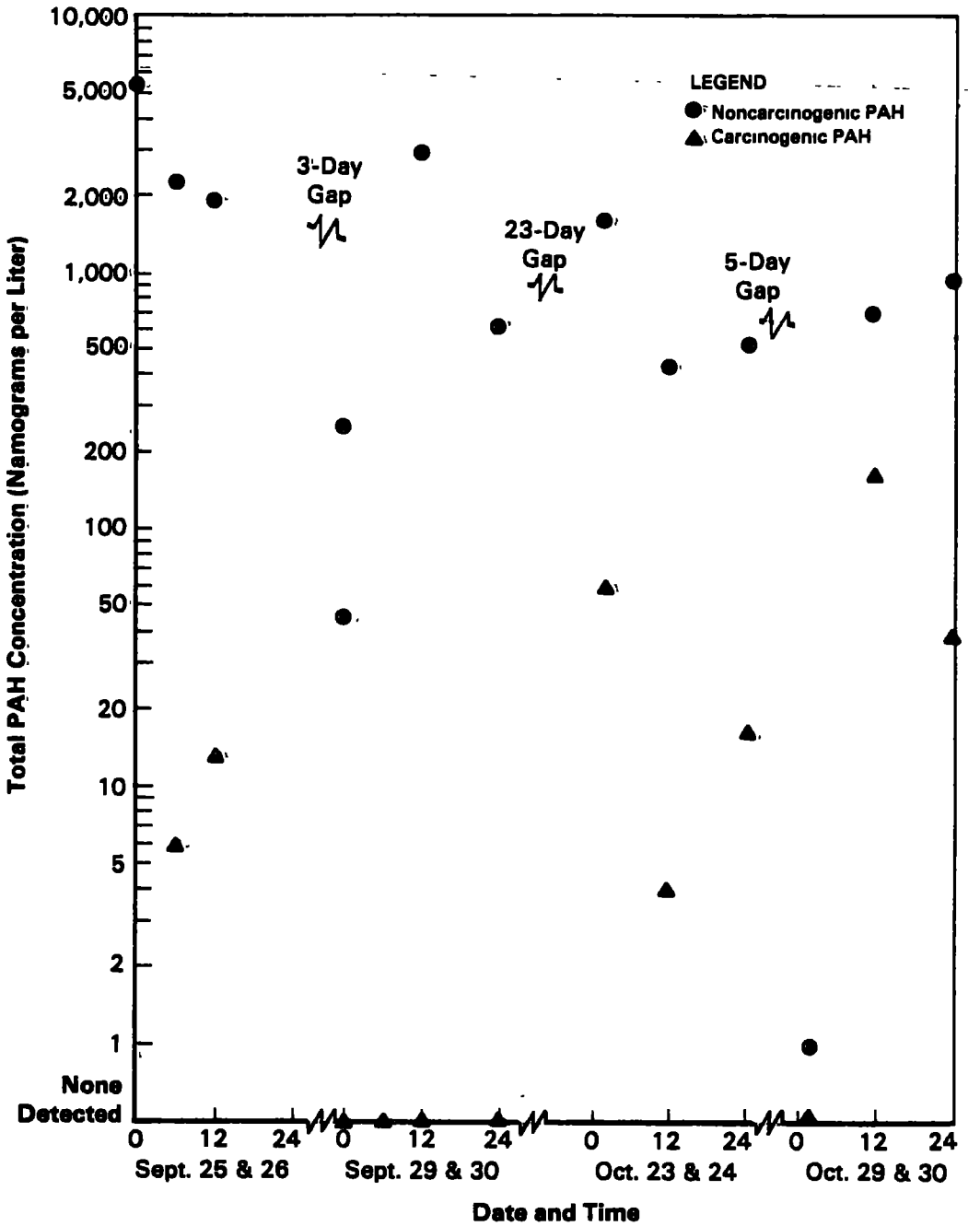

Figure G4-3 Chronological Plot of PAH Concentrations in Untreated Water From Well SLP15 During Hickok's 1980 PAC and GAC Treatment Tests

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G4.2.4 Hydrogen Peroxide Test Results

Hickok collected seven samples during a 24-hour test of hydrogen peroxide injection at well SLP15: three untreated samples at 0, 6 and 12 hours into the test, and four treated samples at 2, 6, 12 and 24 hours. No carcinogenic PAH were detected in any of the samples. The only noncarcinogenic PAH detected were fluoranthene and pyrene, both of which were detected in every sample. The average total concentration of these two compounds was 121 $\pm$ 38 nanograms per liter in the untreated samples and 84 $\pm$ 23 nanograms per liter in the treated samples (both reported as mean $\pm$ standard deviation). The resulting removal efficiency of 31 percent is statistically significant at about the 80 percent confidence interval (i.e., the untreated to treated ratio is 0.69 $\pm$ 0.28, which is less than one at an 80 percent confidence interval). The low removal efficiency is not unexpected, given the very short (20 seconds) UV exposure time (see section G4.3, for example). It is unclear why the PAH concentrations in the untreated water were much lower than those measured four months earlier during the PAC and GAC tests, although analytical difficulties are the likely cause.

G4.2.5 Economic Evaluations

As part of its study, Hickok evaluated the costs of four different options for bringing contaminated St. Louis Park wells back into service. The options considered were PAC treatment, GAC treatment, replacement of sand in iron removal plant filter beds with GAC, and deepening contaminated Prairie du Chien-Jordan wells into the Hinckley formation. The PAC and GAC treatment options were only evaluated for wells SLP4, SLP10 and SLP15, since wells SLP7 and SLP9 are pumped at such low annual rates "that it is not cost effective to treat" them (Hickok 1981, p.44). (Note that SLP5 was not closed down at the time Hickok's report was prepared). Replacement of sand with GAC was only evaluated at SLP10 and SLP15, since the other three closed wells do not have iron removal plants. Deepening into the Hinckley formation was considered for all five wells. All of Hickok's PAC and GAC

treatment cost estimates were derived from Gumerman, Culp and Hansen (1979 a,b,c). The basis of the cost estimates for deepening wells and converting sand filter beds to GAC filters is unclear.

Hickok's design bases for PAC and GAC treatment were conservative. PAC was costed at an injection dose of 15 milligrams per liter and GAC was costed for an empty bed contact time of 20 minutes. Both of these represent the most stringent pilot testing conditions in Hickok's work. The basis for Hickok's choice of these design conditions is unclear. It appears that these conditions may reflect intentional conservatism by Hickok given the lack of a specific finished water design target or criteria by the MDH at the time (Hickok 1981, p. 11). The design bases were also conservative in the assumed equipment design. PAC treatment was costed with 8 days of slurry storage in two basins and GAC treatment included costs for on-site regeneration in a multiple hearth furnace. Hickok noted that "at the present time we have no information concerning carbon exhaustion rates" (Hickok 1981, p. 49). In the absence of specific information, Hickok assumed two regenerations per year. Hickok also noted that the costs and potential problems of disposing of backwash water containing PAC were unknown, and assumed for costing purposes that no extra costs would be involved. This appears to be a reasonable assumption, given Hickok's analysis of one backwash water sample showing 13 micrograms per liter total PAH, which would be a very small additional PAH loading in existing storm or sanitary sewers (see Appendix F).

Hickok's cost estimate for converting the filters in the iron removal plant at wells SLP10 and SLP15 was based on replacing the sand with 36 inches of GAC. Costs of equipment and piping for removing spent carbon and returning reactivated carbon were included. Carbon regeneration was again assumed to take place twice a year. Hickok noted that the feasibility of GAC treatment in this manner (10 minutes empty bed contact time and 2 gallons per minute per square foot hydraulic loading, at 1000 gallons per minute flow rate) was unknown, and assumed for costing purposes that it would work.

Hickok also looked at the cost of deepening all five of the St. Louis Park wells closed at that time into the Hinckley formation from the Jordan. Costs were estimated based on deepening all five wells to 1080 feet and removing, modifying and reinstalling the well pumps. Hickok noted that a positive grout seal would be required to prevent the deepened wells from allowing contaminated water from the Prairie du Chien-Jordan to enter the Mt. Simon-Hinckley and that "a positive grout seal would be difficult [to achieve in Hickok's] opinion" (Hickok 1981, p. 9). No allowance was made for the extra cost of pumping water from a deeper aquifer.

Table G4-7 summarizes Hickok's cost estimates for the four options considered. The costs apply to treating wells SLP4, SLP10 and SLP15 only. In some cases, Hickok's original cost estimates are adjusted in Table G4-7 to reflect this particular set of wells, but such adjustments are made using Hickok's own cost data. The costs for PAC treatment and sand filter conversion at SLP4 both include the cost of building and operating a pressure filter plant at this well, which currently does not have an iron removal plant.* Hickok converted capital costs to an annual cost basis by amortizing costs over 20 years at a 9 percent annual interest rate.

Table G4-7 shows that PAC is the least expensive treatment option. The cost of deepening the wells can not be directly compared with the three treatment options because the incremental cost of pumping deeper wells was not included. Based on its economic evaluations, Hickok concluded that "a PAC treatment system shall be considered as the most cost effective treatment method on the assumption that deepening of the existing wells is not considered safe" (Hickok 1981, p. 11). Hickok also concluded that "specific PAH criteria must be established by the EPA and/or Minnesota Department of Health as well as a criteria on backwash water should PAC treatment be implemented" (ibid.).

*Hickok included this cost for the PAC treatment option, but did not consider sand filter conversion at SLP4.

TABLE G4-7

SUMMARY OF HICKOK'S 1981 ECONOMIC EVALUATION

OF TREATING ST. LOUIS PARK WELLS SLP4, SLP10, AND SLP15[a]

Option	Capital Cost $ Thousands	Annual Operating and Maintenance Cost $ Thousands/Year	Annual Cost,[b] $ Thousands/Year	Annual Cost,[b] $/1000 gallons
PAC Treatment[f]	415[c]	71.4[d]	117	0.34
GAC Treatment				
-Without Regeneration	2129	64.8	298	0.86
-With On-Site Regeneration	3250	113	469	1.36
Conversion of Sand Filters to Carbon Contactors[e]	606[c]	191[d]	257	0.75
Deepen Wells to the Mt. Simon-Hinckley	342	(g)	37.5	0.11

Notes

(a) All costs based on SLP4 operating at 115 million gallons per year and SLP10 and SLP15 operating together at 230 million gallons per year. All costs expressed in 1981 dollars.
(b) Capital costs amortized over 20 years at 9 percent annual interest rate.
(c) Includes $335,000 for building a pressure filter plant at SLP4.
(d) Includes $35,240 annual O&M cost for a new pressure stet filter plant at SLP4.
(e) Derived from cost estimates presented in Table 17 of Hickok (1981), which were for a single conversion of a 500 square foot, 1000 gallon per minute filter operated at 230 million gallons per year. If SLP4 is excluded, the resulting annual cost, derived from Hickok's estimates, for replacing two 500 square foot filters (one each for SLP10 and SLP15) is $123,800 or $0.54/1000 gallons.
(f) Annual cost for wells SLP10 and SLP15 alone (excluding SLP4) is $30,000, or $0.13/1000 gallons.
(g) Not estimated by Hickok. The estimated incremental cost of pumping 300 million gallons per year from the Mt. Simon-Hinckley versus the Prairie du Chien-Jordan is from $25,000 to $45,000 per year, or $0.08 to $0.15 per 1000 gallons (see section 6.4.2 of Chapter 6).

G4.2.6 Summary

Four one-day pilot tests at well SLP15 by Hickok in September and October 1980 showed that PAC and GAC were both effective at achieving substantial removal of PAH. Four different conditions were studied for each type of treatment, with PAC injection doses ranging from 5.5 to 15 milligrams per liter and GAC contact times (empty bed basis) ranging from 5.6 to 22.5 minutes. Removal of noncarcinogenic PAH was greater than 98 percent in every case, and was generally greater than 99.5 percent. Carcinogenic PAH were generally removed to below detectable levels. A single one-day test in February 1981 of hydrogen peroxide injection at 6 milligrams per liter followed by a 20 second UV light exposure showed only 31 percent removal of noncarcinogenic PAH, with no carcinogenic PAH detected in treated or raw water samples.

Analysis of untreated water samples from Hickok's testing by Serco Laboratories using HPLC showed highy variable concentrations of both carcinogenic and noncarcinogenic PAH. Untreated water concentrations for both of these classes varied by up to two orders of magnitude in 13 samples collected over a one-month period. Hickok concluded that this variability "suggest(s) that a PAH flume (sic) exists in the groundwater "(Hickok 1981, p. 8). However, the variability was probably due largely to analytical variability and possibly a long-term trend of reduced concentrations with increased pumpage, rather than to a plume of contaminants in the Prairie du Chien-Jordan (see also Appendix E).

Hickok's economic evaluation showed that PAC injection is much less expensive than GAC treatment, whether separate GAC columns are built or if the sand in the filter beds is replaced by GAC. However, Hickok's cost estimates were based on important design assumptions made with little, if any, supporting data. Hickok also showed that deepening wells into the Hinckley formation is relatively inexpensive compared to PAC or GAC treatment, but recommended against this option because of concerns that it would be difficult to ensure positive grout seals to prevent downward flow of contaminated water from the Prairie du Chien-Jordan into the uncontaminated Mt. Simon-Hinckley.

G4.3 CH2M Hill Studies

CH2M Hill was hired by the MPCA in August 1982 for a multi-task study of drinking water and ground-water treatment applicable to the St. Louis Park problem. Ninety percent of the contract value of some $220,000 is being paid for with Superfund monies. The tasks involved are:

A. Literature Search
B. Technology Assessment
C. Document Sampling and Analytical Procedures
D. Well Sampling and Analysis Program
E. Investigate Existing Treatment at Well SLP15
F. Prepare Bench-Scale Testing Plan
G. Milestone Report/Review for Tasks A through F
H. Bench-Scale Testing
I Milestone Review Meeting for Bench-Scale Testing
J. Prepare Pilot Testing Plan
K. Pilot-Scale Testing
L. Review Alternative Water Supply Studies
M. Milestone Review Meeting for Tasks K and L
N. Cost Estimates for Water Conveyance Systems
O. Cost Estimates for Water Treatment Systems
P. Cost-Effective Analysis
Q. Prepare Draft Report
R. Milestone Review Meeting for Draft Report
S. Prepare Final Report
T. Project Administrative Tasks
U. Community Relations

Tasks A through J have been completed as of the writing of this appendix (early April 1983), and Task K is in progress. The status of the remaining tasks is unknown. The results of Tasks A through J have been documented in a series of Technical Memoranda, which serve as the primary reference for the materials discussed in this section (CH2M Hill 1982a-f and 1983 a&b).

The review of CH2M Hill's work in this section focuses on the results of bench-scale testing, investigation of the existing iron removal treatment plant at SLP15, and plans for pilot-scale testing (Tasks E through J). ERT was invited to participate in the milestone review meetings, which are also summarized here.

G4.3.1 Sampling and Analysis Procedures

All of the samples collected by CH2M Hill have been analyzed by capillary column gas chromatography/mass spectrometry (GCMS) at CH2M Hill's laboratory in Montgomery, Alabama. Samples are analyzed for a standard list of 27 PAH compounds and 8 heterocyclic PAH compounds (Table G4-8). Additional samples have also been analyzed for priority pollutant acid compounds (phenol plus ten chloro-, nitro-, and/or methyl-substituted one-ring phenols) and for priority pollutant volatile organic compounds (31 specific compounds, including benzene, toluene, ethylbenzene and a wide range of light chlorinated solvents, such as trichloroethylene).

Volatile organics are analyzed using EPA Method 624, which generally gives detection limits of from 5 to 10 micrograms per liter (parts per billion) for each compound. PAH analysis is based on EPA Method 625, with some modifications by CH2M Hill. This procedure involves sequential extraction of a 4 liter aqueous sample with methylene chloride at pH greater than 11 and pH less than 2, concentration of the extract, and analyses of the extract by GCMS. The major modification are: 1) "two surrogate standards are used instead of three"; 2) "the volume of the final extract is 0.02 milliliters instead of 1.0 milliliter"; and 3) "internal standards are added just prior to the final concentration (instead of) just prior to analysis"(CH2M Hill 1982a, p. 9). The detection limit for individual PAH and heterocyclic PAH compounds by this method generally ranges from 1 to 5 nanograms per liter (parts per trillion). The detection limit for acid compounds is generally 100 nanograms per liter (parts per trillion).

TABLE G4-8

LIST OF PAH AND HETEROCYCLIC PAH COMPOUNDS

ANALYZED BY CH2M HILL

PAH Compounds	Number of Rings	Carcinogenic[d]
Acenaphthene	3	
Acenaphthylene	3	
Anthracene	3	
Benz(a)anthracene	4	X
Benzo(b&k)fluoranthene	5	X
Benzo(j)fluoranthene	5	X
Benzo(ghi)perylene	6	X
Benzo(a)pyrene	5	X
Benzo(e)pyrene	5	
Biphenyl	2	
Chrysene	4	X
Dibenzo(a,h)anthracene	5	X
2,3-Dihydroindene	2	
Fluoranthene	4	
Fluorene	3	
Indene	2	
1H-Indene	2	
Indeno(1,2,3-cd)pyrene[a]	6	X
1-Methylnaphthalene	2	
2-Methylnaphthalene	2	
Naphthalene	2	
Perylene	5	
Phenanthrene	3	
Phenylnaphthalene	3	
Pyrene	4	
1,2,6,7-Tetrahydropyrene	4	
Triphenylene[b]	4	

Heterocyclic PAH	Number of Rings	Carcinogenic[d]
Acridine	3	
Benzo(b)thiophene	2	
Carbazole	3	
Dibenzofuran	3	
Dibenzothiophene	3	
Indole	2	
Phenanthridine	3	
Quinoline	2	X
Aromatic Amines[c]		
1-Aminobiphenyl	2	
1-Aminonaphthalene	2	
Aniline	1	

Notes:

(a) CH2M Hill also lists O-phenylenepyrene, which is a synonym for indeno(1,2,3-cd)pyrene (see Appendix K).
(b) Listed as 9,10-benzophenanthrene by CH2M Hill, which is synonymous with triphenylene (see Appendix K).
(c) Aromatic amines were added during the second round of well sampling by CH2M Hill and were included in all bench-scale testing samples (CH2M Hill 1982d&e). These compounds were never detected in any of the SLP15 treated or untreated samples.
(d) Per definitions and listings given in Appendix I.

CH2M Hill's sampling and analysis procedures involve extensive quality control and quality assurance procedures. Rigorous chain of custody records and procedures are specified. Provisions are made for field blanks (one per sample set), laboratory blanks, duplicate samples, and spiked samples. Two surrogate standards are added prior to extraction (1-fluoronaphthalene and 2,4,6-tribromophenol) and five internal standards are added to the methylene chloride extract just prior to the final concentration step (naphthalene-d8, anthracene-d10, chrysene-d12, 2-fluorobiphenyl, and phenol-d5). Samples are also split with the MDH and the EPA, although results from these two laboratories were not available at the time of this writing.

G4.3.2 Investigation of the Iron Removal Treatment Plant at Well SLP15

CH2M Hill tested the effects of the existing iron removal plant at well SLP15 on PAH removal by collecting four samples at various points in the treatment plant while it operated under typical conditions with water from SLP15 alone. The test took place on September 15, 1982 and the results are reported in CH2M Hill's Technical Memorandum E (1982f). Well SLP15 was run for 4.75 hours at 1000 gallons per minute prior to sampling and a sample from the wellhead was then collected. At this time, aeration and prechlorination was then started and the flow rate was increased to 1300 gallons per minute. After about two hours of operation, a sample was collected just upstream of the sand filter (after aeration and prechlorination), followed by two samples collected downstream of the filter (aeration, prechlorination and filtration). One of the post-filtration samples was stored for 2 days prior to extraction, the other for 5 days, in order to simulate the effects of the surface storage tank at SLP15. Chlorine injection was then stopped, and another sample was collected just upstream of the sand filter (aeration only). The sample points used correspond to ERT sample point numbers 1D (wellhead), 3A or 3B (filter inlet), and 4A (filter outlet)* (see Figure G4-5).

*The precise filter outlet sample tap used is not reported by CH2M Hill (1982f), although it has since been indicated that ERT sample point 4A was used (Hansel 1983).
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During the test, the aeration and chlorination rates were established at their normal settings. Air was added at 20 percent of full-scale,* or 1.21 standard cubic feet per minute, which is equivalent to 2.0 milligrams per liter oxygen addition at 1300 gallons per minute. Chlorine was added at a rate of 20 pounds per day, or 1.3 milligrams per liter. Residual free chlorine was measured by St. Louis Park personnel at 1.1 milligrams per liter at the filter outlet.

Splits of the four samples collected by CH2M Hill were also collected by Twin Cities Testing for subsequent analysis by Monsanto Research Corporation (MRC) on behalf of ERT and RT&CC.** Monsanto's analytical procedures are described in section G4.4. The complete results of Monsanto's analyses of these split samples are given in Table G8-9A, B and C in section G8 of this appendix. Table G4-9 lists the compounds analyzed by CH2M Hill and MRC during the September 15 test. The two laboratories analyzed 20 compounds in common, with each also analyzing another dozen or so unique to each laboratory. Monsanto's analyses differed primarily in that a number of methylated PAH not included by CH2M Hill were analyzed (i.e., dimethylnaphthalenes, methylphenanthrenes, methylacenaphthenes and methyldibenzofurans).

CH2M Hill also analyzed all of its samples for acid compounds. No such compounds were detected in any of the samples, except for 200 nanograms per liter of phenol in the post-filtration sample stored for

*CH2M Hill's Technical Memorandum E (1982f, p. 3) says that the air rate was set at 20 pounds per day, or 0.3 milligrams per liter oxygen addition. The actual units presumably should be percent of full-scale air flow, based on ERT's understanding of the iron removal plant operation (see sections G2.1 and G4.4).

**MRC analyzed duplicate samples from each sampling point. The extracts from the two duplicates were then combined and further concentrated for a third analysis with lower detection limits. The results discussed in this section are those for the separate duplicate analyses. The results of the analyses at lower detection limits are reported in Table G8-10 in section G8, and are generally consistent with the duplicate results.

TABLE G4-9

LIST OF COMPOUNDS ANALYZED BY CH2M HILL AND MRC

DURING SEPTEMBER 1982 TESTING OF THE IRON REMOVAL PLANT AT WELL SLP15

PAH Compound	Analyzed By CH2M Hill	Analyzed By MRC
TWO-RING COMPOUNDS		
Biphenyl	X	X
2,3-Dihydroindene	X	
Dimethylnaphthalenes		X(a)
Indene	X	
1H-Indene	X	
1-Methylnaphthalene	X	X
2-Methylnaphthalene	X	X
Naphthalene	X	X
THREE-RING COMPOUNDS(d)		
Acenaphthene	X	X
Acenaphthylene	X	X
Anthracene	X	X
Fluorene	X	X
Methylacenaphthenes		X(b)
Methylphenanthrenes		X(c)
Phenanthrene	X	X
Phenylnaphthalene	X	X
FOUR-RING COMPOUNDS(c)		
Benz(a)anthracene	X	X
Benzo(c)phenanthrene		X
Chrysene	X	X
Fluoranthene	X	X
Pyrene	X	X
1,2,6,7-Tetrahydropyrene	X	
Triphenylene	X	
FIVE-RING COMPOUNDS(f)		
Benzo(h&k)fluoranthene	X	
Benzo(j)fluoranthene	X	
Benzo(a)pyrene	X	X
Benzo(e)pyrene	X	
Dibenzo(a,h)anthracene	X	
Perylene	X	X
SIX-RING COMPOUNDS(g)		
Benzo(ghi)perylene	X	X
Indeno(1,2,3-cd)pyrene	X	X

Heterocyclic PAH	Analyzed By CH2M Hill	Analyzed By MRC
TWO-RING COMPOUNDS		
Benzo(b)thiophene	X	
Indole	X	
Quinoline	X	
THREE-RING COMPOUNDS		
Acridine	X	
Carbazole	X	
Dibenzofuran	X	X
Dibenzothiophene	X	X
Methyldibenzofurans	X	X(b)
Phenanthridine	X	

Notes:

(a) Seven isomers analyzed.
(b) Two isomers analyzed.
(c) Five isomers analyzed.
(d) In addition, MRC analyzed for an unidentified peaks of molecular weight 188.
(e) In addition, MRC for unidentified peaks of molecular weight 202 and 228.
(f) In addition, MRC analyzed for unidentified peaks of molecular weight 252 (three isomers).
(g) In addition, MRC analyzed for unidentified peaks of molecular weight 276 (two isomers).

five days. CH2M Hill also analyzed a wellhead sample for volatile organics. Benzene, trichloroethylene, and trans-1,2-dichloroethene were the only compounds detected, although all were detected below their method detection limits of 5 micrograms per liter.

Table G4-10 summarizes the results of CH2M Hill's and MRC's analyses by compound class (two-ring, three-ring and four-ring PAH and carcinogenic and noncarcinogenic PAH). From 75 to 86 percent removal of total PAH was observed across the entire treatment plant (aeration, prechlorination and filtration), depending on the results used. Aeration alone resulted in about 40 percent removal (CH2M Hill results), with the balance resulting primarily from filtration. Aeration and prechlorination together produced similar results as aeration alone. Overall removals were a clear function of molecular weight, as shown by about 60 percent removal for two-ring PAH compared to 98 percent removal for four-ring PAH.

An unusual result found by both CH2M Hill and MRC was that concentrations of naphthalene in all of the samples collected at the three points in the treatment plant were much higher than in wellhead samples. For example, naphthalene in the sample collected after aeration alone was 940 nanograms per liter, versus 17 nanograms per liter at the wellhead (CH2M Hill results--corresponding MRC results are 180 and 28 nanograms per liter, respectively). One possible explanation for the observed increase in naphthalene concentrations is that naphthalene was present in the air added by the aerator, perhaps as a result of contamination from the air compressor exhaust, which is located near the air compressor air intake (see section G4.4).

The data in Table G4-10 also indicate that concentrations determined by MRC are consistently much lower than those by CH2M Hill. To better illustrate this point, Table G4-11 shows results only for the 20 compounds measured in common by both laboratories. The results in Table G4-11 are therefore directly comparable, while those in Table G4-10 are not (because the latter includes compounds measured by only one of the laboratories). The data in Table G4-11 indicate

TABLE G4-10

SUMMARY OF PAH ANALYSIS RESULTS BY CH2M HILL[h] AND MRC[i]

DURING SEPTEMBER 1982 TESTING OF THE IRON REMOVAL PLANT AT WELL SLPi5

(All concentrations in nanograms per liter)

Compound Class[a,g]	Wellhead		After Aeration Alone		After Aeration and Chlorination		After Filtration		Overall Removal, Percent	
	CH2M Hill	MRC[c]	CH2M Hill	MRC[c]	CH2M Hill	MRC[c]	CH2M Hill[d]	MRC[c]	CH2M Hill	MRC
Two-Ring PAH	2812	674	3282	310	3134	1004	1305/1164	225	54/59	67
Three-Ring PAH	5730	3088	2272	345	1900	1312	975/770	376	83/87	88
Four-Ring PAH	770	512	37	15	ND	26	11/ND	10	98/-	98
Noncarcinogenic PAH	9312	4259	5559	669	4958	2342	2280/1925	611	76/79	86
Carcinogenic PAH	ND	15[f]	32[b]	1[e]	76[b]	ND	11[b]11[b]	ND	-/-	--
Total PAH	9312	4274	5591	670	5034	2342	2291/1934	611	75/79	86

Notes:

(a) Compound class designations as per Table G4-9. All classes include any heterocyclic PAH.
(b) Only carcinogen detected was quinoline.
(c) Average of two samples.
(d) Results for samples extracted 2 days/5 days after collection.
(e) Only carcinogen detected was chrysene.
(f) Carcinogens detected were benz(a)anthracene, benzo(c)phenanthrene and chrysene.
(g) No five or six-ring PAH were detected by CH2M Hill or MRC.
(h) Data from CH2M Hill 1982f.
(i) Data from Table G8-9.

TABLE G4-11

SUMMARY OF PAH ANALYSES FOR COMPOUNDS MEASURED IN COMMON[a] BY CH2M HILL[c] AND MRC[d]

DURING SEPTEMBER 1982 TESTING OF THE IRON REMOVAL PLANT AT WELL SLP15

(All concentrations in nanograms per liter)

Compound Class[a]	Wellhead		After Aeration Alone		After Aeration and Chlorination		After Filtration		Overall Removal, Percent	
	CH2M Hill	MRC[b]	CH2M Hill	MRC[b]	CH2M Hill	MRC[b]	CH2M Hill	MRC[b]	CH2M Hill	MRC
Two-Ring PAH	650	278	1280	246	1088	761	255/168	137	61/74	51
Three-Ring PAH	5730	2678	2272	307	1900	1129	975/770	335	83/87	87
Four-Ring PAH	770	498	37	15	ND	25	11/ND	10	99/-	98
Noncarcinogenic PAH	7150	3441	3589	567	2988	1915	1241/938	482	83/87	86
Carcinogenic PAH	ND	13	ND	1	ND	ND	ND	ND	-/-	--
Total PAH	7150	3454	3589	568	2988	1915	1241/938	482	83/87	86

Notes:

(a) See Table G4-9 for list of compounds analyzed in common.
(b) Average of two samples.
(c) Data from CH2M Hill 1982f.
(d) Data from Table G8-9.

that CH2M Hill results for the three different ring-size compound classes were higher than MRC results on the average by a factor of 2.68 ± 1.29 (mean ± 95 percent confidence interval for 11 comparisons).

The cause for this discrepancy appears to lie in the different surrogate and internal spike procedures used by the two laboratories. Both laboratories added surrogate spiking standards to unextracted water samples. CH2M Hill added 1-fluoronaphthalene and 2,4,6-tribromophenol (the former to check PAH extraction efficiencies, the latter to check acid compound extraction efficiencies) and MRC added naphthalene-d8 and chrysene-d12. CH2M Hill's reported surrogate spike recoveries for five samples ranged from 85 to 115 percent for 1-fluoronaphthalene (100 percent average) and from 110 to 126 percent for 2,4,6-tribromophenol (118 percent average). MRC's reported surrogate spike recoveries for eight samples (four duplicates) ranged from 37 to 61 percent (50 percent average) for naphthalene-d8 and from 38 to 72 percent for chrysene-d12 (57 percent average). The reported extraction efficiencies therefore differ by about a factor of two. However, CH2M Hill's internal spiking standards (naphthalene-d8, anthracene-d10, chrysene-d12, 2-fluorobiphenyl and phenol-d5) were added to the extract prior to the final concentration step, while MRC's internal spiking standard (anthracene-d10) was added after the final concentration step immediately prior to analysis. If any losses of CH2M Hill's internal spiking standards occured during the final concentration step, then actual concentrations of the internal spikes would have been less than the assigned values. This would bias all results high, including surrogate spike results, which would make apparent surrogate spike recoveries higher than they actually were.*

*For example, assume that a surrogate spike is added to the water sample at 100 nanograms per liter and that an internal standard is added to the extract prior to final concentration at 50 nanograms per liter. Further assume, for illustration purposes, that the true extraction efficiency for the surrogate spike is 75 percent and that 40 percent of the internal standard is lost during the final concentration step. The actual concentration of the internal standard is then 30 nanograms per liter and for the surrogate spike, 75 nanograms per liter. However, the peak height of the internal standard is assigned a concentration of 50 nanograms per liter because it is assumed that no losses occur. The surrogate spike peak, which is 2.5 times as high as the internal standard peak, is therefore assigned a concentration of 125 nanograms per liter. The apparent recovery of the surrogate spike (i.e., apparent extraction efficiency) is then reported as 125 percent when it is actually only 75 percent.

The fact that surrogate spike recoveries for 2,4,6-tribromophenol were consistently greater than 100 percent (118 ± 8 percent mean ± 95 percent confidence interval) is indirect evidence that internal spike losses occurred during the final concentration step.

It should be noted that CH2M Hill's addition of internal spiking standards prior to the final extract concentration step varies from the approach recommended in EPA method 625, which is to add such standards after the final extract concentration immediately prior to analysis, as done by MRC. CH2M Hill's approach involves assuming that there are no losses of internal standards during the final concentration step or that any losses of internal standards during the final concentration step are reproducible. Neither of these assumptions is reasonable and, more importantly, neither has to be made if the internal standards are added after the final concentration step, as done by MRC and recommended by EPA method 625.

The significance of the results of CH2M Hill's September 1982 test of the iron removal plant at well SLP15 were interpreted differently by ERT and by CH2M Hill and the MPCA at the subsequent milestone review meeting held on October 11, 1982 (Task G). All parties agreed that the results obtained were accurate, based largely on the good agreement between MRC and CH2M Hill results. ERT felt that the observed removals were sufficiently high, particularly in light of the criteria recommended by this report (see Appendix I), that the iron removal plant should be retested to confirm the results and attempt to understand their cause(s) (Craun 1982). CH2M Hill and the MPCA, however, felt that results from retesting of the iron removal plant would be difficult to interpret and potentially inconclusive. In particular, they expressed concern over potential contaminants in the aerator air and the possible presence of residual PAC in the system remaining from earlier testing work* (CH2M Hill 1982f, Harris 1982a). CH2M Hill and the MPCA preferred, instead, to perform

*CH2M Hill's chemist noted the presence of "considerable particulate matter which had the appearance of carbon" in two of the samples collected during the September test, but could not recall in which samples (CH2M Hill 1982f, p. 3).

bench-testing of the different unit operations involved in the iron removal plant (aeration, chlorination and filtration) to further investigate their significance. The outcome of the meeting was that CH2M Hill performed bench-scale testing of the unit operations as part of Task G (described in Subsection G4.3.3 below) and ERT performed further testing at the iron removal plant in December 1982 and February 1983 (described in Sections G4.4 and G4.5). These various tests together indicated that the PAH removals observed during CH2M Hill's September 15, 1982 test were not representative of normal iron removal plant operation, primarily as a result of substantial iron precipitate slime deposits covering the surface of the sand filters, which were only discovered during ERT's December 1982 test (see Section G4.4.5).

G4.3.3 First Round Bench Testing

CH2M Hill performed bench-scale testing to evaluate the ability of a variety of treatment technologies to remove PAH and related compounds from well SLP15 water. Two basic types of technologies were evaluated: adsorption and oxidation. The bench testing was performed in two phases. The first round of testing was to screen a variety of technologies which were identified as a result of the literature search and technology assessment task (Tasks A and B, CH2M Hill 1982b). Screening tests were performed under severe conditions (e.g., high doses, long reaction times), with no attempt to optimize conditions, to see which technologies could possibly meet the MDH criteria for PAH in drinking water (i.e., 28 nanograms per liter for carcinogenic PAH and 280 nanograms per liter for all other PAH - see Chapter 4). Technologies which looked promising as a result of first round testing were then retested during round two to roughly define minimum process conditions required to meet the MDH criteria.

This subsection summarizes the results of CH2M Hill's round one bench testing. The following subsection summarizes the second round test results. All of the results described here are presented in detail in CH2M Hill 1982e.

Test Procedures

During the first round of bench testing, CH2M Hill evaluated carbon adsorption, resin adsorption, and oxidation by five different chemicals. Some of the oxidation testing was oriented towards testing the different unit operations at the SLP15 iron removal plant. First round testing was performed during the week of November 8-12 at CH2M Hill's Montgomery, Alabama laboratory using water from a 55-gallon drum sample from SLP15 collected on November 7, 1982. The drum was sampled upon receipt and 5 days later. The wellhead was sampled when the drum sample was collected.

Adsorption testing consisted of measuring equilibrium adsorption isotherms for five different activated carbons and three different macroreticular resins. Adsorption isotherms were developed for each adsorbent by testing three different dosages: 1, 10 and 25 milligrams per liter. The test procedure consisted of adding the desired adsorbent dose to two liters of SLP15 water, allowing for 2 hours of contact* at 50°F and pH 7.0, filtering the adsorbent from the water, and analyzing the filtrate water for PAH and related compounds. The five granular activated carbons tested were Westvaco Nuchar WV-G, ICI HD 4000, Calgon Filtrasorb 300, Ceca Carborundum and Witco Witcarb. Each carbon was pulverized and sieved to 0.0015 by 0.0029 inches before testing. The three macroreticular resins tested were Rohm and Haas XAD-2, Rohm and Haas XAD-4, and Dow XFS-4022. Because of difficulties in achieving adequate contact between the resin pellets and the water (the resin pellets floated), the resins were washed with acetone and rinsed with water immediately prior to testing, which caused the resins to sink and therefore gave better contacting. It should be noted that macroreticular resins have never been used in a drinking water treatment application anywhere in the U.S. and are currently not approved for such use (CH2M Hill 1982b).

*Two hours contact time was assumed to have allowed equilibrium adsorption to be achieved. This is reasonable based on testing of the time required to achieve equilibrium for some low molecular weight PAH-related compounds reported by Dobbs and Cohen (1980). CH2M Hill did not test the time required to approach equilibrium, although this could have been done and would have provided a measure of the required contact time in a GAC column.

All oxidation tests were conducted in a 3-liter stainless steel cylindrical reactor vessel. The vessel included a cooling water jacket to maintain desired reaction temperatures and a quartz cylinder in which a UV light could be placed. The oxidants tested were air, chlorine, chlorine dioxide, hydrogen peroxide and ozone. The latter three were each tested under two different conditions of pH, temperature, dose or reaction time. Hydrogen peroxide and ozone were both tested with UV light; the others were not. Aeration and chlorination were tested in various combinations alone and together and with or without filtration through a 0.45 micron silver metal membrane. This was done to test the various unit operations employed at the SLP15 iron removal treatment plant. It should be noted that oxidant doses were calculated based on the measured amount of oxidant added to 3 liters of SLP15 water, but were generally not measured by actual testing of the water or of the vent gas from the reactor vessel. This is an important drawback of the ozone testing, since much of the ozone gas could have bubbled through the reactor without being absorbed (Merritt 1983). Dissolved oxygen measurements were made during the aeration tests and showed the water to be saturated with oxygen at all times (about 11 milligrams per liter at 50°F, Kemmer 1979).

CH2M Hill's original bench-scale test plan (CH2M Hill 1982c) did not specify any water quality measurements other than PAH for untreated or treated samples, such as iron, manganese, hardness, or total organic carbon (TOC). However, at the request and expense of Reilly Tar & Chemical Corporation, CH2M Hill did perform TOC analyses on treated samples. ERT and RT&CC made this request to see if TOC would compete with or affect removal of PAH.

Test Results

All of the activated carbons tested showed significant removals of PAH, especially at the high dosages (10 and 25 milligrams per liter), where total PAH concentrations were reduced to less than 1 microgram per liter, compared to 11 micrograms per liter in the untreated water. CH2M Hill presented carbon adsorption test results in the form of Freundlich isotherm plots. The Freundlich model for

adsorption isotherms is $X/M = KC^{1/n}$, where X/M is the equilibrium adsorption capacity (weight of material, X, adsorbed per weight of adsorbent, M), C is the residual equilibrium concentration of the adsorbate, and K and n are constants. This equation plots as a straight line on log-log paper:

$$\log X/M = K + (1/n) \log C$$

Figure G4-4 shows CH2M Hill's plot of isotherms for total PAH for all five of the carbons tested. CH2M Hill (1982e) also presented isotherm plots for two, three and four-ring PAH and selected individual PAH. In all cases, however, including Figure G4-4, the isotherms do not include any of the heterocyclic PAH.* The isotherms in Figure G4-4 are constructed by calculating the total amount of PAH removed (nanograms per liter) divided by the carbon dose (milligrams per liter), which gives the amount of PAH adsorbed by the carbon (nanograms per milligram or parts per million), and plotting this against the concentration of PAH remaining in the water (residual concentration).** The resulting isotherms show the relationship between concentrations of PAH in water and the equilibrium adsorption capacity of carbon. For example, carbon exposed to water containing 1,000 nanograms per liter of total PAH can adsorb from 600 to 1500 nanograms of PAH per milligram of carbon, depending on the brand of carbon.

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*Including heterocyclic PAH in the total PAH isotherms increases their slope somewhat and shifts them slightly upwards. For example, at a residual concentration of 1,000 nanograms per liter, the Calgon and Westvaco carbons each have an adsorption capacity of about 1700 nanograms per milligram based on total PAH and heterocyclic PAH, versus from 1200 to 1500 nanograms per milligram based on total PAH alone (see Figure G4-4 and Table G4-12).

**The isotherms constructed by CH2M Hill made no allowance for the slight PAH removals observed during a blank test (i.e., testing SLP15 water in the test equipment without any carbon). About 10 percent removal of total PAH was observed in the blank test, which would affect the isotherms by shifting them downward by 10 percent (i.e., ten percent of the removal attributed to the carbon's adsorption capacity was actually due to adsorption on equipment glassware or other losses).

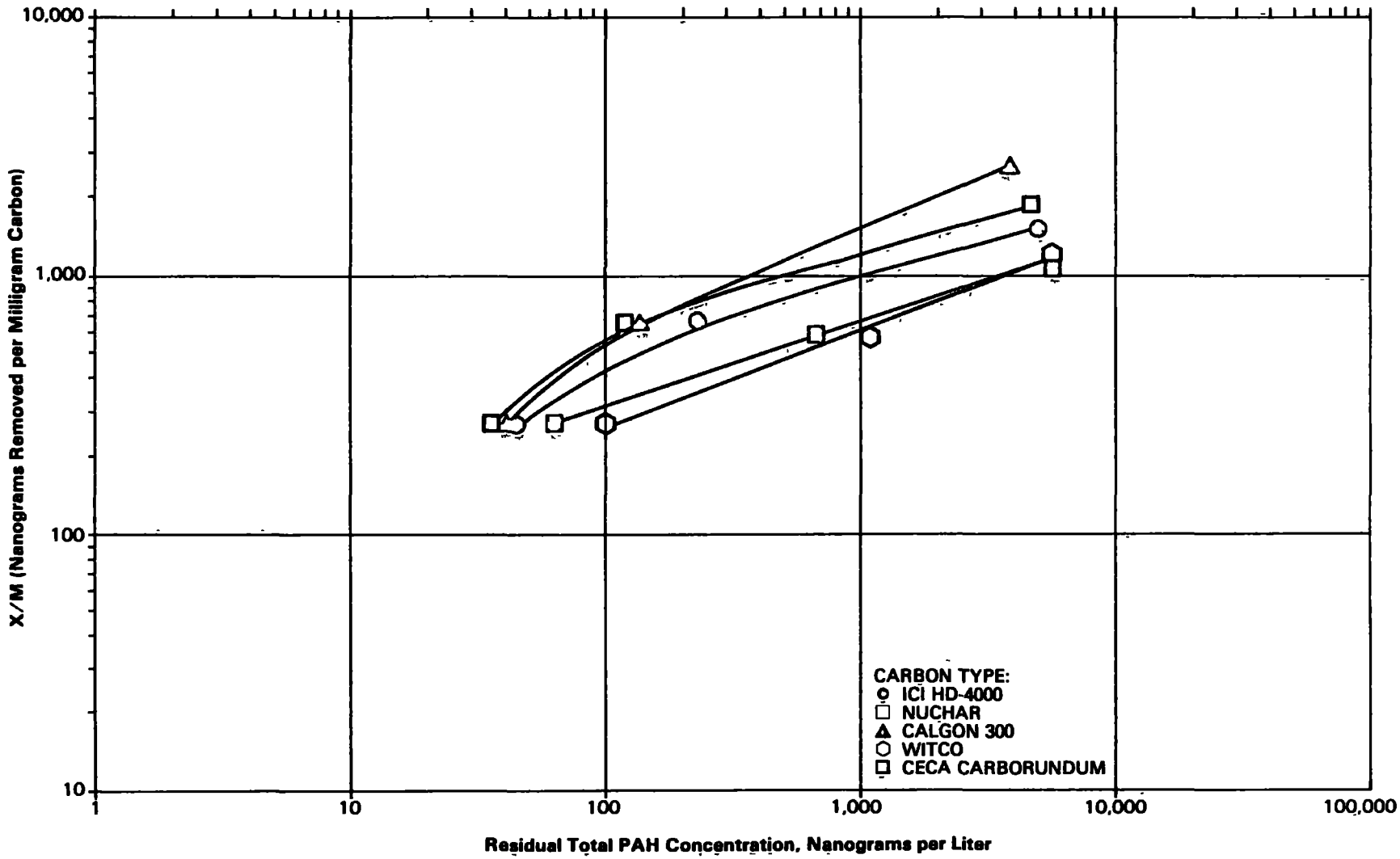

Figure G4-4 Total Adsorption Isotherms Determined by CH2M Hill (Reproduced from CH2M Hill, 1982)

Figure G4-4 shows that the Calgon, Westvaco and ICI carbons had the highest adsorption capacities. Table G4-12 summarizes the test data for the Calgon and Westvaco carbons. The data indicate that higher molecular weight PAH were more readily adsorbed than lower molecular weight PAH. CH2M Hill's isotherm plots for various ring-size classes confirm this (CH2M Hill 1982e). This is an expected result given the solubility and adsorption properties of PAH (see Appendices E and K). It is significant because carcinogenic PAH tend to be higher molecular weight compounds. For example, no carcinogenic PAH were detected in treated water samples, with few exceptions.

Adsorption testing of the three macroreticular resins showed little, if any, PAH removal. CH2M Hill indicated that the lack of removal may have been due to the low PAH concentrations involved, since the significant removals reported in the literature were for tests with much higher PAH concentrations (by orders of magnitude). It is also possible that the acetone washing of the resins adversely affected their adsorption capacities, although this procedure was recommended by the resin manufacturers.

Table G4-13 summarizes the results of CH2M Hill's first round bench testing of chlorine dioxide, hydrogen peroxide and ozone. Chlorine dioxide achieved very little, if any, PAH removal, although lower doses and shorter reaction times were used compared to hydrogen peroxide and ozone test conditions, and no UV light was used to catalyze oxidation reactions. Carcinogenic PAH were reduced by over a factor of two, however. Hydrogen peroxide and ozone treatment, both tested with UV light and at doses of about 10 milligrams per liter, achieved substantial removal of PAH. Removal of noncarcinogenic PAH and heterocyclic PAH ranged from 98.8 to 99.9 percent, while carcinogenic PAH and heterocyclic PAH were reduced to below detectable levels. Ozone gave somewhat better removal than hydrogen peroxide and at shorter reaction times (1 hour versus 4 hours). This fits with the higher oxidation potential of ozone compared to hydrogen peroxide (CH2M Hill 1982b). Removals were somewhat greater at neutral

TABLE G4-12

SUMMARY OF CH2M HILL'S FIRST-ROUND BENCH TESTING RESULTS

FOR PULVERIZED CARBON ADSORPTION TREATMENT OF WATER FROM WELL SLP15[a]

(All concentrations in nanograms per liter)

Compound Class[b]	Untreated Water[c]	Calgon Filtrasorb 300			Westvaco Nuchar WV-G		
		1 milligram/liter	10 milligrams/liter	25 milligrams/liter	1 milligram/liter	10 milligrams/liter	25 milligrams/liter
Two-Ring PAH	3,040 ± 250	2,307	278	90	2,300	192	59
Three-Ring PAH	6,940 ± 410	4,027	100	16	5,001	112	24
Four-Ring PAH	1,050 ± 20	330	3	2	349	4	2
Noncarcinogenic PAH	11,000 ± 670	6,664	381	108	7,641	308	85
Carcinogenic PAH	24 ± 4	ND	ND	ND	9	ND	ND
Total PAH	11,020 ± 670	6,664	381	108	7,650	308	85

Notes:

(a) All data from CH2M Hill 1982e.
(b) Compound classes Table G4-8, with heterocyclic PAH included. No compounds with more than four rings were detected.
(c) Mean and standard deviation for three analyses (wellhead and sample drum one day and five days after collection) rounded to the nearest ten nanograms per liter.

TABLE G4-13

SUMMARY OF CH2M HILL'S FIRST-ROUND BENCH TESTING RESULTS

FOR OXIDATIVE TREATMENT OF WATER FROM WELL SLP15[a]

(All concentrations in nanograms per liter)

Compound Class[b]	Untreated Water[c]	Chlorine Dioxide		Hydrogen Peroxide		Ozone	
		Test 1	Test 2	Test 1	Test 2	Test 1	Test 2
Two-Ring PAH	3,040 ± 250	2,934	2,417	46	53	12	14
Three-Ring PAH	6,940 ± 410	6,786	5,692	11	61	ND	4
Four-Ring PAH	1,050 ± 20	960	848	5	15	ND	2
Noncarcinogenic PAH	11,000 ± 670	10,670	8,949	62	129	12	20
Carcinogenic PAH	24 ± 4	10	8	ND	ND	ND	ND
TOTAL PAH	11,020 ± 670	10,680	8,957	62	129	12	20
Test Conditions							
Dose, milligrams per liter[d]		3	7.5	10	10	10	8.6
Reaction Time, minutes		20	60	240	240	60	60
Initial pH, units		7	7	7	10	7	10
Temperature, °F		50	75	75	75	75	75
UV Light		NO	NO	YES	YES	YES	YES

Notes:

(a) All data from CH2M Hill 1982e.
(b) Compound classes per Table G4-8, with heterocyclic PAH included. No compounds with more than four rings were detected.
(c) Mean and standard deviation for three analyses (wellhead and sample drum one day and five days after collection), rounded to the nearest ten nanograms per liter.
(d) Calculated doses added.

pH than at pH 10 for both oxidants. It should be noted that the actual amount of ozone added to the water might have been significantly less than the calculated dosages given in Table G4-13 due to incomplete absorption of the bubbled ozone gas (Merritt 1983).

Table G4-14 summarizes the results of CH2M Hill's bench testing of the unit operations used in the iron removal treatment plants in St. Louis Park. Table G4-14 shows that any of the tests involving chlorination achieved about 60 percent removal of total PAH, with carcinogenic PAH reduced to below detection limits. Various combinations of aeration, filtration and/or flocculation with chlorination had little additional effect compared to chlorine alone. The chlorine dose was 10 milligrams per liter in each test, however, which is considerably greater than the typical prechlorination dose at the SLP15 iron removal plant of 1.2 milligrams per liter (see section G2.1.2). In addition, some of the tests were run at a pH of 4.5, while the water in the St. Louis Park iron removal plants is near neutral pH (see sections G2.1.2., G4.4, and G4.5). Chlorination removed higher molecular weight PAH somewhat more effectively than lower molecular weight PAH. Chlorine also showed selective removal of PAH, with some compounds being unaffected (dibenzofuran and fluorene) or only slightly reduced (naphthalene, biphenyl and dihydroindene).

Table G4-14 shows that filtration had little effect, if any, on PAH removal when results are compared for tests that were similar except for the added step of filtration or flocculation plus filtration. This indicates that PAH or PAH removal mechanisms are not associated with particulate matter filterable by a 0.45 micron filter. However, a 0.45 micron filter does not necessarily model the PAH adsorption processes that could occur in a sand filter, even though it does give an indication of the filtration processes. Furthermore, the first round test of aeration, chlorination and filtration together was conducted at pH 4.5, which does not represent

TABLE G4-14

SUMMARY OF CH2M HILL'S FIRST-ROUND BENCH TESTING RESULTS OF IRON REMOVAL PLANT UNIT OPERATIONS FOR WATER FROM WELL SLP15[a]

(All concentrations in nanograms per liter)

Compound Class[b]	Untreated Water[c]	Chlorination	Aeration and Chlorination[d]	Aeration and Filtration[d]	Aeration, Chlorination, and Filtration[d]	Aeration, Chlorination, Flocculation, and Filtration[d,e]
Two-Ring PAH	3,040 ± 250	1,713	1,611	1,343	1,343	1,462
Three-Ring PAH	6,940 ± 410	2,916	2,930	6,706	2,923	2,859
Four-Ring PAH	1,050 ± 20	150	230	852	160	290
Noncarcinogenic PAH	11,000 ± 670	4,779	4,771	9,955	4,426	4,611
Carcingenic PAH	24 ± 4	ND	ND	12	ND	ND
Total PAH	11,020 ± 670	4,779	4,771	9,967	4,426	4,611
Test Conditions						
Initial pH, units		4.5	4.5	7.0	4.5	7.0
Temperature, °F		75	50	50	50	50
Chlorine Reaction Time, minutes		60	60	—	60	90
Chlorine Dose, milligrams per liter		10	10	--	10	10

Notes:

(a) All results from CH2M Hill 1982e.
(b) Compound classes per Table G4-8, including heterocyclic PAH. No compounds with more than four rings were detected.
(c) Mean and standard deviation for three analyses (wellhead plus sample drum one day and five days after).
(d) Aeration for 30 minutes at 250 milliliters of air per minute through a 3 liter sample prior to any subsequent steps.
(e) Added 10 milligrams per liter of $FeCl_3$ after chlorination and before filtration. This test was actually performed during the second round of bench testing.

conditions in the iron removal plants in St. Louis Park. The second round test of these three steps (plus flocculation) in December 1983 showed that pH did not affect the results, however.*

The TOC measurements made by CH2M Hill at the request and expense of RT&CC gave surprising results. Fourteen of the 41 treated samples were tested (but not the untreated water) and found to contain from 26 to 65 milligrams per liter of TOC, with an average of 44 milligrams per liter (Harris 1982b). TOC measurements were made on all but a few of the oxidation and macroreticular resin test samples, but none of the activated carbon test samples. The results were unusual in that wellhead TOC values at SLP15 had earlier been shown to be less than 5 milligrams per liter (CH2M Hill 1982d, see also Table G2-3). CH2M Hill attributed the elevated TOC values in the treated bench testing samples to contamination by methylene chloride, which was used in the final rinse in cleaning the test equipment (Harris 1982b). The contamination by methylene chloride is significant because it could have affected the test results for PAH, which were present at concentrations more than 1,000 times lower than the methylene chloride, by inhibiting or enhancing oxidation reactions or adsorption processes.

*Acidic conditions affect the chemistry of iron oxidation and precipitation, primarily by inhibiting the oxidation of ferrous iron (Stumm and Morgan 1970). At the time of CH2M Hill's first-round bench tests, ERT believed that the formation and filtration of ferric iron precipitate flocs could have played a role in the significant PAH removals observed during CH2M Hill's September 1982 test of the iron removal plant at well SLP15 (Craun 1982). Because of the acidic conditions during CH2M Hill's first round tests, and the lack of ferrous and ferric iron measurements to check actual iron oxidation and precipitation chemistry during the tests, ERT felt that CH2M Hill's first round tests did not explain the removals observed during the September 1982 test at SLP15. ERT therefore proceeded to test the iron removal plant at well SLP15 again in December 1982, as described in section G4.4.

G4.3.4 Second Round Bench Testing

After reviewing the results of the first round of bench testing, CH2M Hill and the MPCA decided to focus second round testing on column tests of granular activated carbon (GAC) and further testing of hydrogen peroxide and ozone oxidation.* The objective of the GAC column testing is unclear, since the tests were not run anywhere near sufficient time to achieve breakthrough, although an indication of acceptable contact time was obtained. Hydrogen peroxide and ozone testing was aimed at determining minimum conditions for achieving the MDH criteria.

Test Procedures

Second round bench testing was performed during the week of December 6-10, 1982 at CH2M Hill's Montgomery, Alabama laboratory. Three 55-gallon drums of water from SLP15 collected on December 4 were used for the tests. The wellhead was sampled when the drums were collected and the drums were sampled as they were used (2, 3 and 5 days after collection).

Carbon column tests were made using Calgon Filtrasorb 300 and Westvaco Nuchar WV-G. The column was a 122 centimeter long by 6.7 centimeter diameter glass tube fitted with sample taps at the top, middle and bottom. The column was filled with 89 centimeters of carbon. The column tests were run at a hydraulic loading rate of 4 gallons per minute per square foot, which corresponded to a flow rate of about 560 milliliters per minute. The empty bed contact time was about 5.6 minutes. The Westvaco carbon test was run for 99 bed volumes (310 liters or 82 gallons of water) and the Calgon carbon test was run for 73 bed volumes (228 liters or 60 gallons of water). Samples were collected from the middle and bottom of the bed after nominally 35, 70, 85 and 100 bed volumes.

*ERT was invited to comment on the first round test results and second round test plans and did so. However, ERT's comments were not received (via a telephone conference call) until the second round testing had already been completed. As a result, no TOC analyses were performed during the second test round, even though RT&CC desired and offered to pay for such analyses.

Ozone and hydrogen peroxide testing used the same equipment and procedures as during the first round of bench testing. Six tests were performed for each oxidant, with half of the tests including UV light and the other half not. Reaction times were either 20 or 60 minutes. Hydrogen peroxide was tested at 2 and 5 milligram per liter doses, ozone at nominally 1 and 5 milligrams per liter. The test conditions were established by CH2M Hill based on judgements as to minimum conditions expected to meet the MDH criteria.

Test Results

Both carbon column tests showed very effective PAH removal and no evidence of substantial breakthrough after 70 to 100 bed volumes of testing. Table G4-15 summarizes the test results. Both carbons reduced noncarcinogenic PAH concentrations by 99 percent or more and removed carcinogenic PAH to below detectable or to very low (1 nanogram per liter) levels. There is some evidence of PAH starting to "bleed" through the column during the Calgon carbon test.

Table G4-16 summarizes the results of CH2M Hill's second round tests of hydrogen peroxide treatment. The data indicate that very little removal was achieved without UV light (only about 10 percent removal). The addition of UV light resulted in greatly enhanced removals -- 95 percent under the mildest conditions and over 99 percent under the more severe conditions. Carcinogenic PAH were reduced to below detection limits or to very low levels (1 part per trillion) with UV light.

Table G4-17 summarizes the results of CH2M Hill's second round tests of ozone treatment. Ozone without UV light achieved 75 to 88 percent removal of total PAH and heterocyclic PAH and reduced carcinogenic PAH to 2 nanograms per liter or less. Noncarcinogenic PAH concentrations were reduced to well below the lower bound of the criteria range recommended by this study for noncarcinogenic PAH and heterocyclic PAH of 4 micrograms per liter (see Appendix I and Chapter 4). The addition of UV light again increased removals substantially.

TABLE G4-15

SUMMARY OF CH2M HILL'S SECOND-ROUND BENCH TESTING RESULTS FOR GRANULAR ACTIVATED CARBON COLUMNS AND WATER FROM WELL SLP15[a]

Sample Description	Noncarcinogenic PAH,[b] nanograms per liter	Carcinogenic PAH,[b,e] nanograms per liter
Untreated Water	11,050 ± 260[f]	44 ± 19[f]
Calgon Filtrasorb 300		
o 36 BV[c] middle	26	1.3
o 36 BV bottom	58	ND
o 72 BV middle	110	1.5
Westvaco Nuchar WV-G		
o 32 BV middle	37	ND
o 32 BV bottom	36	ND
o 66 BV middle	34	ND
o 66 BV bottom	33	ND
o 88 BV bottom	34/38[d]	1.1/1.0[d]
o 97 BV middle	33	1.0
o 97 BV bottom	30	1.0

Notes:

(a) All results from CH2M Hill 1982e.
(b) Compounds classes per Table G4-8, including heterocyclic PAH.
(c) BV = bed volumes.
(d) Duplicate samples and analyses.
(e) Quinoline was the only carcinogen detected in any of the samples.
(f) Mean and standard deviation for four analyses (wellhead plus three sample drums 2,3 and 5 days after collection).

TABLE G4-16

SUMMARY OF CH2M HILL'S SECOND-ROUND BENCH TESTING RESULTS

FOR HYDROGEN PEROXIDE TREATMENT OF WATER FROM WELL SLP15[a,d]

(All concentrations in nanograms per liter)

Compound Class[b]	Untreated Water[c]	Without UV Light			With UV Light		
		2 mg/liter, 20 minutes	5 mg/liter, 20 minutes	5 mg/liter, 60 minutes	2 mg/liter, 20 minutes	2 mg/liter, 60 minutes	5 mg/liter, 60 minutes
Two-Ring PAH	3,080 ± 210	2,735	2,570	2,680	216	24	6
Three-Ring PAH	7,050 ± 170	5,678	6,653	6,110	267	16	58
Four-Ring PAH	960 ± 90	796	866	897	51	5	10
Noncarcinogenic PAH	11,050 ± 260	9,185	10,065	9,662	533	45	74
Carcinogenic PAH	44 ± 19	24	24	25	1	ND	ND
Total PAH	11,090 ± 260	9,209	10,089	9,687	534	45	74

Notes:

(a) All results from CH2M Hill 1982e.
(b) Compound classes per Table G4-8, with heterocyclic PAH included. No compounds with more than four rings were detected.
(c) Mean and standard deviation for four analyses (wellhead plus three sample drums 2,3 and 5 days after collection), rounded to the nearest ten nanograms per liter
(d) All tests performed at pH 7.0 and 40 to 50°F.

TABLE G4-17

SUMMARY OF CH2M HILL'S SECOND-ROUND BENCH TESTING RESULTS

FOR OZONE TREATMENT OF WATER FROM WELL SLP15[a,d]

(All concentrations in nanograms per liter)

Compound Class[b]	Untreated Water[c]	Without UV Light			With UV Light		
		1.2 mg/liter, 20 minutes	5.3 mg/liter, 20 minutes	5.6 mg/liter, 60 minutes	1.1 mg/liter, 20 minutes	1.2 mg/liter, 60 minutes	6.0 mg/liter, 60 minutes
Two-Ring PAH	3,080 ± 210	1,047	752	516	72	23	51
Three-Ring PAH	7,050 ± 170	1,776	1,403	857	80	8	33
Four-Ring PAH	960 ± 90	8	4	1	8	4	4
Noncarcinogenic PAH	11,050 ± 260	2,829	2,157	1,374	160	35	88
Carcinogenic PAH	44 ± 19	2	2	ND	ND	ND	ND
Total PAH	11,090 ± 260	2,831	2,159	1,374	160	35	88

Notes:

(a) All results from CH2M Hill 1982e.
(b) Compound classes per Table G4-8, with heterocyclic PAH included. No compounds with more than four rings were detected.
(c) Mean and standard deviation for four analyses (wellhead plus three sample drums 2,3 and 5 days after collection) rounded to the nearest ten nanograms per liter.

(d) All tests performed at pH7.0 and 40 to 50°F.

GCMS data files from two of the ozonation tests were searched by CH2M Hill to check for the presence of partially oxidized PAH by-products -- one test without UV light (5.3 milligrams per liter for 20 minutes) and one with (1.2 milligrams per liter for 60 minutes). A number of compounds with mass spectra characterestic of oxidized PAH were detected in the sample treated without UV light. While all of the compounds could not be identified, ketone or diketone derivatives of dihydroindene, fluorene, phenanthrene, anthracene, and phenanthridine and a sulfoxide derivative of dibenzothiophene were tentatively identified (no concentrations were reported for these compounds by CH2M Hill). No oxidation by-products were detected in the sample treated with UV light. The literature indicates that carboxylic acid and aldehyde derivatives are the primary by-products from ozonation of PAH (Kruithof 1979), but CH2M Hill's analytical procedure would not have detected these types of compounds (CH2M Hill 1982e).

G4.3.5 Economic Evaluations

After completing bench-scale testing, CH2M Hill performed a screening economic evaluation of the treatment technologies shown to be capable of achieving the MDH criteria of 28 nanograms per liter for carcinogenic PAH and 280 nanograms per liter for all other PAH. The technologies evaluated were GAC treatment, ozone oxidation with UV light, and hydrogen peroxide oxidation with UV light. CH2M Hill performed a technical and economic evaluation of these three technologies in order to recommend the best candidate for pilot scale testing (CH2M Hill 1983a).

CH2M Hill's cost estimates were order of magnitude estimates (plus 50 to minus 30 percent) on a January 1983 basis. Common cost bases for all three technologies were as follows:

- electricity cost of 5 cents per kilowatt-hour with sufficient capacity available;
- annual maintenance costs at 10 percent of identifiable equipment costs;
- labor costs at $27,000 per year, including fringe benefits;

- contingency costs at 25 percent of total equipment costs;
- engineering, administrative and legal fees at 10 percent of capital cost (equipment plus contingencies);
- building costs for a pre-engineered steel building with insulation and heating and no unusual soils conditions;
- piping only for interconnections within the treatment building;
- analytical costs for monitoring plant performance of $350 per sample, with one influent sample per month, one effluent sample per week for GAC, and two effluent samples per week for oxidative treatment.

The difference between effluent sampling frequencies for GAC and oxidative treatment in the last item reflects CH2M Hill's view that GAC treatment is better able to handle any "slug" loadings of PAH which might be encountered and is less susceptible to mechanical failures than the oxidative treatment process.

CH2M Hill's cost estimates were all based on treatment systems installed at well SLP15, with a nominal total PAH concentration of 7,000 nanograms per liter (excluding heterocyclic PAH). The systems were costed for a design flow rate of 800 gallons per minute. The basis for choosing this flow rate is unclear. The design capacity of well SLP15 is 1200 gallons per minute and the well is generally run at from 1000 to 1200 gallons per minute when it is operated. However, the well is only operated about 40 percent of the time, so the annual average flow rate is only about 460 gallons per minute (see section G2.1.1). If CH2M Hill's costs had been based on 1200 gallons per minute capacity and 460 gallons per minute average operating rate, then capital cost estimates would have been about 28 percent higher (based on the six-tenths rule) and annual operating and maintenance could have been higher or lower (depending on the relative proportion of fixed and variable costs).

Table G4-18 summarizes the cost estimates made by CH2M Hill. GAC treatment is seen to be much less expensive that either of the oxidation alternatives. Based on these cost estimates, plus other

TABLE G4-18

SUMMARY OF CH2M HILL'S COST ESTIMATES FOR

VARIOUS TREATMENT ALTERNATIVES AT WELL SLP15

Treatment Technology	Capital Cost	Annual Operating and Maintenance Cost	Annual Cost[b]
Original CH2M Hill Estimates[a]:			
GAC Columns	$691,500	$72,700	$139,900
Ozone/UV	$659,000	$183,800	$247,800
Hydrogen Peroxide/UV	$1,158,000	$281,500 [c]	$394,000 [c]
ERT Adjustments of CH2M Hill Estimates:			
GAC Columns With One-Year Breakthrough	$691,500	$120,300 [f]	$187,500
Ozone Without UV[d]	$84,000	$88,000	$96,000
Hydrogen Peroxide Without UV[e]	$62,000	$98,000	$104,000

Notes:

(a) Data from CH2M Hill 1983a. Costs on a January 1983 basis.
(b) Capital costs amortized at 7.375 percent per year over 20 years.
(c) Reflects fact that lamp replacement cost given in CH2M Hill 1983a is low by a factor of two.
(d) Derived from original CH2M Hill estimates as follows:
- o capital costs -- same cost for ozone generator; half of original estimate for piping, electrical, instrumentation and controls; one quarter of original estimate for building; no UV reactor or booster pump;
- o operating costs -- same cost for labor, laboratory and miscellaneous; maintenance at 10 percent of equipment cost; electricity at 10 percent of original estimate; no cost for lamp replacement.

(e) Derived from original CH2M Hill estimates as follows:
- o capital costs -- same cost for peroxide feed pump, storage tank and static mixer; other adjustments as in note (d);
- o operating costs -- some cost for peroxide; other adjustments as in note (d).

(f) Based on all operating and maintenance costs originally estimated by CH2M Hill, except carbon replacement/regeneration cost of $56,000 is used to reflect an assumed breakthrough time (replacement time) of one year (80,000 pounds of carbon per year at 70¢ per pound).

technical considerations, CH2M Hill recommended that GAC be selected for pilot-scale testing. The design and cost bases for each of the three options, and the technical advantages and disadvantages noted by CH2M Hill, are briefly described below.

GAC Treatment

CH2M Hill's cost estimates for GAC treatment were based on two columns in series, with each column containing 40,000 pounds of carbon. The columns were sized for a hydraulic loading rate of 4 gallons per minute per square foot and an empty bed contact time of 30 minutes (15 minutes per column). These were both viewed as conservative design bases. An ultimate adsorption capacity of 2,000 nanograms per milligram (2 pounds of PAH per 1,000 pounds of carbon) was assumed, based on the isotherms shown in Figure G4-4. This corresponds to a breakthrough period of 6.7 years.* The actual breakthrough time is unknown from CH2M Hill's bench testing work, and could be much less than this, which would significantly increase carbon replacement costs. A one-year breakthrough time, for example, would increase carbon regeneration or replacement costs by $47,600 per year, based on carbon at 70¢ per pound. This would increase the annual cost to $188,000 per year (see Table G4-18).

CH2M Hill listed the following advantages of GAC treatment.

- "GAC is a state-of-the-art technology for removal of organics from drinking water supplies" (CH2M Hill 1983a, p. 6). However, GAC columns are not widely applied in drinking water treatment for other than taste and odor control (Gumerman, Culp and Hansen 1979a).
- A GAC system is simple to maintain because it has few moving mechanical parts.

*800 gallons per minute of water containing 7 micrograms per liter total PAH gives an annual PAH loading of 24 pounds per year, compared to an ultimate carbon adsorption capacity of 160 pounds of PAH for two 40,000 pound GAC columns.

- A GAC system has substantial reserve capacity for handling any "slugs" of PAH which could be encountered in untreated water. However, the occurrence of such "slugs" is not expected on a short term basis given the nature and distribution of PAH contaminants in the Prairie du Chien-Jordan (see Appendix E).
- GAC has no potential to generate oxidized PAH by-products.

CH2M Hill also noted that GAC treatment does not oxidize iron, so that no additional iron removal facilities would be required at wells that currently do not have such facilities, as would be required with ozone or hydrogen peroxide treatment. However, CH2M Hill also noted that biological growths in the GAC columns could occur and increase existing chlorine requirements. In fact, as ERT observed during its December 1982 test of the iron removal plant at well SLP15, iron bacteria will grow in any treatment system unless sufficient doses of chlorine or other oxidants to kill bacteria are applied. However, sufficient chlorine doses to kill iron bacteria will also oxidize the ferrous iron (see Sections G4.4 and G4.5), so that chlorine injection upstream of a GAC column to prevent bacterial growth will result in precipitation of ferric iron, which will presumably be filtered by the GAC column. This could require more frequent backwashing and might affect the PAH adsorption behavior of the carbon.

Ozone/UV Treatment

CH2M Hill's cost estimates for ozonation in the presence of UV light were based on a 1 milligram per liter ozone dose and a 10 minute reaction time, with UV light exposure for the entire reaction time.* These conditions were achieved by an 8,000 gallon reactor containing 900 65-watt UV lamps and an air-feed ozone generator with sufficient capacity to deliver a 1.5 milligram per liter dose.

The estimated capital and operating costs of the ozone/UV treatment system are strongly dominated by the required UV light equipment. Fully 75 percent of the total estimated equipment cost is for the UV reactor, including pumps, lamps and tubes, and 40 percent of the estimated operating costs is for electricity and lamp

replacement, with most of the electricity required by the UV lamps. The large expense associated with the UV light requirement is important because UV light is only required with ozone to meet the MDH criterion for noncarcinogenic PAH (280 manograms per liter). No UV light is needed to meet the lower bound of the noncarcinogen criterion recommended by this study (4 micrograms per liter - see Table G4-17). If the cost of a UV reactor is eliminated from CH2M Hill's cost estimates, the estimated annual cost is reduced to about $98,000 per year. This is about 60 percent lower than the estimated cost with the UV reactor and is less expensive than CH2M Hill's estimated cost of GAC treatment (see Table G4-18).

CH2M Hill listed three advantages for ozone/UV treatment. The system has the lowest space requirements of the three alternatives evaluated; the system does not generate waste products (such as spent GAC); and ozone oxidation of ferrous iron could reduce chlorine requirements at existing treatment plants. CH2M Hill also identified a number of disadvantages. High iron concentrations could foul the UV lamps (it is unclear if this refers to ferrous or ferric iron), so that ozone/UV treatment might need to be located downstream of an iron removal plant. Similarily, ozonation will oxide ferrous iron, so that iron removal facilities would be required at wells that do not currently have iron removal treatment. The ozone generator and UV lamps "will require a good deal of maintenance to ensure consistently high performance of the treatment system" (CH2M Hill 1983a, p. 12). "Slug" loads of PAH could pass undetected and unaffected through the system, although it is doubtful that such "slugs" would occur on a short-term basis. Long-term changes in influent water quality, however, might occur and, as noted by CH2M Hill, could require future system modifications to ensure adequate ozone generator capacity. If all or part of the UV lamps fail or foul, then oxidized PAH by-products could be left in the water. However, such by-products should not be carcinogenic or more toxic than noncarcinogenic PAH (Santodonato 1983, see also Section G3.2). Finally, the use of ozone and UV in drinking water treatment is limited, although they are

*The possibility of initially catalyzing PAH oxidation reactions with a short exposure to UV light followed by a longer reaction time was not investigated during CH2M Hill's bench testing program.

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state-of-the-act techniques. It should be noted that many of these disadvantages are removed or reduced if no UV light is required. For example, possible fouling of lamps would be eliminated and high maintenance requirements would be reduced.

Hydrogen Peroxide/UV Treatment

CH2M Hill's cost estimates for hydrogen peroxide/UV light treatment were based on 5 milligrams per liter hydrogen peroxide with 20 minutes reaction time, since 2 milligrams per liter and 20 minutes barely met the MDH criteria.* These conditions were achieved with a conceptual design involving two 8,000 gallon reactors in series, each with 900 65-watt UV lamps, and a peroxide feed tank and pump for a 50 percent peroxide solution.

As for ozone/UV treatment, the estimated capital and operating costs of hydrogen peroxide/UV treatment are dominated by the costs for the UV light requirement. Eight-five percent of the estimated total equipment cost was for the UV reactor and 41 percent of the estimated operating cost was for electricity and lamp replacement. Excluding the UV light equipment would reduce CH2M Hill's estimated annual cost to about $104,000. This is a 74 percent reduction from CH2M Hill's estimated annual cost when the reactor is included (see Table G4-18). However, hydrogen peroxide without UV light was not very effective in removing noncarcinogenic PAH. Total PAH concentrations were only reduced by about 10 percent during bench testing of hydrogen peroxide, although carcinogenic PAH concentrations were reduced by about 50 percent (see Table G4-16).

CH2M Hill listed advantages and disadvantages for hydrogen peroxide/UV treatment similar to those for ozone/UV treatment. CH2M Hill also noted that the hydrogen peroxide/UV combination has not been

*CH2M Hill did not include heterocyclic PAH in evaluating compliance with the MDH criteria. See Table G4-16, for example.

applied for drinking water treatment. ERT's modifications of CH2M Hill's cost estimate indicate that hydrogen peroxide treatment is also estimated to be slightly more expensive than ozone treatment, without UV light. This apparently reflects the relative expense of providing and feeding these two types of oxidants.

CH2M Hill Pilot Testing Recommendations

Based on its economic and technical evaluation of GAC, ozone/UV, and hydrogen peroxide/UV treatment at well SLP15, CH2M Hill recommended that GAC be selected for pilot scale testing (CH2M Hill 1983a). The MPCA agreed with this recommendation and CH2M Hill submitted a test plan for pilot testing of GAC (CH2M Hill 1983b). Testing was planned to determine required contact times and perhaps breakthrough times, if breakthrough occurs relatively quickly. Testing began in mid-February and ended on April 1 (Minneapolis Star and Tribune, March 30, 1983). The results of the pilot testing work were not available to ERT before this report was completed.

G4.3.6 Summary

CH2M Hill's testing of the iron removal treatment plant at well SLP15 on September 15, 1982 showed substantial removal of PAH and heterocyclic PAH. Removal of total PAH was over 75 percent, with a marked trend of higher removals for higher molecular weight PAH. Two-ring PAH removal was just over 50 percent, while four-ring PAH removal was 98 percent. The finished water contained about 2 micrograms per liter of noncarcinogenic PAH and 11 parts per trillion of carcinogenic PAH, well within the criteria recommended by this study, but above the 280 nanogram per liter MDH criterion for noncarcinogenic PAH. Samples collected after each step in the iron removal treatment plant showed that aeration alone achieved about 50 percent removal, chlorination had little effect, and filtration achieved an additional 50 percent removal.

Split samples from CH2M Hill's September 1982 test analyzed by Monsanto Research Corporation (MRC) on behalf of RT&CC and ERT gave removal results comparable to those obtained by CH2M Hill, although

each laboratory analyzed a slightly different set of individual PAH compounds. However, results for the 20 compounds analyzed in common by both laboratories indicate that CH2M Hill's reported concentrations were over twice as high as Monsanto's on average. One explanation for this consistent difference between the two laboratories' results is the different procedures used for adding internal standards. Monsanto's procedure followed recommended EPA protocols while CH2M Hill's procedure was modified slightly in such a way that the results could be biased high.

CH2M Hill's bench testing program evaluated a variety of possible drinking water treatment technologies for removing PAH and heterocyclic PAH. The testing was performed in two phases, with all testing performed on drum samples collected from well SLP15. The results from the two rounds of testing are summarized below. The untreated water samples for these tests contained about 11 micrograms per liter noncarcinogenic PAH and 30 to 40 nanograms per liter carcinogenic PAH.

- Activated carbon achieved very high PAH removals. Isotherm tests were conducted on five different pulverized carbons at three different doses to measure ultimate adsorption capacities for PAH. At a dose of 10 milligrams of carbon per liter, for example, the two best carbons reduced noncarcinogenic PAH to less than 400 nanograms per liter and carcinogenic PAH to below detectable levels. Bench-scale column testing of these two carbons for up to 100 bed volumes (9 hours of operation, 5.6 minutes contact time) resulted in less than 100 nanograms per liter of noncarcinogenic PAH and 1 or 2 nanograms per liter of carcinogenic PAH, with no sign of major breakthrough occurring.

- Oxidative destruction of PAH with ozone gave substantial removals, both with and without UV light to catalyze reactions. Low ozone doses (1 to 6 milligrams per liter) and relatively short reaction times (20 to 60 minutes) reduced noncarcinogenic PAH to less than 3 micrograms per

liter without UV light and less than 0.2 micrograms per liter with UV light. Carcinogenic PAH were reduced to 2 nanograms per liter or less in every test. Oxidized PAH by-products (ketones and diketones) were detected in samples treated without UV light, but not in samples with UV light. Carboxylic acid and aldehyde by-products are also expected, but were not analyzed.

- Oxidation of PAH with hydrogen peroxide only gave significant removals in the presence of UV light, in which case removals were comparable to, although somewhat less effective, than those obtained with ozone. Hydrogen peroxide treatment without UV light only reduced noncarcinogenic PAH by about 10 percent, although carcinogenic PAH were reduced by about 50 percent.

- Oxidation of PAH by chlorine dioxide and adsorption of PAH on macroreticular resins were both shown to remove little, if any, PAH.

- Bench testing of the unit operations employed in iron removal plants in St. Louis Park (aeration, chlorination and filtration) showed that chlorination at 10 milligrams per liter achieved about 60 percent removal of noncarcinogenic PAH and reduced carcinogenic PAH to below detection limits. Neither aeration nor filtration (through a 0.45 micron filter) showed significant PAH removal. The bench scale tests and conditions did not completely match operations at St. Louis Park iron removal plants, however. Differences in pH, operating pressure, chlorine dose, and filtering medium could all play a role in PAH removals observed during bench testing.

CH2M Hill evaluated the technical and economic aspects of applying the three most promising technologies, based on bench testing results, to treating contaminated St. Louis Park wells. Conceptual designs and screening economic evaluations were developed for treatment at well SLP15 by granular activated carbon, ozone/UV, and

hydrogen peroxide/UV. The design basis used by CH2M Hill for treatment at SLP15 did not reflect actual operating practices at the well, however. CH2M Hill's estimates were based on 800 gallons per minute plants, while SLP15 generally pumps at 1000 to 1200 gallons per minute when it is operated. The well is only operated about 40 percent of the time, however, so the annual average flow rate is only 400 to 500 gallons per minute.

CH2M Hill's cost estimates showed that GAC was over 40 percent less expensive than ozone/UV and 65 percent less expensive than hydrogen peroxide/UV, based on GAC achieving its ultimate adsorption capacity for PAH. However, the UV lamps and reactors are the major cost component of CH2M Hill's estimates for both ozone and hydrogen peroxide treatment, and UV light is not required to meet the lower bound of the noncarcinogen criteria range recommended by this study (4 micrograms per liter) with ozone, and might not be required with hydrogen peroxide, if a noncarcinogen criterion is established somewhat above the recommended lower bound. Without the UV light requirement, ozone and hydrogen peroxide treatment are estimated to be comparable in cost, and both are about 30 percent less expensive than GAC treatment, based on modifying CH2M Hill's cost estimates.

As a result of its technical and economic evaluations of GAC, ozone/UV, and hydrogen peroxide/UV, CH2M Hill recommended that GAC be tested at pilot-scale at well SLP15. This recommendation was accepted by the MPCA and pilot testing was completed at the end of March, 1983. The results of pilot testing were not available in preparing this report, however.

G4.4 ERT's December 1982 Test of the Iron Removal Treatment Plant at Well SLP15

This section and the following section present the results of ERT's independent studies of PAH removal techniques applicable to the St. Louis Park municipal water supply system. ERT's studies focused on determining the effect of iron removal treatment plant operations on the removal of trace quantities of PAH. This focus was chosen because of 1) the widespread use of iron removal treatment in the St.

Louis Park area, 2) indications from the scientific literature that conventional drinking water treatment technologies can be effective at removing trace quantities of PAH (see section G3); and 3) the significant PAH removals measured during CH2M Hill's testing of the iron removal treatment plant at St. Louis Park Station No. 1 when operated with water from well 15 (see Section G4.3.2).

The results of CH2M Hill's September 1982 testing of the existing iron removal treatment at St. Louis Park well 15 showed from 76 to 80 percent removal of total PAH, with percentage removals steadily increasing for higher molecular weight PAH (see Table G4-10). The total PAH concentration in the treated water was about 2 micrograms per liter with no detectable carcinogenic PAH. This treated water clearly met the criteria for potable water proposed in this report of 28 nanograms per liter for carcinogenic PAH and heterocyclic PAH and 4 to 400 micrograms per liter for noncarcinogenic PAH and heterocyclic PAH. However, it also clearly exceeded the MDH criterion of 280 nanograms per liter for noncarcinogenic PAH. Split samples analyzed for ERT by Monsanto Research Corporation (MRC) yielded removals very similar to those observed by CH2M Hill (see Table G4-11).

In response to the September 1982 test results at St. Louis Park Station No. 1, CH2M Hill performed some limited bench testing of the individual treatment steps involved in the iron removal process at Station No. 1 (see Section G4.3.3). No further testing at St. Louis Park Station No. 1 was performed due to a concern that it would be difficult - if not impossible - to obtain representative and reproducible results (Harris 1982). ERT, on the other hand, felt that further testing of the full-scale iron removal plant at Station No. 1 was important in order to check the results obtained during the September 1982 test and to begin to understand the responsible removal mechanisms. While recognizing the value of bench-scale testing - particularly in elucidating removal mechanisms - ERT was concerned that the potentially complex removal mechanisms present in the sand filter beds could not be readily simulated at bench scale (Craun 1982). ERT felt that representative and reproducible results could be obtained from a test at St. Louis Park Station No. 1 and proposed a second test in November, 1982 (ERT 1982).

ERT's test for PAH removal at Station No. 1 was performed on December 6-8, 1982. A few selected split samples from this test were also analyzed by CH2M Hill. A major finding from this test was that the sand filter beds at Station No. 1 were affected by substantial deposits of iron precipitate and growths of iron bacteria. These deposits were probably present during CH2M Hill's September 1982 test as well, although this cannot be documented. Because of the distinct possibility that these deposits affected PAH removals observed during both the September and December tests, ERT retested the system again on February 1-2, 1983 after St. Louis Park Water Department personnel had taken steps to eliminate the problem.

This section presents the results from ERT's December test of the iron removal plant at St. Louis Park Station No. 1. The results of the February test are described in the next section. Both tests were conducted when the plant was treating water only from well SLP15.

G4.4.1 Test Objectives

The objectives initially estabilished for the test were (ERT 1982):

1) "Measure the overall effectiveness of the treatment system in removing PAH when treating water from well 15. This will serve as a check on the results from the September 1982 test.

2) Measure the effectiveness of the individual unit operations at Station No. 1 in removing PAH and attempt to understand the mechanisms for their performance. This will serve both to check and to expand the September 1982 results.

3) Compare the quality of the finished water currently provided by Station No. 1 with the quality of treated water from well 15. This will provide a basis for assessing the significance of the well 15 treatment results.

4) Begin to investigate the operating and design parameters at Station No. 1 that will be necessary in designing any modifications of the Station No. 1 treatment system or in designing any new systems required to provide St. Louis Park with finished water of acceptable quality with respect to PAH."

St. Louis Park well SLP11 was unexpectedly taken out of service immediately prior to implementing ERT's original test plan due to a broken shaft. The portion of the test plan aimed at addressing objective number 3 was therefore dropped from the test. The manner in which the test addressed the other three objectives is indicated in the test description that follows.

G4.4.2 Test Description

ERT's first test at St. Louis Park Station No. 1 lasted from the morning of December 6 until noon on December 8, 1982. The morning of the first day was devoted to backwashing the filter unit to be tested. Selected filter cells were inspected both before and after backwashing by partially draining the filter unit and inspecting the filter bed surface through the manways located along the top of the filter unit (see Figures G2-6 and 8). Samples of sand from the surface of selected filter cells were collected. Samples of feed and wastewater from backwashing one of the cells were also collected. After backwashing and filter cell inspections were completed, the iron removal plant was placed in normal operation with water obtained solely from St. Louis Park well SLP15.

In the afternoon of the first day, time-series grab samples of wellhead water from well SLP15 were collected. Samples were also collected of aerator inlet and outlet water with only the aerator operating (no prechlorination) and with only the prechlorinator operating (no aeration). The purpose of these samples was to separately determine the effects of the aeration and prechlorination steps. Some temporary adjustments were also made in plant operating conditions in order to help assess the dynamics and operation of the

system based on field measurements of general water quality parameters such as iron, dissolved oxygen and residual chlorine. The plant was left running overnight under normal operating conditions.

On December 7, an attempt was made in the morning to test the effects of maximum aeration and prechlorination rates. This was done at the suggestion of the MPCA and CH2M Hill. However, the chlorinator experienced an equipment failure soon after this test was initiated and it took St. Louis Park Water Department personnel the rest of the morning to repair the chlorinator. While the chlorinator was out of service, the aerator was also shut off to allow for the collection of samples showing the effects of filtration alone on PAH removal. This again was based on a suggestion from the MPCA. Once the chlorinator was back in service, the plant was operated for about two hours under normal conditions before any further sampling was performed. After this equilibration period, composite samples were collected from various points throughout the treatment system. The composites were comprised of four grab samples collected at 1 1/2 hour intervals, for a total compositing period of 4 1/2 hours. Composite sampling was performed to help ensure collection of representative samples of the plant's performance. After the composite sampling, a second attempt was made to test the effects of maximum aeration and prechlorination rates and this attempt was successful. Field measurements of the plant's performance were made throughout the second day.

In addition to the various water and sand samples described above, two extended air samples were collected using air sampling pumps to draw air through cartridges of XAD absorbent resin. The air samplers were operated continuously from the afternoon of December 6 to the end of the day on December 7. One air sample was collected near the intake of the air compressor to check the possibility that trace airborne PAH contaminants were being added to the water via the aerator. The other air sample was collected at the exhaust outlet of the air pressure relief line on the filter unit (see Figures G2-6 and 7) to check for losses of volatile PAH from the system.

On the morning of December 8, a final time-series sample of wellhead water from Well 15 was collected and then the plant was shut down. The tested filter unit was drained to permit the collection of sand samples. The filter was then backwashed, with backwash feed and wastewater samples again collected, and drained once more to collect a final set of sand samples. The test was complete after collecting the final set of sand samples and the plant was returned to normal operation with water from well 3.

Figure G4-5 shows the sample tap locations used during ERT's test and the sample tap numbers assigned by ERT. Figure G4-6 shows a chronological chart of the test, with major sample collection periods indicated. Figure G4-6 also shows how major operating conditions (aeration rate, prechlorination rate and system pressure) were adjusted during the test. The flow rate of water from well SLP15 was kept nearly constant throughout the test at about 1050 gallons per minute.

A total of 78 different samples were collected during the three-day test (not counting duplicates and field blanks). The majority of these were water samples, with 36 water samples for PAH analysis, 18 for analysis of selected inorganic constituents and 8 for volatile organics analysis. Non-aqueous samples included 13 sand samples from the filter beds, 2 air samples and 1 sample of the powdered activated carbon (PAC) used in earier tests by Hickok (see Section G4.2) and kept in reserve for use if well SLP15 is needed in an emergency. Table G4-19 lists all of the samples collected, including the date and time of collection and a brief description of the sample. Table G4-20 indicates how the various samples addressed different test objectives.

Five basic types of analyses were performed on the various samples. These are described briefly below, with further details on the analytical procedures used presented in the next subsection.

1) PAH Scanning Analyses - Yield semi-quantitative data by means of selected ion monitoring (SIM) GC/MS chromatograms.

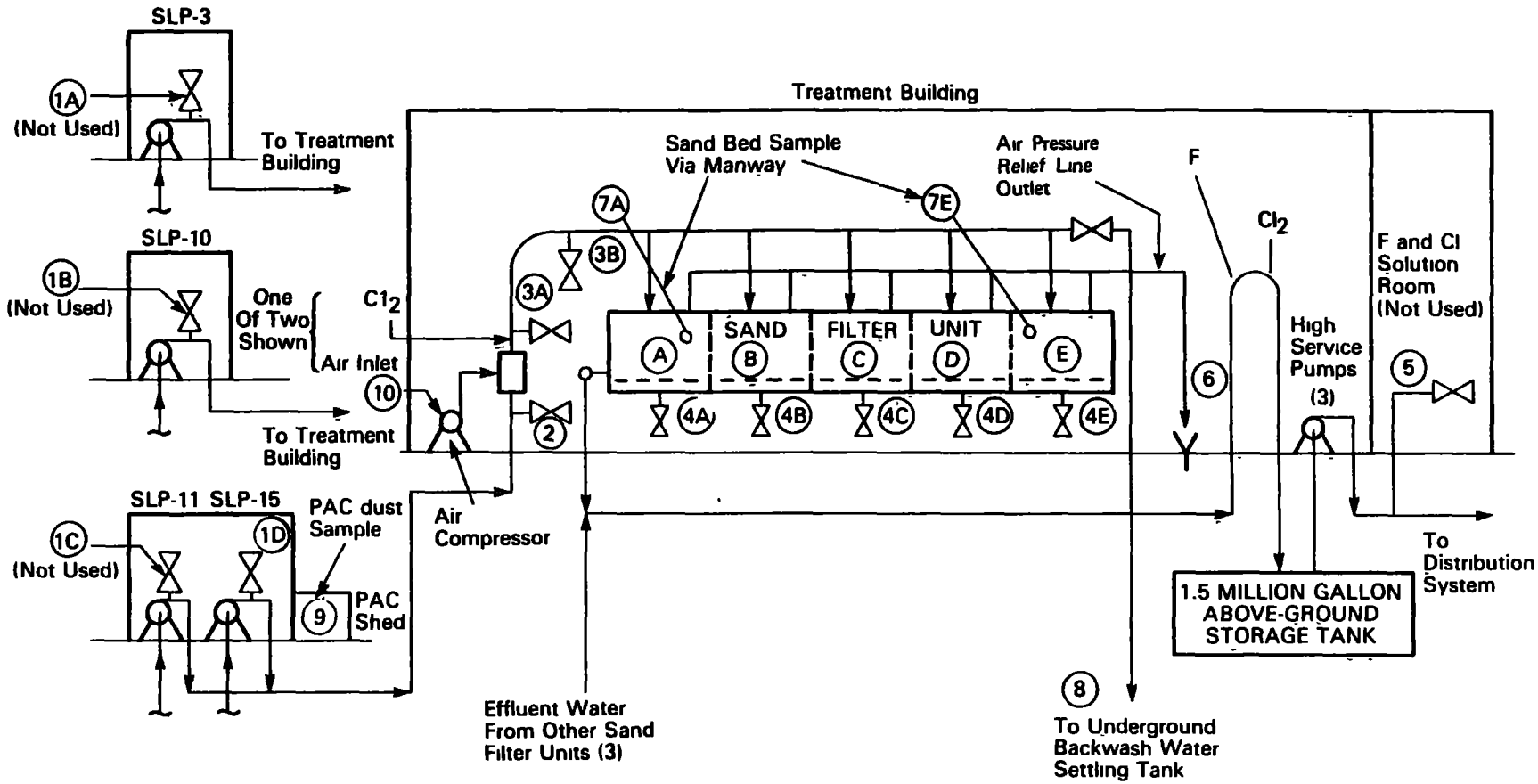

Figure G4-5 Sample Tap Locations and Numbers for ERT's December 6-8, 1982 Test at St. Louis Park Water Treatment Station No. 1

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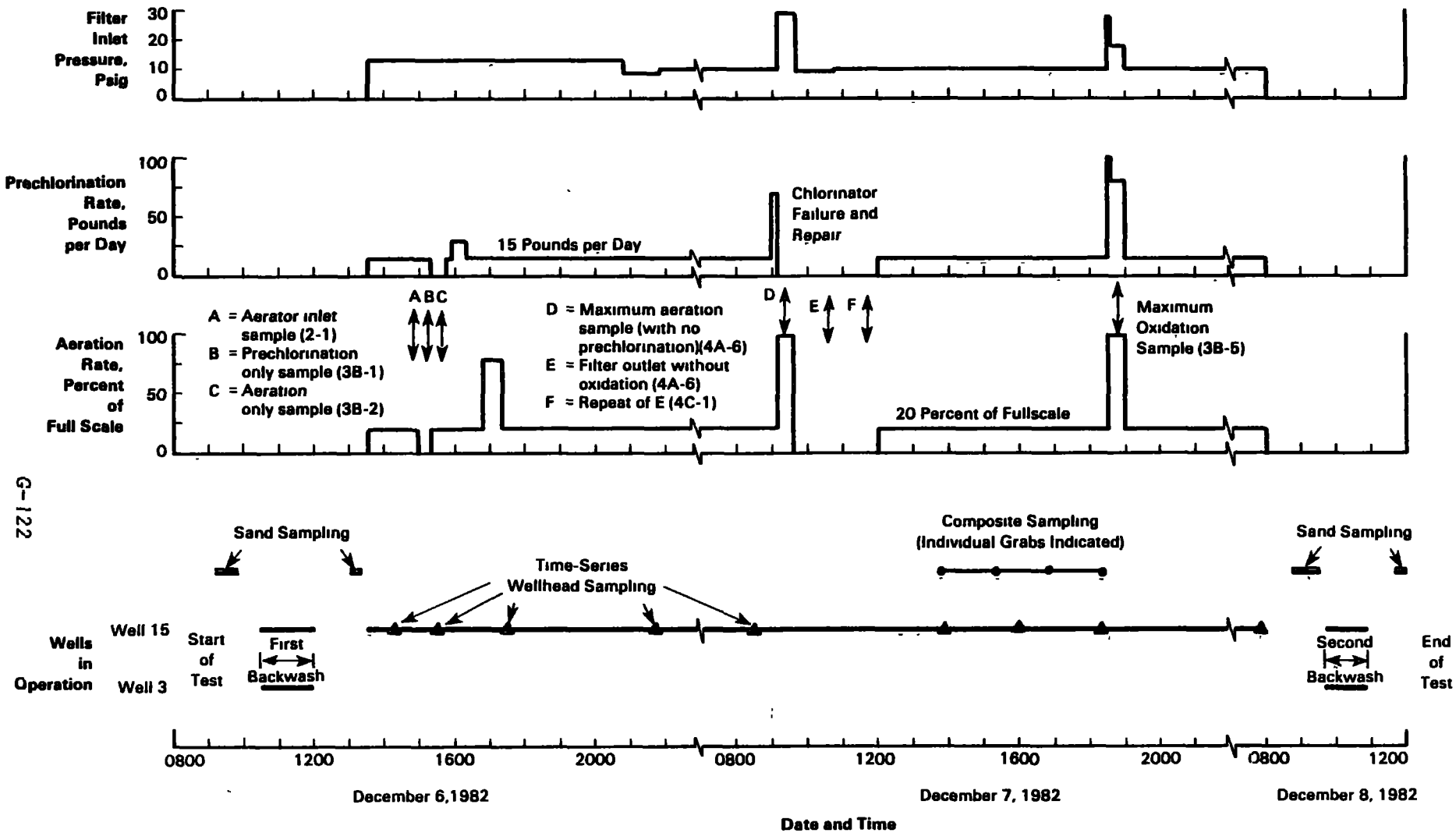


Figure G4-6 Chronological Chart of Operating Conditions and Sample Collection During ERT's December 1982 Test at St. Louis Park Water Treatment Station No. 1

TABLE G4-19

LIST OF ALL SAMPLES COLLECTED
DURING ERT'S DECEMBER 6-8, 1982 TEST
AT ST. LOUIS PARK STATION NO. 1

Sample Number[a]	Date	Time	Description
1D-1-S	12/06/82	1416	Time-series grab sample at SLP-15 Wellhead
1D-2-S	12/06/82	1527	Time-series grab sample at SLP-15 Wellhead
1D-3-S	12/06/82	1732	Time-series grab sample at SLP-15 Wellhead
1D-4-S	12/06/82	2142	Time-series grab sample at SLP-15 Wellhead
1D-5-S	12/07/82	0830	Time-series grab sample at SLP-15 Wellhead
1D-6-S	12/07/82	1345	Grab sample during compositing period.
1D-7-S	12/07/82	1600	Grab sample during compositing period.
1D-8-S	12/07/82	1815	Grab sample during compositing period.
1D-9-P,V&O	12/07/82	1345-1825[b]	Composite sample at wellhead.
1D-9-F/R-W&F	12/07/82	1345-1825[b]	Composite collected in parallel with 1D-9-P for subsequent filtration and analysis.[c]
1D-10-P	12/07/82	1345-1825[b]	Composite sample at wellhead with 1.0 milligram per liter calcium hypochlorite added in the field.[d]
1D-10-F/R-W&F	12/07/82	1345-1825[b]	Composite collected in parallel with 1D-10-P (including calcium hypochlorite addition) for subsequent filtration and analysis.[c]
1D-11-S	12/08/82	0748	Grab sample at wellhead.
2-1-P&O[h]	12/06/82	1450	Aerator inlet grab. (For comparison with 3B-1 and 3B-2).
2-2-P&O[h]	12/07/82	1345-1825[b]	Aerator inlet composite sample during normal operation.
2-2-F/R-W&F	12/07/82	1345-1825[b]	Composite collected in parallel with 2-2-P for subsequent filtration and analysis.[c]

TABLE G4-19 (CONTINUED)

Sample Number[a]	Date	Time	Description
3B-1-P,V&O[h]	12/06/82	1515	Filter inlet grab with prechlorination only (no aeration).
3B-2-P,V&O[h]	12/06/82	1543	Filter inlet grab with aeration only (no prechlorination).
3B-3-P,V&O[h]	12/07/82	0917	Filter inlet grab with maximum aeration only (no prechlorination).
3B-4-P&O	12/07/82	1345-1825[b]	Filter inlet composite during normal operation.
3B-5-P,V&O	12/07/82	1850	Filter inlet grab with maximum aeration and prechlorination.
4A-1-S	12/07/82	1345	Grab sample from Cell A filter outlet during compositing period.
4A-2-S&O[h]	12/07/82	1600	Grab sample from Cell A filter outlet during compositing period.
4A-3-S	12/07/82	1815	Grab sample from Cell A filter outlet during compositing period.
4A-4-P,V&O	12/07/82	1345-1825[b]	Composite sample from Cell A filter oulet during normal operation.
4A-4-F/R-W&F	12/07/82	1345-1825[b]	Composite collected in parallel with 4A-4-P for subsequent filtration and analysis.[c]
4A-5-P	12/07/82	1345-1825[b]	Composite sample from Cell A filter oulet during normal operation with 1.0 milligram per liter calcium hypochlorite added in the field.[d].
4A-5-F/R-W&F	12/07/82	1345-1825[b]	Composite collected in parallel with 4A-5-P (including calcium hypochlorite addition) for subsequent filtration and analysis.[c]
4A-6-P,V&O	12/07/82	1035	Grab sample from Cell A filter outlet without aeration or prechlorination.
4B-1-P&O	12/06/82	1125	Backwash feed water for Cell E collected from Cell D sample tap.[e]
4B-2-P&O	12/08/82	1035	Backwash feed water for Cell E collected from Cell D sample tap.[e]
4C-1-P,V&O	12/07/82	1145	Grab sample from Cell C filter outlet without aeration or prechlorination.

TABLE G4-19 (CONTINUED)

Sample Number[a]	Date	Time	Description
6-1-S-F&B	12/06/82 to 12/07/82	1728 to 1657	XAD resin (front and back tubes) from air sampling train located at the filter unit air relief line exhaust point.[g]
7-1-1-X	12/06/82	0920	Sand sample from surface of Cell A prior to first backwash.
7-4-1-X	12/06/82	0915	Sand sample from surface of Cell D prior to first backwash.
7-5-1-X	12/06/82	0910	Sand sample from surface of Cell E prior to first backwash.
7-5-2-P/C	12/06/82	0930	Sand sample from surface of Cell E prior to first backwash.
7-5-3-P/C	12/06/82	1315	Sand sample from surface of Cell E after first backwash.
7-3-P/C-1T	12/08/82	0845-0930[f]	Slime sample from surface of Cell A prior to second backwash.
7-3-P/C-1B	12/08/82	0845-0930[f]	Sand sample from surface of Cell A prior to second backwash.
7-3-P/C-5T	12/08/82	0845-0930[f]	Slime sample from surface of Cell E prior to second backwash.
7-3-P/C-5B	12/08/82	0845-0930[f]	Sand sample from surface of Cell E prior to second backwash.
7-4-P/C-1T	12/08/82	1140-1200[f]	Slime sample from surface of Cell A after the second backwash.
7-4-P/C-1B	12/08/82	1140-1200[f]	Sand sample from surface of Cell A after the second backwash.
7-4-P/C-5T	12/08/82	1140-1200[f]	Slime sample from surface of Cell E after the second backwash.
7-4-P/C-5B	12/08/82	1140-1200[f]	Sand sample from surface of Cell E after the second backwash.
7-5-9-P/C	NA	NA	Benzene spiked with EPA WP-880 PAH spike.[i]

TABLE G4-19 (CONTINUED)

Sample Number[a]	Date	Time	Description
8-1-S&O	12/06/82	1115-1120	Backwash wastewater from first backwash.
8-2-S&O	12/06/82	1120-1125	Backwash wastewater from first backwash.
8-3-S&O	12/08/82	1035-1040	Backwash wastewater from second backwash.
8-4-S&O	12/08/82	1040-1045	Backwash wastewater from second backwash.
9-1	12/06/82	1530	Sample of Westvaco Nuchar powdered activated carbon from shed alongside the pumphouse for Wells 11 and 15.
10-1-S-F&P	12/06/82 to 12/07/82	1218 to 1657	XAD resin (front and back tubes) from air sampling train located at air compressor air intake.[g]

NOTES TO TABLE G4-19

First digit (or digit and letter) indicates the sample tap used (see Figure G4-5). Second digit indicates the numercial sequence of the sample for a particular sample tap.

(a) Letter(s) at the end of sample number designate(s) types of analyses performed:

P = PAH analysis by SIM GC/MS with quantification and tabulation of results.

S = PAH scanning analysis yielding an SIM GC/MS chromatogram.

F/R-W = PAH analysis of filtrate (water) from filtering a sample through a 0.5 micron Teflon filter.

F/R-F = PAH analysis of extract from the filter used to produce the F/R-W sample.

O = Analysis for inorganic constituents, including total organic carbon, iron, manganese, alkalinity and hardness.

P/C = PAH analysis by SIM GC/MS with quantification and tabulation of results plus microscopic analysis to check for PAC particles.

V = Volatile organics analysis by GC/MS.

X = Assorted analysis of sand samples, including total iron content, volatile solids, carbon residue, acid digestibles and nondigestibles, and hexane and methylene chloride extractable.

(b) Composite samples consisted of four grabs collected at 1345 to 1400, 1515 to 1525, 1645 to 1655 and 1815 to 1825 (i.e., grabs spaced every 1 1/2 hours).

(c) Samples were filtered through a 0.45 micron Teflon filter upon receipt in the laboratory by MRC.

(d) Septum vials containing 5 milliliters of a 0.2 milligram per liter solution of calcium hypochlorite -- $Ca(OCl)_2$-- were added to each 1 liter sample bottle, yielding a 1.0 milligram per liter dose of Cl_2. A distilled water blank was field tested and gave a reading of 0.9 milligrams per liter Cl_2.

(e) Sample was mislabeled as being from sample tap 4B. It was actually collected from sample tap 4D.

(f) All four sand and slime samples were collected during this period.

(g) See Figure G4-7 for a description of the air sampling equipment and procedures.

(h) Samples also collected for dissolved iron (ferrous iron) analysis by filtering about 250 milliliters of sample through a 0.5 micron Millipore filter into a filter flask containing about 0.5 to 1.0 milliliter of concentrated (12N) nitric acid.

(i) Four microliters of EPA WP-880 PAH spike was added to 4.0 milliliters of benzene, together with 250 microliters of MRC surrogate spiking solution. The vial was sonicated and an aliquot shipped to MRC for GC/MS analysis.

TABLE G4-20

SUMMARY OF SPECIFIC TEST OBJECTIVES DURING
ERT's DECEMBER 6-8, 1982 TEST AT
ST. LOUIS PARK STATION NO. 1

Test Objective	Samples That Address the Objective
Assess changes in quality of well 15 water as it is pumped over an extended period, especially for PAH.	1D-1 through 1D-11
Check for the presence of residual PAC in the system:	
1) in the pipe from the PAC injection point to where wells 11 & 15 join	2-1 and 2-2 vs. 9-1
2) in the sand filter	7-1 to 7-5 vs. 9-1 8-1 to 8-4 vs. 9-1
Check quality of backwash water after normal operation & after operation with well 15 (also checking for residual PAC).	4B-1, 8-1 and 8-2 (normal operation) 4B-2, 8-3 and 8-4 (well 15 operation)
Check effects of normal system operation on PAH removal for SLP-15:	
- aeration effects	2-1 vs. 3B-2
- prechlorination effects	2-1 vs. 3B-1
- aeration/prechlorination effects	2-2 vs. 3B-4
- overall effect	1D-9 vs. 4A-4
- effect & extent of system variability	1D-6 to 9, 4A-1 to 4
- possible air stripping of light PAH	6-1
- possible addition of PAH in aeration air.	10-1
Check effects of system adjustments on PAH removal:	
- maximum aeration rate (no prechlorination)	2-2 vs. 3B-3
- maximum aeration and prechlorination rates	2-2 vs. 3B-5
- filtration without aeration or prechlorination	2-2 vs. 4A-6 and 4C-1

TABLE G4-20 (CONTINUED)

Test Objective	Samples That Address the Objective
Check for PAH sorption on filter sand	7-5-2 vs. 7-5-3 (normal operation) 7-3 vs. 7-4 (well 15 operation)
Check suspended vs. dissolved PAH throughout the system.	1D-9, 2-2, and 4A-4
Check for PAH sorption on iron precipate particles.	1D-10 & 4A-5

Such data are valuable for screening time-series samples without incurring the additional expense required to quantify the results, when such quantitative results may not be required.

2) PAH Quantitation Analyses - Yield quantitative determination of concentrations of individual PAH compounds by means of SIM GC/MS analyses obtained in item 1 above.

3) Other Water Quality Constitutent Analyses - Yield quantitative data for non-PAH water quality parameters, namely, iron, manganese, total organic carbon, alkalinity and hardness.

4) Field Water Quality Measurements - Yield data on water quality parameters which need to be measured in the field in order to obtain reliable and timely results, namely, pH, conductivity, turbidity, dissolved oxygen, total residual chlorine, iron and temperature.

5) Volatile Organics Analyses - Yield quantitative data on volatile organic constituents in water samples, such as benzene, toluene, and chlorinated organics.

ERT's original test plan for Station No. 1 included performing microscope examination of selected samples to look for powdered activated carbon (PAC)(ERT 1982). These analyses were included because of a concern resulting from CH2M Hill's September test at St. Louis Park Station No. 1 that residual traces of PAC might be present at various points in the treatment plant and be affecting observed PAH removals (Harris 1982). The PAC slurry injection system set up by Hickok during its pilot testing work in 1980 (see Section G4.2) is still present at the pumphouse for well SLP15. This system was used to inject PAC into water from well SLP15 during a brief period in the summer of 1982 when the well was brought into service in response to a potential major fire emergency. A total of about 2.9 pounds of PAC was added at the wellhead over a 3-hour period on July 20-21, 1982. (Tollefsrud 1982). Over 100 million gallons of water from wells SLP3

and SLP11 passed through the treatment plant between July 21 and CH2M Hill's September 15 test (ibid), with many millions of gallons more by the time of ERT's December 6-8 test. In addition, the filters were backwashed 5 or 6 times between July 21 and September 15, with about 8 additional backwashes by December 6.

In spite of the substantial flushing of the system implied by these flow rates and backwash frequencies, ERT felt it was important to investigate the possibility of residual PAC traces in the system, and so samples were collected during the December test for this purpose. However, only a few sand and slime samples were microscopically examined for PAC because of the unexpected presence of substantial iron precipitate and bacteria slime deposits in the filter beds. These deposits significantly affected the interpretation of ERT's December 1982 test results and CH2M Hill's September 1982 test with respect to the possible significance of residual PAC in the system (see section G4.4.5). It should be noted that no unusual particles were observed in any of the water samples analyzed by MRC.

Five of the water samples collected for PAH analysis (plus two duplicate samples) were filtered in the laboratory through a 0.5 micron Teflon filter before being analyzed. The resulting filtrates and the extracted residues from the filters were then analyzed for PAH. The intent of these tests was to determine whether a significant portion of the PAH in the water samples was associated with particulate matter. Two of the filtered samples (1D-10 and 4A-5) were dosed with 1.0 milligram per liter of calcium hypochlorite in the field immediately after they were collected. This dosage was intended to oxidize all of the iron in the samples to test the hypothesis that filterable ferric iron precipitates might adsorb PAH.

G4.4.3 Sampling, Handling and Analysis Methods

Each water sample for PAH analysis was collected in four one-liter amber glass bottles. The samples were placed in cartons with blue ice and shipped by overnight delivery to MRC on the day they were collected. Samples were stored at 4 degrees Centigrade by MRC until they were extracted. Water samples for inorganic constituent analyses were collected in clear or amber glass bottles and shipped

on the same day by overnight delivery to MRC. Samples for iron, manganese and hardness determinations were preserved with nitric acid in the field. Samples for volatile organic analyses were collected in four 40 milliliter Pierce vials with septum caps and were filled and capped in a manner to exclude any air bubbles. Further details on sample procedures are given in MRC 1982, 1983a and 1983b.

Water from the various sample taps was allowed to run a few minutes before sample bottles were filled. All water samples were collected directly from the tap except for the backwash wastewater samples, which were collected by holding a small plastic buket in the wastewater stream in the air brake pit (see photo in Exhibit G4-1) and filling the sample bottles from the bucket. Sample bottles were cleaned by MRC prior to use, but were not rinsed in the field before filling.

Composite water samples were made up of four grab samples collected at 1 1/2 hour intervals. For PAH and volatile organics samples, where four bottles or vials are required to make up a single sample, composites were obtained by filling one bottle or vial during each grab sampling period. For inorganic constituent samples, graduated cylinders were used to measure out equal portions of water into the sample bottles during each grab sampling period. The graduated cylinders were thoroughly rinsed and the sample bottles were kept closed between successive grab samples. All of the required sample bottles and cartons for the many composite samples were prelabeled and arranged in an organized manner prior to sample collection in order to avoid incorrect sample identifications. The photo in Exhibit G4-2 shows the sample bottles and cartons arranged for some of the samples prior to the composite sampling period.

Samples of filter bed sand were collected in wide mouth, one-quart amber glass bottles. Sand was collected from a depth of one or two inches over an area of one-half to one square foot by forcing sand into the bottles by hand. Photographs of the bed surface in the areas sampled were taken after most of the samples were collected. During the collection of filter bed samples before and after the second backwash on December 8 (sample series 7-3 and 7-4), separate

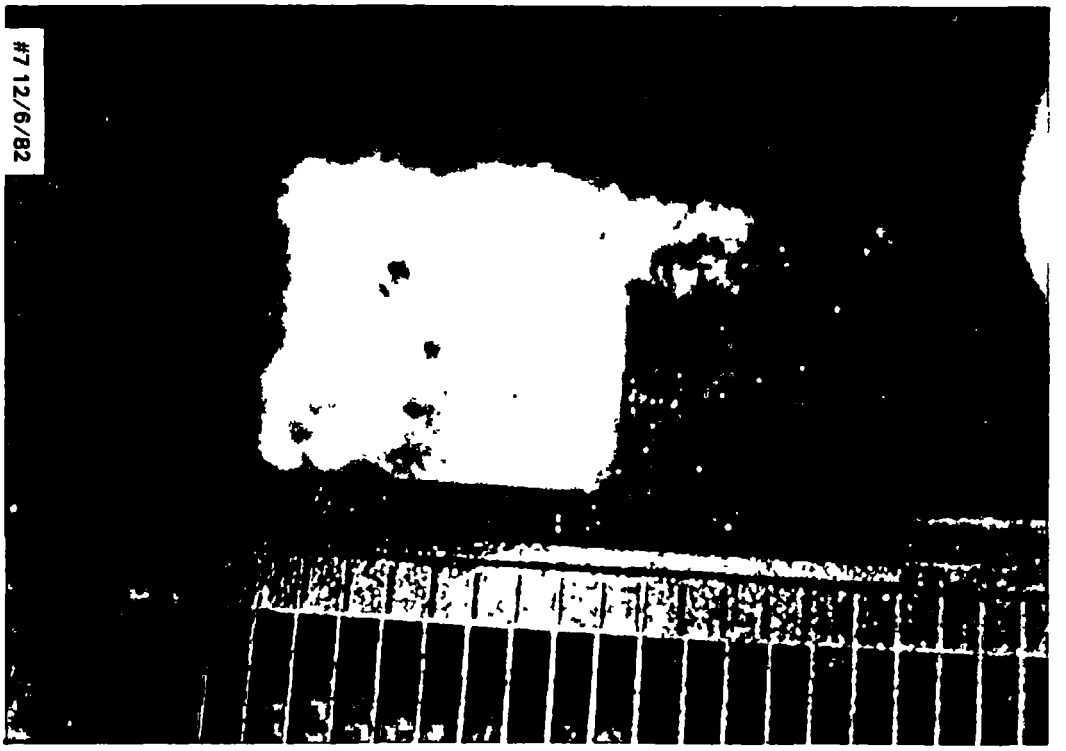


Exhibit G4-1 Backwash Wastewater Being Discharged to the Storm Sewer During the First Backwash

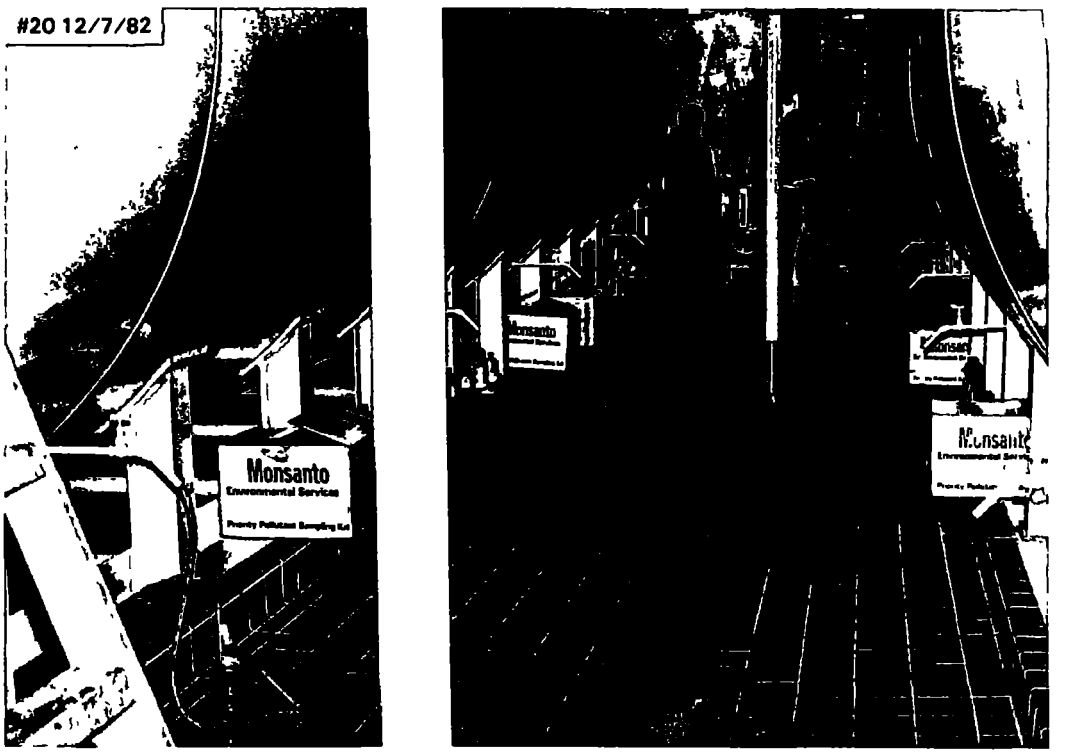
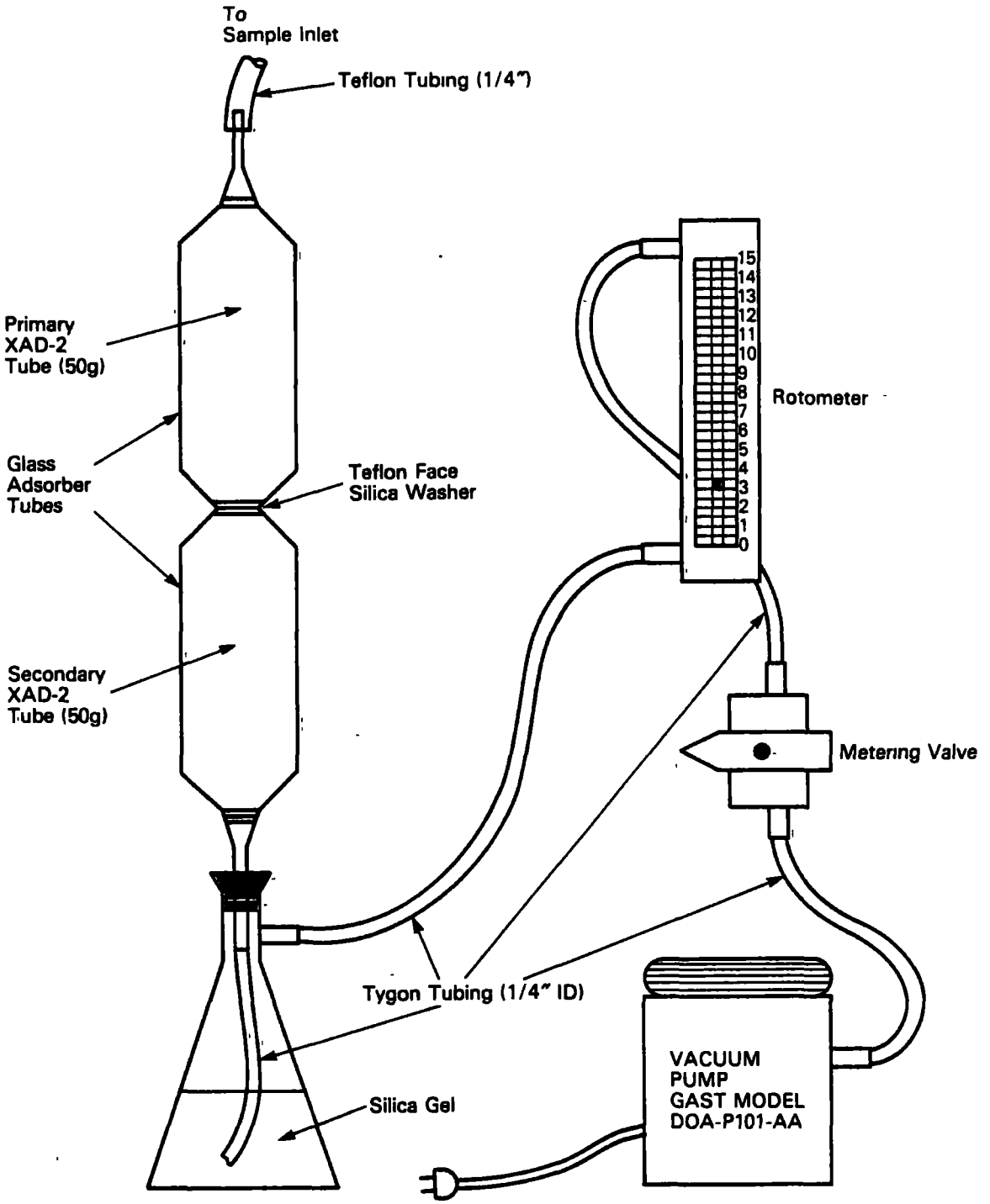


Exhibit G4-2 Sample Bottles and Cartons in Position for Composite Sampling on December 7, 1982

samples of the iron precipitate and bacteria slime overlying the sand and the underlying sand were collected. Slime samples were collected in 40 milliliter Pierce vials by hand, taking care not to obtain any underlying sand. The remaining slime was then scraped off the sand over a one-half to one square foot area and the underlying sand was then sampled. The photographs in Exhibits G4-5, 6 and 7 (see pages G-153 and G-154) illustrate the results of scraping the slime layer from the sand beds.

Air samples at the air compressor intake (sample 10-1-S) and air relief line exhaust (sample 6-1-S) were obtained by using high-speed sampling pumps to draw air through tubes containing XAD-2 absorbent resin. Each air sampling train contained two resin tubes connected in series. Figure G4-7 shows the equipment arrangement used in the air sampling trains provided by ERT. The rotameters were calibrated in ERT's laboratory prior to the test and the sample trains were tested for leaks in the field immediately prior to sampling. Figure G4-7 indicates the flow rate settings and total air flows through each of the sampling trains.

Careful chain of custody procedures were followed for all of the samples obtained during the test. Chain of custody forms accompanied each sample from collection to shipping in the field. The samples and chain of custody forms then followed MRC's and ERT's chain of custody procedures upon receipt in their laboratories. All water samples were sent directly to MRC. Sand samples and the air sample XAD resins were sent to ERT's laboratory for surrogate spiking and extraction and the extracts were sent to MRC for analysis. In the field, all sample bottles were sealed with tape immediately after collection and sample cartons were sealed with numbered chain of custody tape. Sample bottles were usually within sight of ERT or SEC personnel during the test and generally were kept locked in the treatment building when ERT or SEC personnel were not present. Further details on chain of custody procedures in the field and during analysis are provided elsewhere (SEC 1982 and MRC 1983).



	6-1	10-1
Flow Meter No.	POR0183003	MAT0183004
Flow Rate, liters per minute	8.7	14.9
Leak Flow, liters per minute	0.70	5.4
Actual Flow, liters per minute	8.0	9.5
Time, On	1728 (12-6)	1815 (12-6), 1218(12-7)
Time, Off	1657(12-7)	0915(12-7), 1657(12-7)
Total Time, minutes	1409	1179
Total Flow, liters	11,272	11,201
Total Flow, cubic meters	11.3	11.2

Figure G4-7 Schematic Diagram of Air Sampling Apparatus Used During ERT's December 6-8, 1982 Test at St. Louis Park Station No 1

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Table G4-21 summarizes the analytical methods used for the samples from this test. Further details on the field measurement methods have been provided by SEC (1982). Further details on PAH and volatile organics analytical procedures have been provided by MRC (1983). The techniques used by ERT for analyzing the sand samples for gross characteristics are somewhat unique to this study and are described in detail in Table G4-21.

G4.4.4 Results

Complete analytical results for the samples from ERT's December 6-8, 1982 test are presented in Section G8 at the end of this appendix. Tables G8-1A to 1K present PAH analysis results. Each table identifies the sample by the numbers given in Table G4-19 plus a unique extract number assigned by MRC (in the form RTCC-XXX). The concentrations reported are in nanograms per liter (parts per trillion) without any correction for extraction efficiencies. The tables report extraction recoveries for naphthalene-d8 and chrysene-d12 surrogate spiking compounds* which were added to each sample prior to extraction.

Tables G8-2A to 2D present results of inorganic analyses by MRC for samples collected during the test. Tables G8-3A to 3C present the results of all field measurements made by SEC during the test. Table G4-27 (page G-159) presents the results of gross characterization analyses performed by ERT on sand and slime samples.

Figures G8-1 to G8-4 show PAH selected ion monitoring chromatograms for all of the samples analyzed for PAH in either a scanning (chromatogram only) or quantification (tabular data as in Table G8-1) mode. Figure G8-1 shows chromatograms for water samples and includes chromatograms for a few samples which were not quantified

*These are PAH compounds with all of the hydrogen atoms replaced by deuterium, which is a hydrogen atom with one extra neutron. This additional atomic mass gives the deuterated compounds unique mass spectra which do not interfere with the analysis of native naphthalene and chrysene and does not substantially alter their physical properties compared to the native PAH compounds.

TABLE G4-21

SUMMARY DESCRIPTIONS OF ANALYTICAL METHODS

USED FOR SAMPLES COLLECTED DURING ERT'S

DECEMBER 6-8, 1982 TEST AT ST. LOUIS PARK STATON NO. 1

Type of Analysis	Summary Description
FIELD MEASUREMENTS	
pH	Orion Research model 221 digital pH/temperature meter.
Dissolved Oxygen	Yellow Springs model 51A oxygen meter. Probe left in beaker for a few minutes with constant flow of sample water entering below the water surface via a rubber tube connected to the sample tap until dissolved oxygen reading was steady.
Turbidity	Hach Turbidimeter model 2100A.
Specific Conductance	Hach conductivity meter model 16300-00.
Iron	Hach model IR-18 test kit.
Total Residual Chlorine	Titration with phenylarsine oxide standard (0.00564N).
Temperature	CMS catalog no. 227-637 partial immersion thermometer.
INORGANIC ANALYSES	
Total Organic Carbon	EPA Method 415.1 using a Dohrmann TOC analyzer.
Iron and Manganese	EPA Method 200.7 (inductively coupled atomic absorption photometry).
Hardness	EPA Method 200.7 (hardness reported as $CaCO_3$ calculated from calcium and magnesium as determined by ICAAP).
Alkalinity	EPA Method 403 (acidimetric titration).
ORGANICS ANALYSES	
PAH Scan or Quantification	4-liter sample extracted with methylene chloride. Extract concentrated to 1 milliliter and analyzed by selected ion monitoring GC/MS techniques, monitoring 18 different feature masses. Extract analyses produced selected ion chromatograms. Quantification analyses result in tabulated concentration data. Naphthalene-d_8 and

TABLE G4-21 (continued)

Type of Analysis	Summary Description
PAH Scan or Quantification-cont'd	chrysene-d_{12} surrogate spiking compounds were added to water samples at a concentration of 100 nanograms per liter to measure extraction efficiencies. A 25 nanogram per liter anthracene-d_{10} internal standard was added to the 1 milliliter extract immediately prior to sample injection to assure proper GC/MS operation.
Volatile Organics	Organic compounds that could be sparged from the water matrix were analyzed by GC/MS using an approach similar to EPA Method 624. A 5 milliliter sample was spiked with benzene -d_6 at a concentration of 20 micrograms per liter.
SAND ANALYSES	
Moisture Content	Measured weight loss from drying overnight at 110°C.
Volatile Solids	Measured weight loss from dried sample after heating for two hours at 550°C.
Hexane and Methylene Chloride Extractables	About 5 to 10 grams of dried sample was sonicated twice with 10 milliliters of hexane for 10 minutes each time. The solvent was separated by centrifugation, decanted into a tared beaker and allowed to evaporate. The measured weight gain in the beaker was calculated as hexane extractables. The sample remaining from the hexane extraction was then extracted with methylene chloride in an identical manner.
Acid Digestibles, Non-Acid Digestibles, and Carbon Residue	Sample remaining from the hexane and methylene chloride extractions was digested with 5 milliliters of concentrated nitric acid and sufficient 30 percent hydrogen peroxide to destroy all organic matter. Digestion usually took 4 to 6 hours and 50 to 100 milliliters of hydrogen peroxide. The digested sample was decanted and filtered through tared Whatman No. 40 filter paper. The sample was gently swirled to allow suspended particles to be filtered while leaving heavier sand particles in the beaker. The gain in weight of the filter paper after drying at 110°C was reported as carbon residue*. The remaining sand and

*The bulk of this filtered material was confirmed to be powdered activated carbon by optical and scanning electron microscopy.

TABLE G4-21 (continued)

Type of Analysis	Summary Description
Acid Digestibles, Non-Acid Digestibles, and Carbon Residue (Cont'd)	solids in the beaker were rinsed into a second tared filter which was then dried at 110°C and reweighted. The calculated weight gain was reported as non-acid digestible residue. Filtrate from the first filtering step was diluted to 100 milliliters with deionzed water. A 50 milliliter aliquot was oven dried overnight in a tared beaker at 110°C and the calculated weight gain was reported as acid digestible residue.*
Total Iron	The remaining filtrate solution from the first filtering of acid digested sample (see description above) was analyzed for iron by atomic absorption spectroscopy.
SOLID SAMPLE EXTRACTIONS Sand and Slime Samples	Sand samples from ERT's December 1982 test were extracted ultrasonically. An aliquot of about 5 grams of sample was placed in a tared 5 milliliter Wheaton septum vial together with 4.0 milliliters of Burdick and Jackson benzene and 250 microliters of surrogate spiking solution provided by MRC. The vial was immediately sealed using a Teflon-lined septum and aluminum crimp seal. The vial was ultrasonicated for 12 minutes at a setting of 40 percent of full-scale using an Ultra Clean Equipment Co. ultrasonic bath. Aliquots of 1.0 milliliter were shipped to MRC for analysis. Sand samples from ERT's February 1983 test were soxhlet extracted. An aliquot of about 60 to 80 grams of air-dried sample was mixed with anhydrous sodium sulfate and placed on a layer of pre-extracted glass wool in a soxhlet extractor. The sand mixture was covered with glass wool and a 100 microliter volume of surrogate spiking standard supplied by MRC was injected through the glass wool into the sand. The sample was then extracted

*The calculated weight gain was corrected for salts formed from the acid by testing blank samples.

TABLE G4-21 (continued)

Type of Analysis	Sample Description
Sand and Slime Samples (Cont'd)	overnight with Burdick and Jackson methylene chloride. The extract was concentrated to about 3 milliliters using a Kuderna-Danish evaporative concentrator equipped with a 3-ball Snyder column. A micro Snyder column was then used to further concentrate the extract to less than 1 milliliter. The final concentrated extract was diluted to a final volume of 1 milliliter and shipped to MRC for analysis.
XAD-2 Resin Samples	The XAD-2 resin and glass wool plugs were removed from the sampling tubes, split in half, and placed in each of two glass extraction thimbles. A 100 microliter volume of surrogate spike solution provided by MRC was injected into the XAD-2 resin in each of the two thimbles. The thimbles were extracted overnight in soxhlet extractors with Burdick and Jackson methylene chloride. The two extracts were combined in a Kuderna-Danish evaporator and concentrated to about 3 milliliters. A micro Snyder column was used to further contrate the extract to less than 1 milliliter. The concentrated extract was diluted to 1 milliliter and shipped to MRC for analysis.

(e.g., 1D-4-S through 1D-8-S). Figure G8-2 shows chromatograms for extracts from sand and slime samples, most of which were not quantified. Figure G8-3 shows chromatograms for extracts for the XAD resins used in collecting air samples, none of which were quantified. Figure G8-4 shows various quality assurance chromatograms, including spiking standards and method blank analyses.

The chromatograms in Figures G8-1 to G8-4 are intended to provide semi-qualitative results. They are interpreted by comparing peak heights at different retention times. The concentration of the full-scale peak is reported in the upper right-hand corner of each chromatogram. The concentrations of other peaks are roughly in proportion to their height compared to the full-scale peak, but this is only approximate because of differing response factors. Some sense of response factor effects can be obtained by studying chromatograms which have been quantified and reported in Table G8-1. The identities of the peaks can be determined from the retention times given in Table G8-4.

Figure G8-5 shows total ion chromatograms obtained from volatile organic analyses. Major features in these chromatograms are labeled when they first appear. The identity of the shoulder peak occurring immediately before the benzene-d_6 internal spike has been confirmed by GC/MS as trichloroethylene. The identities of the other peaks (other than methylene chloride) have not been confirmed. The methylene chloride peaks are probably due to residual contamination from cleaning of the sample vials. Note that the full-scale peak concentrations in the chromatograms are reported in micrograms per liter (parts per billion). Concentrations of other peaks are roughly proportional to their peak-height relative to the full-scale peak, but this is only approximate due to different response factors.

Figures G8-6, 7, and 8 are copies of recording charts for the flow rates of well SLP15, well SLP3, and backwash water during the test. The recording charts contain notations of the total flow over the duration of the test basd on a digital flow integration counter that is part of the recorder. Data on other major operating variables during the test (aeration rate, prechlorination rate, and system pressure) are given in Figure G4-6.

G4.4.5 Data Interpretation-Plant Operation

The discussion and interpretation of the results from the December 1982 test are divided into two main topics. This subsection discusses the data obtained which characterize the behavior of the treatment plant at St. Louis Park Station No. 1 from the viewpoint of its intended purpose as an iron removal treatment plant. The next subsection then discusses the data which characterize the behavior of PAH in the treatment plant.

Normal Operation

Table G4-22 shows concentrations of inorganic constituents at various points throughout the treatment plant during the composite sampling period on the afternoon of December 7, when the plant was operating under normal conditions. Alkalinity, hardness, TOC, turbidity, specific conductance and pH are seen to not have been substantially affected by any of the treatment operations. Iron was reduced from about 0.77 milligrams per liter in the feed water to about 0.1 milligrams per liter in the filtered water (based on average of duplicate sample analyses). Very slight manganese removal was obtained, with 0.102 milligrams per liter in the feed water and 0.094 milligrams per liter in the filtered water. Field measurements of iron levels using a Hach test kit gave results about 0.2 milligrams per liter higher than laboratory analysis results. As expected, most of the iron (93 percent) in the feed water was ferrous (dissolved). Most of the iron in the filtered water was also ferrous (about 70 percent), indicating that the ferrous iron in the feed water was not completely oxidized. The behavior of dissolved oxygen and chlorine in the system is discussed later in this subsection.

Table G4-23 shows the results of field measurements at sample taps for the individual filter cells. These measurements were made on the afternoon of December 6 when the plant was operating normally except for a brief adjustment in the prechlorination rate (see Figure G4-6). The results in Table G4-23 show that consistent results for dissolved oxygen, iron and residual chlorine were obtained from all five cells.

TABLE G4-22

INORGANIC CONSTITUENT CONCENTRATIONS AT VARIOUS POINTS IN THE IRON REMOVAL PLANT DURING THE COLLECTION OF COMPOSITE SAMPLES UNDER NORMAL OPERATING CONDITIONS ON DECEMBER 7, 1982

(All concentrations in milligrams per liter unless otherwise noted)

Parameter	Wellhead (1D-9)[a]	Aerator Inlet (2-2)[b]	Filter Inlet (3B-4)[c]	Filter Outlet Cell A (4A-4)[d]	Filter Outlet Cell C	Filter Outlet Cell E
FIELD MEASUREMENTS						
pH	7.3	7.2	7.2	7.2	-	-
Conductance, μmho/cm	600	595	600	610	-	-
Turbidity, NTU	1.3	1.3	1.75	1.4	-	-
Dissolved Oxygen	-[e]	0.2	1.5	1.7	-	1.6
Chlorine, Total Residual	0	0	0.44	0.09	0	0
Iron (Hach Kit)	1.0	1.05	1.0	0.3	-	-
LABORATORY ANALYSES						
TOC	2.5/2.4[f]	2.9	2.6	2.3/2.3[f]	-	-
Alkalinity (as $CaCO_3$)	306/312	310	309	308/308	-	-
Hardness (as $CaCO_3$)	330/335	331	311	329/338	-	-
Total Iron	0.769/0.776	0.771	0.758	0.065/0.125	-	-
Dissolved Iron	-	0.719[g]	-	0.068[g]	-	-
Manganese	0.102/0.103	0.102	0.097	0.093/0.095	-	-

Notes:

(a) Field measurements are average of two determinations (1353 and 1710 hours), except for a single turbidity determination.

(b) Field measurements are average of two determinations (1518 and 1704 hours), except for a single dissolved oxygen determination.

(c) Field measurements are average of from two to four determinations (1352, 1523, 1533 and 1608 hours) depending on the analyte.

(d) Field measurements are average of from two to four determinations (1357, 1517, 1613 and 1606 hours) depending on the analyte.

(e) Dash indicates no data.

(f) Results of analyzing duplicate samples.

(g) Results of grab sample preserved in the field for dissolved iron during the compositing period.

TABLE G4-23

FIELD MEASUREMENTS OF INDIVIDUAL FILTER
CELL SAMPLE TAPS ON DECEMBER 6, 1982
(All concentrations in milligrams per liter)

	Sample Location[a]				
Parameter	Cell A	Cell B	Cell C	Cell D	Cell E
Iron	0.6	0.55	0.45/0.4[c]	1.3/0.5[c]	1.2/0.55[c]
Dissolved Oxygen	2.1	-(b)	2.3	-	-
Chlorine, Total Residual	0	-	0	-	-

Notes:

(a) Cell A nearest to effluent end (See Figure G4-5).Note that sample points designations in Table G8-3A are reversed. All measurements made between 1600 and 1650 hours.

(b) Dash indicates no measurement.

(c) Duplicate measurements made 10 to 15 minutes apart.

Some difficulty was experienced in obtaining accurate iron measurements from cells D and E, but duplicate analyses gave reasonable results. Again, it should be noted that field measurements for iron appear to be biased high by 0.2 to 0.3 milligrams per liter compared to laboratory analyses. Even with an allowance for this bias, Table G4-23 indicates that the filtered water from the various cells contained on the order of 0.2 or 0.3 milligrams per liter of iron. This indicates rather poor performance, given that iron removal plants in St. Louis Park have been shown by MDH testing to be able to produce treated water containing less than 0.05 milligrams per iter of iron (see Table G2-4 in section G2.1.2).

Operating Adjustments

Tables G4-24 and 25 show the effects of operating adjustments in aeration and prechlorination rates on concentrations of inorganic constituents. The data show that, as expected, pH, specific conductance, turbidity, TOC, alkalinity, hardness and manganese were not affected by these adjustments.*

A significant conclusion from the data in Tables G4-24 and 25 is that the prechlorination step is responsible for oxidizing most of the ferrous iron under normal operating conditions, not the aeration step. This can be seen by comparing the total and dissolved iron concentrations in Table G4-24. Prechlorination at normal rates (1.2 milligrams per liter chlorine dose) oxidized half of the ferrous iron while aeration at normal rates (2.5 milligrams per liter oxygen dose) only oxidized about 5 percent of the ferrous iron. This is consistent with the kinetics of ferrous iron oxidation reactions at neutral and alkaline pH values, which are relatively slow with oxygen and much more rapid with chlorine (Stumm and Morgan 1970, Luthy 1982). Further evidence for this result is the fact that the difference between calculated chlorine dosages and measured residual chlorine levels was typically about 0.8 milligrams per liter over a range of prechlorination rates. This compares favorably with the calculated chlorine

*The single exception to this is that maximum aeration (sample 3B-3, see Table G4-24) decreased the pH from 7.2 to 6.6.

TABLE G4-24

EFFECTS OF DIFFERENT AERATION AND PRECHLORINATION RATES ON INORGANIC CONSTITUENTS DURING ERT'S DECEMBER 6-8, 1982 TEST

(All concentrations in milligrams per liter unless otherwise noted)

Parameter	12/6/82 Tests			12/7/82 Tests			
	Aerator Inlet (2-1)	Prechlorination Only (3B-1)	Aeration Only (3B-2)	Aerator Inlet (2-2)[b]	Maximum Aeration (3B-3)	Normal Operation (3B-4)[c]	Maximum Aeration & Prechlorination (3B-5)
FIELD MEASUREMENTS							
pH	6.9	7.1	7.1	7.2	6.6	7.2	-
Conductance, μmhos/cm	585	590	545	595	600	600	-
Turbidity, NTU	0.8	1.75	1.1	1.3	-[a]	1.75	-
Dissolved Oxygen	0.25	0.20	0.35	0.2	1.4	1.5[f]	0.95[d]
Chlorine, Total Residual	0	0.32	0	0	0	0.44[g]	5.4[d]
Iron (Hach Kit)	0.95	1.20	1.05	1.05	1.0	1.0	-
LABORATORY ANALYSES							
TOC	2.9	3.4	2.8	2.9	2.5	2.6	2.5
Alkalinity (as $CaCO_3$)	304	306	308	310	309	309	300
Hardness (as $CaCO_3$)	324	322	329	331	320	311	333
Total Iron	0.829	0.749	0.798	0.771	0.768	0.758	0.767
Dissolved Iron	0.761	0.375	0.728	0.719	0.249	-	-
Manganese	0.099	0.098	0.099	0.102	0.098	0.097	0.102
CALCULATED DOSAGES[e]							
Oxygen	0	0	2.5	0	12.3	2.5	12.3
Chlorine	0	1.2	0	0	0	1.2	6.3

Notes to Table G4-24

(a) Dash indicates no data.

(b) Field measurements are average of two determinations (at 1518 and 1704) except for a single dissolved oxygen value.

(c) Field measurements are average of from two to four determinations (at 1352, 1523, 1533 and 1608) depending on the analyte (see Table G8-3B).

(d) Field measurements are average of two determinations.

(e) Calculations based on flow rate of 1050 gallons per minute (see Figure G8-6) and aeration and prechlorination rates shown in Figure G4-6 (based on full-scale aeration being 6.07 standard cubic feet per minute).

(f) Two measured values were 2.4 and 0.55 milligrams per liter.

(g) Four measured values were 0.13, 0.70, 0.62 and 0.29 milligrams per liter.

Notes to Table G4-24

(a) Dash indicates no data.

(b) Field measurements are average of two determinations (at 1518 and 1704) except for a single dissolved oxygen value.

(c) Field measurements are average of from two to four determinations (at 1352, 1523, 1533 and 1608) depending on the analyte (see Table G8-3B).

(d) Field measurements are average of two determinations.

(e) Calculations based on flow rate of 1050 gallons per minute (see Figure G8-6) and aeration and prechlorination rates shown in Figure G4-6 (based on full-scale aeration being 6.07 standard cubic feet per minute).

(f) Two measured values were 2.4 and 0.55 milligrams per liter.

(g) Four measured values were 0.13, 0.70, 0.62 and 0.29 milligrams per liter.

TABLE G4-25

RESULTS OF FIELD MEASUREMENTS DURING
OPERATIONAL ADJUSTMENTS MADE ON DECEMBER 6, 1982
(All concentrations in milligrams per liter)

Parameter	Aerator Inlet (1430)[a]	Normal Dosage Rates		Adjusted Dosage Rates	
		Prechlorination Only (1503)	Aeration Only (1526)	Doubled Prechlorination (1605)	Quadrupled Aeration (1655)
FIELD MEASUREMENTS					
Dissolved Oxygen	0.25	0.20	0.35	No Data	0.7
Chlorine, Total Residual	0	0.32	0	1.28	0.61
CALCULATED DOSE[b]					
Dissolved Oxygen	0	0	2.5	2.5	9.8
Chlorine	0	1.2	0	2.4	1.2

Notes:

(a) Time of field measurement. See Table G8-3A.

(b) Based on flow rate of 1050 gallons per minute (Figure G8-6) and aeration and prechlorination rates shown in Figure G4-6.

dose of 0.6 milligrams per liter required to completely oxidize the dissolved iron and manganese (based on 0.75 milligrams per liter ferrous iron and 0.1 milligrams per liter manganese - assumed to be entirely in the +2 valence state).

An important item related to the relative roles of chlorine and oxygen in oxidizing ferrous iron is the residence time for mixing and reaction. Sample tap 3B is located about 8.5 feet downstream of the prechlorination injection point. At a flow rate of 1050 gallons per minute in an 18 inch pipe this yields a residence time between prechlorination injection and the sample tap of 11 seconds. This short residence time is apparently insufficient for the oxygen added by the aerator to become fully dissolved, since measured dissolved oxygen levels at sample tap 3B were always far below calculated dosages - even at very high aeration rates (see Tables G4-24 and 25). The added oxygen does dissolve eventually, as indicated by the filter outlet measurements reported in Tables G4-23 and 23.

Table G4-26 shows concentrations of inorganic constituents in the filter outlet when the plant was operated with no aeration or prechlorination on the morning of December 7 (see Figure G4-6). All of the results are as expected except for the high dissolved oxygen level in the outlet from cell A and the fact that substantial iron removal was achieved. The iron removal achieved without aeration or prechlorination was comparable to that achieved in normal operation (compare Tables G4-22, 23 and 28). This is an unexpected result because the lack of air or chlorine to oxidze the ferrous iron should mean that the iron is not precipitated and filtered. The significance of this result and the high dissolved oxygen level observed in cell A are discussed below.

Iron Precipitate and Bacteria Slime Deposits

A major finding during the opening and inspection of selected filter cells before and after backwashing at the start and end of the test was the presence of substantial deposits of iron precipitate and iron bacteria slime in the filter cells. This subsection discusses the causes and significance of these slime deposits.

TABLE G4-26

INORGANIC CONSTITUENT CONCENTRATIONS IN FILTER OUTLET WATER WITH NO AERATION OR PREHCLORINATION DURING TESTING ON DECEMBER 7, 1982

(All concentrations in milligrams per liter unless otherwise noted)

Parameter	Aerator Inlet (2-2)[a]	Filter Outlet Cell A (4A-6)[b]	Filter Outlet Cell C (4C-1)[c]
FIELD MEASUREMENTS			
pH	7.2	7.1	-[d]
Conductance, μmhos/cm	595	605	-
Turbidity, NTU	1.3	1.0	-
Dissolved Oxygen	0.15	3.3	0.25
Chlorine, Total Residual	0	0	-
Iron (Hach Kit)	1.05	0.4	0.3
LABORATORY ANALYSES			
TOC	2.9	2.8	3.1
Alkalinity (as $CaCO_3$)	310	306	308
Hardness (as $CaCO_3$)	331	323	327
Total Iron	0.771	0.125	0.100
Dissolved Iron	0.719	-	-
Manganese	0.102	0.095	0.084

Notes:

(a) Field measurements are average of two determinations at 1518 and 1704 hours, except dissolved oxygen is average of two determinations at 1148 and 1704.
(b) Field measurements made once at 1046.
(c) Field measurements made at 1113 and 1130.
(d) Dash indicates no data.

Exhibits G4-3 through G4-8 are photographs of the inside of filter cells at various points throughout the test. Exhibit G4-3 shows the surface of the filter bed in cell E prior to the first backwash on the morning of December 6. The pebble-like objects on the surface of the bed are masses of iron bacteria slime and precipitated iron called "mudballs" in the water treatment industry (Goplin 1982). These mudballs have the consistency of wet, clayey mud. The mudballs are embedded in a slimey deposit of iron precipitates and iron bacteria covering the entire surface of the sand bed. These slime deposits covered the entire surface of all of the filter cells inspected (cells, A, D and E).

Exhibit G4-4 shows the surface of the filter bed in all E after the first backwash. The disturbance of the bed surface is largely due to the collection of a sand sample in this area prior to the backwash. Portions of the actual bed are visible as the darker, grainy material. The key point illustrated by Exhibit G4-4 is that backwashing had little apparent effect in removing iron precipitate deposits and mudballs from the bed. This point is better illustrated by Exhibits G4-5 and 6 which show the surface of the same area of the filter bed in cell E before and after the second backwash on the morning of December 8. In each of these photographs the slime deposits were scrapped off an area of the sand in order to collect samples of the deposits. The scrapping revealed that the slime deposits in cell E in general were anywhere from one-half to one inch thick. The contrasting appearance of the sand surface and the deposits is apparent from these photographs. Again, the two photos show that backwashing had little effect in removing the deposits.

Exhibit G4-7 shows the surface of the filter bed in cell A prior to the second backwash after a portion of the slime layer was scrapped off. The slime deposits in this cell were thinner than those in cell E, ranging from about one-quarter to one-half inch in thickness.

Exhibit G4-8 shows the growth of iron bacteria slime on the inlet water distribution pipe inside cell E after the first backwash. This sort of growth was present on the distributor pipes in all of the cells inspected (cells A, D and E).

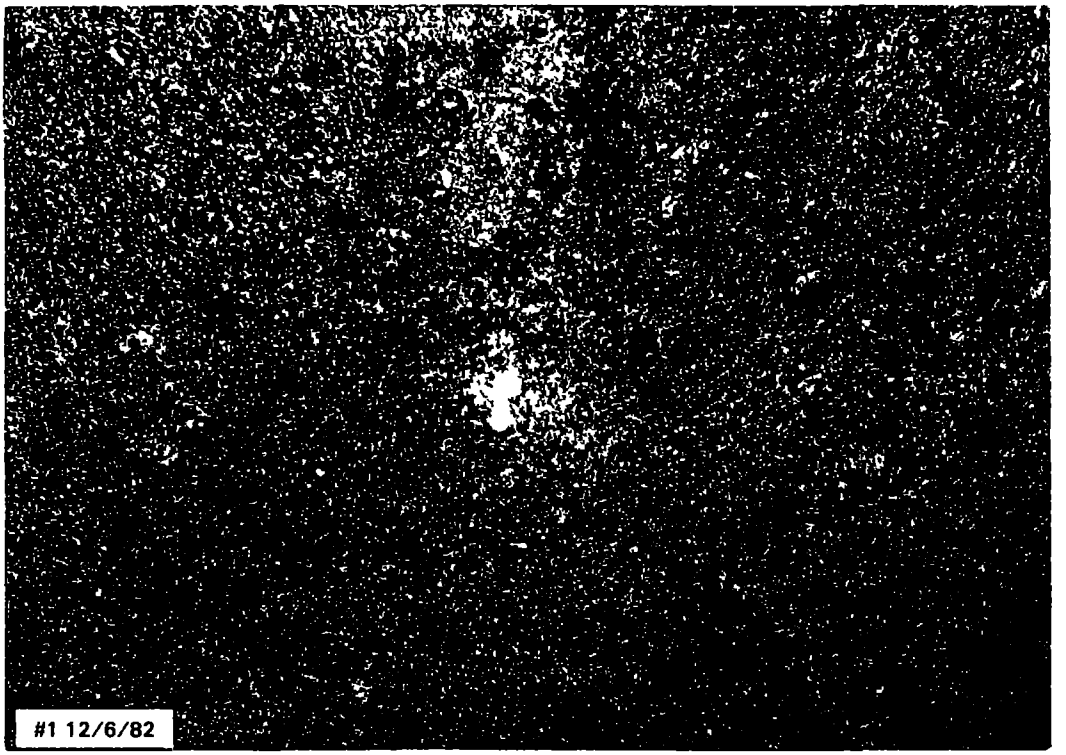


Exhibit G4-3 Surface of the Filter Bed in Cell E Before the First Backwash

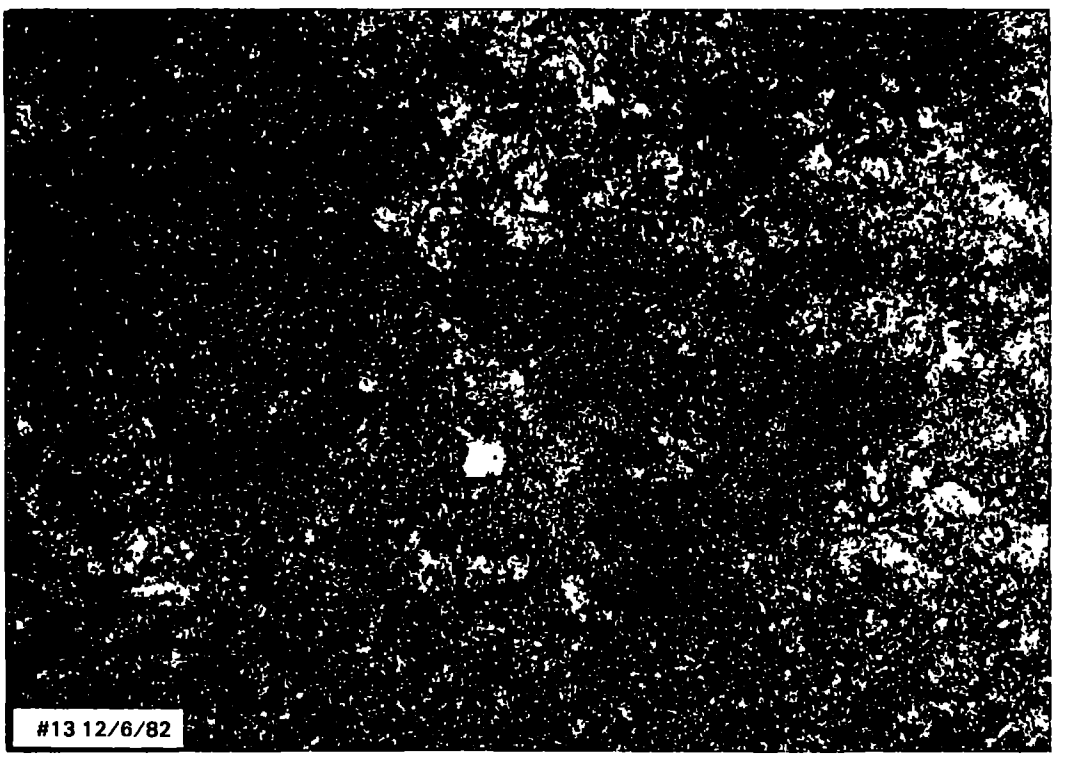


Exhibit G4-4 Surface of the Filter Bed in Cell E After the First Backwash

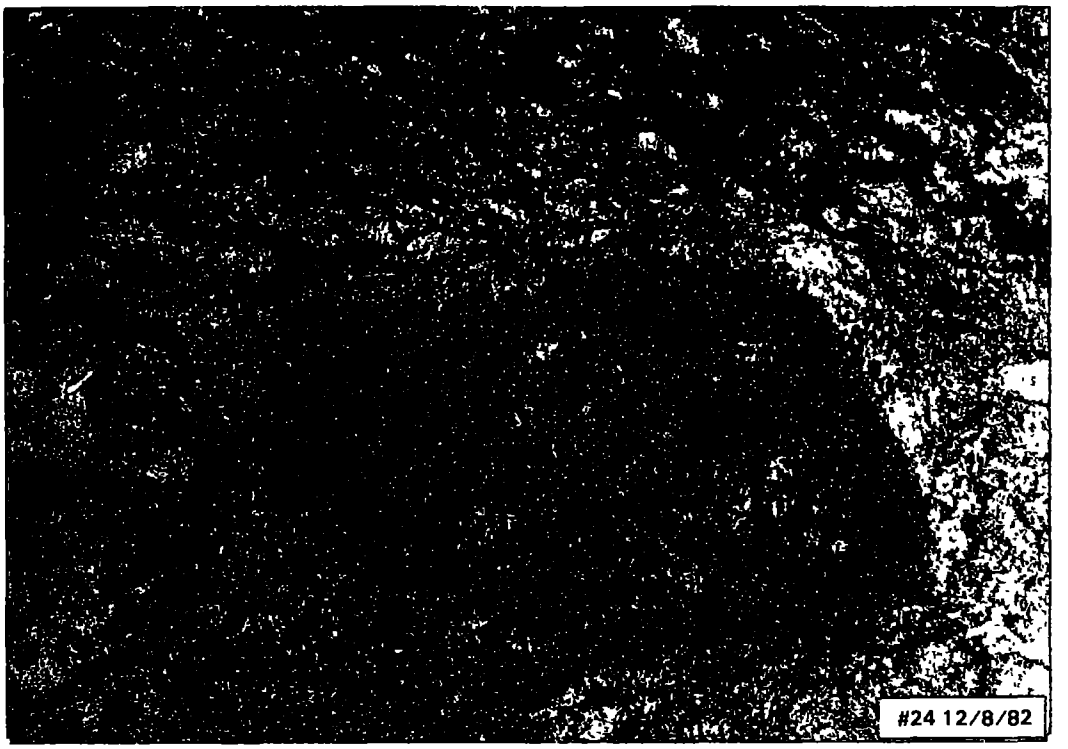


Exhibit G4-5 Surface of the Filter Bed in Cell E Before the Second Backwash

Exhibit G4-6 Surface of the Filter Bed in Cell E After the Second Backwash (Pen Laying on Sand for Size Reference)

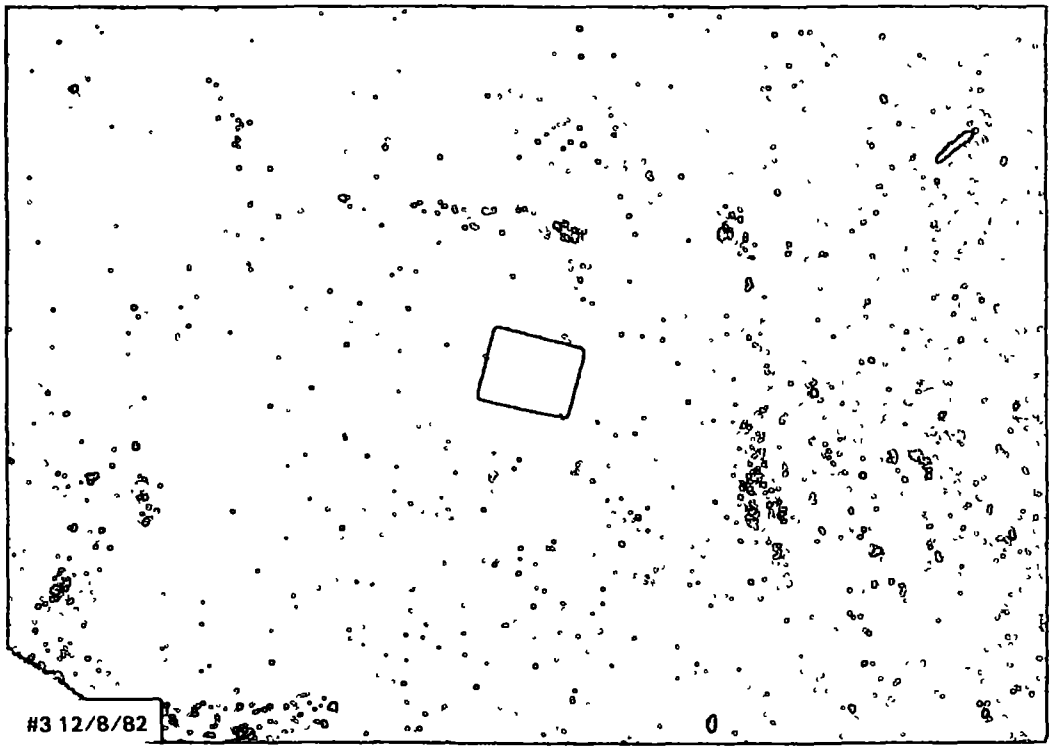


Exhibit G4-7 Surface of the Filter Bed in Cell A Before the Second Backwash (Matchbook Laying on Sand for Size Reference)

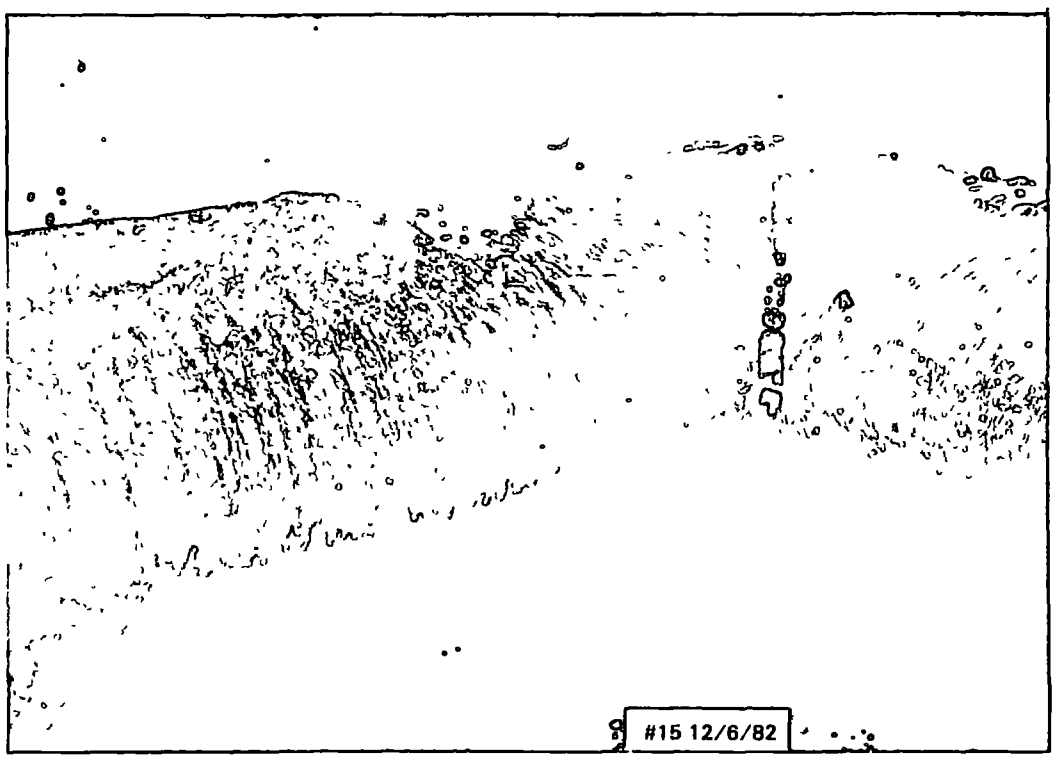


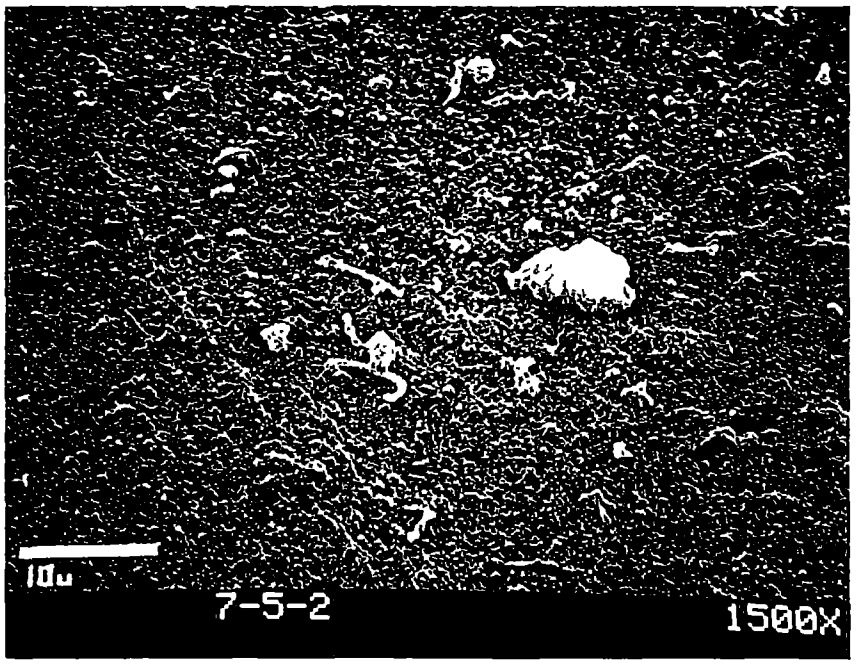
Exhibit G4-8 Distributor Pipe in Cell E After the First Backwash

The presence of iron bacteria in the slime deposits was determined by optical and scanning electron microscopy. Exhibits G4-9 and 10 show scanning electron microscope (SEM) photographs* of slime samples collected from cell E before the first backwash (sample 7-5-2) and from cell A before the second backwash (sample 7-3-1T), respectively. Each exhibit includes photographs at 1500X and 5000X magnification. The 1500X magnification photos show that iron bacteria were widely scattered through the slime and not present as a concentrated mass of bacteria. This is consistent with results of optical microscope examinations of various slime samples.

Based on visual observation and expected behavior of the system, the bulk of the slime deposits probably consist of inorganic iron precipitates. These precipitates would be expected to be iron oxyhydroxides such as ferric hydroxide ($Fe(OH)_3$) or lepidocrocite (α - FeOOH) (Robison, Demirel and Baumann 1981).

The high magnification (5000X) SEM photographs in Exhibits G4.9 and 10 show single bacteria in the slime samples. While the identity of the bacteria observed was not confirmed, their shapes and sizes are consistent with those of iron bacteria (Standard Methods 1976). It is likely that the bacteria are aerobic or anaerobic oxidizing bacteria (i.e., bacteria that oxidize ferrous iron to ferric iron) since they are present in ground water in the Minneapolis area and their growth in iron removal treatment plants is not an unusual problem (Goplin 1982). The species of bacteria present were not confirmed so it is unknown if they were reducing or oxidizing bacteria. Oxidizing bacteria (those that oxidize ferrous iron to ferric iron) are present in ground waters in the Minneapolis area and their growth in iron treatment plants is not an unusual problem (Goplin 1982). It is possible that reducing bacteria (those that reduce ferric iron to ferrous iron) were present, but this seems unlikely because of the presence of dissolved oxygen and chlorine.

*The slime samples for SEM were prepared by filtering an aqueous suspension of the slime through a 0.2 micron filter. Portions of the filter were then analyzed by SEM. Slime samples for optical microscopy were prepared by placing a smear of the slime on a glass plate.



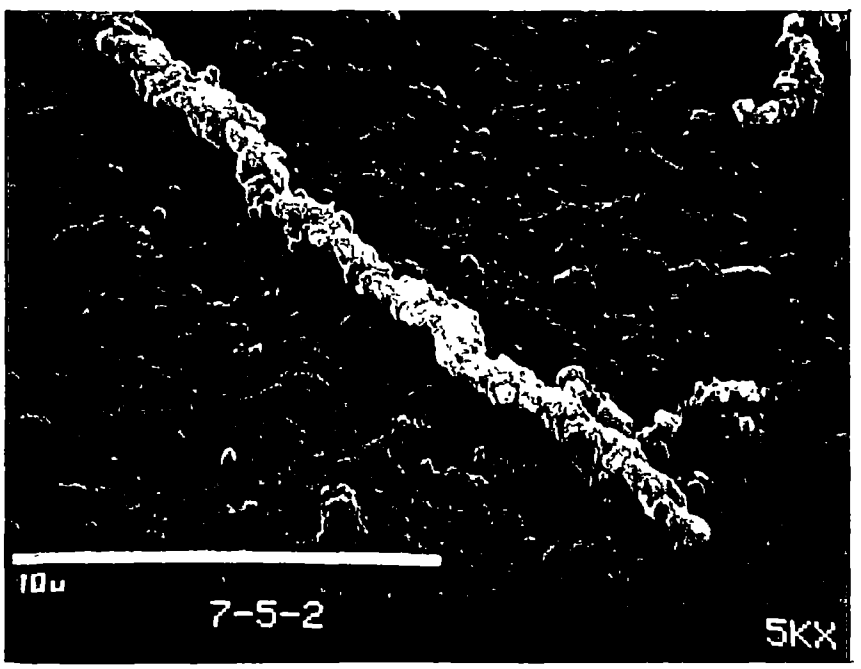
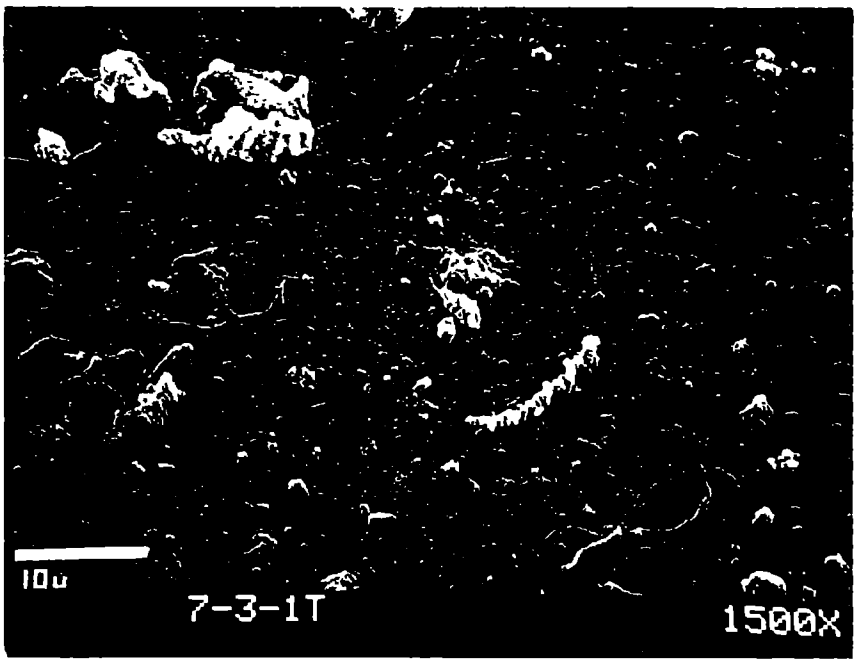


Exhibit G4-9 Scanning Electron Microscope Photographs of Slime Sample Collected from Cell E Before the First Backwash (12/6/82) at 1500X and 5000X Magnification



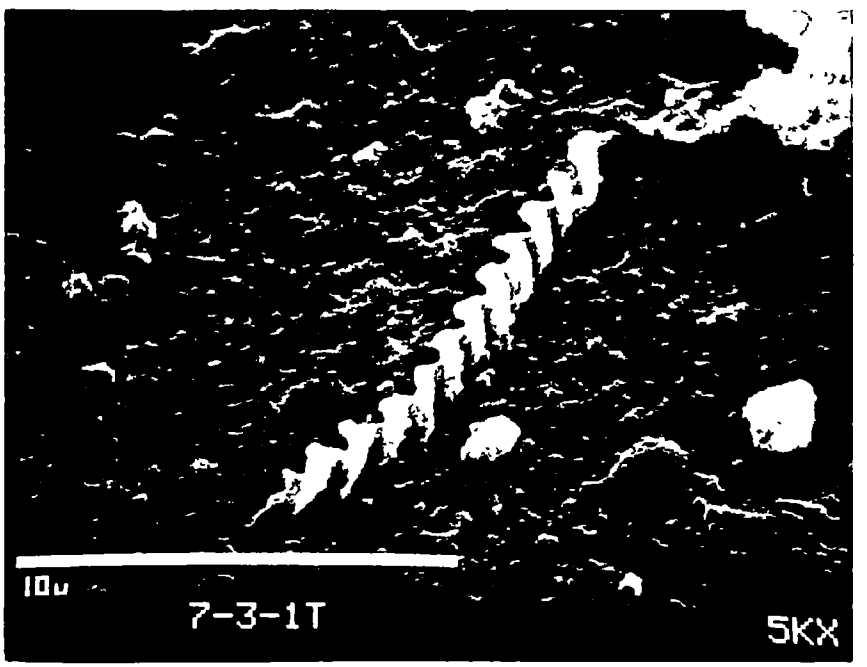


Exhibit G4-10 Scanning Electron Microscope Photographs of Slime Sample Collected from Cell A Before the Second Backwash (12/8/82) of 1500X and 5000X Magnification

The bulk characterization analyses performed by ERT on the sand and slime deposit samples are reported in Table G4-27. These data add further evidence for the presence of iron bacteria growths in the filter cells and the minimal effect of backwashing on these growths. The data in Table G4-27 show that slime deposit samples consistently contained higher levels of total iron, volatile solids and acid digestible residues and lower levels of non-acid digestibles compared to sand samples. This is consistent with a greater presence of iron bacteria in the slime samples, since these bacteria would report as volatile solids in the analysis scheme employed. The higher iron levels would result both from deposits of iron precipitates and from the fact that iron bacteria incorporate reduced iron into their structures (Stanier, Doudoroff and Adelberg 1963, Kemmer 1979).

The acid digestible residues in the slime samples generally contained about 50 percent iron.* This iron content is consistent with a ferric hydroxide precipitate ($Fe(OH)_3$), which would contain 52 percent iron, 45 percent oxygen and 3 percent hydrogen. However, ferric hydroxide is actually not an identifiable crystalline material and is probably better represented as $FeOOH \ X H_2O$, where X is a function of the temperature and vapor pressure during drying of the precipitate (Robinson, Demirel and Baumann 1981). Slime samples after the second backwash (7-4P/C-1T and 5T) contained acid digestible residues comprised entirely of iron. The cause of the higher iron content in the acid digestible residues in these later samples is unknown, but may be due to differences in sampling or analytical procedures.

A significant finding of the analyses reported in Table G4-27 was the presence of significant carbon residues in the slime and sand samples, with significantly higher carbon residues present in slime samples. These carbon residues were shown by microscopic examination to be similar to the powdered activated carbon used for the PAC slurry injection system at the wellhead of St. Louis Park well SLP15. This

*The acid digestible residues contained any iron in the sample, so that the percentage of iron in the acid digestible residues can be calculated by dividing the total iron content by the acid digestible residue content.
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TABLE G4-27

GROSS CHARACTERIZATION ANALYTICAL RESULTS FOR SAND AND SLIME SAMPLES COLLECTED DURING ERT'S DECEMBER 6-8, 1982 TEST AT ST. LOUIS PARK STATION NO. 1[a,b]

(All results in weight percent, dry basis)

Sample Number	Total Iron	Carbon Residue	Volatile Solids	Acid Digestible Residue	Non-Acid Digestible Residue	Sum[c]
BEFORE FIRST BACKWASH						
7-1-1-X	6.9	1.54	1.1	11.4	80.7	94.7
7-4-1-X	3.9	0.73	1.0	8.7	70.9	81.3
7-5-1-X	2.7	0.53	0.8	4.8	93.8	99.9
7-5-2-P/C						
Slime	14.6	19.3	13.2	29.8	8.85	71.2
Sand	2.5	0.63	0.5	4.8	100.2	106.1
AFTER FIRST BACKWASH						
7-5-3-P/C	2.9	0.67	1.0	3.4	119.5	124.6
BEFORE SECOND BACKWASH						
7-3-P/C-1T	8.1	2.30	2.7	14.7	85.3	105.0
7-3-P/C-1B	4.6	0.17	1.0	4.7	100.4	106.3
7-3-P/C-5T	3.7	0.84	1.1	7.1	82.8	91.8
7-3-P/C-5B	3.0	0.20	0.8	3.6	103.4	108.0
AFTER SECOND BACKWASH						
7-4-P/C-1T	7.1	2.47	2.3	7.0	78.7	90.5
7-4-P/C-1B	4.3	0.13	0.4	5.1	104.4	110.0
7-4-P/C-5T	3.6	1.19	1.2	3.0	90.9	96.3
7-4-P/C-5B	2.3	< 0.01	0.9	2.4	86.9	90.2
AVERAGE RESULTS[d]						
Slime Samples	5.6 ± 2.3	1.7 ± 0.8	1.8 ± 0.8	8.0 ± 4.9	84.4 ± 5.1	
Sand Samples	3.6 ± 1.1	0.13 ± 0.08	0.8 ± 0.3	4.0 ± 1.2	98.8 ± 8.1	

Notes to Table G4-27

(a) See Table G4-21 for description of analytical procedures.

(b) All samples were analyzed for hexane extractables and methylene chloride extractables and all yielded no detectable extracts with either solvent (0.01 percent detection limit).

(c) Sum does not include total iron, since this is included in the acid digestible residue yield. Average of the 14 sums is 98.3 percent, with a standard deviation of 13.3 percent.

(d) Mean $\pm$ standard deviation for 4 slime samples (all samples ending in T) and 4 sand samples (all samples ending in B).

indicates that the slime deposits on top of the sand beds must have been present in July 1982 when the PAC injection systems was last used (see Section G4.4.2). It is even possible that some of the PAC observed in the slime deposits orginated from Hickok's pilot testing of PAC injection back in 1980 (see Section G4.2), since the deposits probably built up gradually up over a period of a few years (Goplin 1982). If the average carbon residue content of 1.7 ± 0.8 percent for the slime deposits samples analyzed is assumed to be representative of the entire slime deposit in the tested filter unit, then the entire slime deposit contained on the order of 50 pounds of PAC (assuming an average slime thickness of 1/2 inch and bulk density of 130 pounds per cubic foot). This calculation indicates that most of the observed PAC must have come from Hickok's 1980 tests, since only 3 pounds of PAC was added to well 15 in July 1982 (see Section G4.4.2).

Origin of Slime Deposits

The origin of the slime deposits observed at St. Louis Park Station No. 1 is unknown, but two factors seem to be important in having allowed the deposits to accumulate. The first factor is that the backwash flow rates used at Station No. 1 were not high enough to flush the slime deposits from the filter beds. This was clearly shown by inspecting the cells before and after the two backwashes made during ERT's test, as illustrated by the photographs in Exhibits G4-3 to 6. The second factor is that most of the prechlorination dose appeared to be consumed in oxidizing ferrous iron.

The backwash cycle at Station No. 1 is controlled so that each filter cell is backwashed sequentially for about 12 minutes each. For the first 4 or 5 minutes the cells are backwashed at a low rate (about 1000 gallons per minute, or 10 gallons per minute per square foot). This is followed by backwashing at a higher rate (about 1500 gallons per minute or 15 gallons per minute per square foot) (see Figure G8-8). Table G4-28 shows field measurements and laboratory analysis results for samples collected during the backwashing of cell E at the start and end of ERT's test. Somewhat lower iron concentrations were observed in the wastewater from the second backwash. The plant had

TABLE G4-28

INORGANIC CONSTITUENT CONCENTRATIONS IN BACKWASH FEED
AND WASTEWATER SAMPLES COLLECTED DURING ERT'S DECEMBER 6-8, 1982 TEST

(All concentrations in milligrams per liter unless otherwise noted)

Parameter	First Backwash (12/6/82)			Second Backwash (12/8/82)		
	Backwash Feed Water (4B-1)	Wastewater First Half (8-1)	Wastewater Second Half (8-2)	Backwash Feed Water (4B-2)	Wastewater First Half (8-3)	Wasterwater Second Half (8-4)
FIELD MEASUREMENTS						
pH	6.3	6.7	6.8	7.2	7.3	7.3
Conductance, µmhos/cm	560	540	520	580	505	505
Turbidity, NTU	24	22	22	7.9	2.5	4.9
Iron (Hach Kit)	2.7	5.0	11.2	3.05	4.25	6.0
LABORATORY ANALYSES						
TOC	2.2	2.7	2.5	3.9	2.8	2.9
Alkalinity (as $CaCO_3$)	296	294	292	308	272	280
Hardness (as $CaCO_3$)	318	315	308	322	287	287
Iron	1.51	3.89	8.47	3.61	4.66	6.17
Manganese	0.092	0.121	0.117	0.086	0.128	0.124

only operated from two days since the first backwash and the filter units had therefore not built up as much iron precipitate as before the first backwash. The iron concentrations are consistently higher for wastewater samples collected during the second half of the backwashing cycles because of the higher backwash flow rates during this period.

The data in Table G4-28 provide additional evidence for the poor efficiency of the backwashing during the December 1982 test. The data show that backwash wastewater samples generally contained only from 1 to 3 milligrams per liter more iron than the backwash feed water, except for the second half of the first backwash, which showed an increase of from 7 to 8 milligrams per liter. These increases are much lower than the increase of from 40 to 80 milligrams per liter which was observed between the backwash feed water and wastewater during ERT's February 1983 test after the backwash flow rate was substantially increased (see Table G4-43 in Section G4.5.5).

The backwash flow rates during ERT's December test were near the design rate of 15 gallons per minute per square foot of filter area, but significantly below the rate of 18 gallons per minute per square foot subsequently recommended by Layne Minnesota Company, who were the sales engineers for the treatment plant at St. Louis Park Station No. 1 (Goplin 1982). St. Louis Park Water Department personnel have adjusted the backwash controller since the December test to give backwash rates of about 19 gallons per minute per square foot during the second stage of the backwash cycle and this has considerably improved the efficiency of the backwashing (see Section G4.5).

The second factor which appears to have allowed the slime deposits to accumulate, or at least the iron bacteria in the deposits, is the fact that most of the prechlorination dose at Station No. 1 was consumed in oxidizing ferrous iron. The residual chlorine level in the water entering the filter was only 0.3 to 0.4 milligrams per liter (see Table G4-24) at normal prechlorination rates. This residual chlorine dose was apparently too low to kill all of the iron bacteria in the raw water and the filter units, nor was it sufficient to

oxidize all of the ferrous iron in the time allowed. This is supported by the fact that residual chlorine levels in the filtered water were generally non-detectable (see Tables G4-22 and 23), which indicates an incompletely satisfied chlorine demand in the filter unit, presumably due to the iron bacteria or other organic matter trapped in the filter.

It is unknown how long the iron precipitate deposits were present in the filter tested at Station No. 1, but the indications are that they were there for at least a few years. A representative of Layne Minnesota Company who later inspected the filter unit cells together with ERT personnel (January 1983) and studied ERT's photographs of the filter bed surfaces taken during the December 1982 test has indicated that, based on his experience, the amount of deposits observed probably took a few years to develop (Goplin 1983). The high concentrations of powdered activated carbon measured in the slime deposits indicates that much of the carbon must have come from Hickok's tests during the fall of 1980. Furthermore, MDH analyses of treated water from Station No. 1 during MDH inspections in May 1980 and September 1981 showed high iron levels, indicating that performance problems existed then (see Table G2-4). St. Louis Park Water Department personnel had not inspected the insides of the cells since at least 1975; and perhaps since the construction of the plant in 1970 (Tollefsrud 1982). All of these items indicate that the slime deposits were probably present during CH2M Hill's September 1982 test, although the cells were not inspected during this test.

As a result of the discovery of the slime deposits during ERT's December 1982 test, St. Louis Park Water Department personnel inspected the other three filter units at Station No. 1 and found slime deposits in all of them. However, the slime deposits were most severe in the filter unit tested in December (the western-most unit - see Figure G2-3). With the advice of Layne Minnesota Company, St. Louis Park Water Department personnel took a number of steps to eliminate the slime deposits and prevent their reoccurence. The filter units were treated with high dosages of sodium hypochlorite and allowed to stand filled overnight in order to kill the iron bacteria.

The backwash controller was adjusted to give higher backwash rates (19 gallons per minute per square foot during ERT's February 1982 test) and the prechlorination rate was adjusted to give higher chlorine doses (2.5 milligrams per liter during ERT's February 1982 test). Subsequent inspections of selected filter cells by ERT, Layne Minnesota and St. Louis Park personnel on January 12 and February 1-2 indicated that these steps were successful in removing the slime deposits (see section G4.5). ERT, Layne Minnesota and St. Louis Park Water Department also inspected selected filter cells at the other four iron removal plants in St. Louis Park on January. These inspections showed that none of the other plants showed signs of slime deposits, except for a single cell out of the eight cells at Station No. 8, which had a deposit about 1/2 inch thick. The cause of this single cell at Station No. 8 being affected while the other seven were not is currently unknown.

Significance of Slime Deposits

The iron precipitate and iron bacteria deposits observed at St. Louis Park Station No. 1 could have had two important effects on the behavior of PAH observed in the treatment plant during CH2M Hill's September 1982 test and ERT's December 1982 test. First, the deposits probably changed the filtration or adsorption of PAH in the filter unit compared to filtration through a sand filter without the deposits. Second, the deposits probably affected the flow patterns of water through the filter cells. Neither of these effects can be clearly documented, however.

The probable effect of the slime deposits on filtration or adsorption of PAH is based on the distinctly different particle size and surface area characteristics between filter bed sand and slime deposits. Filter bed sand consists of uniformly sized 0.55 to 0.65 millimeter sand particles, which during operation become coated with a thin layer of iron precipitate. Scanning electron microscopic examination of sand samples collected during ERT's February 1982 clearly showed this coating, which was about 3 or 4 microns thick.

The slime deposits, on the other hand, consist of an amorphous mass of iron precipitate interspersed with well sand, powdered activated carbon, and iron bacteria. The deposits would be expected to have a very high surface area and very small void passages. The higher surface area and the presence of organic matter (PAC and bacteria) on the surface would be expected to provide enhanced filtration and/or adsorption potential for PAH compared to the sand bed.

The likely effect of the slime deposits on flow patterns in the filter unit is based on Layne Minnesota's experience with similar problems in other iron removal plants (Goplin 1983a). Slime deposits tend to cause water to channel along the filter cylinder walls around the sand bed itself because this flow path offers less resistance than flow through the amorphous deposits. This channeling, or short circuiting, occurs both during normal downflow filter operation and during backwashing.

Channeling during backwashing has two effects. First, it reduces the effectiveness of the backwashing. This compounds the problem because the slime deposits are not removed, continue to accumulate and lead to more and more severe channeling. Second, channeling during backwashing can disrupt the supporting gravel bed, which again compounds the channeling problem and can ultimately lead to portions of the sand bed collapsing. Channeling during backwashing was evidenced by the observation of mounding of the slime deposits along the cylinder walls during ERT's filter cell inspections. This mounding results from channeled backwash water overturning the deposits along the sides of the filter bed.

The result of channeling during normal operation is that little, if any, iron is filtered from the channeled water so that overall iron removal is decreased. This is consistent with the relatively high iron levels observed in the filtered water during ERT's December 1982 test (see Tables G4-22 and G4-23) compared to expected levels during normal operation of less than 0.05 milligrams per liter (see Table G2-4). This may also explain the significant amount of dissolved (ferrous) iron observed in the filter outlet on December 7 (0.068 milligrams per liter - see Table G4-22).

Further evidence of channeling is provided by time-series measurements of dissolved oxygen levels in filtered water from the various cells. These measurements were made on December 7 after the aerator was shut off as a check on the dynamics of the filter units. The results are chronologically plotted in Figure G4-8. Immediately prior to being shut off, the aeration rate had been set at 100% of full-scale for about 25 minutes, which amounted to adding 13 milligrams per liter of oxygen to the water. It was expected that the dissolved oxygen levels in the filter outlet water would slowly decline from a level of 13 milligrams per liter, based on a calculated hydraulic residence time of 16 minutes*. However, as shown in Figure G4-8, dissolved oxygen levels were only 0.4 milligrams per liter 10 minutes after shutting off the aerator. Within 30 minutes the dissolved oxygen had dropped to only 0.2 milligrams per liter, which is the same as the level observed in non-aerated water (see Table G4-24). This result can be explained by channeling around the filter bed, which would cause the effective hydraulic residence time to be much shorter than 16 minutes. Similarly, the dissolved oxygen levels in the filter outlet cell taps responded quickly when the aerator was later restarted (see Figure G4-8).

The time series measurements shown in Figure G4-8 indicate that cell A responded to shutting off the aerator much differently than the other four cells. Seventy minutes after shutting off the aerator, the dissolved oxygen level in the filtered water from cell A was 3.3 milligrams per liter and two hours afterwards was still 1.6 milligrams per liter. This indicates that either 1) air was being trapped in cell A due to restriction or blockage in the air relief vent line for the cell or, 2) the flow rate through cell A was much lower than the other cells. St. Louis Park Water Department personnel checked the air vent line for cell A at the conclusion of ERT's test and found

*Based on a volume of 440 cubic feet being open to water flow in ech filter cell above the underdrain plate. This volume is based on the dimensions shown in Figures G2-6 and 9, assumed void fractions of 0.3 in the sand bed and 0.4 in the gravel support bed, and a total flow rate of 1050 gallons per minute (0.47 cubic feet per second per cell).

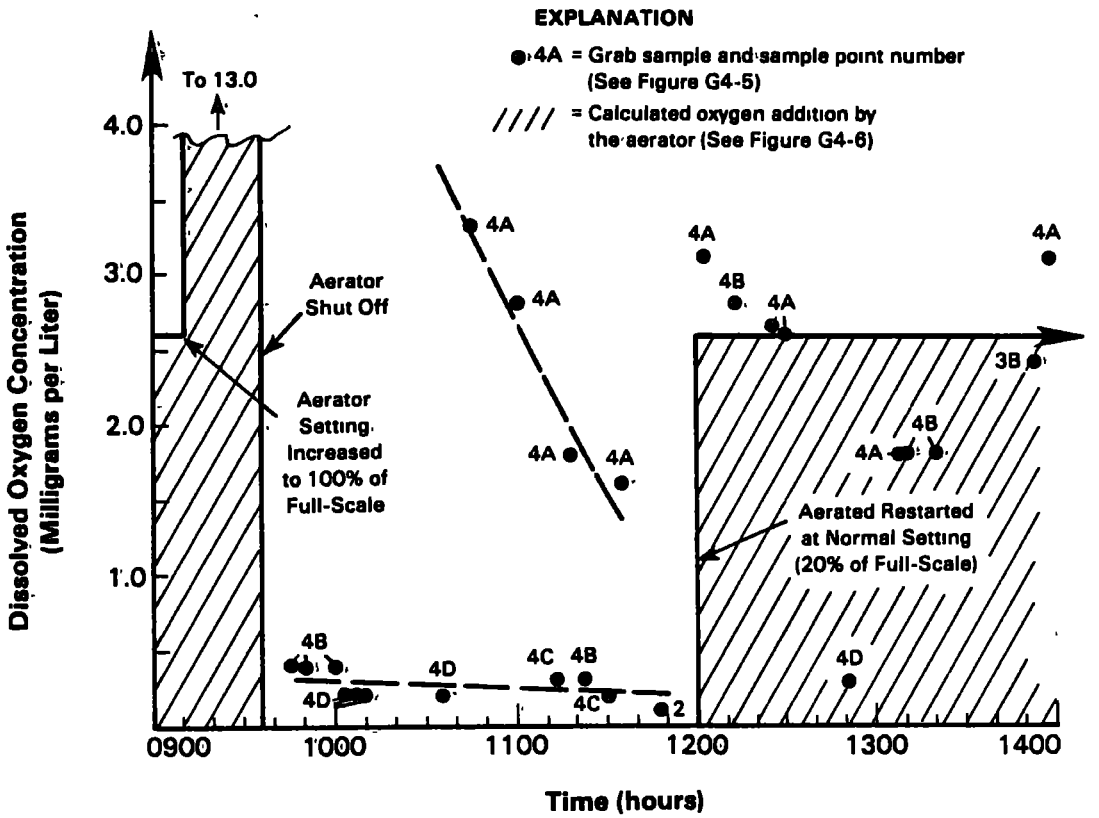

Figure G4-8 Results of Time-Series Measurements of Dissolved Oxygen in the Outlet of Various Filter Unit Cells, December 7, 1982

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that it was not blocked. This indicates that the flow rate through cell A was somehow reduced compared to the other cells, although the cause of such a reduced flow rate is unknown. Based on an exponential decay of dissolved oxygen in response to shutting off the aerator, a flow rate of about 60 gallons per minute through cell A is indicated by the data shown in Figure G4-8. This is well below the rate of 210 gallons per minute expected if flow was evenly divided among all five cells.

Channeling may have affected the representativeness of the filter outlet samples collected during CH2M Hill's September 1982 test and ERT's Dcember 1982 test. The basis for this concern is the placement of the filter outlet sample tops located under each filter bed. Figure G4-9 shows that the sample taps draw water from immediately below the bed support plate right alongside the cylinder wall. Figure G2-9 (in section G2.1.2) shows that the bed support plate and cylinder wall meet in a very acute angle at the location of the sample taps. It seems likely that a sample collected from one of the filter outlet taps would contain a significant amount of channeled water because of the positioning of the taps.

A rough indication of the effect of channeling on filter outlet samples can be obtained by assuming that the sampled filter outlet water is a mixture of channeled water containing about 0.8 milligrams per liter of iron (i.e., no iron removal - see Tables G4-22 and 24) and filtered water containing 0.05 milligrams per liter of iron (assumed value for effective iron removal - see Table G2-4). With this model, the measured iron levels of 0.1 to 0.3 milligrams per liter in samples from the filter outlet taps (Tables G4-22 and 23, assuming field measured values are biased high by 0.2 to 0.3 milligrams per liter) indicate that anywhere from 10 to 30 percent of the water sampled was channeled around the filter beds. Note that this calculation does not indicate the relative proportion of channeled and filtered water over the entire filter unit; it simply indicates the relative amount of channeled water in the sample. These two proportions are not necessarily the same because flow patterns near a given sample tap may have caused mixing of channeled and filtered water in different proportions at that particular point than

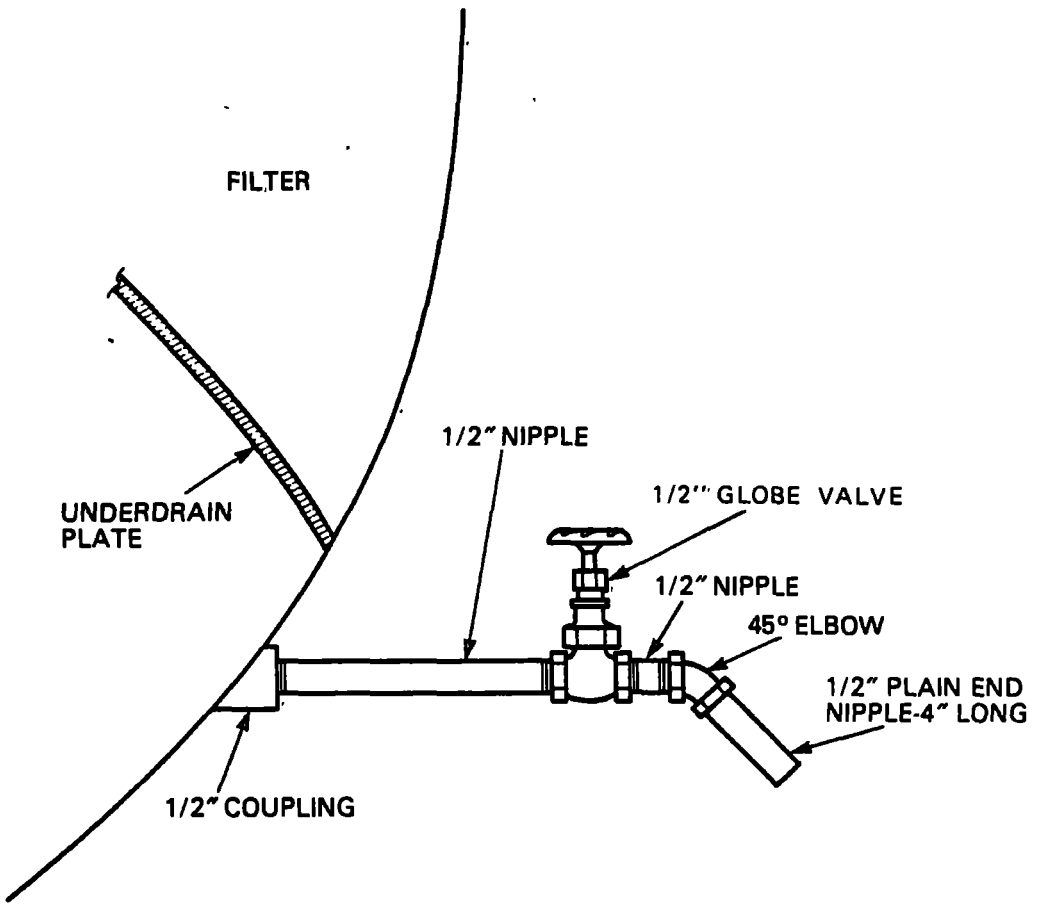

Figure G4-9 Sketch of Sampling Cock for the Sand Filter Cells at St. Louis Park Water Treatment Station No. 1 (Reproduced from General Filter Company 1969, Drawing A-9882-F)

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occurred throughout the entire filter. For example, 75 percent of the overall flow could have been channeled and yet only 25 percent of the water sampled from a given cell could have consisted of water channeling around that cell.

G4.4.6 Data Interpretation - PAH Removal

As indicated by Table G4-20, ERT's December 1982 test at St. Louis Park involved a number of individual test objectives related to the behavior of PAH in the iron removal plant. The data that address these objectives are discussed in this subsection, starting with the results of composite samples collected to assess the overall performance of the plant in removing PAH under normal operating conditions. This is followed by discussions of the results that address individual aspects of the overall plant operation, including changes in well water quality, effects of aeration and prechlorination under various conditions, evaluation of PAH behavior in the filter, and effects of backwashing.

All of the PAH data presented in the tables in this subsection have been summarized by grouping them according to compound classes. Two-ring PAH are all compounds from indene through dimethylnapthalenes; three-ring PAH are all compounds from acenaphthylene through anthracene, plus acridine and carbazole; and four-ring PAH are benzo(a)anthracene, chrysene, fluoranthene and pyrene (see Table G8-1). No five or six-ring PAH were detected in any of the samples, except for some of the backwash wastewater samples, in which case these compounds are grouped separately.

In some instances, data are also grouped according to carcinogenic and noncarcinogenic PAH, based on the definitions and lists of carcinogenic and noncarcinogenic PAH given in Appendix I. It should be noted that the only carcinogenic PAH detected in any of the samples, except for some of the backwash wastewater samples, were benz(a)anthracene and chrysene. These are also the only carcinogenic PAH detected by any of CH2M Hill's analyses of well SLP15 (see Section G4.3), except that CH2M Hill also detected quinoline in some samples, which was not analyzed by MRC.

Reporting PAH analysis results by compound class simplifies data interpretation and presentation but in general does not mask distinctly different trends for individual compounds compared to compound classes. In other words, individual compounds generally showed similar behavior to their respective compound classes. Notable exceptions to this general trend are noted in the discussions that follow.

Normal Operation

Table G4-29 summarizes the results of PAH analyses of 4 1/2 hour composite samples collected at four points throughout the treatment plant on December 7. Average results are reported for the wellhead water and the filtered water. These averages are both derived from triplicate samples, one of which was treated with 1.0 milligram per liter of calcium hypochlorite, plus the sum of the PAH concentrations measured in the filtrate and the filter residue from filtering each of these triplicate samples through a 0.5 micron Teflon filter. All of these samples were averaged to obtain a sense of the accuracy of the results. Averaging these various types of samples, which are not strictly replicates, is judged to be correct because the 0.5 micron filtering step was shown to result in 100 percent recovery of the PAH in the unfiltered water (within the accuracy of the data - see Table G4-33) and because the calcium hypochlorite addition step was shown not to affect PAH concentrations (within the accuracy of the data - see Table G4-32).

Table G4-29 shows that concentrations of two and three-ring PAH were the same in all of the composite samples, within the accuracy of the data. This indicates that no measurable removal of these compounds took place in the length of about 350 feet of pipe from the wellhead to the aerator inlet (see Figure G2-4), during aeration or prechlorination, or during filtration. Four-ring PAH did show about 30 percent removal across the entire treatment plant, which is statistically significant at the 99 percent confidence limit, based on comparing average wellhead results and average filter outlet results for six samples in each case. The observed removal of four-ring PAH may have occurred between the wellhead and the filter inlet, although

TABLE G4-29

PAH CONCENTRATIONS IN COMPOSITE SAMPLES
COLLECTED AT VARIOUS POINTS FROM THE IRON
REMOVAL PLANT AT ST. LOUIS PARK STATION NO. 1
ON DECEMBER 7, 1982

(All concentrations in nanograms per liter)[a]

Compound Class	Wellhead (1D-9)[c]	Aerator Inlet (2-2)	Filter Inlet (3B-4)	Filter Outlet (4A-P)[d]	Ratio of Filter Outlet to Wellhead Concentrations[f]
2-Ring PAH	1720 ± 270	1860	1780	1520 ± 700	0.88 ± 0.44
3-Ring PAH[b]	2900 ± 580	3050	2430	2800 ± 480	0.97 ± 0.25
4-Ring PAH	730 ± 130	550	480	500 ± 60	0.68 ± 0.15
TOTAL PAH	5350 ± 650	5460	4690	4820 ± 850	0.90 ± 0.37
Noncarcinogenic PAH	5310 ± 650	5420	4640	4820 ± 850	0.91 ± 0.37
Carcinogenic PAH	39 ± 15	40	45	ND[e]	< 0.23

Notes:

(a) Complete results given in Table G8-1.

(b) Includes acridine and carbazole.

(c) Mean ± standard deviation for samples 1D-9-P, 1D-9-P-Duplicate, 1D-10-P and the sum of the F/R-W and F/R-F analyses for each of these samples (i.e., six results in all).

(d) Mean ± standard deviation for samples 4A-4-P, 4A-4-P-Duplicate, 4A-5-P and the sum of the F/R-W and F/R-F analyses for each of these samples.

(e) Not detected, with detection limit of 9 nanograms per liter.

(f) Standard deviation of the ratio obtained by $s_r^2 = (s_F/W)^2 + (Fs_W/W^2)^2$ where s is the standard deviation for the ratio (s_R), filter outlet samples (s_F) or wellhead samples (s_W), and W and F are the wellhead and filter outlet concentrations, respectively. This expression is derived from $s_A^2 = (\partial A/\partial X)^2 s_X^2 + (\partial A/\partial Y)^2 s_Y^2$ where $A = f(X,Y)$.

this is uncertain within the accuracy of the data. Other results from the test indicate, however, that the observed removal of four-ring PAH resulted from the filtration step. In addtion, carcinogenic PAH (benz(a)anthracene and chrysene) were removed by over 75 percent to below detectable concentrations. The removal of these carcinogenic PAH appears to have occurred entirely due to filtration.

During the composite sampling period, a check was made on potential variability in the treatment plant's effects on PAH by collecting grab samples at the start, middle and end of the compositing period. The SIM GG/MS chromatograms for these grab samples are shown in Figure G8-1. The chromatograms for the three wellhead grab samples (1d-6-S, 1D-7-S and 1D-8-S) are all very similar to the chromatograms for the duplicate composite wellhead samples (1D-9-P). The only major differences are in the full-scale peak concentration, but these probably reflect different extraction efficiencies and the overall accuracy of the sampling and analysis procedures. As shown by the means and standard deviations for six nominally replicate analyses* in Table G4-29, this overall accuracy is on the order of 20 to 30 percent relative standard deviation. Similar results are indicated by comparing the chromatograms of three filter outlet grab samples (4A-1-5, 4A-2-5, and 4A-3-5) with the chromatograms of the duplicate composite samples (4A-1-P).

Changes in Wellhead Water Quality

Another check of variability in the behavior of PAH at Station No. 1 was made by collecting time-series grab samples of wellhead water throughout the test. Nine time-series samples were collected, beginning one hour after well SLP15 was started and ending 42 hours after starting the well**. Figure G8-1 contains SIM GC/MS

*The six samples were not time replicates because one had calcium hypochlorite added and three samples represent the sum of filtrate and filter residue results.

**Well SLP15 was run from 10 30 to noon on the morning of December 6 to provide water for backwashing. The well was then restarted at 1330 and run for the duration of the test (see Figure G4-6). The timing of the time-series samples has been related to the second starting of the well.

chromatograms for all of the time-series samples (1D-1-5 through 1D-11-15). The peak patterns are very similar in all of these samples, although the full-scale peak height concentrations vary.

Figure G4-10 shows a chronological plot of the time-series results, with the triplicate composite samples (1D-9, 1D-9 Duplicate and 1D-10) also included. The upper portion of Figure G4-10 shows total PAH concentrations for samples which were quantified by SIM GC/MS analyses. The lower portion shows the full-scale peak height concentrations from the SIM GC/MS chromatograms. These two types of data are not directly comparable because not all of the time-series samples were quantified and because the full-scale peak height concentrations are not directly proportional to total PAH concentrations (due to different extraction efficiencies and slight shifts among individual peaks). Both types of data are consistent, however, in showing that PAH concentrations in the wellhead water dropped by about 50 percent over the 42-hour sampling period. PAH concentrations decreased rapidly at first, with most of the decrease having occurred within about 12 hours.

The time-series sampling results for St. Louis Park well SLP15 are significant for two reasons. Within the context of ERT's test at St. Louis Park Station No. 1, they are important in showing that PAH concentration in wellhead water were a steady after about 12 hours. This means that all of the testing on December 7 and 8 was performed with stable wellhead PAH concentrations, while testing on December 6 took place while wellhead PAH concentrations were declining.

In a broader context, the time-series results have important implications regarding the collection of representative ground water samples for PAH from contaminated wells. They indicate that samples collected from a contaminated well after only an hour or two hours of pumping may yield PAH concentrations that are twice as high as a more representative sample collected after half a day or a day of pumping. The cause of this marked pumping time effect is currently unknown, but it warrants further investigation in light of the need to obtain representative samples for ground water monitoring (see Appendix J).

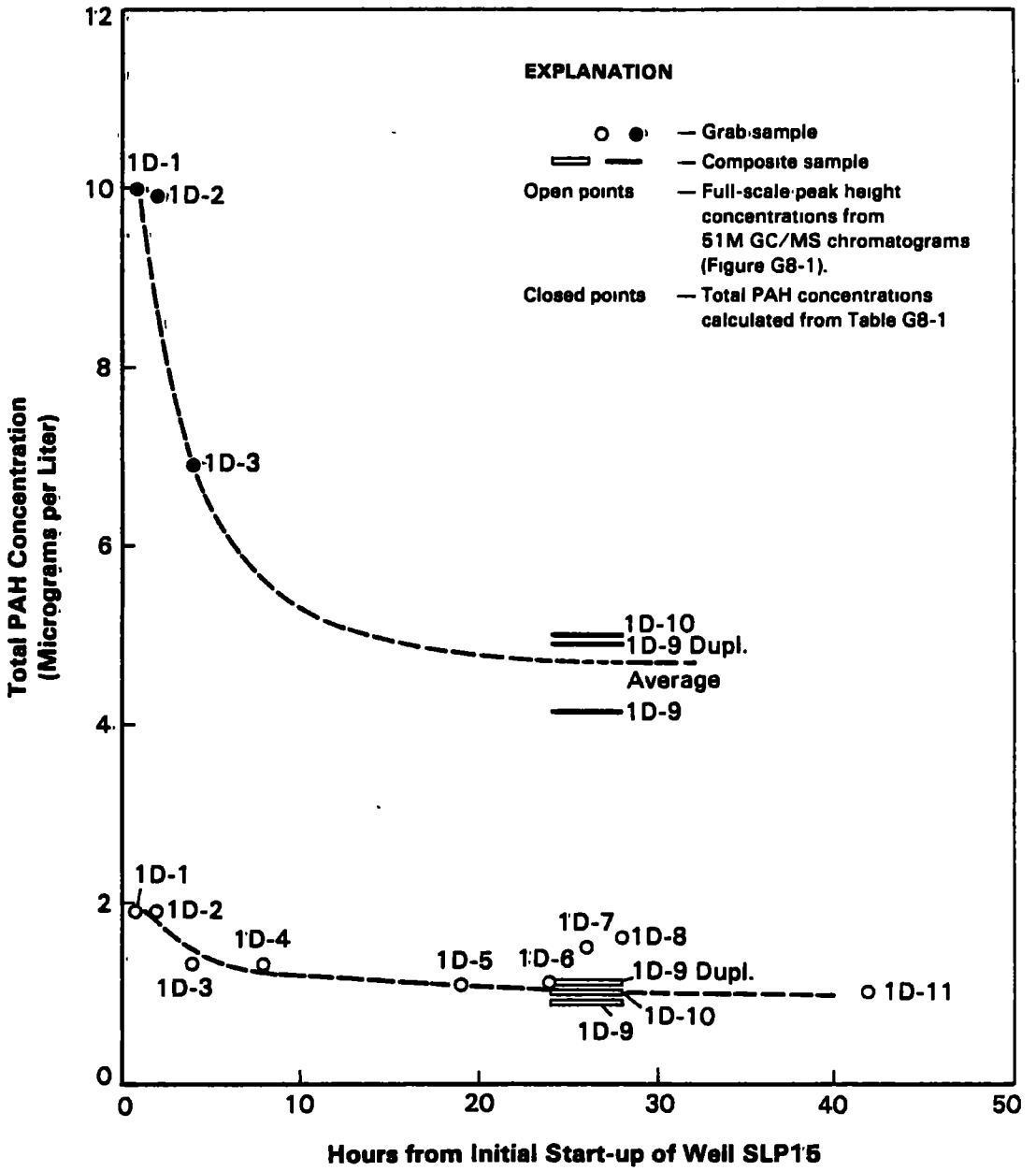

Figure G4-10 Results of Time-Series Sampling for PAH in Well SLP15, December 6-8, 1982

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Aeration and Prechlorination Effects

Table G4-30 summarizes the results of PAH analyses for samples of filter inlet water collected at various aeration and prechlorination rates. The different conditions tested were:

Description	Oxygen Added, milligrams per liter	Chlorine Added, milligrams per liter	Filter Inlet Pressure, pounds per square inch
Normal Operation	2.5	1.2	10
Aeration Only	2.5	0	13
Prechlorination Only	0	1.2	13
Maximum Aeration	12.3	0	29
Maximum Aeration & Prechlorination	12.3	1.2	18

In every case, the chlorine was quickly dispersed in the water but the oxygen took much longer to dissolve (see section G4.4.5). The residence time of the water between the chlorine injection point and the filter inlet sample was about 11 seconds, but additional reaction probably occurred in the sample bottles.

Table G4-30 shows that none of the aeration and prechlorination conditions tested resulted in significant PAH reductions, except for the case of maximum aeration and prechlorination. PAH concentrations for the other cases were not significantly different than the aerator inlet water within the accuracy of the results (20 to 30 percent relative standard deviation). This indicates that the observed removal of four-ring PAH in composite samples from throughout the treatment plant (Table G4-29) resulted from filtration, not aeration or prechlorination. Maximum aeration and prechlorination conditions resulted in about a 60 percent decrease in total PAH concentration, with about 40 percent reduction for two-ring PAH and about 70 percent reductions for three and four-ring PAH.* A close examination of the complete PAH quantitation data for the maximum aeration and prechlorination samples (number 3B-5-P, Table G8-1E) compared to the

*Based on comparing samples 2-2 and 3B-5.

TABLE G4-30

EFFECTS OF DIFFERENT AERATION AND PRECHLORINATION RATES ON PAH REMOVAL DURING ERT'S DECEMBER 6-8, 1982 TEST

(All concentrations in nanograms per liter)[a]

Compound Class	12/6/82 Tests			12/7/82 Tests			
	Aerator Inlet (2-1)	Prechlorination only (3B-1)	Aeration Only (3B-2)	Aerator Inlet (2-2)	Maximum Aeration (3B-3)	Normal Operation (3B-4)	Maximum Aeration and Prechlorination (3B-5)
2-Ring PAH	2880	2810	2580	1860	2080	1780	1090
3-Ring PAH[b]	3710	3600	4050	3050	3320	2430	900
4-Ring PAH	1100	1020	1050	550	900	480	200
TOTAL PAH	690	7430	7680	5460	6300	4690	2190
Noncarcinogenic PAH	7360	7360	7610	5420	6240	4640	2180
Carcinogenic PAH	64	67	68	40	57	45	11

Notes:
(a) Complete data given in Table G8-1.
(b) Includes acridine and carbazole.

aerator inlet sample (number 2-2-P, Table G8-1D) shows that reductions varied widely among individual compounds within a given ring-size class. For example, among four-ring aromatics, pyrene was reduced by 99 percent compared to 72 percent for benzo(a)- anthracene and chrysene and 34 percent for fluoranthene. Other compounds showing substantial reductions were dimethylnaphthalenes, acenaphthylene, dihydroacenaphthylene and anthracene. It appears that the PAH removals observed during maximum aeration and prechlorination were predominantly due to oxidation by chlorine, not by oxygen. This is apparent by noting that maximum aeration by itself had no observable effect in reducing PAH concentrations (sample number 3B-3 in Table G4-30).

The results of the maximum aeration and prechlorination test are consistent with CH2M Hill's results for bench testing of chlorination (see Section G4.3.). CH2M Hill tested chlorination at a 10 milligrams per liter dose with a one hour reaction time at a pH of 4.5 and temperatures of 50° and 75°F. In both cases, total PAH concentrations were reduced by about 70 percent, with some compounds being much more effectively removed than other (CH2M Hill 1982). CH2M Hill's test results are generally consistent with ERT's test in showing which compounds are particularly susceptible to chlorine oxidation (e.g., acenaphthylene, dihydroacenaphtlylene and pyrene).

The results from air sampling with 100 gram XAD-2 resin samples for compressor intake air (sample number 10-1-S) and air pressure relief line exhaust air (sample number 6-1-S) are relevant to the behavior of PAH during the aeration step. These two samples showed no significant PAH at levels compared to the XAD-2 blank except for traces of indene, methylnaphthalenes and biphenyl (see Figure G4-8C). There was also a large naphthalene peak that masks the naphthalene $-d_8$ spike peak in the chromatograms. Naphthalene and methylnaphthalenes have been reported as degradation products during storage of XAD-2, (Hunt, Pangars and Zelinski 1980), and it appears that this was the origin of the observed naphthalene, since it was also observed at high levels in the XAD-2 blank sample. Because of this problem, the XAD-2 resin results have not been quantified. However, they do indicate qualitatively that no significant PAH levels were observed in the air

samples. This is supported by the fact that concentrations of individual two-ring PAH in aerator inlet and filter inlet samples are not significantly different (see Tables G8-1D and G8-1E).

The results of volatile organics analyses are also relevant to the aeration and prechlorination steps. The GC/MS chromatograms in Figure G8-5 indicate that water samples generally did not contain detectable volatile organics, except for traces of methylene chloride and toluene (identity not confirmed) in most of the samples. The methylene chloride is probably an artifact from prior cleaning of the sample vials.

Toluene may be associated with the spectrum of PAH contaminants in the water from well SLP15, since it was found in some of the replicate sample vials of wellhead water (sample 1D-9V) and in the filter outlet water samples collected without aeration or prechlorination (samples 4A-6V and 4C-1V). Toluene concentrations in these samples ranged from 5 to 50 micrograms per liter. However, toluene was also detected in one of the field blank samples at about 15 micrograms per liter. Toluene was also observed in filter inlet samples collected with aeration only (3B-2-V), with prechlorination only (3B-3-V), and with maximum aeration and prechlorination (3B-5-V). Concentrations in all of these samples were comparable to wellhead water samples. However, this cannot be taken as an indication that toluene was not formed as a byproduct of oxidation or chlorination reactions, since such reactions would have involved nanaogram per liter quantities of PAH (see Table G4-30), while toluene concentrations were in the microgram per liter range.

Two unidentified peaks were observed in the sample collected during maximum aeration and prechlorination at from 10 to 30 micrograms per liter (3B-5-V). These peaks were not seen in any of the other samples collected, which indicates that they may represent byproducts from the oxidative destruction of selected PAH observed under these maximum oxidation conditions (see Table G4-30).

It is noteworthy that a small peak corresponding to trichloroethylene (identity confirmed) occurred as a shoulder preceeding the benzene-d_6 spike peak in almost all of the samples

collected at a concentration of about 1 to 2 micrograms per liter, including wellhead water samples (1D-9-V) and filter outlet samples with no aeration or prechlorination (4A-6-V and 4C-1-V). CH2M Hill also detected trichloroethylene in SLP15 wellhead sample from its September 1982, but at an unreported concentration below the detectable limit of 5 micrograms per liter (CH2M Hill 1982d). CH2M Hill did not analyze for volatile organics in split samples collected during ERT's December 1982 test. It should also be noted, however, that two of the four organic-free water and field blank samples analyzed by MRC showed a small trichloroethylene peak, although the other two did not (see Figure G8-5). It is therefore possible that the trichloroethylene observed in the various field samples was a contaminant introduced somehow during sampling, handling, or analysis. On the other hand, it is possible that well SLP15 wellhead water may contain traces of trichloroethylene that pass unaffected through the iron removal treatment plant. The origin of the trichloroethylene, and whether it was truly present in the samples or was a contaminant introduced in sampling or analysis, is currently unknown.

Filtration Effects

The results from PAH analyses for composite sampling collected under normal operating conditions indicates that the slight removals (about 30 percent) observed across the system for three and four-ring PAH largely occurred across the sand filters (see Table G4-29). Other tests of filtration effects performed during ERT's test confirm this result and provide some insight into the causes.

Table G4-31 shows the results of testing PAH removal across the sand filter without any aeration or prechlorination. The two filter outlet samples (4A-6 and 4C-1) showed very different PAH concentrations. It is unclear if these differences are due to analytical variations or if they reflect real differences, perhaps related to the unusual flow patterns suspected in cell A (see section G4.4.5). Average results from these two samples indicates about 35 percent removal of four-ring PAH, with this removal being

TABLE G4-31

PAH CONCENTRATIONS IN FILTER OUTLET SAMPLES WITH NO AERATION OR PRECHLORINATION COLLECTED DURING TESTING ON DECEMBER 7, 1982
(All concentrations in nanograms per liter)[a]

Compound Class	Filter Inlet (Average)[c]	Filter Outlet Samples		Ratio of Outlet to Inlet[d,e]
		Cell A (4A-6)	Cell C (4C-1)	
2-Ring PAH	1720 ± 270	1490	3180	1.36 ± 0.73
3-Ring PAH[b]	2900 ± 580	2130	3860	1.03 ± 0.47
4-Ring PAH	730 ± 130	310	620	0.64 ± 0.32
Total PAH	5350 ± 650	3930	7660	1.08 ± 0.51
Noncarcinogenic PAH	5310 ± 650	3930	7660	1.09 ± 0.51
Carcinogenic PAH	39 ± 15	ND[f]	ND	<0.23

Notes:

(a) Complete data given in Table G8-1.
(b) Including acridine and carbzaole.
(c) Mean ± standard deviation of 6 pre-filter samples (1D-9-P, 1D-9-P-Duplicate, 1D-10-P, and the sum of F/R-W and F/R-F analyses for these three samples.
(d) Standard deviation of the ratio based on mean ± standard deviation for 4A-6-P and 4C-1-P results and calculated as described in note (e) to Table G4-29.
(e) Ninety percent confidence intervals for these ratios are 0.49, 0.20, 0.33 and 0.26 for 2,3,4-ring and total PAH, respectively. These confidence intervals are obtained by replacing the standard deviations in the formula in note (e) of Table G4-29 with the corresponding confidence intervals.
(f) Not detected, with detection limit of 9 nanograms per liter.

statistically significant at about the 70 percent confidence level. Carcinogenic PAH were again removed by over 75 percent to below detectable concentrations. No significant removal was observed for two-ring or three-ring PAH. Comparing these removals with those observed under normal operation indicates that oxidation of ferrous iron or of PAH themselves do not play a significant role in effecting PAH removal in the sand filters, since the filter removals in both cases are similar within the accuracy of the data (compare Tables G4-29 and G4-31). This result indicates that PAH removal in the sand filters was due to filtration of PAH containing particulate matter or adsorption of PAH on the filter media or some combination of these two mechanisms.

As a further test of the PAH removal mechanisms involved in the sand filters, ERT tested the effects of filtering various samples through 0.5 micron Teflon filters in the laboratory. The results of these tests are summarized in Table G4-32. A statistical summary of the results in the form of average ratios of filtered to unfiltered samples is presented in Table G4-33. The results in Tables G4-32 and 33 indicate that only slight PAH removals occurred by filtering through a 0.5 micron filter. On average, no removal was observed for two and three-ring PAH and about 7 percent removal was observed for four-ring PAH. These removals are based on residues measured on the filter, corrected for method blank results. It should be noted that these slight removals could not have been detected by simply comparing raw water and filtered water samples. They were only detectable by measuring PAH in the filter residues because the accuracy of the water analyses was insufficient to detect such a slight difference. The fact that the PAH removals observed from filtering through a 0.5 micron filter were much less than those observed in the sand filter indictes that adsorption was the primary mechanism for the observed PAH removals across the sand filters, not filtration of microparticulates containing PAH (at least not particles larger than nominally 0.5 micron).

TABLE G4-32

RESULTS OF FILTERING VARIOUS SAMPLES COLLECTED DURING ERT'S DECEMBER 6-8, 1982 TEST AT ST. LOUIS PARK STATION NO. 1

(All results in nanograms per liter)[a]

Compound Class	Wellhead Sample (1D-9-P and F/R)			Duplicate Wellhead Sample (1D-9-P and F/R-Duplicate)			Wellhead Sample Treated With 1.0 Milligram per Liter $Ca(OCl)_2$ (1D-10-P and F/R)			Aerator Inlet Sample (2-2-P and F/R)		
	Unfiltered	Filtrate	Residue[d]	Unfiltered	Filtrate	Residue	Unfiltered	Filtrate	Residue	Unfiltered	Filtrate	Residue
2-RING PAH	1450	2160	15	1540	1630	19	1560	1890	22	1860	2020	20[c]
3-RING PAH[b]	2070	2990	27	2760	3050	27	2660	3800	48	3050	3340	28
4-Ring PAH	640	770	58	570	580	91	760	840	85	550	710	51
Total PAH	4160	5920	100	4880	5200	137	4980	6520	155	5460	6070	99

Compound Class	Filter Outlet Sample (4A-4-P and F/R)			Duplicate Filter Outlet Sample (4A-4-P and F/R-Duplicate)			Filter Outlet Sample Treated With 1.0 Milligram per Liter $Ca(OCl)_2$ (4A-5-P and F/R)			Method Blank		
	Unfiltered	Filtrate	Residue	Unfiltered	Filtrate	Residue	Unfiltered	Filtrate	Residue	Unfiltered	Filtrate	Residue
2-Ring PAH	1520	2120	8[c]	1670	1430	21	2130	2170	26	49	66	17[c]
3-Ring PAH[b]	2520	3580	16	3150	2560	21	2310	2600	15	64	57	27
4-Ring PAH	490	490	26	450	410	27	500	570	38	16	20	13
Total PAH	4530	6190	50	5270	4400	69	4940	5340	79	129	143	57

Notes:
(a) Complete data given in Table G8-1.
(b) Includes acridine and carbazole.
(c) Poor recovery of naphthalene-d_8 surrogate spike (less than 12%).
(d) PAH concentrations in the filter residue extract are back-calculated to an unfiltered water basis.

TABLE G4-33

STATISTICAL SUMMARY OF RESULTS FROM FILTERING
SAMPLES COLLECTED DURING ERT'S DECEMBER 6-8, 1982
TEST AT ST. LOUIS PARK STATION NO. 1

Compound Class	Average Ratios for all Filtered Samples		
	Filtered to Unfiltered[a]	Residue to Unfiltered[a]	Method Blank Residue to Unfiltered[b]
2-Ring PAH	1.16 ± 0.20	0.011 ± 0.003	0.010 ± 0.001
3-Ring PAH	1.20 ± 0.22	0.010 ± 0.004	0.010 ± 0.002
4-Ring PAH	1.09 ± 0.12	0.092 ± 0.032	0.024 ± 0.004
TOTAL PAH	1.17 ± 0.19	0.020 ± 0.007	0.012 ± 0.001

Notes:

(a) Mean ± 95 percent confidence interval for 7 samples for ratios indicated based on the results reported in Table G4-32.

(b) Mean ± 95 percent confidence interval for ratio of method blank residue concentrations to unfiltered concentrations in each of the seven samples in Table G4-32.

Table G4-32 also includes results for the two samples which were treated in the field with 1.0 milligrams per liter of calcium hypochlorite and were then filtered in the laboratory (sample numbers 1D-10 and 4A-5). This test was designed to determine if PAH adsorbed on ferric iron precipitates created by oxidizing the ferrous iron. The fact that filtration results for these two samples were comparable to those for corresponding samples which were not treated with calcium hypochlorite indicates that adsorption of PAH on iron precipitate floc does not play a significant role in PAH removal in the sand filters. This confirms the results obtained from testing the sand filter without aeration or prechlorination.

One other check of the sand filter's effect on PAH removal was attempted by extracting sand or slime samples and analyzing them for PAH. Figure G8-2 shows the PAH SIM GC/MS chromatograms for the various sand and slime samples collected. The full-scale peak height concentration is 200 nanogram per milliliter of extract for each chromatogram. This corresponds to a concentration in the sand or slime sample of about 160 nanograms per gram (parts per billion), since each sample of about 5 grams was extracted with 4.0 milliliters benzene (see Table G4-21). The chromatograms show that no PAH other than compounds in the spiking standard were detected in any of the sand or slime samples except for two peaks at about 24 minutes retention time in samples 7-4-P/C-1B, and 7-3-P/C-1B. These two peaks correspond to the retention times of fluoranthene and pyrene (see Table G8-4), although these identities were not confirmed from their complete mass spectra. The approximate concentration of each of these peaks is about one-tenth of the full-scale peak height concentration, or about 16 nanograms per gram.

The failure to observe any PAH in any of the sand or slime samples, other than traces of fluoranthene and pyrene, seems to contradict the results from analyses of water entering and exiting the filter unit. The PAH removals acrosss the filter shown in Table G4-29, for example, indicate that about 50 nanograms per gram of four-ring PAH were distributed throughout the filter bed between the

two backwash cycles at either end of ERT's test*. The measurement of about 16 nanograms per gram of fluoranthene and pyrene in two of the sand samples from cell A (7-3-P/C-1B and 7-4-P/C-1B), and at a somewhat lower concentration in a slime sample from cell A (7-4-P/C-1T, see Figure G8-2) is within reasonable agreement of the 50 nanogram per gram value expected for four-ring PAH, considering the effects of extraction inefficiencies and the fact that pyrene and fluorenthene were the predominant compounds in the four-ring PAH class. The failure to detect any four-ring PAH in any other samples could be caused by extraction ineffiencies or by unrepresentative samples. For example, no PAH would be detected if PAH were adsorbed further down in the sand bed than the top few inches where the samples were collected.

Taken as a whole, the results of analyzing sand and slime samples for PAH do not allow for any firm conclusions regarding PAH removal in the filter unit. This is because of uncertainties in the sampling and extraction procedures. However, the results do not contradict the conclusions derived from water samples and, in the case of fluoranthene and pyrene, add some support to the water sample results.

Backwashing Effects

Table G4-34 summarizes the results of PAH analyses for backwash feed and wastewater samples collected while cell E was being backwashed at the start of the test (December 6) and at the end of the test (December 8). During the first backwash, PAH concentrations were higher in the backwash wastewater than in the feed water, especially

*Based on 42 1/2 hours operation of well 15 at 1050 gallons per minute and an assumed bulk density of 100 pounds per cubic foot for the filter bed.

TABLE G4-34

PAH CONCENTRATIONS IN BACKWASH FEED AND
WASTEWATER SAMPLES COLLECTED DURING ERT'S DECEMBER 6-8, 1982 TEST

(All concentrations in nanograms per liter)[a]

Compound Class	First Backwash (12/6/82)			Second Backwash (12/8/82)		
	Backwash Feed Water (4B-1)	Backwash Wastewater First Half (8-1)	Backwash Wastewater Second Half (8-2)	Backwash Feed Water (4B-2)	Backwash Wastewater First Half (8-3)	Backwash Wastewater Second Half (8-4)
2-Ring PAH	1530	1500	1280	1170	290	420
3-Ring PAH[b]	1870	2370	1860	2080	450	620
4-Ring PAH	190[c]	910	550	730	140	160
5&6-Ring PAH	ND[d]	630	260	ND	100	ND
Total PAH	3590	5410	3950	3980	980	1200

Notes:
(a) Complete data given in Table G8-1.
(b) Including acridine and carbazole.
(c) Results for fluoranthene and pyrene assumed to be reported low in Table G4-8H by a factor of ten.
(d) ND indicates none detected.

for PAH containing four or more rings*. This indicates that PAH adsorbed on the filter bed were removed during backwashing. This removal is reasonable because PAH adsorbed in the bed material would adsorb on iron precipitates which covered the sand bed or else on iron precipitate deposits which grow on the individual sand particles. Backwashing is intended to remove these iron deposits, and would therefore remove PAH adsorbed to these surfaces. The PAH concentrations in the wastewater decreased somewhat during the latter half of the backwash cycle; however, the backwash flow rate increased by 50 percent during the latter half of the cycle. Overall, PAH were removed at comparable rates during each half, with rates in the second half being a bit lower.

The results of the second backwash are in many ways contradictory to those of the first. During the second backwash, PAH concentrations were much lower in the backwash wastewater than in the feed water (only about one-quarter as great, except for five and six-ring PAH) and backwash wastewater PAH concentrations were very similar in the two halves of the backwash cycle. These results indicate that PAH were apparently being adsorbed by the filter bed during the second backwash.

The cause of the observed differences between the two backwashes is unclear. The only apparent differences in the two backwash operations were 1) the first backwash occurred after a few days of operation with water from St. Louis Park well SLP3 while the second occurred after 42 1/2 hours of operation with water from well SLP15, and 2) flow rates during the first backwash were somewhat lower than during the second (about 900 and 1350 gallons per minute as low and high rates during the first backwash versus about 1000 and 1500 gallons per minute during the second). It is also unclear why the

*The feed water PAH concentrations shown in Table G4-34 are significantly lower than PAH concentrations reported for well SLP15 wellhead or filtered water because the backwash feed water was a mixture (about 50/50) of water from wells SLP3 and SLP15 and well SLP3 is not contaminated by PAH.

first backwash showed significant removal of PAH from the filter bed because the filter had been run with water from wells SLP3 and SLP11 for 2 1/2 months prior to ERT's test and these wells are not contaminated by PAH*.

In spite of the inexplicable differences between the first and second backwashes, they both showed that the backwash wastewater contained significant concentrations (100 to 700 nanograms per liter) of five and six-ring PAH. This result is noteworthy because such high molecular weight PAH were not detected in the feed water and, in fact, were never detected in any of the other water samples collected during ERT's test or during any of CH2M Hill's tests (bench-scale or in the field) with water from St. Louis Park well SLP15. It is possible that these heavy PAH were contaminants introduced during sampling, because a plastic bucket was used to collect backwash wastewater samples. No blank samples using this bucket were collected, so this possibility cannot be verified.

If the observed five and six-ring PAH concentrations are true and do not reflect sample contamination, then one explanation may be that heavy five and six-ring PAH are present in water from well SLP15 but at concentrations far too low to be detected. These heavy PAH are then adsorbed during filtration and then removed from the filter bed during backwashing. For example, the five and six-ring PAH concentrations in the wastewater from the second backwash represent about 2 milligrams of PAH being stripped from the filter bed in cell E**. Assuming that these five and six-ring PAH are removed completely from wellhead water during filtration and then completely removed from the filter bed during backwashing yields a calculated concentration of about 1 nanogram per liter of total five and six-ring PAH in the

*The possibility that samples 8-1 and 8-2 were switched or mislabeled with samples 8-3 and 8-4 has been ruled out based on chain-of-custody records.

**Based on 5000 gallons of backwash water passing through cell E during the first half of the backwash cycle.

filter inlet water*. Such a concentration is well below the detection limits of the analytical method in this or other studies of St. Louis Park well SLP15.

Results of Split Analyses by CH2M Hill

CH2M Hill analyzed six split samples from ERT's December 1982 test for PAH (CH2M Hill 1982f). The samples were analyzed for the list of PAH compounds given in Table G4-8. All of the split samples were collected on December 7 and included: 1) a split of the wellhead sample at 0830 (corresponding to ERT number 1D-5-S); splits of the first grab of the composite samples collected under normal operating conditions 2) at the aerator inlet (ERT number 2-2), 3) at the filter inlet (ERT number 3B-4), and 4) at the filter outlet (ERT number 4A-4); 5) split of the filter inlet sample during maximum aeration and prechlorination (ERT number 3B-5); and 6) a split of the filter outlet sample without aeration or prechlorination (ERT number 4C-1).

Table G4-35 summarizes the results of CH2M Hill's split sample analyses. The results obtained by CH2M Hill are consistent with those of Monsanto Research Corporation (MRC). Splits of the initial grabs of the composite samples collected during normal operation show no significant differences between the wellhead, aerator inlet, and filter inlet samples, consistent with MRC's results (compare Tables G4-29 and G4-35). CH2M Hill's results show about 35 percent removal of four-ring PAH, consistent with MRC's results. CH2M Hill's results also show that benz(a)anthracene and chrysene were reduced to below detectable levels by filtration, consistent with MRC's results, but that quinoline, the only other carcinogenic PAH detected by CH2M Hill, was not affected by filtration. This is not unexpected, since quinoline only contains two rings, and both CH2M hill and MRC results show that two-ring PAH were not removed significantly by filtration.

CH2M Hill's results for the filter inlet split sample during maximum aeration and prechlorination show that this adjustment did achieve significant removal of PAH, as did MRC's results. However,

*Based on 42 1/2 hours of operation at 1050 gallons per minute with 20 percent of the flow passing through cell E.

TABLE G4-35

SUMMARY RESULTS OF SPLIT SAMPLES FROM ERT'S TEST

DECEMBER 7, 1982 ANALYZED BY CH2M HILL (a,d)

(Concentrations in nanograms per liter)

Compound Class[b]	Wellhead(1D) (0830)	Aerator Inlet(2) (1347)	Filter Inlet(3B) Standard Conditions(1348)	Filter Outlet(4A) Standard Conditions (1349)	Filter Inlet(3B) Maximum Aeration & Chlorination(1845)	Filter Outlet(4C) Without Aeration or Chlorination(1145)
Two-Ring PAH	2,578/2,384[c]	2,527	2,371	2,587	2,014	2,539
Three-Ring PAH	5,612/5,283	5,342	4,777	4,997	2,665	5,330
Four-Ring PAH	820/710	760	668	500	170	440
Noncarcinogenic PAH	8,979/8,349	8,598	7,788	8,076	4,849	8,299
Carcinogenic PAH[e]	31/28	31	28	8[f]	ND	10[f]
Total PAH	9,010/8,377	8,629	7,816	8,084	4,849	8,309

Notes:

(a) Data from CH2M Hill 1982f.
(b) List of compounds analyzed and designation of compound classes per Table G4-8. Compound classes include heterocyclic PAH.
(c) Results of duplicate sample analyses.
(d) Sample times listed as per CH2M Hill 1982f. ERT sample point numbers also listed.
(e) Carcinogenic PAH detected were benz(a)anthracene, chrysene and quinoline.
(d) Quinoline was the only carcinogenic PAH detected.

the removals observed by CH2M Hill were generally a bit less than those measured by MRC (compare Tables G4-30 and G4-35). CH2M Hill's results from the filter outlet split sample without aeration or prechlorination are also consistent with MRC's results (compare Tables G4-31 and G4-35). Analyses by both laboratories showed about 40 percent removal of four-ring PAH by filtration alone, with no significant effect on two and three-ring PAH. Benz(a)anthracene and chrysene, the two four-ring carcinogenic PAH detected, were shown by both laboratories to be removed to below detectable levels. Quinoline, the only other carcinogenic PAH detected by CH2M Hill, which was not analyzed by MRC, was not affected by filtration alone.

Table G4-36 compares PAH analyses results by CH2M Hill and MRC for the six samples split between the two laboratories. The compound class comparisons in Table G4-36 are only made for the 25 compounds analyzed in common by both laboratories, 8 of which were five and six-ring PAH that neither laboratory detected. The data in Table G4-36 indicate that CH2M Hill consistently reported higher concentrations than MRC for a given compound class. In fact, CH2M Hill's results, on average, were about 50 percent higher than Monsanto's. As discussed in section G4.3.2, this consistent discrepancy appears to result from the different internal spike procedures used by the two laboratories. CH2M Hill added internal spikes to the methylene chloride extract prior to the final concentration step, while MRC, following recommended EPA procedures, added them to the final extract immediately prior to analysis. This difference means that any sample or internal spike losses during CH2M Hill's final concentration step would be undetected and show up in the results as reported concentrations that were biased high. Losses during CH2M Hill's final concentration step are supported by the comparisons shown in Table G4-36, which indicate significantly less bias between the two laboratories for four-ring PAH compared to two and three-ring PAH. This is consistent with volatilization losses during CH2M Hill's final concentration step, since four-ring PAH are the least volatile of the compounds detected (see Appendix K).

TABLE G4-36

COMPARISON OF CH2M HILL AND MONSANTO RESEARCH RESULTS

FOR PAH ANALYZED IN COMMON BY BOTH LABS FOR SPLIT SAMPLES[a]

(Concentrations in nanograms per liter)

Compound Class	Wellhead(1D-5-S) CH2M Hill	Wellhead(1D-5-S) MRC[b]	Aerator Inlet(2-2) CH2M Hill	Aerator Inlet(2-2) MRC[c]	Filter Inlet Standard Conditions(3B-4) CH2M Hill	Filter Inlet Standard Conditions(3B-4) MRC[c]	Filter Outlet Standard Conditions(4A-4) CH2M Hill	Filter Outlet Standard Conditions(4A-4) MRC[d]
Two-Ring PAH	2,187/2,026	1,350 ± 240	2,136	1,500	2,011	1,390	2,219	1,160 ± 700
Three-Ring PAH	4,512/4,283	2,900 ± 580	4,242	3,050	3,797	2,430	4,057	2,800 ± 480
Four-Ring PAH	820/710	730 ± 130	760	550	668	480	500	500 ± 60
Noncarcinogenic PAH	7,499/6,999	4,940 ± 640	7,118	5,060	6,458	4,260	6,776	4,460 ± 850
Carcinogenic PAH	20/20	39 ± 15	20	40	18	45	ND[f]	ND
Total PAH	7,519/7,019	4,908 ± 640	7,138	5,100	6,476	4,300	6,776	4,460 ± 850

Filter Inlet with Maximum Aeration & Chlorination (3B-5) CH2M Hill	Filter Inlet with Maximum Aeration & Chlorination (3B-5) MRC	Filter Outlet Without Aeration or Chlorination (4C-1) CH2M Hill	Filter Outlet Without Aeration or Chlorination (4C-1) MRC	Ratio of CH2M Hill to MRC Results[g]
1,955	1,080	2,159	2,560	1.50 ± 0.38
1,715	900	4,330	3,860	1.49 ± 0.26
170	200	440	620	1.06 ± 0.28
3,840	2,170	6,929	7,040	-
ND	11	ND	ND	-
3,840	2,180	6,929	7,040	1.44 ± 0.25

Notes:

(a) Compounds analyzed in common by MRC and CH2M Hill that were actually detected by either laboratory are as follows:
two-ring PAH: biphenyl, 2,3-dihydroindene, indene, 1 and 2-methylnaphthalenes, and naphthalene;
three-ring PAH: acenaphthene, acenaphthylene, acridine, anthracene, carbazole, fluorene, and phenanthrene;
four-ring PAH: benzo(a)anthracene, chrysene, fluoranthene, and pyrene
five-ring PAH: (none ever detected by either lab): benzo(b&k)fluoranthenes, benzo(a&e)pyrenes, dibenzo(a,h)anthracene, and perylene;
six-ring PAH: (none ever detected by either lab): benzo(ghi)perylene and indeno(1,2,3-cd)pyrene.
This common list corresponds to all of the compounds measured by MRC except for dimethylnaphthalenes, and to all of the compounds ever detected by CH2M Hill except for benzo(b)thiophene, dibenzofuran, and quinoline.

(b) Mean and standard deviation for samples 1D-9-P, 1D-9-P- Duplicate, 1D-10-P, and the sum of the F/R-W and F/R-F analyzes for each of these samples (i.e., six samples in all). The ERT sample split with CH2M Hill (1D-5-S) was not quantified by MRC.

(c) MRC results are for composite samples comprised of four grab samples. Only the first grab was split with CH2M Hill, and the ERT grab samples were not quantified by MRC.

(d) Mean and standard deviation for samples 4A-4-P, 4A-4-P-Duplicate, 4A-5-P, and the sum of the F/R-W and F/R-F analyses for each of these samples (i.e., six samples in all). The ERT sample split with CH2M Hill was a grab sample not quantified by MRC.

(e) Mean and standard deviation for six comparisons.

(f) ND indicates not detected.

(g) Mean and standard deviation for six rations, using the average of CH2M Hill or MRC results for any replicate samples.

G4.4.7 Summary

The major findings from ERT's December 1982 test of the iron removal plant at St. Louis Park Water Treatment Station No. 1 operating with water from well 15 are summarized below.

1) PAH concentrations in samples collected at the wellhead of St. Louis Park well 15 decreased by about 50 percent after extended pumping. The full decrease was attained after about 12 hours of pumping (see Figure G4-10). The cause of this decrease is currently unknown; however, these results have significant implications concerning sampling procedures to obtain a representative sample from a well contaminated by PAH. Because of these implications, this result warrants further study to determine the cause of the observed decrease and to develop sampling protocols which take proper account of the results.

2) The filter unit tested contained significant deposits of iron precipitate slime laying on top of the sand beds. These deposits consisted primarily of inorganic iron precipitates with traces of iron bacteria and powdered activated carbon. These deposits were most likely present during CH2M Hill's September 1982 test and probably for a few years before then. They were first discovered during ERT's December 1982 test. The deposits appear to have accumulated because of insufficient backwashing rates and prechlorination dosages. St. Louis Park Water Department personnel subsequently discovered that such deposits occurred in the other three filter units at Station No. 1 and took corrective actions to eliminate the deposits and prevent their reoccurrence. Subsequent inspections of the other four iron removal plants in St. Louis Park by ERT and St. Louis Park Water Department personnel showed that the slime deposit problem was limited to Station No. 1 (with the exception of single filter cell at Station No. 8).

3) The iron precipitate slime deposits at St. Louis Park Station No. 1 appear to have affected the results of ERT's December 1982 test (and presumably CH2M Hill's September 1982 test) in two ways. First,

the deposits appear to have caused some of the filter feed water to channel around the sides of the sand beds. Samples of filter outlet water may have contained significant quantities of channeled water because of the location of the sample taps used. This would add a high bias to results because little, if any, filtration would be effected on channeled water. Second, the deposits probably affected the behavior of PAH in the filter unit differently than a normal sand bed because of the different surface areas and void passage sizes in the deposits compared to filter bed sand.

4) The overall removal of PAH in the iron treatment plant at Station No. 1 was about 30 percent for four-ring PAH, with no significant removal of two and three-ring PAH. No larger PAH were detected. The observed removals were attributable to the filtration step, with no significant effect by aeration or prechlorination under normal operating conditions. The removals in the filter were primarily caused by adsorption on the filter material (the iron precipitate slime deposits and/or the filter bed sand). The observed removals were not a direct result of filtration of particulate matter containing adsorbed PAH, whether as particles naturally present in the well water or iron precipitate floc particles created by oxidizing the ferrous iron present in the well water.

5) Backwashing the filter unit appeared to remove at least some of the PAH adsorbed in the filter bed, although the results obtained were inconsistent. The backwash wastewater contained significant concentrations of five and six-ring PAH (over 100 nanograms per liter), which were never detected in any of the other samples. This indicates that these compounds may be present in the wellhead water at levels considerably below detection limits and may then be at least partially removed by the sand filter.

6) The overall PAH removals observed during ERT's December 1982 test were significantly lower than those observed during CH2M Hill's September 1982 test.

7) Analysis of six split samples by CH2M Hill gave results consistent with those obtained by Monsanto Research. However, CH2M Hill's results appear to be biased high by about 50 percent because of the different internal spiking procedure used.

G4.5 ERT's February 1983 Test of the Iron Removal Plant at Well SLP15

ERT's December 1982 test showed that the sand filter beds at St. Louis Park Water Treatment Station No. 1 were affected by deposits of iron precipitate slime. These deposits do not reflect desired operation of an iron removal plant and yet they most likely affected the behavior of PAH in the treatment plant at Station No. 1 during both ERT's December 1982 test and CH2M Hill's September 1982 test. ERT therefore performed another test at Station No. 1 on February 1-2, 1983 after St. Louis Park Water Department personnel had taken steps to eliminate the slime deposits problem. The purpose of this second test was to determine the behavior of PAH in an iron removal plant unaffected by slime deposits. This section presents the results of this second test.

G4.5.1 Test Objectives

The primary objective of ERT's February 1983 test was to determine the behavior of PAH in the iron removal plant at Station No. 1 without the presence of iron precipitate deposits when operating with water from well SLP15. This objective was addressed by collecting composite water samples from various points throughout the treatment plant while it was operating under normal conditions. No tests of variations in operating conditions were performed because the December 1982 test had already studied such variations and it was felt that further study of such variations should await the results of testing under normal conditions without the presence of iron precipitate deposits.

G4.5.2 Test Description

ERT's second test at St. Louis Park Water Treatment Station No. 1 took place on February 1-2, 1983, with preliminary work also taking place on January 31. The test was performed by personnel from ERT and Soil Exploration Company (SEC), with the assistance of St. Louis Park Water Department personnel, based on a test plan prepared by ERT (1983). No split samples were collected by CH2M Hill or the MPCA during the test. All sample analyses were performed by Monsanto Research Corporation (MRC), except for field measurements, which were performed by SEC, and extraction of sand samples, which was performed by ERT.

Table G4-37 provides a chronological summary of activities during the February 1983 test. The test was originally planned for January 31 and February 1 using the same filter unit (number 1) that was tested in December. However, inspection of cells A and E in this filter unit by SEC personnel on January 31 and by ERT personnel on the morning of February 1 indicated that there were still traces of iron bacteria slime on the distributor pipes and of mudballs on the surface of the filter beds. Although these slime deposits and mudballs were present to a much lesser extent than during the December 1982 test, ERT wanted to test a filter unit with no traces of iron precipitate deposits if possible. Cells A and E in the immediately adjacent filter unit (number 2) were therefore inspected by ERT on the morning of February 1. It was found that these cells were free of any visual signs of iron precipitate deposits or iron bacteria slime. It was therefore decided to perform the test using filter unit 2.

After making the decision to perform the test with filter unit 2, sand samples were collected from the surface of the filter beds in cells A and E (at about 1415 hours). St. Louis Park well SLP15 was then restarted and run through filter unit 2 under normal operating conditions through the composite sampling period on the morning of the next day (February 2). Well SLP15 had already been operated since the

TABLE G4-37
CHRONOLOGICAL SUMMARY OF ERT'S FEBRUARY 1-2, 1983
TEST AT ST. LOUIS PARK STATION NO. 1[a]

Date	Time	Item
1/27 & 28/83	-	St. Louis Park Water Department personnel treat the filter units with sodium hypochlorite and then backwash the filters twice.
1/31/83	0740	Water Department personnel start well 15 running through filter unit no. 1 under normal conditions.
	0905	Water Department personnel beginning draining filter unit no. 1.
	0955	SEC personnel collect sand sample from cell E of filter unit no. 1 (sample no. 7E-20-S/X).
	1015	SEC personnel collect sand sample from cell A of filter unit no. 1 (sample no.7A-20-S/X).
	1040	Well 15 is restarted and filter unit no. 1 is backwashed again using water from wells 3 and 15.
	1200	Backwashing completed. Water from well 15 run through filter unit no. 1 under normal conditions for the rest of the day.
	1600	Wellhead sample from well 15 collected by SEC personnel (sample no. ID-20-P&O).
2/1/83	1045	Water Department personnel begin to drain filter units 1 and 2 (well 15 shut off).
	1100-1200	ERT personnel inspect cells A and E in filter units 1 and 2. Traces of iron bacteria slime and mudballs are still present in filter unit 1. Cell A in filter unit 1 has a very strong chlorine odor. The cells in filter unit 2 are free of apparent iron bacteria slime and mudballs and have no chlorine odor. It is decided to perform the test using filter unit 2.
	1200	Started refilling the filter units with water from well 15.
	1315	Filter unit 2 is redrained to allow collection of sand samples (well 15 shut off).
	1415	Sand samples from cells A and E of filter unit 2 are collected by ERT personnel (sample numbers E-7A-20 and E-7E-20).

TABLE G4-37 (continued)

Date	Time	Item
	1430	Well 15 is restarted to refill filter unit 2, which is then operated under normal conditions throughout the rest of the day.
2/2/83	0745-0755	First grab samples for composite samples are collected at various points throughout the treatment plant (sample numbers 1D-21-P,O & I, 2-20-P & O, 20-20-P & O-Duplicate, 3B-20-P & O, E4A-20-P & O, E11-20-P & O, E11-20-P & O-Duplicate and W12-20-P & O).
	0845-0858	Second grab sample for composite samples are collected.
	0945-0956	Third grab samples for composite samples are collected.
	1045-1055	Fourth and final grab samples for composite samples are collected.
	1100	Well 15 is shut off and filter unit 2 drained.
	1150-1200	Collected sand samples from cells A and E of filter unit 2 (sample numbers E-7A-21 and E-7E-21).
	1200	Started backwashing filter unit 2 with water from wells 3 and 15.
	1242-1256	Cell D being backwashed. Samples collected of backwash feed water (sample no. E4C-20-P & O at 1248) and wastewaters (sample nos. 8-20-P & O at 1245 and 8-21-P & O at 1253).
	1310	Backwashing completed. Filter unit 2 drained.
	1400	Sand samples from cells A and E of filter unit 2 collected by SEC personnel (samples nos. E7A-22 and E7E-22).
		Test completed. Station no. 1 returned to normal service.

Notes:

(a) Filter unit no. 1 is the westernmost filter unit in the treatment building. This was the filter unit tested by ERT in December 1982. Filter unit no. 2 is the immediately adjacent filter unit to the east. See Figure G4-11.

morning of the previous day (January 31) with filter unit 1*, with occasional shut-down periods for draining filter units, and therefore was expected to have achieved steady-state PAH concentrations. A period of 18 hours of operation with filter unit 2 was expected to be sufficient to allow the filter to achieve steady-state conditions with respect to the behavior of PAH.

Composite samples at various points throughout the treatment plant were collected from 0745 to 1055 on February 2, 1983. Composites were made up of four grab samples collected at one hour intervals. Composite samples were collected at the wellhead (sample 1D-21), the aerator inlet (sample 2-20), the filter inlet (sample 3B-20) and at three different filter outlet sample points (samples E4A-20, E11-20 and W12-20). Figure G4-11 shows the sample tap locations and numbering, which in general correspond to those used during the December 1982 test.

Three different filter outlet sample taps were used to ensure that samples were obtained which were unaffected by possible channeling around the filter bed. Sample point E4A used the filter outlet sampling tap located under cell A in filter unit 2. This sampling position is analogous to the sample point used during the December 1982 test of filter unit 1 (sample point 4A). A second sample from filter unit 2 (sample point E11) used the 3 inch drain line located at the bottom of the filter near the effluent end (i.e. the cell A end - see Figures G2-6, 7 and 8 in section G2.1.2). This drain line is located far enough below the bed support plate from cell A that it should not have been affected by any channeling in cell A. St. Louis Park Water Department personnel provided piping to reduce the 3-inch drain line down to a 1-inch line to make the use of this sampling point easier. The third filter outlet sample (number W12) used the

*Water from well SLP15 also flowed through filter unit 2 during this period, but in a reversed flow mode. That is, filtered water from filter unit 1 was routed to the storm sewer by passing it up through the filter beds in unit 2 and into the backwash wastewater piping from unit 2.

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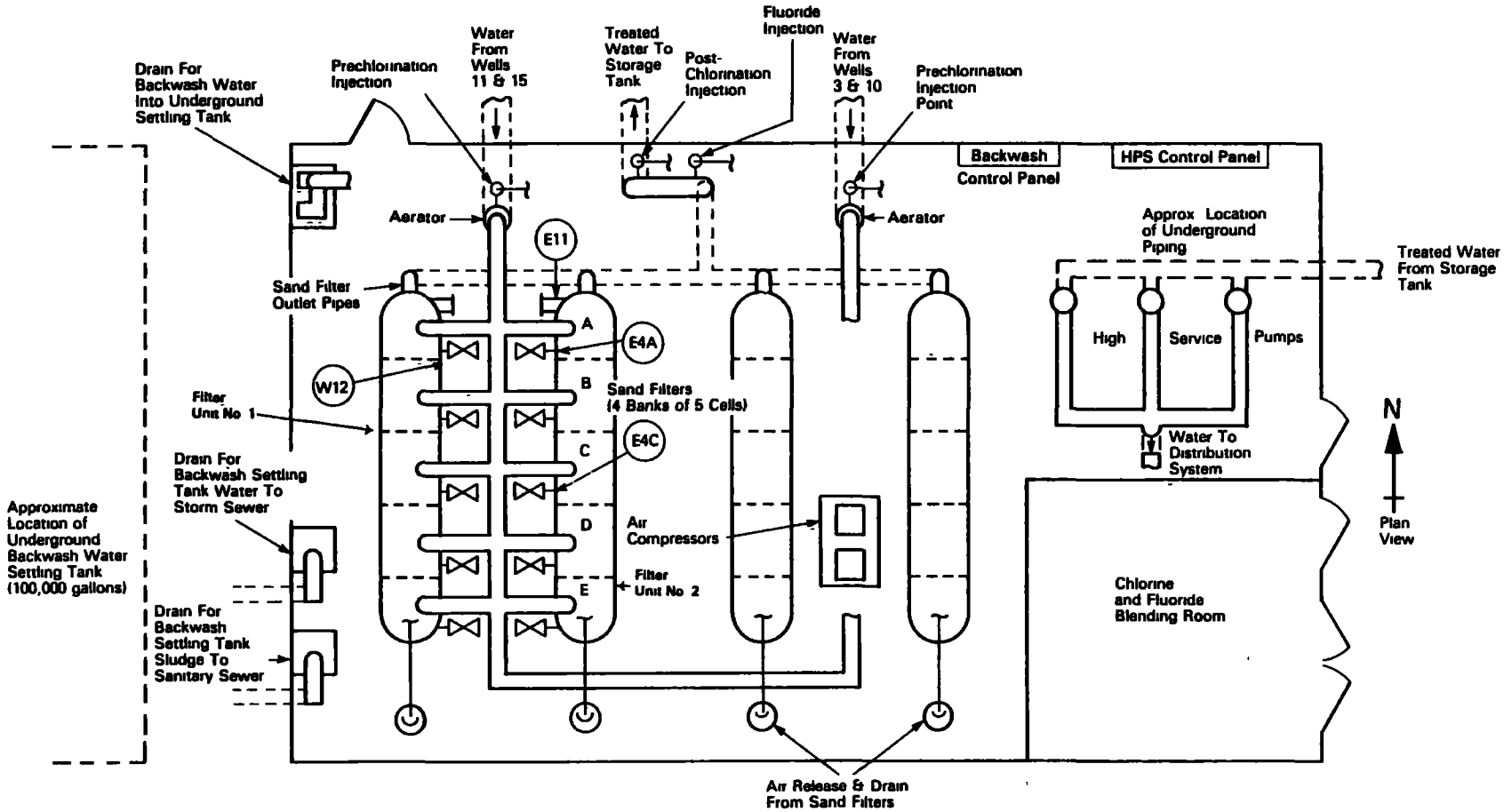

Figure G4-11 Sample Tap Locations and Numbers for ERT's February 1-2, 1983 Test at St. Louis Park Water Treatment Station No. 1

(Other sample tap locations and numbers as per Figure G4-5)

sample tap located under cell A of filter unit 1. This was the same sample tap used in the December 1982 test (number 4A). Water from this sample tap represented the total flow of filtered water from filter unit 2 because this flow was directed to the storm sewer by passing it through filter unit 1 in a reversed flow mode.

After the composite sampling period on February 2 the filter unit was backwashed. Samples of backwash feed water and wastewater were collected while cell D was being backwashed. The filter unit was partially drained before and after backwashing to allow sand samples to be collected from the filter beds in cells A and E.

G4.5.3 Sampling, Handling and Analysis Methods

The procedures for sample collection, preservation, storage and analysis during the February 1983 test were the same as those used during the December 1982 test (see section G4.4.3 and Table G4-21). The only difference in analytical procedures was that sand samples were extracted with benzene in a soxhlet extractor instead of by ultrasonication, as was used for sand samples from the December 1982 test. Sample collection differed in that three different points were used to collect filtered water samples. Sample analyses differed in that all PAH samples were quantified (i.e., no scanning results alone by SIM GC/MS chromatograms), all samples were analyzed for dissolved (ferrous) iron as well as total iron, alkalinity analyses were not performed, and one sample of wellhead water (1D-21-I) was analyzed for a complete list of anions and cations.

G4.5.4 Test Results

Tables G8-5A, B, and C present the results of SIM GC/MS analyses by Monsanto Research Corporation (MRC) for all of the water samples collected. Tables G8-6A and B present the results of SIM GC/MS analyses by MRC of extracts from the sand samples, which were extracted by ERT. Tables G8-7A, B, and C present the results of inorganic constituent analyses by MRC. Table G8-8 presents the results of field measurements made by SEC personnel during the

collection of PAH and inorganic analysis samples. The results from all of these various analyses are discussed in the following subsection.

Table G4-38 summarizes the operating conditions for the iron removal plant during the composite sampling and backwashing on February 2. These conditions were steadily maintained from the time that operation with filter unit 2 started at 1415 hours on February 1. The operating conditions are similar to those during the December 1982 test except that 1) the prechlorination dosage was increased from 1.2 to 2.5 milligrams per liter, 2) the system pressure was somewhat higher during the February test (17 versus 10 pounds per square inch gauge), and 3) the backwashing flow rate during the high flow period of the backwash cycle was significantly increased in February (1950 gallons per minute versus 1500 gallons per minute). Figures G8-9 and 10 show copies of the recording charts for well SLP15 and backwash feed water flow rates, respectively, during the Febuary test.

G4.5.5 Data Interpretation

The results of the February test are discussed in three main areas: composite sample results, backwashing results, and sand sample results. In contrast to the results discussion for the December 1982 test, which separately discussed plant operation results and PAH removal results, both PAH and inorganic constituent results are considered together in the three main discussion areas that follow. This approach is possible because of the understanding of the iron removal plant operation provided by the December 1982 test.

Composite Sample Results

Table G4-39 summarizes the data from inorganic constituent analyses for the composite sampling period. The table presents the average results of four separate field measurements corresponding to each grab sample and the results of laboratory analyses of composite samples. The results in general are consistent with those from the December 1982 test, with pH, specific conductance, turbidity, total organic carbon and hardness all remaining essentially constant throughout the treatment system.

TABLE G4-38

SUMMARY OF OPERATING CONDITIONS DURING
ERT'S FEBRUARY 1-2, 1983 TEST AT ST. LOUIS PARK STATION NO. 1

Parameter	Value
Flow Rate	1000 gallons per minute
Filter Inlet Pressure	17 pounds per square inch (gauge)
Aeration Rate	20 percent of full-scale (2.6 milligrams per liter oxygen addition)
Prechlorination Rate	30 pounds per day (2.5 milligrams per liter chlorine addition)
Backwash Flow Rate	1000 gallons per minute during low flow portion (9.8 gallons per minute per square foot) 1950 gallons per minute during high flow portion (19.0 gallons per minute per square foot)

TABLE G4-39

SUMMARY OF INORGANIC CONSTITUENT ANALYSES DURING COMPOSITE SAMPLING PERIOD ON FEBRUARY 2, 1983

(All results in milligrams per liter unless otherwise noted)

Parameter	Wellhead (1D-21)	Aerator Inlet (2-20)	Filter Inlet (3B-20)	Filter Outlet (E4A-20)	Filter Outlet (E11-20)	Filter Outlet (W12-20)
FIELD MEASUREMENTS[a]						
pH	7.2[b]	7.1[b]	7.1[b]	7.1[b]	7.1[b]	7.1[b]
Conductance, μmho/cm	598	584	590	600	598	600
Turbidity, NTU	1.1	0.27	0.68	0.27	0.31	0.31
Dissolved Oxygen	0.85[b]	0.3[b]	0.4[b]	0.45[b]	0.45[b]	0.5[b]
Residual Chlorine	ND[c]	ND	1.08	1.31[e]	1.27	1.30
Iron (Hach test kit)	0.84	0.92	0.81	0.36	0.32	0.34
LABORATORY ANAYSES						
Total Organic Carbon	1.9	2.0/2.9[d]	1.9	2.2	1.9/1.8[d]	2.0
Hardness (as $CaCO_3$)	310	314/313	313	309	312/314	309
Total Iron	0.65	0.68/0.65	0.73	0.046	0.078/0.083	0.12
Manganese	0.10	0.10/0.10	0.10	0.087	0.087/0.089	0.087
Dissolved Iron	0.52	0.58/0.59	0.23	0.03	0.037/0.042	0.021

Notes:
(a) Average of results for the four grab samples making up the composite samples.
(b) Average of results for third and fouth grab samples only, since the pH and dissolved oxygen probes appear to have been fouled or miscalibrated during the first two grab samples (see Table G8-8).
(c) ND indicates not detected.
(d) Results of duplicate sample analyses.
(e) Value of 0.34 milligrams per liter during the first grab sample assumed to actually be 1.34 milligrams per liter (typographic error).

Comparing Tables G4-22 and G4-39 shows that residual chlorine levels in the filter inlet and outlet water were significantly higher during the February test than those observed in the December test. This is because of the increased prechlorination rate during the February test. Chlorine demand was about 1.2 milligrams per liter between the injection point (2.5 milligrams per liter chlorine added) and the filter outlet (about 1.3 milligrams per liter measured), which is consistent with the December results. Dissolved oxygen values during the February test were inconsistent with the results from the December test, being higher at the wellhead (0.85 versus about 0.2 milligrams per liter) and lower at the filter outlet (about 0.5 versus about 2.5 milligrams per liter). The cause for this discrepancy is unknown, but may be due to difficulties with the dissolved oxygen probe during the February test.

Iron removal was good during the February test, with 0.05 to 0.1 milligrams per liter total iron measured in the filtered water, based on laboratory analyses. Field measurements for iron again appeared to be biased high by about 0.2 milligrams per liter. Total iron concentrations appeared to be significantly higher in samples E11-20 and W12-20, indicating that rust deposits or iron precipitates in the drain pipe and effluent pipe may have added iron to the filtered water. This explanation is supported by the fact that disolved (ferrous) iron concentrations were similar in samples from all three filter outlet sample taps. Analyses of samples from the three taps for other constituents gave similar results, indicating that sample E4A-20 was not significantly affected by channeling. About 10 percent manganese removal was also observed during the test, although resulting concentrations of about 0.09 milligrams per liter are still above the suggested water quality criterion of 0.05 milligrams per liter (EPA 1976).

Table G4-40 summarizes PAH data by compound class for all of the composite samples. The two duplicate samples (2-20 and E11-20) both gave very similar results. Duplicate sample results generally agreed within 30 percent for a given compound class.

TABLE G4-40

SUMMARY OF PAH CONCENTRATIONS IN COMPOSITE SAMPLES

COLLECTED DURING ERT'S FEBRUARY 1983 TEST AT

ST. LOUIS PARK WATER TREATMENT STATION NO. 1

(Concentrations in nanograms per liter)[a]

Compound Class	Wellhead		Aerator Inlet		Filter Inlet	Filter Outlet			
	1D-20	1D-21	2-20	2-20 Dupl.	3B-20	E4A-20	E11-20	E11-20 Dupl.	W12-20
Two-Ring PAH	1420	1730	2170	1380	2150	1390	1800	1770	1820
Three-Ring PAH[b]	2460	2800	3510	2520	2900	2180	2990	2380	2510
Four-Ring PAH	580	500	980	840	660	610	620	720	600
Noncarcinogenic PAH	4420	4990	6590	4660	5710	4150	5410	4870	4900
Carcinogenic PAH[c]	43	44	71	77	ND	34	ND	ND	33
Total PAH	4460	5030	6660	4740	5710	4180	5410	4870	4930

Notes:

(a) Complete data given in Table G8-5.
(b) Includes acridine and carbazole.
(c) Benz(a)anthracene and chrysene were the only carcinogens detected.

The data in Table G4-40 do not show any significant removal of PAH occurring in the iron removal plant, with the possible exception of carcinogenic PAH (benz(a)anthracene and chrysene). This is confirmed by Table G4-41, which shows average concentrations of each PAH compound before and after filtration, together with 95 percent confidence intervals. The results of the December 1982 test and the results in Table G4-40 indicate that it is reasonable to average results from wellhead, aerator inlet and filter inlet samples, since piping from the wellhead and aeration and prechlorination at normal rates do not appear to significantly affect PAH concentrations. Similarly, the four filter outlet sample (three sample taps plus one duplicate) are averaged because the different taps appear to have yielded equivalent samples with respect to PAH.

Table G4-41 shows that the ratio of outlet to inlet averages for individual PAH compounds is always unity within the accuracy of the data, with few exceptions. The only exceptions are anthracene and benz(a) anthrancene, which both showed about 70 percent removal, with these removals being statistically significant at the 95 percent confidence level. In addition, acenaphthylene and chrysene showed removals of about 40 and 65 percent, respectively, which are statistically significant at the 90 percent confidence level (but not at the 95 percent level). In summary, no significantly measurable PAH removal occurred during filtration, with the exception of a few individual compounds. However, two of these compounds were carcinogenic PAH (benz(a)anthracene and chrysene).

Table G4-42 summarizes averages PAH removal data for the February test by compound class. Again it is clear that no statistically significant PAH removal occurred for any ring-size class. This contrasts with the December test, which showed about 30 percent removal for four-ring PAH. However, the February test showed about 70 percent removal of carcinogenic PAH (benz(a)anthracene and chrysene), which is consistent with the results of the December test, which showed greater than 75 percent removal to below detectable concentrations for these compounds. The different removals observed in ERT's two tests is probably due to the presence of iron precipitate

TABLE G4-41

SIMPLIFIED STATISTICAL ANALYSIS OF PAH DATA OBTAINED DURING FEBRUARY 1983 TEST AT ST. LOUIS PARK TREATMENT STATION NO. 1

Compound	Average Concentration, nanograms/liter[e]		Outlet to Inlet Ratio[f]
	Before Filtration[a]	After Filtration[b]	
TWO-RING PAH			
Indene	48 ± 10	37 ± 15	0.77 ± 0.35
2,3-Dihydroindene	864 ± 228	850 ± 218	0.98 ± 0.36
Naphthalene	25 ± 7	25 ± 6	1.00 ± 0.35
2-Methylnaphthalene	7.3 ± 3.4	6.4 ± 1.9	0.88 ± 0.48
1-Methylnaphthalene	113 ± 46	120 ± 40	1.06 ± 0.56
Biphenyl	228 ± 83	245 ± 41	1.07 ± 0.43
C_2-Naphthalenes	484 ± 124	413 ± 105	0.85 ± 0.31
THREE-RING PAH			
Acenaphthylene	464 ± 128	290 ± 178	0.63 ± 0.42
Dihydroacenaphthylene	842 ± 200	745 ± 255	0.88 ± 0.37
Fluorene	626 ± 122	668 ± 167	1.07 ± 0.34
Phenanthrene	654 ± 241	723 ± 99	1.11 ± 0.16
Anthracene	224 ± 68	77 ± 59	0.34 ± 0.28
FOUR-RING PAH			
Fluoranthene	404 ± 138	395 ± 65	0.98 ± 0.37
Pyrene	262 ± 123	228 ± 53	0.87 ± 0.46
Benz(a)anthracene	34 ± 11(c)	8 ± 14[d]	0.24 ± 0.42
Chrysene	25 ± 19(c)	9 ± 17[d]	0.36 ± 0.73
HETEROCYCLIC PAH			
Acridine	16 ± 7	ND	ND
Carbazole	15 ± 8	13 ± 6.4	0.87 ± 0.63

Notes:

(a) Mean ± 95% confidence interval for five samples (1D-20, 1D-21, 2-20, 2-20 Dup. & 3B-20).
(b) Mean ± 95% confidence interval for four samples (E4A-20, E11-20, E11-20 Dup.& W12).
(c) ND values for sample 3B-20 not considered.
(d) ND values for samples E11-20 and E11-20 dup. treated as zero.
(e) Averages from data in Table G8-5.
(f) Confidence interval of the ratio calculated by $(CI_R)^2 = (CI_{OUT}/IN)^2 + (OUT \times CI_{IN}/IN^2)^2$ where CI is the confidence interval of the ratio (CI_R), after filtration concentration (CI_{OUT}) or before filtration concentration (CI_{IN}), IN is the average before filtration concentration and OUT is the average after filtration concentration.

TABLE G4-42

AVERAGE COMPOUND CLASS PAH CONCENTRATIONS IN COMPOSITE SAMPLES COLLECTED ON FEBRUARY 22, 1983 (All results in nanograms per liter)[a]

Compound Class	Filter Inlet Water (Average)[c]	Filter Outlet Water (Average)[d]	Inlet to Outlet Ratio[e]
2-Ring PAH	1770 ± 280	1700 ± 250	0.96 ± 0.21
3-Ring PAH[b]	2840 ± 370	2520 ± 370	0.89 ± 0.17
4-Ring PAH	730 ± 190	640 ± 90	0.88 ± 0.26
TOTAL	5340 ± 500	4860 ± 460	0.91 ± 0.12
Noncarcinogenic PAH	5280 ± 500	4840 ± 460	0.92 ± 0.12
Carcinogenic PAH	59 ± 28	17 ± 31	0.29 ± 0.54

Notes:

(a) Complete data in Table G8-5.

(b) Includes acridine and carbazole.

(c) Mean ± 95 percent confidence interval for five samples calculated from results in Table G4-41.

(d) Mean ± 95 percent confidence interval for four samples calculated from results in Table G4-41.

(e) Confidence interval for ratio calculated as described in footnote (f) of Table G4-33.

deposits during the December test (and their absence during the February test). The presence or absence of these deposits was the only major difference between the two tests which can explain the observed differences, since other operating conditions were similar during the two tests. This explanation fits with the likely role of the deposits in PAH removal, namely providing a large surface area, small effective pore size medium for filtering and adsorption.

Backwashing Results

Table G4-43 presents data for inorganic constituents measured in the backwash feed water and wastewater during the backwashing of cell D at the end of the February test. The key point indicated by these data is the greatly improved efficiency of the backwashing compared to the December test. This is apparent from the iron concentrations in the wastewater samples, which ranged from 39 to 86 milligrams per liter, versus 4 to 8 milligrams per liter during the December test (see Table G4-28). The improved efficiency was due to increasing the backwash flow rate to 19 gallons per minute per square foot during the latter half of the cycle, compared to 15 gallons per minute per square foot or less during the December test.

Table G4-44 summarizes the results of PAH analyses for the backwash feed water and wastewater. The results indicate that PAH concentrations in the wastewater were significantly lower than in the feed water during both the low flow and high flow portions of the backwash. This is consistent with the results from the second backwash performed during the December test, but is still somewhat unexpected and difficult to explain. The lower PAH concentrations in the backwash wastewater either indicate that PAH were removed by the filter during backwashing or that the characteristics of the backwash wastewater somehow prevented accurate analytical results. Possible explanations for PAH actually being removed by the filter during backwashing are that more vigorous mixing of the filter bed material and the feed water resulted in significant adsorption of PAH on the bed material or that stripping iron precipitates off the sand particles in the bed provided better adsorption surfaces, either on

TABLE G4-43

SUMMARY OF INORGANIC CONSTITUENT ANALYSES DURING BACKWASHING ON FEBRUARY 2, 1983

(All results in milligrams per liter unless otherwise noted)

Parameter	Backwash Feed Water (E4C-20)	Backwash Wastewater First Half (8-20)	Backwash Wastewater Second Half (8-21)
FIELD MEASUREMENTS			
pH	7.12	6.95[a]	
Conductance, μmho/cm	5.50	540	
Turbidity, NTU	0.44	34	
Dissolved Oxygen	1.5	0.6	
Residual Chlorine	ND[b]	ND	
Iron (Hach test kit)	0.4	24	
LABORATORY ANALYSES			
Total Organic Carbon	1.8	3.2	2.5
Hardness (as $CaCO_3$)	309	285	308
Total Iron	0.50	38.8	85.9
Manganese	0.085	0.66	0.20
Dissolved Iron	0.18	2.03	0.47

Notes:
(a) Field measurements made midway between collecting the first and second backwash wastewater samples.
(b) ND indicates not detected.

TABLE G4-44

PAH CONCENTRATIONS IN BACKWASH WATER SAMPLES
COLLECTED ON FEBRUARY 2, 1983

(All concentrations in nanograms per liter,
corrected for surrogate spike extraction recoveries)[a]

Compound Class	Feed Water (E4C-20-P)	Backwash Wastewater First Half (8-20-P)	Backwash Wastewater Second Half (8-21-P)
2-ring PAH	2430	380	1700
3-ring PAH[b]	4040	660	2360
4-ring PAH	760	110	570
Total PAH	7230	1150	4630

Notes:

(a) Complete data given in Table G8-5.

(b) Includes acridine and carbazole.

the sand particles or on the precipitates dispersed in the wastewater. The latter explanation (PAH adsorption on precipitates dispersed in the wastewater) is related to the question of analytical accuracy, since lower PAH concentrations in the wastewater would only be measured if the precipitate-adsorbed PAH were not appreciably desorbed by extracting the samples with methylene chloride. The total organic carbon concentration in the backwash wastewater was about 1 milligram per liter higher than in the feed water (see Table G4-43), and it is possible that PAH in the feed water were chemi-sorbed or complexed with this organic matter (presumably high molecular weight humic and fulvic acids) and then not appreciably extracted from the TOC material.

Sand Sample Results

Table G4-45 summarizes the results of analyzing extracts of filter bed sand samples for PAH. In contrast to results from the December 1982 test, measurable quantities of a large number of PAH (see Table G8-6) were detected in all eight of the sand samples collected in February. It appears that PAH were measured in sand samples from the February test and not the December test because of the larger sample sizes extracted during the February test. Ultrasonic extraction of about 5 grams of sand with 4 milliliters of benzene was the procedure for the December samples, while soxhlet extraction of 60 to 80 grams of sand with methylene chloride was the approach taken for the February samples (see Table G4-21).

A significant result from Table G4-45 is the measured presence of five and six-ring PAH in all but one of the eight sand samples. These heavy molecular weight PAH have never been measured in any of the water samples during testing at St. Louis Park Station No. 1 by either ERT or CH2M Hill, with the exception of three of the four backwash wastewater samples collected during ERT's December 1982 test.

TABLE G4-45

SUMMARY OF PAH CONCENTRATIONS IN SAND SAMPLES COLLECTED
DURING ERT'S FEBRUARY 1-2, 1983 TEST AT ST. LOUIS PARK STATION NO. 1

(All concentrations in nanograms per gram)[a]

Compound Class	Prior to Test (2/1/82)		Prior to Backwashing (2/2/82)		After Backwashing (2/2/82)	
	Cell A (E7A-20)	Cell E (E7E-20)	Cell A (E7A-21)[c]	Cell E (E7E-21)[c]	Cell A (E7A-22)	Cell E (E7E-22)
2-Ring PAH	6.2	8.2	14 / 3.0	88/73	46	73
3-Ring PAH[b]	2.7	1.9	8.3/7.7	22/27	9.5	16
4-Ring PAH	7.3	2.0	13/18	16/19	11	5.5
5&6-Ring PAH	ND[d]	0.4	1.5/3.0	27/1.2	0.3	0.2
Total PAH	16	12	37/32	153/120	67	95

Notes:
(a) Complete data given in Table G8-6.
(b) Includes acridine and carbazole.
(c) Results of duplicate sample analyses.
(d) ND indicates none detected.

The results in Table G4-45 indicate that measurable quantities of PAH were adsorbed on the filter bed sand prior to starting the test. The concentrations of all classes of PAH in the filter bed sand increased significantly during the test and were reduced again by backwashing, although not down to the concentrations observed before the test. The presence of PAH in the filter bed sand prior to the text can be explained by the fact that well SLP15 water was run through the filter bed in reverse flow mode for about 24 hours from the morning of January 31 to the morning of February 1. This was done to route filtered well 15 water from filter unit 1 up through filter unit 2 (the unit tested) in order to discharge the water to the storm sewer. Some PAH from well SLP15 water was apparently adsorbed by the sand in filter unit 2 during this reverse flow period.

The observed increases in PAH concentractions in the filter bed sand during the test period can be used to roughly estimate the corresponding decreases in PAH concentrations in water passing through the filter. This estimate is only approximate because of the limited representativeness of the sand samples, which were collected from the top few inches of a small portion of the bed surface and may not reflect the distribution of PAH across the full area or throughout the full depth of the filter bed. However, duplicate sample analyses gave generally comparable results and concentrations in cells A and E were similar for most sample pairs, so it is reasonable to assume that the results are representative of at least the top few inches of the entire surface of the filter bed. The estimate is based on 20 1/2 hours of testing at 1000 gpm (4.7 million liters of water) and an estimated quantity of 102,000 pounds (46 million grams) of sand in the entire filter bed. These relative quantities of sand and feed water mean that every nanogram of PAH removed from the feed water by absorption results in a concentration of 0.1 nanograms per gram distributed throughout the entire bed (24 inches deep) or 1 nanograms per gram distributed in the top 2 1/2 inches. Similar calculations can be made to estimate the increased PAH loadings in the backwash wastewater resulting from the observed decreases in filter bed sand PAH concentrations after backwashing.

Table G4-46 presents the results of estimates made in the manner described above. Table G4-46 indicates that the observed increases in PAH concentrations in the sand bed during the test correspond to total PAH removals from the filter inlet water of from 65 to 650 nanograms per liter, depending on the assumed distribution of PAH through the sand bed. Such removals would probably not have been detected by comparing filter inlet and outlet water samples given the accuracy limitations of the analyses. Similarly, Table G4-45 indicates that the observed decreases in PAH concentrations in the sand bed during backwashing correspond to increases in backwash wastewater concentrations of from 130 to 1300 nanograms per liter, depending on the assumed distribution of PAH in the sand bed. Analyses of backwash wastewater samples showed, however, that PAH concentrations actually decreased compared to the backwash feed water. This indicates that the measured backwash wastewater concentrations do not reflect all of the PAH present in the sample. In otherwords, PAH concentrations in the backwash wastewater had to increase (or at least stay at the same level as the feed water, within the accuracy of the analyses) and the fact that they did not indicates that the analytical results were biased low, perhaps due to PAH being strongly bound to organic materials or iron precipitates and not being extracted. The alternative explanation offered earlier for the observed decrease in backwash wastewater PAH concentrations - that PAH were actually adsorbed in the filter bed during backwashing - does not fit with the observed decrease in filter bed sand PAH concentrations.

G4.5.6 Summary

The February test was successful in achieving the stated objective of determining the behavior of PAH in the iron removal plant at St. Louis Park Station No. 1 when operated under normal conditions with water from well SLP15 without the presence of iron precipitate slime deposits. The plant operated as expected, with high iron removals observed (about 0.05 milligrams per liter of iron in the filtered water). No significant channeling of flow along the outside of the filter bed was apparent during the test.

TABLE G4-46

CALCULATED CORRESPONDENCE BETWEEN CHANGES IN FILTER BED SAND PAH CONCENTRATIONS AND FILTER INLET WATER AND BACKWASH WASTEWATER PAH CONCENTRATIONS

Compound Class	Corresponding Removal from Filter Inlet Water (a), nanograms per liter		Corresponding Addition to Backwash Wastewater (b), nanograms per liter	
	PAH in Top 2½ Inches Only	PAH Evenly Distributed Throughout Bed	PAH in Top 2½ Inches Only	PAH Evenly Distributed Throughout Bed
2-Ring PAH	37	370	(d)	(d)
3-Ring PAH	14	140	35	350
4-Ring PAH	12	120	82	820
5&6-Ring PAH (c)	2	17	16	160
Total PAH	65	650	133	1330

Notes:

(a) Calculation based on average increases in filter bed sand PAH concentrations during the test (average of E7A-21 and E7E-21 with duplicates minus average of E7A-20 and E7E-20 in Table G4-45). Average sand concentration increase back-calculated to corresponding inlet water concentration decrease based on 4.7 million liters of water processed during test and 46,000 kilograms of sand in the entire filter bed (24" deep).

(b) Calculations based on average decreases in filter bed sand PAH concentrations during backwashing (average of E7A-21 and E7E-21 with duplicates minus average of E7A-22 and E7E-22 in Table G4-45). Backwash wastewater concentration increase based on total backwash flow of 430,000 liters (see Figure G8-10).

(c) Result for sample E7E-21 of 27 nanograms per gram not included in the averages.

(d) Average concentration after backwashing greater than before backwashing.

The results of PAH analyses for composite samples collected at various points throughout the treatment plant showed that no significant removal of PAH occurred within the accuracy of the data, with the exception of from 40 to 70 percent removal for a four specific compounds. Significantly, two of these compounds (benz(a)anthracene and chrysene) are carcinogenic PAH. Sand samples collected from the surface of the filter bed before and after 20 hours of operation showed that concentrations of PAH absorbed on the filter bed sand did increase significantly during the test. However, these increased sand concentrations correspond to removals from the filter feed water which probably could not have been detected given the accuracy of the water analyses. Any PAH removal which did occur during the test appears to have resulted primarily from the filtration step.

The PAH removal results obtained during the February 1983 test do not completely agree with those obtained during ERT's December 1982 test and are much different than the results of CH2M Hill's September 1982 test. The apparent cause of this disagreement is the presence of substantial iron precipitate slime deposits on the filter bed during the September and December tests compared to the absence of these deposits in February. The deposits appear to have effected significant removal of PAH by filtration and/or adsorption, while a clean filter bed effected only slight adsorption.

Samples collected during backwashing after the test gave conflicting results. Analyses of backwash feed water and wastewaster samples showed that PAH appeared to be removed by the filter bed during backwashing, yet filter bed sand samples collected before and after backwashing showed that the amount of PAH adsorbed on the sand significantly decreased during backwashing. A possible explanation for these apparently conflicting results is that adsorbed PAH were indeed stripped from the filter bed during backwashing and that these desorbed PAH plus PAH in the backwash feed water were than adsorbed on or complexed with the iron precipitates and/or trace organic matter (humic and fulvic acids) removed from the bed and suspended in the wastewater during backwashing. This explanation requires the

assumption that the adsorbed or complexed PAH in the backwash wastewater were not efficiently extracted during sample analysis, resulting in the observed apparent decreases in PAH concentrations in the backwash wastewater.

G4.6 Summary of PAH Removal Studies at St. Louis Park

Four different investigators have studied treatment alternatives for removing PAH from contaminated municipal supply wells in St. Louis Park. All of the studies to date have been performed at, or using water from, well SLP15, which is one of the more contaminated wells. This well is also representative of most of the other St. Louis Park municipal supply wells in that it has an associated iron removal treatment plant. The key results from the various tests performed at well SLP15 are summarized in Table G4-47. These results, and their significance, are summarized below.

G4.6.1 Serco Tests

Serco Laboratories performed the first tests at well SLP15 (see section G4.1). Serco tested the effects of injecting powdered activated carbon (PAC) at the wellhead in July and November 1979. Two different PAC dosages were tested, each for a period of one to two days. Sample analyses performed by the MDH using HPLC showed that injecting 1 to 2 milligrams per liter of PAC achieved about 60 percent removal of noncarcinogenic PAH and 9 to 12 milligrams per liter of PAC achieved over 99 percent removal (Table G4-47). No carcinogenic PAH were detected in any of the samples analyzed by the MDH.

Split analyses by Serco showed very poor agreement with MDH results, with the latter appearing to be more accurate. Samples collected at regular intervals during the testing indicated that PAH removal increased during the tests, particularly at the higher PAC injection dosage. This indicates that build-up of PAC on the sand filter beds improved the efficiency of PAH removal.

TABLE G4 - 47
SUMMARY OF KEY RESULTS FROM
PAH REMOVAL STUDIES AT ST. LOUIS PARK WELL SLP15
(Concentrations in nanograms per liter)

Description of Treatment Studied	Untreated Water		Treated Water	
	Noncarcinogenic PAH	Carcinogenic PAH	Noncarcinogenic PAH	Carcinogenic PAH
SERCO TESTS[a] (July 1979)				
PAC injection at 1 to 2 milligrams per liter	4,300	ND	1,700	ND
PAC injection at 9 to 12 milligrams per liter	4,300	ND	35	ND
HICKOK TESTS (September and October 1980)				
PAC injection at 5.5 milligrams per liter[b]	400	60	2	ND
GAC column at 7.5 minutes contact time[c]	850	26	3	ND
CH2M HILL TESTS				
Existing Iron Removal Plant at well SLP15				
-September 1982 Test[d]	9,300	ND	2,100	11
-December 1982 Test[e]	8,700	30	8,100	8
Ozone Bench-scale Testing at 1 milligram per liter dose[f]				
-without UV light	11,000	44	2,800	2
-with UV light	11,000	44	160	ND
PAC Bench-scale Testing[g]				
-1 milligram per liter PAC	11,000	24	6,700	ND
-10 milligrams per liter PAC	11,000	24	380	ND
GAC Column Bench Testing[h]	11,000	44	34	1
ERT TESTS				
Existing Iron Removal Plant at Well SLP15				
-September 1982 Test[i]	4,300	15	610	ND
-December 1982 Test[j]	5,300	39	4,800	ND
-February 1983 Test[k]	5,300	59	4,800	17

Notes to Table G4-47

(a) Average of MDH results given in Table G4-3, excluding the July 19, 5am sample for 9 to 12 milligrams per liter PAC injection.

(b) Average of results given in Table G4-5, exlcuding the untreated water sample at 2 hours.
Note that PAC treatment was applied to combined water from wells SLPM and SLP15 (see section G4.2.2).

(c) Average of results given in Table G4-6.
(d) Results from Table G4-10, using average of the two post-filtration analyses.
(e) Results from Table G4-35, using average of the two wellhead analyses.
(f) Results from Table G4-17.
(g) Results from Table G4-12 for isotherm testing of pulverized Calgon Filtrasorb 300 carbon.
(h) Average of all results reported in Table G4-15 for Westvaco Nuchas WV-G.
(i) Results of wellhead and filter outlet results from Table G4-29.
(k) Average of wellhead and filter outlet results from Table G4-42.

G4.6.2 Hickok Tests

Eugene A. Hickok and Associates testing PAC injection and pilot-scale granular activated carbon (GAC) columns at well SLP15 in September and October 1980 (see section G4.2). All analyses were performed by Serco Laboratories using HPLC. All tests lasted 24 hours, with three or four samples of both treated and untreated water collected during each test. PAC was tested at four different injection dosages (5.5, 8, 11 and 15 milligrams per liter) and GAC was tested at four different contact times (5.6, 7.5, 11.2 and 22.5 minutes). PAC injection was tested for combined water from wells SLP11 and SLP15 (only the latter is contaminated by PAH), while GAC was tested only with water from well SLP15. All eight tests showed substantial PAH removals. Carcinogenic PAH were generally reduced to below detectable levels and noncarcinogenic PAH were generally reduced to less than 20 nanograms per liter (Table G4-47, also see Tables G4-5 and G4-6). Hickok also performed a single test of hydrogen peroxide/UV treatment, but only about 30 percent removal was observed due to the short reaction time tested (20 seconds - see section G4.2.4).

As part of its study, Hickok evaluated the costs of four different options for bringing contaminated municipal supply wells back into service: 1) PAC treatment, 2) GAC treatment, 3) replacing the sand in iron removal plant filter beds with GAC, and 4) deepening contaminated wells from the Prairie du Chien-Jordan into the Mt. Simon-Hinckley. Hickok concluded from this analysis that PAC injection was the least expensive alternative, noting that deepening contaminated wells might not be effective because of difficulties in grouting them properly.

G4.6.3 CH2M Hill Tests

CH2M Hill started a testing program for a variety of treatment techniques in September 1982 (see section G4.3). This testing program is still in progress, with a pilot-scale test of GAC columns recently completed (early April 1983) at well SLP15. CH2M Hill has performed all of its PAH analyses using GC/MS.

CH2M Hill began its program with a test of the existing iron removal treatment plant at well SLP15 on September 15, 1982. Samples from this test were split and analyzed by Monsanto Research Corporation for ERT and Reilly Tar & Chemical Corporation. Results from both laboratories showed that about 80 percent removal of total PAH occurred in the iron removal plant (Table G4.47), primarily as a result of the filtration step. However, CH2M Hill's results were greater than Monsanto's by an average factor of 2.7, apparently because of a high bias in CH2M Hill's results caused by adding internal spike standards prior to the final extract concentration step, which does not conform with recommended EPA procedures.

There was some disagreement between ERT and CH2M Hill and the MPCA over the significance of the September test results from the iron removal plant at well SLP15. ERT believed that the test should be repeated to confirm and explain the results, while CH2M Hill and the MPCA believed that interpretation of results from the iron removal plant could be complicated by various factors and further testing should be performed at bench scale. In addition, there was disagreement over the proper criteria for PAH, which clearly affected the potential significance of the observed removals. ERT therefore developed and proceeded with plans to retest the iron removal plant, while CH2M Hill proceeded with bench-scale testing of various PAH treatment alternatives, including tests to simulate the treatment steps in an iron removal plant.

CH2M Hill's bench-scale testing was performed in two phases. The first round of testing was intended to screen among treatment alternatives to determine which techniques warranted further testing and study. The screening tests included developing equilibrium absorption isotherms for five different activated carbons and three different maccoreticular resins and testing five different oxidizing agents (air, chlorine, chlorine dioxide, hydrogen peroxide and ozone). Tests were also performed to simulate the various treatment steps in an iron removal plant (aeration, chlorination and filtration). First round testing showed that activated carbon, hydrogen peroxide/UV, and ozone/UV were all capable of sufficient PAH

removal to meet the MDH criteria of 28 nanograms per liter for carcinogenic PAH and 280 nanograms per liter for noncarcinogenic PAH. The testing also showed that the nominal treatment steps in an iron removal plant achieved little PAH removals. However, these tests were not performed at conditions that accurately simulated the operation of iron removal plants in St. Louis Park. TOC analyses performed on some of the treated samples by CH2M Hill at the request and expense of Reilly Tar & Chemical indicated substantial contamination by methylene chloride (tens of milligrams per liter), which may have affected the validity of the first round test results.

Based on the first round test results, CH2M Hill's second round of testing examined hydrogen peroxide and ozone, each at six different combinations of dose and residence time, both with and without UV light, and granular activated carbon, tested in bench-scale columns with two different carbons. These tests confirmed that all three techniques could achieve the MDH criteria. It was also shown that ozonation without UV light achieved significant PAH removal, although not sufficient to meet the MDH criterion for noncarcinogenic PAH (Table G4.47). The GAC column tests showed that a contact time of 5.6 minutes was effective, although the tests were run for too short a time to detect any breakthrough.

CH2M Hill performed a screening economic evaluation of GAC, ozone/UV, and hydrogen peroxide/UV treatment at well SLP15 in order to help select the most promising technology for pilot-scale testing. This evaluation showed that GAC treatment was clearly the least expensive alternative, although the design basis was inaccurate in using equal plant capacity and operating flow rates. In addition, costs were not estimated for hydrogen peroxide or ozone treatment without UV light, which accounts for most of the capital and operating costs in CH2M Hill's estimates. As a result of its evaluation, CH2M Hill recommended pilot-scale testing of GAC treatment at well SLP15. This testing was completed at the beginning of April 1983, but the results were unavailable for this report.

G4.6.4 ERT Tests

ERT retested the iron removal plant at well SLP15 in December 1982 with the primary objectives of confirming the September 1982 test results and understanding the cause(s) of the observed PAH removals. The test lasted three days and was very broad in scope, involving 78 different air, water, and filter bed sand samples, time-series and composite sampling, various operating adjustments during the test, testing of backwash effects before and after the test, and field and laboratory measurements of key inorganic constituents as well as laboratory PAH analyses. A major finding from this test was that substantial deposits of iron precipitates and iron bacteria had accumulated on the surface of the filter beds, probably over the course of a few years. These deposits apparently resulted from insufficient backwashing rates and prechlorination dosages. The deposits were significant because they probably affected the PAH removal results observed during the September and December tests and because they do not represent normal or desirable operation of an iron removal plant.

Despite the presence of the iron precipitate deposits, a number of important findings resulted from ERT's December 1982 test. The concentration of total PAH in wellhead water from SLP15 was found to decrease by about 50 percent after about 12 hours of pumping. This is significant in establishing procedures to obtain representative samples from contaminated wells. Aeration and prechlorination at normal dosages were shown to have no observable effect in removing PAH. The slight removals of PAH which were observed occurred as a result of adsorption in the filter bed. Adsorption was indicated as the primary removal mechanism because of the insignificant association of PAH with filterable particulate matter, whether naturally occurring particles or iron precipitate floc. The filter bed achieved about 30 percent removal of four-ring PAH, with no significant effect on two or three-ring PAH. Selected split samples analyzed by CH2M Hill confirmed Monsanto's results, although CH2M Hill's results were again biased high (by about 50 percent on average). Of the three

carcinogenic PAH detected in the untreated water, benz (a) anthracene and chrysene were removed by over 75 percent to below detectable levels, while quinoline (only analyzed by CH2M Hill) was not significantly removed (Table G4.47).

Because of the possible effects of the iron precipitate deposits on the behavior of PAH in the iron removal plant at well SLP15, ERT retested the plant in February 1983, after St. Louis Park Water Department personnel had taken steps to eliminate the deposits. This test was more limited in scope than the December test. Composite samples were collected at various points in the treatment plant, together with samples of sand from the filter beds and backwash wastewater from before and after the test.

Results from the February test showed that most PAH compounds were not affected by the iron removal plant treatment, although four of the heavier PAH were reduced by from 40 to 70 percent by adsorption in the filter bed. Significantly, two of these compounds (benz(a)anthracene and chrysene) are carcinogenic PAH and together were reduced by an average of 70 percent (Table G4-47). In addition, analyses of sand sample extracts and backwash wastewater samples showed low but detectable levels of carcinogenic five and six-ring PAH, none of which were ever detected in any of the water samples from well SLP15 or the iron removal plant in any of CH2M Hill's or ERT's tests. This indicates that these compounds may be present in the wellhead water at very low concentrations (less than a nanogram per liter), but are significantly removed by the sand filter.

G5. ESTIMATED COSTS OF DRINKING WATER TREATMENT ALTERNATIVES

G5.1 Introduction

This section presents estimated costs for drinking water treatment alternatives for producing finished water that meets the proposed criteria for PAH in potable water. As described in Appendix I, these criteria are:

- the sum of all carcinogenic PAH and carcinogenic heterocyclic PAH should be less than 28 nanograms per liter (parts per trillion); and

- the sum of noncarcinogenic PAH and noncarcinogenic heterocyclic PAH should be less than a value between 4.0 and 400 micrograms per liter (parts per billion).

Recommended procedures for monitoring compliance with these criteria are described in Appendix J.

The drinking water treatment alternatives evaluated in this section are based on the results of testing specific to the St. Louis Park problem, as described in Section G4. These results show that two basic types of drinking water treatment warrant study: granular activated carbon and addition of ozone or powdered activated carbon to iron removal treatment.

Granular activated carbon (GAC) has been shown to be capable of producing finished water that meets the proposed PAH criteria. While the results of GAC studies to date have not provided all of the data required to provide a final design and cost for GAC treatment, sufficient data exist to reasonably bound the design and cost of GAC treatment.

Studies to date have shown that equipment and operating modifications to pressure sand filter iron removal treatment should be capable of producing finished water that meets the proposed PAH

criteria. In particular, injection of ozone or powdered activated carbon (PAC) upstream of the filter bed should be effective. While significant additional study would be required to show that such modifications are practical and effective, and to design and cost them, sufficient preliminary data are available to provide likely bounds on the costs of these modifications. The exercise of bounding possible iron removal plant modification costs, based even on limited experimental data, is valuable because comparing these costs with those for GAC treatment, which is clearly capable of meeting the proposed PAH criteria, indicates the incentive, if any, to further study iron removal plant modification alternatives.

Most of the cost estimates presented in this section were developed from open literature data and reports, in particular from the U.S. EPA report "Estimating Water Treatment Costs" (Gumerman, Culp and Hansen 1979a,b,c). These cost estimates have been compared with those developed under previous drinking water treatment studies at St. Louis Park, particularly CH2M Hill's study. The major exception to this approach is that capital and operating costs for pressure sand filter iron removal plants were largely developed from actual cost data for the iron removal plants in St. Louis Park.

Cost estimates for all of the treatment cases considered were developed for a range of design capacities and flow rates. These estimates were then used to develop cost curves, with capital and operating and maintenance costs expressed as a function of plant capacity and/or flow rate. This approach was taken so that treatment costs for any given well could be readily obtained without developing a separate cost estimate. The cases considered were capacities of 1000, 3000 and 5000 gallons per minute and operating rates of 100, 300 and 500 million gallons per year (equivalent to 190, 570 and 950 gallons per minute). These capacities and operating rates span the range of values for municipal wells or clusters of municipal wells in St. Louis Park and neighboring communities (see section G2). It is important to note that design capacity and operating flow rates are not the same, since municipal wells in the area are operated at or near capacity when they are operated, but are not operated continuously.

All of the cost estimates presented in this section are based on December 1982 costs. Cost data used to develop these cost estimates that were reported on a different basis were adjusted to a December 1982 basis by using the Engineering News Record Construction Cost Index. Table G5-1 presents construction cost indices for various times relevant to the cost data sources used in this study. All cost estimates are based on labor at $14 per hour* and 5¢ per kilowatt-hour for power. Costs for engineering, legal and administrative fees, contractors overhead and profit, interest and contingencies are included in all capital cost estimates.

An important cost element in any drinking water treatment technology for removing trace quantities of PAH is the cost of monitoring the performance of the treatment plant to ensure that the finished water is meeting the proposed PAH criteria. The need to monitor plant performance is related to, but distinctly different than, the need for compliance monitoring as discussed in Appendix J. Plant performance needs to be monitored frequently, on about a weekly basis, while compliance monitoring is required less frequently. This section therefore includes a discussion of plant performance monitoring requirements, options for satisfying these requirements, and estimated costs for these options.

The material in this section is presented in four parts. Section G5.2 presents the design bases and cost estimates for modified iron removal plant treatment alternatives. Section G5.3 presents comparable information for granular activated carbon treatment. Plant performance monitoring techniques and costs are discussed in Section G5.4. Section G5.5 compares the various drinking water treatment alternatives and presents conclusions and recommendations.

*Based on $45,300 total salaries for two St. Louis Park Water Department personnel, plus 25 percent for fringe benefits (Tollefsrud 1983b).

TABLE G5-1

ENGINEERING NEWS RECORD CONSTRUCTION COST INDICES

Year or Month/Year	ENR Construction Cost Index[a]	Conversion Factor to Yield 12/82 Costs	Comment
1967	1070	3.674	
1970	1385	2.838	
1974	2020	1.946	
1977	2577	1.525	Cost basis for Zanitsch & Stenzel (1978)
Oct. 1978	2851	1.379	Cost basis for Gumermam, Culp and Hansen (1979a,b,c)
Dec. 1982	3931	1.000	Cost basis for this study

Notes:
(a) From Engineering News Record, March 18, 1982.

G5.2 Modified Iron Removal Plant Alternatives

The two modified iron removal plant treatment alternatives considered in this study are injection of ozone or powdered activated carbon upstream of the pressure sand filter beds. Tests performed on St. Louis Park well SLP15 water by Serco, Hickok and CH2M Hill indicate that these alternatives should be capable of achieving the proposed PAH criteria (see Section G4.6). However, significant additional studies would be required to verify the practicality and effectiveness of these techniques and to design and cost a treatment system. The design bases and costs presented in this section are therefore based on some design assumptions which would need to be verified. These assumptions have been expressed as a range of design values which should encompass final design conditions. These ranges therefore serve to bound the likely costs of these alternatives.

This section also presents estimated costs for building and operating a pressure sand filter iron removal plant. These cost estimates are needed because some of the St. Louis Park wells which have been taken out of service by PAH contamination (i.e., St. Louis Park wells SLP4, SLP5, SLP7 and SLP9) and some wells which might be affected by PAH contamination in the future (e.g., Edina well E2) do not currently have iron removal treatment (see section G2). Treatment based on modifying iron removal plants would require that an iron removal plant be built at these wells. Alternatively, these wells might be piped to a nearby well which does have an iron removal plant (e.g., pump water from SLP4 to SLP6, see Figure G2-1). This option is considered in section G5.5.

It is possible to envision other modifications to iron removal treatment that could achieve significant PAH removal. For example, polymers or other chemicals which improve filtration or coagulation performance might be added to enhance the adsorption and filtration of PAH associated with fine particulate matter or iron precipitate floc. However, there are no test data available for these alternatives. Therefore, no effort was made to estimate their costs, since such estimates would be purely speculative.

G5.2.1 Iron Removal Plant Costs

The estimated cost of building and operating an iron removal plant is based on a plant design similar to those of the existing iron removal plants in St. Louis Park. This design involves the use of pressure sand filters contained in horizontal, multi-celled cylindrical tanks with aeration and prechlorination before the filter and postchlorination and fluoridation after the filter. In some instances, chlorination and fluoridation all take place before the filter (e.g., St. Louis Park Station No. 8), although this has little effect on costs.

Actual contract costs for bulding the five iron removal plants in St. Louis Park are presented in Table G5-2. These costs are converted to a December 1982 basis and plotted as a function of plant capacity in Figure G5-1. A factor of 3.3 was applied to the equipment costs given in Table G5-2 to arrive at total capital cost.* The total capital cost includes all excavation, erection, equipment, piping, controls, electrical work, and a building to house the equipment (Goplin 1983a), plus engineering, legal and administrative fees and contractor's overhead and profit.

Reported operating costs in 1982 for St. Louis Park iron removal plants numbers 1 and 8 are given in Table G5-3 (Tollefsrud 1983b). These costs include costs for chemicals, electric power, gas for heating, and charges for backwash wastewater sent to the sanitary sewer. These costs were used in conjunction with cost data from Gumerman, Culp and Hansen (1979c) to develop the estimated operating and maintenance costs shown in Table G5-4. Electric power costs from St. Louis Park plants were not used in estimating costs because the power requirements at these plants are primarily for well pumps and

*The factor of 3.3 is based on the contract cost to equipment cost ratios for plants 1, 6, 8 and 10 in Table G5-2, plus 10% for engineering, legal and administrative fees. The ratio of 6.1 for plant 16 was excluded because it includes an unusually well-finished and landscaped building and an underground storage tank.

TABLE G5-2

CONSTRUCTION COSTS FOR THE IRON REMOVAL PLANTS
IN ST. LOUIS PARK, MINNESOTA

(Reproduced from Goplin 1983b)

Plant Number	Year Constructed	Contract Cost	Equipment Cost	Capacity gpm	Filters	Total Filter Area ft^2	Filter Rate gpm/ft^2
1	1970	$860,000 for both plts 1 & 8	$237,796	5000	4-5 cell units	2048	2.44
8	1970		$ 43,668	1000	2-4 cell units	420	2.38
6	1967	$465,193 for both plts 6 & 10	$ 86,784	3000	2-5 cell units	1200	2.5
10	1967		$ 81,095	2500	2-5 cell units	1000	2.5
16	1974	$735,200	$120,466	1100	2-4 cell units	452	2.4

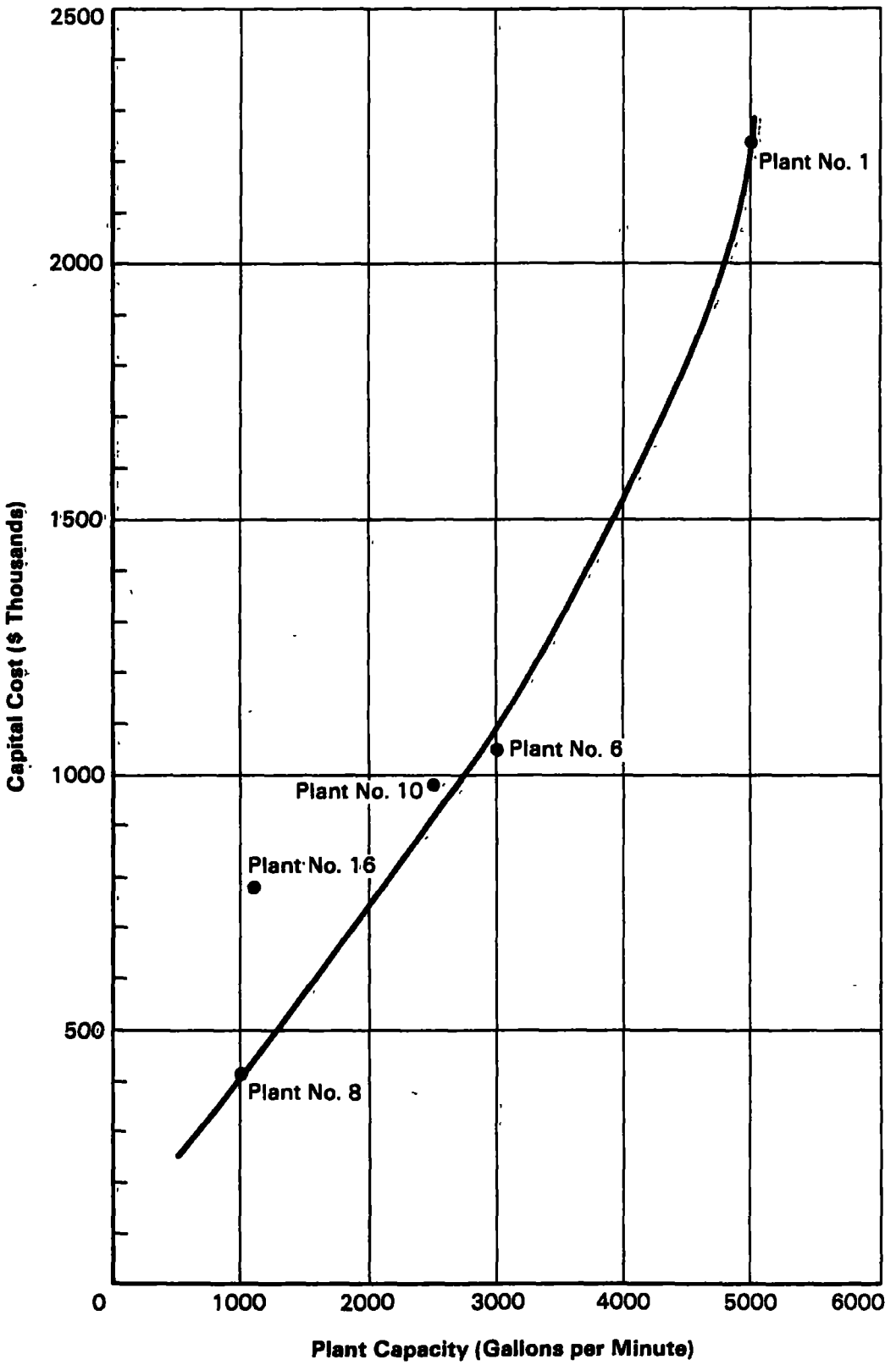

Figure G5-1 Capital Costs for Pressure Sand Filter Iron Removal Plants (December 1982 cost basis, derived from Table G5-2)

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TABLE G5-3

1982 OPERATING COSTS FOR IRON REMOVAL PLANTS
IN ST. LOUIS PARK
(From Tollefsrud, 1983b)

Plant Number	Total Flow Treated in 1982, Millions of Gallons	Operating Costs			
		Chemicals[a,c]	Electric Power	Gas Heating	Sanitary Sewer Charges[d]
1	532.1[b]	$3,635	$55,082	$5,600	$964
8	412.7	$3,222	$23,168	$2,994	$107

Notes:

(a) Based on chlorine at $219 per ton or $23.88 per cylinder. Fluoride at 8.6¢ per pound.

(b) Includes 7.9 million gallons of water from testing of well 15. All other pumpage was from wells 3 and 11.

(c) Chemical machine repairs costs are $150 to $200 per year on average at each iron removal plant. These costs are not included in the totals shown.

(d) Based on sanitary sewer charge of $0.89/hundred cubic feet. Total backwash waste water sent to the sanitary sewer in 1982 was 810,000 gallons for station no. 1 and 90,000 gallons for station no. 8.

TABLE G5-4

ESTIMATED OPERATING COSTS FOR
PRESSURE SAND FILTER IRON REMOVAL PLANTS

Plant Flow Rate, Millions of Gallons Per Year (gallons per minute)	Operating Costs					
	Process Energy [a]	Maintenance Material [a]	Chemicals [b]	Labor [c]	Heating Costs	Sanitary Sewer Charges
100 (190)	$ 700	$ 650	$ 770	$ 2,700	(d)	(e)
300 (570)	$1,800	$1,100	$2,310	$ 8,100	(d)	(e)
500 (950)	$3,200	$1,400	$3,850	$13,500	(d)	(e)

Notes:

(a) From Gumerman, Culp and Hansen 1979c, page 31, with power at 5¢/kilowatt hour.
(b) Based on $7.70 per million gallons, which is average cost for St. Louis Park plants 1 and 8, per Table G5-3.
(c) Based on $27 per million gallons, which is systemwide average for St. Louis Park based on total labor costs of $45,261 (plus 25% for fringe benefits) and total system production of about 2100 million gallons in 1982 (Tollefsrud 1983).
(d) Heating costs are a function of plant size (capacity), not operating rate. St. Louis Park heating costs reported in Table G5-3 were used to estimate costs of $3,000, $4,500 and $5,500 per year for plant capacities of 1000, 3000 and 5000gallons per minute, respectively.
(e) Sanitary sewer charges for discharging backwash waste water depend primarily on plant capacity (i.e., square feet of filter area), since backwashing occurs at regular intervals at a given rate. Sanitary sewer charges were estimated at $300, $900 and $1300 per year for plant capacities of 1000,3000 and 5000gallons per minute, respectively, based on 2.5 gallons per minute per square foot filter bed sizing, 15 gallons per minute per square foot backwash flow rate for 12 minutes, 36 backwashes per year (one every ten days), 10 percent of the settled backwash wastewater going to the sanitary sewer, and sanitary sewer charges of $ 0.89 per 100 cubic feet (Tollefsrud 1983).

high service booster pumps, which are already present at all wells in the St. Louis Park area, even if they do not have iron removal plants. The power costs shown in Table G5-4 are instead derived from Gumerman, Culp and Hansen (1979c) and reflect costs of backwash water pumping. The labor costs given in Tble G5-4 are based on system-wide Water Department labor costs in St. Louis Park. Heating costs and sanitary sewer charges are expressed as a function of plant capacity, not plant flow rate (see notes d and e to Table G5-4). Figure G5-2 plots the operating and maintenance costs in Table G5-4 as a function of plant flow rate and capacity.

G5.2.2 Ozone Injection Costs

The design basis for an ozone injection system is based on the results of bench-scale ozonation tests performed with water from well SLP15 by CH2M Hill. The results of CH2M Hill's tests for ozone without ultraviolet light are summarized below (see section G4.3 and CH2M Hill 1982e for more details):

Ozone Dose, milligrams per liter	Reaction Time, minutes	Total PAH, micrograms per liter	Carcinogenic PAH, nanograms per liter
1	20	2.83	1.9
5	20	2.16	2.5
5	60	1.37	none dectected

These tests clearly show that ozone treatment without ultraviolet light can meet the recommended PAH criteria. In each test, total PAH concentrations were reduced to less than 4 micrograms per liter, with no detectable carcinogenic PAH or only trace quantities of carcinogenic PAH (concentrations about a factor of ten below the 28 nanograms per liter criterion). The fact that this is achievable without UV light has significant cost implications, as discussed in section G4.3.

CH2M Hill noted that various oxidized PAH byproducts were detected in water treated by ozone, especially in water treated without ultraviolet light (CH2M Hill 1982e). Compounds detected included six

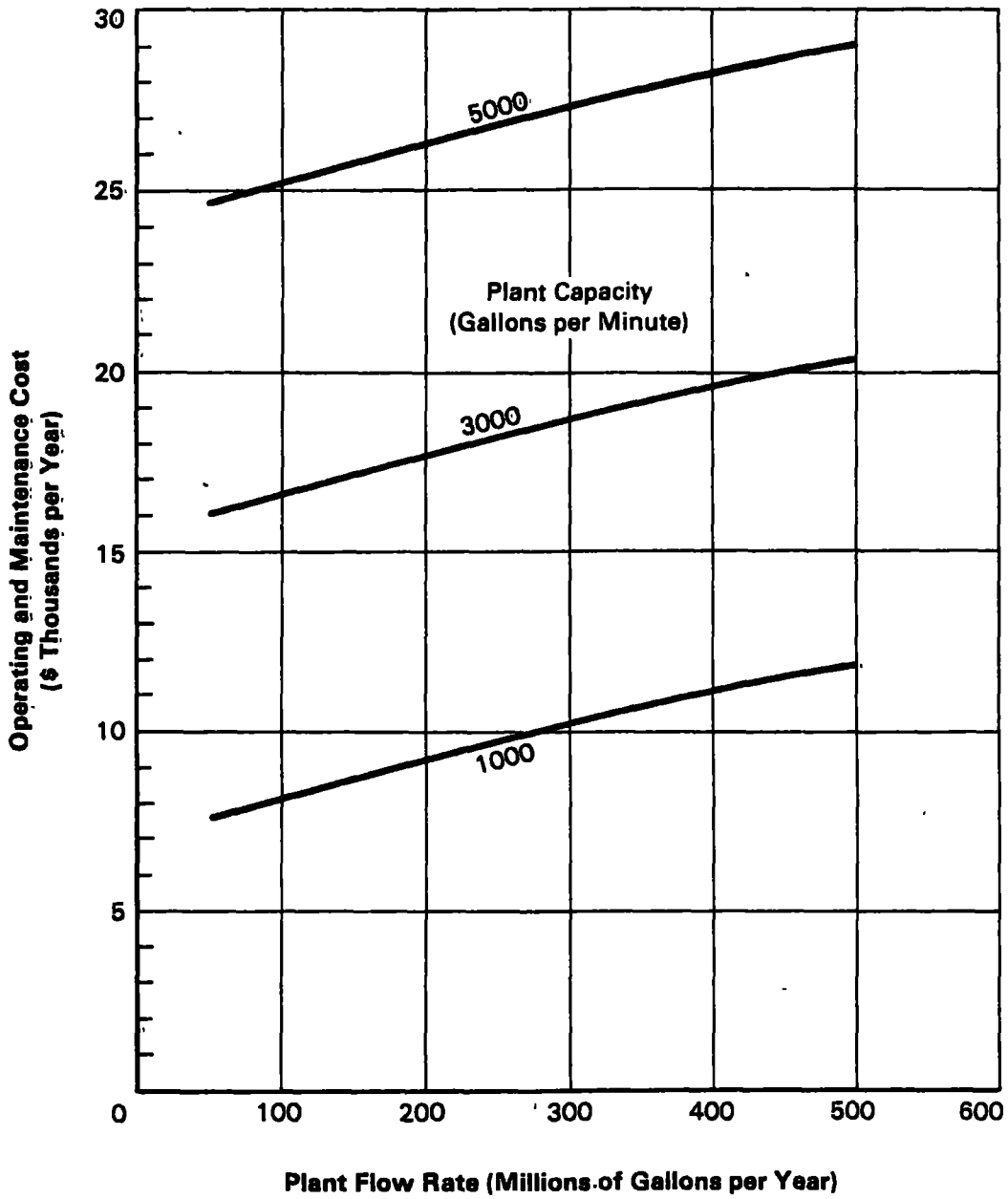

Figure G5-2 Operating and Maintenance Costs for Pressure Sand Filter Iron Removal Plants (Developed from data in Table G5-3)

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ketone derivative of two and three-ring PAH compounds. Available literatue indicates that carboxylic acid and aldehyde derivatives are also expected byproducts, although these would not have been detected by the analytical procedures used by CH2M Hill (Kruithof 1979, CH2M Hill 1982e). For purposes of costing the ozone injection treatment option, it is assumed that these oxidized PAH derivatives would either 1) not produce undesirable health effects at expected concentrations in the finished water or 2) be significantly removed by adsorption on iron precipitates or in the filter sand bed. The first assumption would need to be studied more thoroughly as part of any further study of ozone injection treatment. However, there are indications in the scientific literature that oxidized PAH derivatives are not carcinogenic (see section G3), and there is no reason to expect that such derivatives would be more toxic than non-oxidized, noncarcinogenic PAH (Santodonato 1983). The second assumption is based on the fact that oxidized PAH byproducts have distinctly different physical and chemical properties than their parent PAH precursors, and the hypothesis that these distinctly different properties could allow for their removal by adsorption. This, too, would require further study during any further investigation of ozone injection treatment.

The conceptual design for ozone injection treatment is to provide an ozone generator and injection piping at the wellhead. The required residence time for reaction would be obtained in the sand filter beds, which have hydraulic residence times of about 15 minutes (see section G4.4.4). Costs were estimated based on ozone doses of from 1 to 2 milligrams per liter. The lower dose was found to be effective in CH_2M Hill's tests. The higher dose is included to allow for ozone demand for oxidizing iron and manganese or bacteria in the wellhead water*.

*One mole of ozone takes up two electrons in aqueous reactions (Rice, et al 1979) and can therefore oxidize two moles of iron (Fe^{+2}) or one mole of manganese (Mn^{+2} to Mn^{+4}). This indicates that 0.4 milligrams per liter of ozone would be required to oxidize 0.8 milligrams per liter iron and 0.1 milligram per liter manganese, which are typical levels for the Prairie du Chien-Jordan aquifer (see sections G2.1 and G4.4).

Table G5-5 presents estimated capital costs for an ozone injection system for various plant capacities at the two different design dosages. On-site generation from air is assumed for the small generator sizes required. Construction costs include gas preparation equipment, the ozone generator, dissolution and off-gas recycling equipment, electrical and instrumentation costs, housing, and required safety and monitoring equipment (Gumerman, Culp and Hansen 1979b). Capital costs were estimated by adding 35 percent to construction costs for engineering, administrative and legal fees, contractor's overhead and profit, and contingencies.

Figure G5-3 plots capital costs from Table G5-5 as a function of plant capacity and ozone dose. This figure also shows the cost estimate made by CH2M Hill (1982) for an 800 gallons per minute, 1.5 milligram per liter ozone injection system. CH2M Hill's original estimate included an ultraviolet light reactor, but the cost shown in Figure G5-3 is only for CH2M Hill's estimated cost of an ozone generator, plus half of the total piping, electrical, and instrument costs, 25% contingency, and 10% for engineering, legal and administrative fees. CH2M Hill's estimated cost is about half that indicated by the cost curves in Figure G5-3.

Table G5-6 presents estimated operating and maintenance costs for an ozone injection system for various flow rates. Operating costs for the low ozone generation rates required are small and not very sensitive to flow rate. Labor is the main operating cost component. In theory, an operating cost credit should be taken for the fact that ozone injection upstream of an iron removal plant will eliminate the need for aeration and prechlorination (a final chlorination dose to yield a chlorine residual will still be required). This credit would be relatively small, however, and has not been taken into account in these estimates. Figure G5-4 plots operating and maintenance costs from Table G5-6 as a function of flow rate.

Ozone injection without an iron removal plant downstream was not considered a viable option. This is because ozone injection will oxidize ferrous iron to ferric iron, requiring an iron removal plant

TABLE G5-5

ESTIMATED CAPITAL COST FOR OZONE GENERATION EQUIPMENT

Treatment Capacity, gallons per minute	Ozone Required, pounds per day		Capital Cost, $Thousands (12/82 basis)[a]	
	1 milligram per liter dose	2 milligrams per liter dose	1 milligram per liter dose	2 milligrams per liter dose
1000	12	24	108	170
3000	36	72	230	350
5000	60	120	320	500

Notes:

(a) From Gumerman, Culp and Hansen 1979b, page 30, updated to 12/82 basis using construction cost indices presented in Table G5-1. Construction cost increased by 35 percent to give capital cost to allow for engineering, legal and administrative fees, contingencies and contractor's overhead and profit.

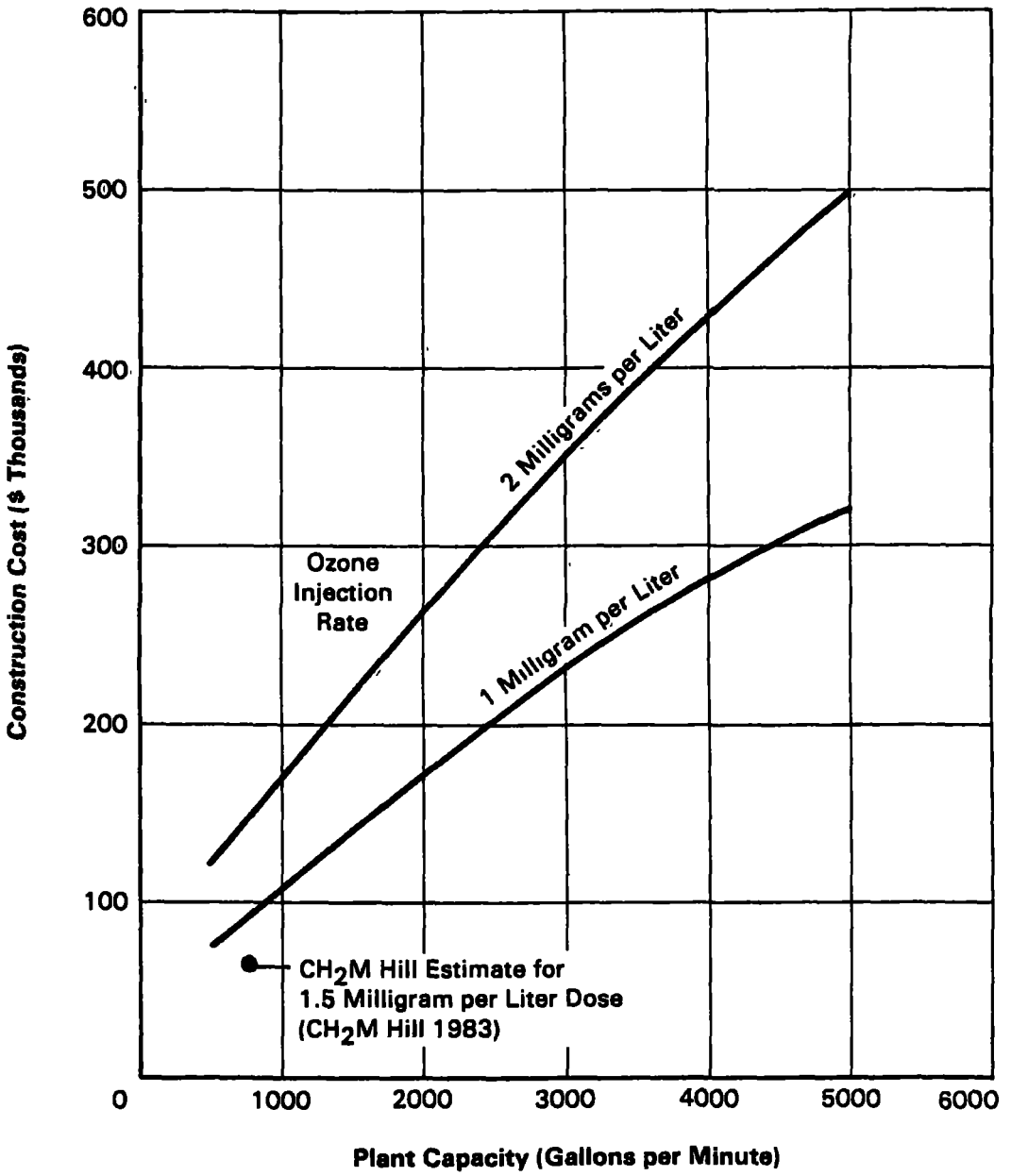

Figure G5-3 Construction Costs for Ozone Injection Equipment (Derived from Table G5-5, December 1982 cost basis)

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TABLE G5-6

ESTIMATED OPERATING AND MAINTENANCE COSTS
FOR OZONE GENERATION SYSTEMS[b]

Item	Annual Cost, $Thousand (12/82 Basis) at Various Flow Rates[a]		
	100 million Gallons per Year	300 million Gallons per Year	500 million Gallons per Year
Building Energy[c,d]	800/800	800/800	800/800
Process Energy[c]	600/1100	1500/2700	2400/4500
Maintenance Material	1000/1100	1100/1300	1200/1500
Labor[e]	7700/7700	7700/7700	7700/7700
	$10,100/$10,700	$11,100/$12,500	$12,100/$14,500

Notes:

(a) Costs based on actual ozone usage at 1 milligram per liter/2 milligrams per liter doses for various flow rates.
(b) All costs from Gumerman, Culp and Hansen 1979b page 34.
(c) Based on 5¢ per kilowatt hour electrical costs.
(d) Building energy based on 120 pounds per day ozone capacity system, the largest considered in this study (see Table G5-5), with correction factor of 2.2 for Minneapolis area (Gumerman, Culp and Hansen 1979a, page 96).
(e) Based on $14 per hour labor rate.

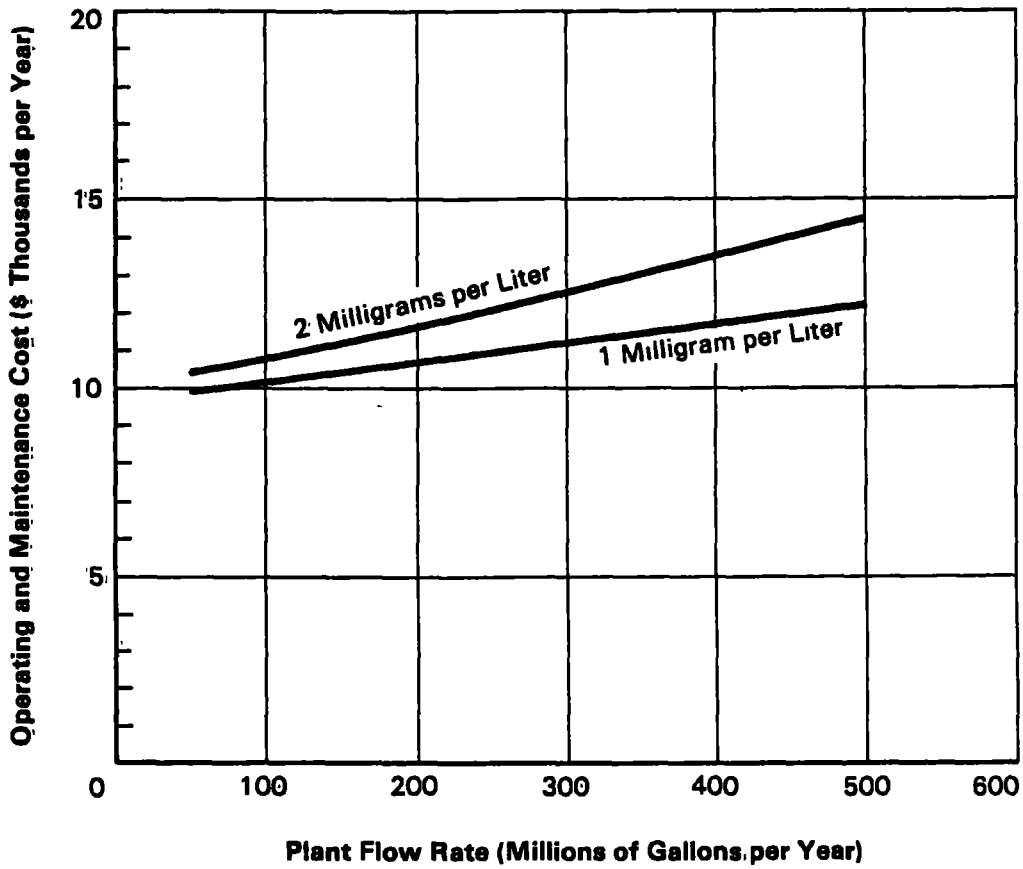

Figure G5-4 Operating and Maintenance Costs for Ozone Injection Systems (Derived from Table G5-6)

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to prevent iron precipitates from getting into the water distribution system. Ozone injection downstream of an iron removal plant would require tankage to provide sufficient reaction residence time, which would be an extra cost compared to obtaining the required residence time in existing sand filter beds.

G5.2.3 PAC Injection Costs

The design basis for a powdered action carbon (PAC) injection system is derived from on test results obtained by Serco, Hickok and CH2M Hill. Serco's 1979 pilot testing of PAC injection at the wellhead of SLP15 showed that PAH concentrations were reduced by about 60 percent at a dose rate of 1 to 2 milligrams per liter and by over 99 percent at a dose of 9 to 12 milligrams per liter (see section G4.1). Similar pilot testing at the SLP15 wellhead by Hickok in 1980 showed that either no PAH were detected or total PAH concentrations were below 50 nanograms per liter in water treated with 5.5, 8, 11 or 15 milligrams per liter of PAC (see section G4.2). However, both of these studies involved PAH analyses using HPLC, so that the full spectrum of compounds and lower detection limits associated with GCMS analyses, as used in studies by CH2M Hill and ERT, were not obtained.

As described in section G4.3, CH2M Hill did not perform pilot or bench-scale testing of PAC injection per se, but did measure PAH equilibrium adsorption isotherms with granular activated carbon which had been pulverized to 0.0015 by 0.0029 inches (no. 200 by no. 400 sieve size). Results of these tests can be considered to indicate removals achievable by PAC after 2 hours of contact time, which was the isotherm test period used by CH2M Hill. It should be noted that the rate at which PAH approach equilibrium adsorption capacity is unknown, but could be rapid. For example, 2-chloronaphthalene has been shown to achieve 75 percent of equilibrium adsorption capacity in about 25 minutes (Dobbs and Cohen 1980). CH2M Hill's isotherm tests showed that 10 milligrams per liter of pulverized GAC reduced total PAH concentrations to about 300 to 400 nanograms per liter, with no detectable carcinogenic PAH. At 1 milligram per liter of pulverized GAC, total PAH concentrations remained at about 7 micrograms per liter.

These various tests indicate that PAC should be effective in removing PAH when injected at the wellhead. The results, however, do not allow for accurately determining the dosage required to achieve the proposed PAH criteria for potable water. For purposes of estimating costs, therefore, a range of PAC doses from 2 to 10 milligrams per liter was considered, including an intermediate dose at 5 milligrams per liter. The 10 milligram per liter dose should be more than adequate to achieve the criteria. However, the 2 milligram per liter dose is the minimum likely to achieve the PAH criteria, based on Serco's and CH2M Hill's test results. In fact, it is an optimistic dose, based on CH2M Hill's isotherm test results for pulverized GAC. These isotherms show that 2 milligrams per liter of the best PAC tested (Calgon 300) would remove about 8 micrograms per liter of PAH if equilibruim adsorption was obtained, based on 10 micrograms per liter total PAH in the feed water (see Figure G4-4).

Table G5-7 presents estimated capital costs for powdered activated carbon feed systems of various capacities. Capital costs for two different design cases are presented (Gumerman, Culp and Hansen 1979b & c). The more elaborate and expensive design is based on PAC slurry storage in two underground concrete tanks providing 8 days of slurry storage capacity, with related pumping and metering equipment. The simpler, less expensive design uses two 55-gallon slurry tanks. In either case, PAC is slurried at a strength of 11 weight percent. The storage capacity of these two 55-gallon tanks ranges from 1 to 22 days for the operating rates considered (see Table G5-8). The simpler system is considered to be more appropriate for injection rates less than about 2 pounds per hour, which will provide a storage capacity of at least 2 days. All but the very highest flow rate and PAC dose combinations considered in this study provide a storage capacity of about 2 days or more (see Table G5-8), so costs for PAC injection are based on the simpler design. Figure G5-5 plots capital costs as a function of flow rate for various PAC dose rates.

Table G5-8 presents operating and maintenance costs for various flow rate and PAC dose combinations. The resulting PAC injection rates, in pounds per hour, and slurry storage tank capacities, in

TABLE G5-7

ESTIMATED CAPITAL COST FOR POWDERED ACTIVATED CARBON FEED SYSTEMS[c]

Treatment Capacity, gallons per minute	PAC Feed Rate, pounds per hour			Capital Cost, $Thousands (12/82 Basis)[a,b]		
	2 milligrams per liter dose	5 milligrams per liter dose	10 milligrams per liter dose	2 milligrams per liter dose	5 milligrams per liter dose	10 milligrams per liter dose
1000	1.0	2.5	5.0	115 (13)	119 (14)	127 (15)
3000	3.0	7.5	15	122 (14)	132 (15)	139 (17)
5000	5.0	12.5	25	127 (15)	136 (16)	153 (18)

Notes:

(a) From Gumerman, Culp and Hansen 1979b, page 106, updated to Dec. 1982 basis using construction cost indices presented in Table G5-1. Costs based on 8-day capacity slurry storage in two underground concrete tanks using a diaphragm metering pump.

(b) Values in parentheses from Gumerman, Culp and Hansen 1979c, page 69, updated to Dec. 1982 basis. Costs based on two 55 gallon slurry tanks with vacuum bag unloading system, without housing. Estimated cost of $5,000 for housing is added to all costs from Gumerman, Culp and Hansen.

(c) Capital cost includes 35 percent addition to construction cost for engineering, legal & administrative fees, contingencies and contractor's overhead and profit.

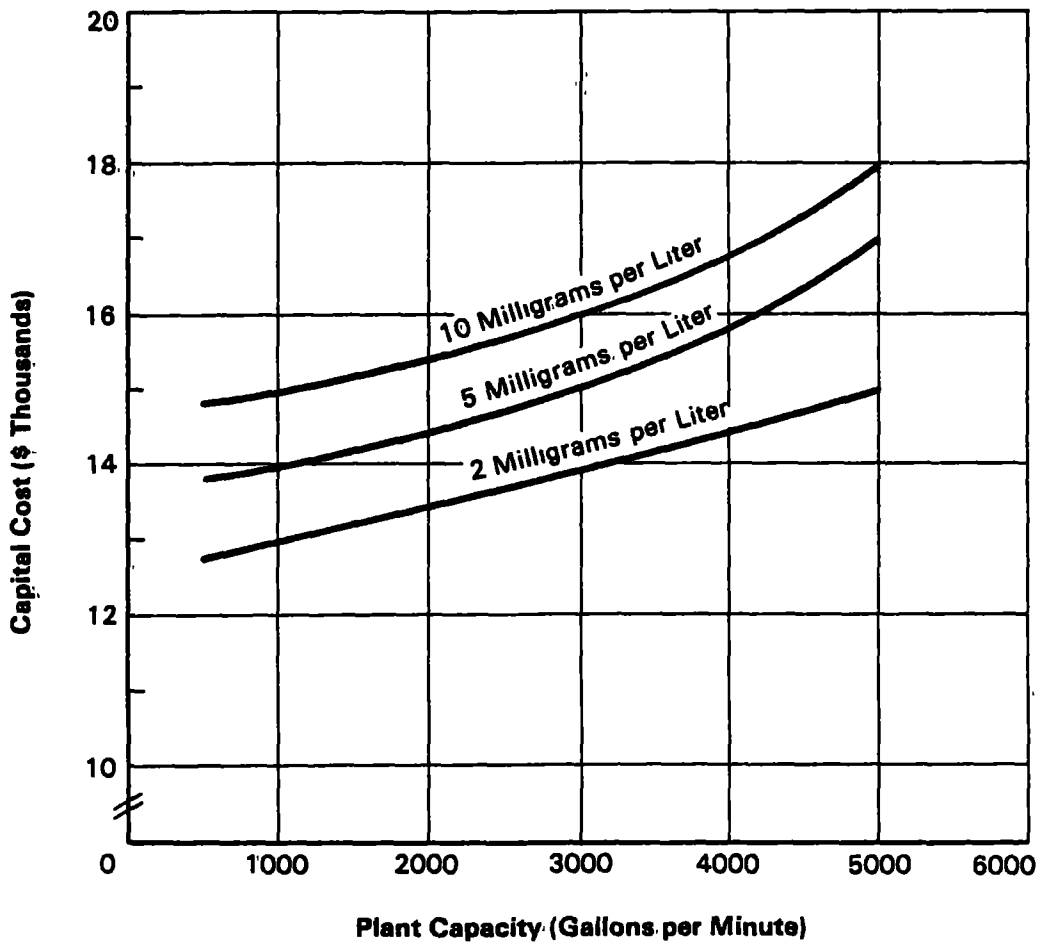

Figure G5-5 Capital Costs for Powdered Activated Carbon Injection Systems (Derived from Table G5-7, December 1982 cost basis)

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TABLE G5-8

ESTIMATED OPERATING AND MAINTENANCE COSTS
FOR POWDERED ACTIVATED CARBON INJECTION

Flow Rate, Millions of Gallons per Year	PAC Dose, milligrams per liter	PAC Injection Rate, Pounds per Hour	Slurry Tank Storage Capacity, Days[c]	Operating Costs, $Thousands per Year			
				Process & Building Energy, plus Maintenance Materials[a]	Labor[a]	PAC[b]	Total
100	2	0.19	22	330	1,700	1,000	3,000
100	5	0.48	8.7	340	2,200	2,500	5,000
100	10	0.95	4.4	360	2,800	5,000	8,200
300	2	0.57	7.3	350	2,400	3,000	5,800
300	5	1.42	2.9	360	3,200	7,500	11,100
300	10	2.85	1.5	380	4,000	15,000	19,400
500	2	0.95	4.4	360	2,800	5,000	8,200
500	5	2.38	1.8	380	3,800	12,500	16,700
500	10	4.75	0.9	410	5,000	25,000	30,400

Notes:

(a) From Gumerman, Culp and Hansen 1979c, pp. 71, with labor at $14 per hour and power at 5¢/kilowatt hour. Building energy requirement assumed at 4000 kilowatt-hours per year.
(b) Based on 60¢ per pound for PAC (Chalmers 1983).
(c) Based on two 55-gallon tanks containing 11 weight percent slurry (See Table G5-7).

days, are also shown. Operating costs are seen to be dominated by the cost of PAC, especially at higher injection rates. Figure G5-6 plots the operating and maintenance costs presented in Table G5-8.

The PAC injected at the wellhead should accumulate on the surface of the sand filter beds in the iron removal plant downstream. This will need to be verified, however, to ensure that PAC does not break through the sand beds and foul pumps or enter the distribution system. It is assumed that PAC accumulated on the filter beds would be readily removed by normal backwashing, and would ultimately be discharged to the sanitary sewer, to the extent that PAC settles in the backwash wastewater settling tank, or to the storm sewer, to the extent that the PAC does not settle. Costs for permitting storm sewer discharges or for extra strength charges for sanitary sewer discharges are not included in the PAC system cost estimates because of uncertainties in estimating these costs. However, these costs are not expected to be significant compared to the overall cost of a PAC injection system.

There is a possibility that the layer of PAC that should accumulate on top of the sand filter beds could 1) continue to effect additional PAH removal and/or 2) lead to higher pressure drops across the filter. Over the course of 10 days - the maximum interval allowed between backwashes at the St. Louis Park iron removal plants (Tollefsrud 1982a) - up to about a quarter of an inch of PAC could accumulate on top of the sand bed.* At the other extreme, only about 0.01 inch of PAC would build up at the lowest injection rate. If higher pressure drops occur across the filter beds because of these PAC accumulations, operating costs for the iron removal plant would increase as a result of higher pumping heads and/or more frequent backwashing. On the other hand, if PAC accumulated on the filter bed continues to effect PAH removal, then the PAC injection rate might be

*Based on the highest PAC injection rate shown in Table G5-8, a bulk density of 120 pounds per cubic foot for PAC, and a filter bed area of 500 square feet.

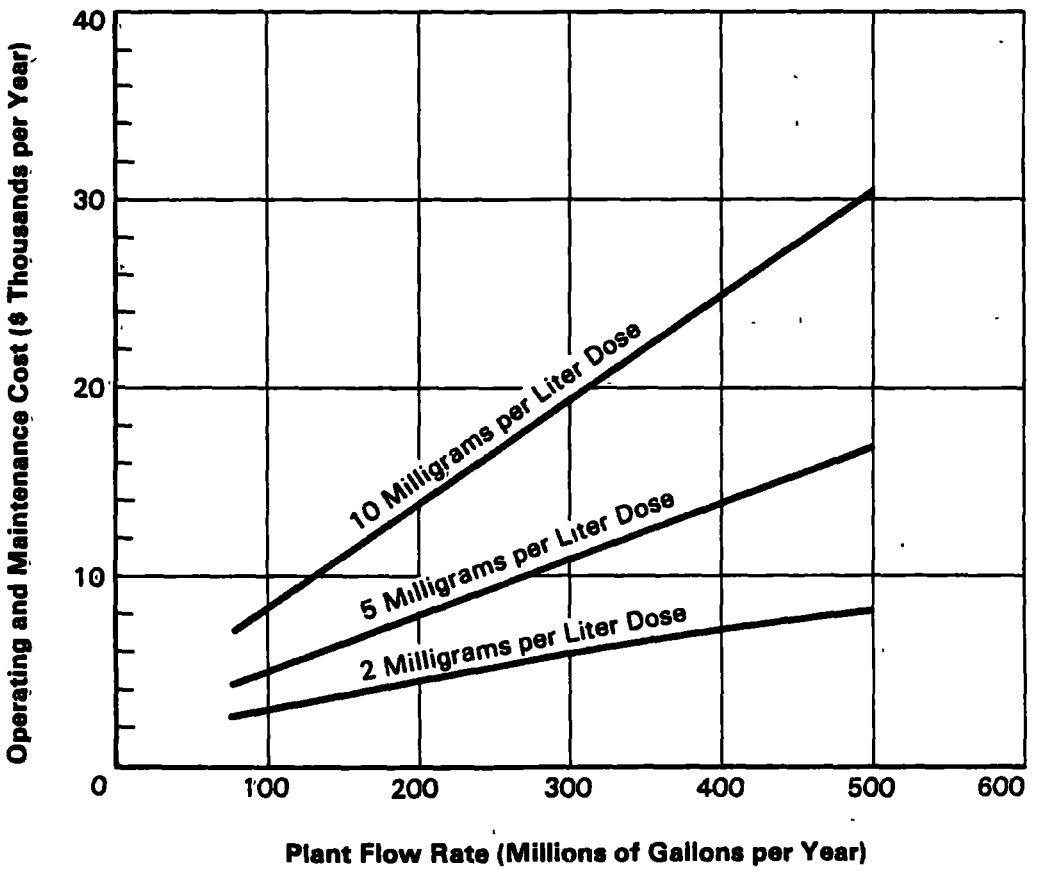

Figure G5-6 Operating and Maintenance Costs for Powdered Activated Carbon Injection Systems (Derived from Table G5-8)

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decreased, or PAC injection might be stopped for a few days prior to backwashing. Either of these possibilities would reduce PAC injection costs. Allowances for cost increases, as a result of higher pressure drops, or for cost savings resulting from effective PAH removal by accumulated PAC, were not considered in this study because of the significant uncertainties involved in estimating these costs. It is assumed that these costs and savings would roughly balance each other, so that the net effect on the cost estimates presented here would not be substantial.

PAC injection at wells without iron removal treatment was not considered in this study because such a system would require some means for removing PAC from the water before it entered the distribution system. Required removal techniques could include coagulation, clarification, filtration, or some combination of these steps. Any system for removing PAC would likely be of comparable or even greater cost than a pressure sand filter iron removal plant. An iron removal plant also has the advantage of improving the quality of the treated water in performing its function of removing iron. In cases where PAC was evaluated for contaminated wells without iron removal plants, therefore, the cost of building and operating an iron removal plant was included.

G5.3 Granular Activated Carbon Treatment

Granular activated carbon treatment of St. Louis Park well SLP15 has been studied by both Hickok and CH2M Hill (see sections G4.2 and G4.3, respectively). Hickok performed pilot tests in the field in 1980. CH2M Hill completed bench tests in December 1982 and commenced pilot testing in the field in mid-February 1983. The results of CH2M Hill's pilot testing were not available at the time this report was prepared.

CH2M Hill's studies of granular activated carbon treatment are more definitive than Hickok's earlier tests and were therefore used to provide the design bases for the cost estimates presented in this section. CH2M Hill's studies provide more definitive design data

because of the better analytical techniques used (GCMS vs. HPLC) and the more useful design information obtained (e.g., equilibrium adsorption isotherms).

Both CH2M Hill's and Hickok's tests of granular activated carbon treatment applied to water from St. Louis Park well SLP15 indicate that treated water that meets the proposed PAH criteria can readily be achieved. Hickok's pilot GAC column tests showed no detectable carcinogenic PAH in any of the treated water samples (with the exception of from 3 to 36 nanograms per liter of carcinogenic PAH in four of thirteen samples) and total detectable noncarcinogenic PAH of at most 56 nanograms per liter (see Table G4-6). CH2M Hill's bench GAC column tests showed less than 2 nanograms per liter of total carcinogenic PAH (due solely to quinoline) and total noncarcinogenic PAH concentrations ranging from 30 to 110 nanograms per liter (see section G4.3).

G5.3.1 Design Basis

The two design variables which primarily affect the cost of granular activated carbon treatment are contact time and breakthrough time. Contact time is a nominal measure of how long the water being treated is in contact with the carbon. Sufficient contact time must be allowed to achieve the desired removal efficiencies. The contact time and design flow capacity determine the size of the carbon columns, so that the contact time is a primary determinant of capital costs.

Breakthrough time is a measure of how long a carbon column can operate before the carbon's effective adsorption capacity is exhausted and contaminants appear in the effluent at concentrations above the desired level. Breakthrough time can also be expressed as a carbon exhaustion rate; that is, the rate (e.g., pounds per day) at which the carbon looses its effective adsorptive capacity and must be replaced or regenerated. The breakthrough time determines how often the carbon must be replaced or regenerated, and is therefore a primary factor in determining operating costs.

Contact Time

Unfortunately, the studies performed to date for GAC treatment at well SLP15 have not provided definitive data for establishing contact and breakthrough times. Pilot testing of GAC at well SLP15 in progress by CH2M Hill should provide the required data. For the purpose of estimating GAC treatment costs, however, currently available test results have been used to bound likely design values for contact time and breakthrough time. Empty bed contact times of 7.5, 15 and 30 minutes were selected for costing purposes based on the following factors:

1) CH2M Hill's bench-scale column testing showed effective PAH removal at a contact time of 5.6 minutes (see section G4.3);

2) Hickok's pilot-scale column testing showed effective PAH removal at contact times ranging from 5.6 to 22.5 minutes (see section G4.2);

3) CH2M Hill's conceptual design basis for a GAC plant at SLP15 was based on a 30-minute contact time based on vendor recommendations (CH2M Hill 1982), although this was said to probably be conservative (Harris 1983);

4) Contact times for drinking water treatment for taste and odor removal are reported to be as low as 7 minutes (Zanitsch and Stanzel 1978).

These facts indicate that on the order of 7.5 minutes contact time is a likely best-case, while 30 minutes represents a worst-case. Figure G5-7 shows how the total carbon bed size (expressed as pounds of carbon) varies as a function of design capacity (gallons per minute) and empty-bed contact time.

Breakthrough Time

Breakthrough time is determined by the inlet loading of contaminants (i.e., flow rate and concentration) and the adsorptive capacity of the carbon for the contaminants being removed. This study

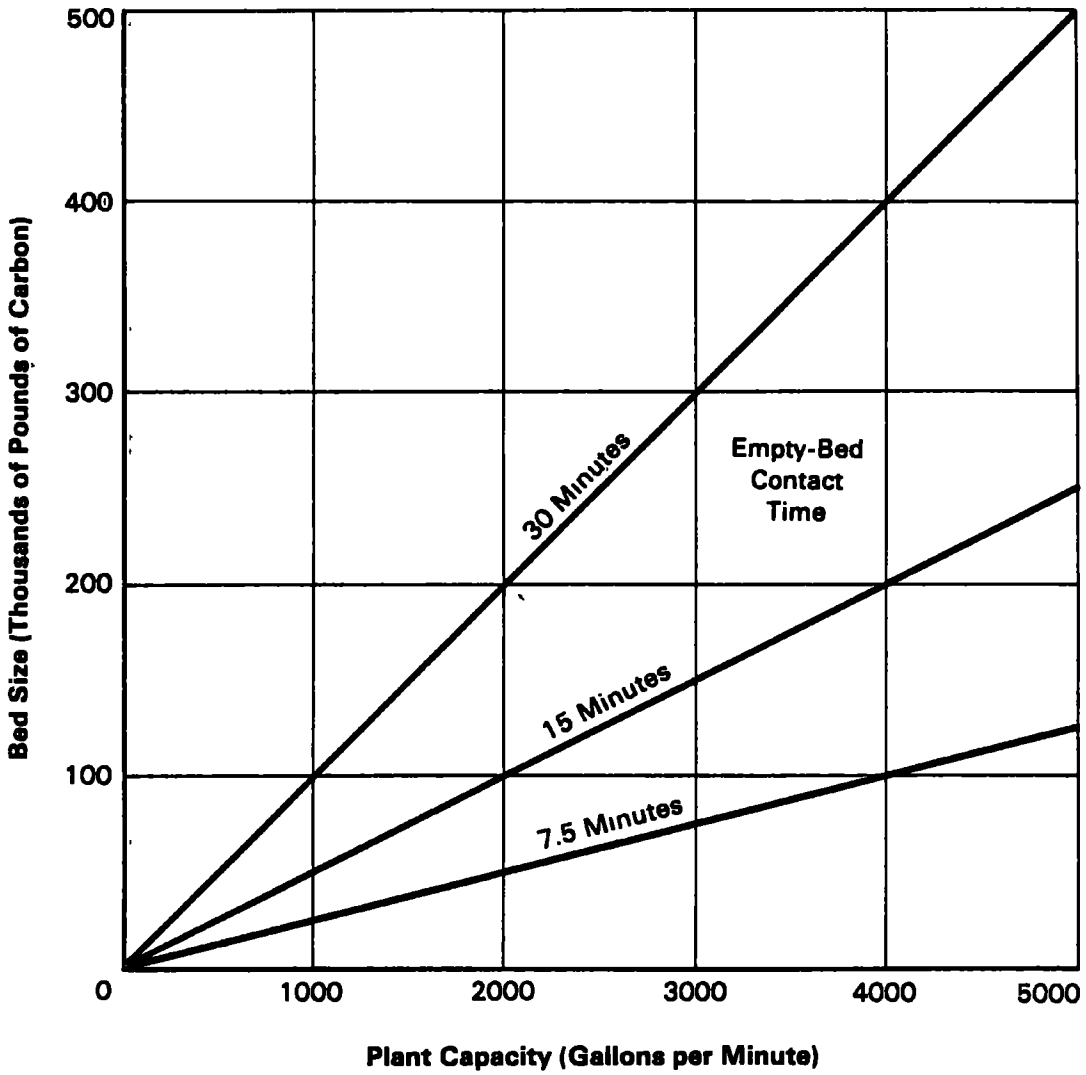

Figure G5-7 Granular Activated Carbon Column Bed Size as a Function of Plant Capacity and Contact Time (Based on 25 pounds per cubic foot GAC bed density)

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developed parametric cost estimates for various inlet loadings, based on flow rates of 100, 300 and 500 million gallons per year and 10 micrograms per liter total PAH and heterocyclic PAH, which is near the highest concentrations observed at well SLP15 (see sections G4.3, G4.4, and G4.5). The resulting PAH loadings of 8.3, 25.0, and 41.7 pounds per year can also be viewed as resulting from other flow and concentration combinations, however (e.g. 20 micrograms per liter total PAH at 50, 150 and 250 million gallons per year).

CH2M Hill's bench-scale isotherm testing results yielded equilibrium PAH adsorption capacities for five different brands of carbon (see section G4.3). At an inlet concentration of 10 nanograms per liter, the highest adsorption capacity was about 4 milligrams PAH per gram of carbon (for Calgon 300 carbon), with the other carbons yielding adsorption capacities of about 1.5 to 2.5 milligrams PAH per gram carbon (see Figure G4-4). Adsorption capacity varied as the 0.3 to 0.4 power of inlet concentration for each carbon tested, so that changing the inlet concentration by a factor of ten only changed the adsorption capacity by a factor of 2 to 2.5. This means that a ten-fold increase in inlet concentrations for a given carbon bed would only reduce the breakthrough time by a factor of 4 or 5.

Adsorption capacities determined by isotherm tests do not always translate directly to ultimate adsorption capacities during actual operation. This is particularly true for adsorption of trace contaminants, since the adsorption capacity for trace materials can be affected by the much larger quantities of other materials in the water. A good example of this is removal of trihalomethanes by GAC, where much faster breakthrough (i.e., lower ultimate adsorption capacity) has been observed during extended testing than predicted by equilibrium isotherm data (Luthy 1982).

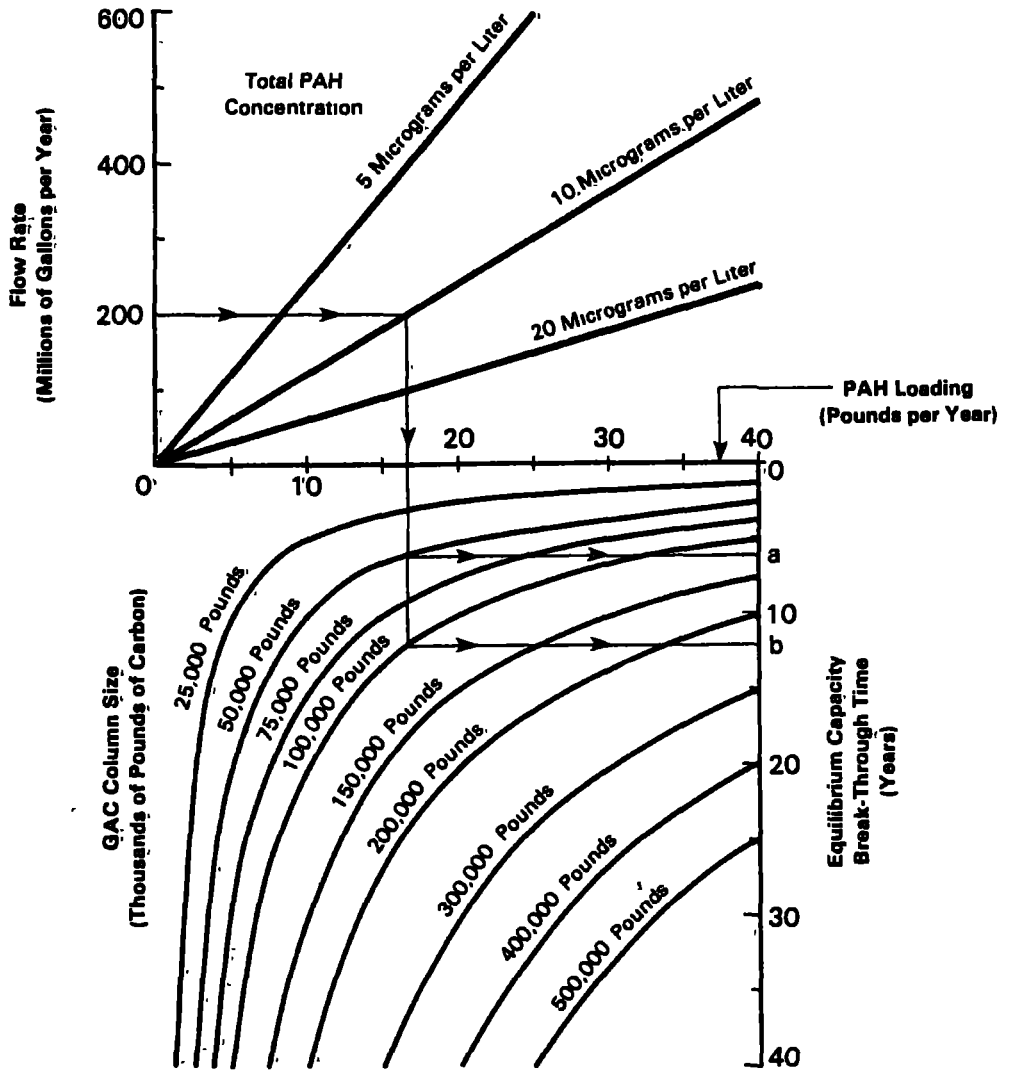
In order to account for the fact that the ultimate PAH adsorption capacity of GAC is currently unknown, cost estimates were developed for two widely different breakthrough times. For the optimistic case, it was assumed that breakthrough times correspond to closely attaining equilibrium adsorption capacity, which, base on CH2M Hill's isotherm

tests, was assumed to be 2 milligrams PAH per gram carbon (2 pounds per 1000 pounds). Figure G5-8 shows the equilibrium capacity breakthrough times that result from various PAH loadings and carbon bed sizes based on this assumed capacity. A maximum breakthrough time of 10 years was assumed in order to keep the cost estimates realistic.

The other case considered was a breakthrough time of one year, independent of bed size or PAH loading. This breakthrough is believed to be more realistic than attaining equilibrium adsorption capacity, but it is currently unknown if this case is too pessimistic or even still too optimistic (i.e., actual breakthrough times would be less than one year). The ultimate adsorption capacities implied by a one year breakthrough time for the various cases considered can be determined from Figure G5-8. For example, a 50,000 pound carbon bed, which would result from 15 minutes contact time and 1000 gallons per minute capacity (see Figure G4-7), treating an inlet PAH loading of 16.7 pounds per year (200 million gallons per year at 10 micrograms per liter total PAH, for example, see Figure G4-8), would have a breakthrough time of 12 years if the assumed equilibrium adsorption capacity of 2 pounds PAH per 1000 pounds carbon were achieved. Using a one-year breakthrough time instead is therefore equivalent to assuming an ultimate adsorption capacity of 0.17 pounds PAH per 1000 pounds carbon.

Effects of Iron

An important design consideration in installing GAC treatment for wells in the St. Louis Park area is the effect of iron and iron bacteria in the well water on the operation and performance of the GAC plant. As discussed in sections G2 and G4.4, water from the Prairie du Chien-Jordan contains about 0.8 milligrams per liter of iron and also contains oxidizing iron bacteria. The carbon column in a GAC plant treating wellhead water would be expected to provide a suitable environment for iron bacteria to flourish. The resulting growth of iron bacteria slime could adversely affect the performance of a GAC plant. At wells that currently have iron removal plants, GAC treatment is assumed to be installed downstream of the iron removal



Example. 200 million gallons per year of flow containing 10 micrograms per liter total PAH gives a PAH loading of 16 7 pounds per year This loading applied to a 50,000 pound GAC column (sized for 1000 gallons per minute flow and a 15-minute contact time) yields an equilibrium capacity breakthrough time of 6 years (case a) For a 100,000 pound GAC column (sized for 1000 gallons per minute flow and 30-minute contact time), the equilibrium capacity breakthough time increases to 12 years (case b).

Figure G5-8 Nomograph for Determining Eqilibrium Capacity Breakthrough Time (Based on eqilibrium adsorption capacity of 2 pounds total PAH per 1000 pounds of carbon)

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plant in order to avoid this problem. At wells without iron removal treatment, it is assumed that the GAC plant would be operated in part as an iron removal plant. It is assumed that this could be done by injecting a sufficient chlorine dose upstream of the GAC plant to oxidize ferrous iron and kill any iron bacteria.* The resulting ferric precipitate would be filtered by the carbon bed, requiring regular backwashing to remove accumulated iron precipatates, as for a sand filter bed, and proper disposal of the backwash wastewater.

The potential effects of iron bacteria growths and the feasibility and design of a GAC plant operating in an iron removal mode, in addition to removing PAH, are areas requiring further study if GAC treatment is are to be installed at wells without iron removal plants. The GAC cost estimates made below are based on the assumption that a GAC plant would need to be and could be operated in part as an iron removal plant in order to prevent adverse effects by iron bacteria growths. The assumed design is prechlorination, using chlorination equipment currently installed at all wells in the St. Louis Park area, followed by the GAC columns. The GAC columns are assumed to be backwashed every 10 days, with the wastewater sent to a settling tank, settled sludge going to a sanitary sewer, and clarified wastewater going to a storm sewer.

G5.3.2 Cost Estimates

Table G5-9 presents estimated capital costs for GAC treatment plants for various combinations of plant capacities and contact times. The costs represent total installed costs for a two-stage configuration, including indirect costs such as legal, engineering and administrative fees and contractor's overhead and profit. These estimates were derived from Zanitsch and Stenzel (1978), but are comparable to estimated costs that can be derived from Gumerman, Culp and Hansen (1979b).

*Note that ERT's December 1982 test indicated that a chlorine dose just to kill iron bacteria is not possible, since chlorine also oxidizes ferrous iron very rapidly (see section G4.4.5).

TABLE G5-9

ESTIMATED CAPITAL COST FOR GRAUNULATED ACTIVATED CARBON TREATMENT

Treatment Capacity, Gallons per Minute	Carbon Volume, Cubic Meters			Total Installed Cost, $Thousands[b]		
	7.5-Minute Contact Time[a]	15-Minute Contact Time	30-Minute Contact Time	7.5-Minute Contact Time	15-Minute Contact Time	30-Minute Contact Time
1000	28	57	114	310	470	760
3000	85	170	340	620	1040	1900
5000	142	284	570	910	1680	3100

Notes:

(a) Superficial (empty bed) contact times.
(b) For two-stage configuration. Installed cost includes pumps, adsorbers, flow control, piping, electrical, foundations, winterization, initial fill and indirects. Estimates based on lined carbon steel adsorbers with lined piping and valving (Zanitsch and Stenzel, 1978). Costs updated from mid-1977 to December, 1982 basis using construction cost indices presented in Table G5-1. Fees, contingencies and contractor's overhead and profit are assumed to be covered by "indirects".

Table G5-10 presents estimated capital costs for backwash wastewater surge basins. These costs need to be included for GAC plants installed at wells without iron removal plants. Backwash wastewater settling basins are required to operate a GAC plant to effect iron removal, which is needed to prevent growths of iron bacteria slime. Surge basin costs from Gumerman, Culp and Hansen (1979b) have been used to represent underground settling tanks costs, including settling tank pumps and piping to storm and sanitary sewers. No cost is included for chlorination equipment for iron removal in GAC plants, because it is assumed that chlorination equipment currently used at all wells in the St. Louis Park area has sufficient capacity to provide the additional chlorine dose required.

Figure G5-9 plots capital costs for GAC plants as a function of plant capacity and contact time, with and without the inclusion of a backwash wastewater surge basin. CH2M Hill's cost estimate for an 800 gallon per minute, two-stage GAC plant sized for a 30-minute contact time is also shown in Figure G5-9 (see Section G4.3.5 and CH2M Hill 1983a). It can be seen that CH2M Hill's estimate is within a few percent of the appropriate cost curve.

Table G5-11 presents estimated operating and maintenance costs for a GAC plant operated at various flow rates, excluding carbon replacement costs. The estimated cost for building energy is based on flow rate, not capacity, even though capacity gives better measure of building size and therefore of building energy requirements. This was done to reflect the assumption that GAC equipment would make as much use as possible of extra space within existing iron removal plants, minimizing or even eliminating the need for additional building space. It is not possible to estimate accurately building requirements and associated costs without more detailed design of each particular installation, which is beyond the scope or needs of this study. The approach taken here will result in over-estimated costs to the extent that GAC equipment could be entirely located within existing iron removal plant buildings, and in under-estimated costs to the extent that larger GAC buildings are required (which is particularly the case for wells without existing iron removal

TABLE G5-10

ESTIMATED CAPITAL COST FOR BACKWASH WASTEWATER SURGE BASINS FOR GAC TREATMENT WITHOUT IRON REMOVAL TREATMENT PLANTS

Plant Capacity, Gallons per Minute	Carbon Volume, cubic feet [a]	Number of Contactors [a,b]	Backwash Wastewater Surge Basin volume, gallons [c]	Construction Cost, $Thousands (12/82 Basis) [d]
1000	1,000/2,000/4,000	2/4/8	22,500	180
3000	3,000/6,000/12,000	4/8/16	34,000	210
5000	5,000/10,000/20,000	6/12/24	38,000	240

Notes:

(a) Based on 7.5-minute/15-minute/30-minute superficial contact time.
(b) Results in contactors which are 12.6 to 16.3 feet in diameter with a 4 foot bed depth.
(c) Based on 4 gallons per minute per square foot hydraulic loading, 15 gallons per minute per square foot backwash rate, 12 minutes backwashing per contactor, and contactors backwashed one at a time. Note that same surge basin volume is required for any contact time shown.
(d) From Gumerman, Culp and Hansen 1979b, page 178, updated to 12/82 cost basis using construction cost indices presented in Table G5-1, with 35 percent added for fees, contingencies and contractor's overhead and profit.

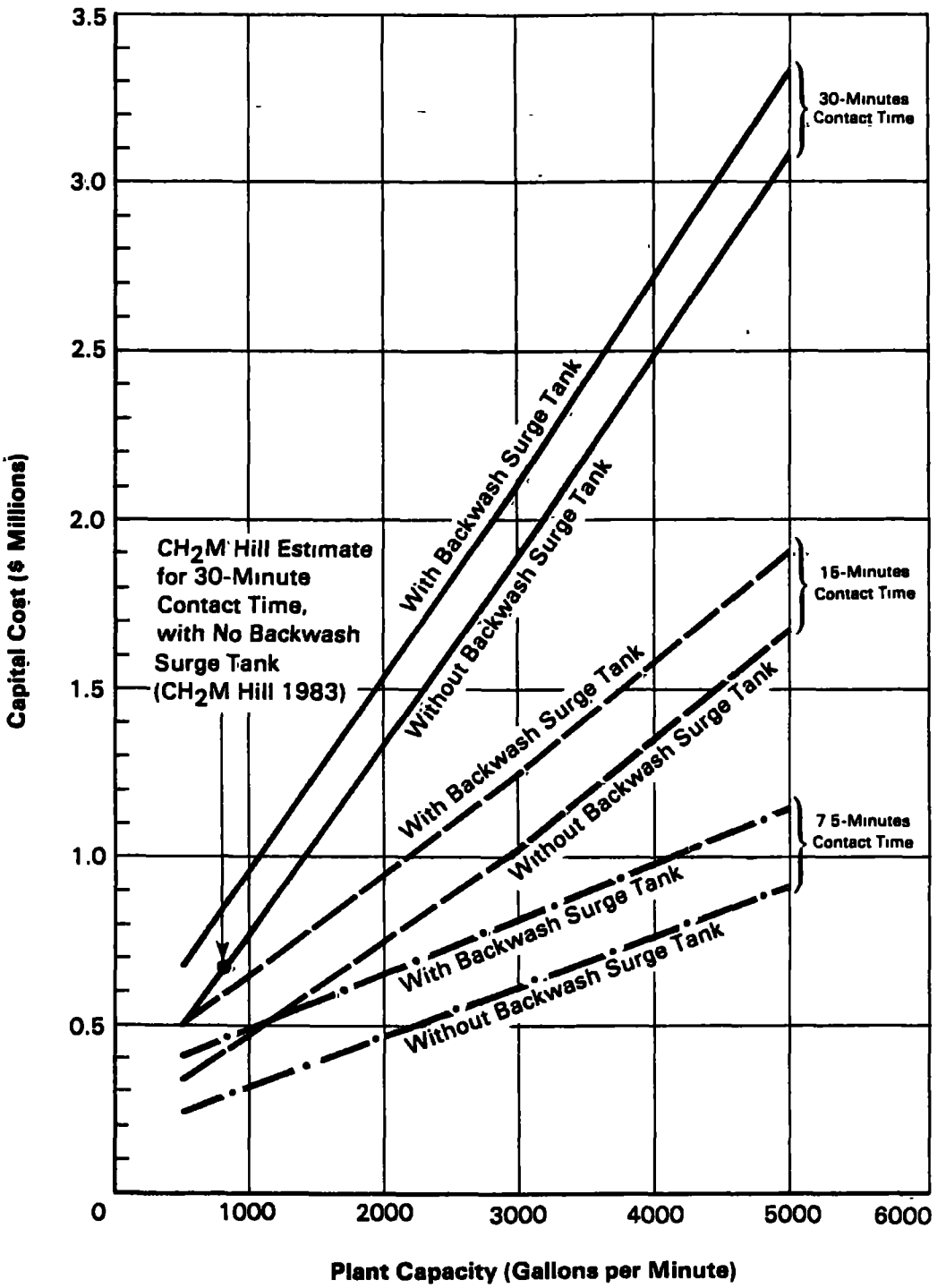

Figure G5-9 Capital Costs for Granular Activated Carbon Treatment (Derived from Tables G5-9 and 10, December 1982 costs basis)

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TABLE G5-11

ESTIMATED OPERATING AND MAINTENANCE COSTS FOR GRANULAR ACTIVATED CARBON TREATMENT, EXCLUDING CARBON COSTS[a]

Flow Rate, Millions of Gallons per Year	Operating Cost, $/Year				
	Process Energy[b]	Building Energy[b,d]	Maintenance Materials	Labor[c]	Total
100	600	3,800	2,600	2,900	9,900
300	1,600	4,900	7,100	4,800	18,400
500	2,600	6,700	11,500	6,100	26,900

Notes:

(a) All costs from Gumerman, Culp and Hansen 1979c, pp. 61-62.
(b) Based on 5¢/kilowatt hour for power.
(c) Based on $14/hour for labor.
(d) Incorporates factor of 2 for Minneapolis climate (Gumerman, Culp and Hansen 1979a).

plants). In any case, building energy costs are a small fraction of total operating costs for most of the GAC treatment cases considered in this study.

Table G5-11 also does not include additional costs for GAC plants operated in part as iron removal plants. This is because these costs are uncertain, but likely to be relatively small. The cost of additional chlorine would be less than $600 per year, based on an increased dose of 1.2 milligrams per liter (see section G4.5.5) and chlorine at $219 per ton (Table G5-3). Backwash wastewater disposal charges are expected to be less than $1500 per year (see note e to Table G5-4).

Table G5-12 presents carbon replacement costs for various bed sizes, as determined by plant capacity and contact time. Replacement carbon is costed at 80¢ per pound (Chalmers 1983), except for carbon usage greater than 180,000 pounds per year, when the estimated cost is reduced to 40¢ per pound. This is intended to serve as a rough approximation of the cost savings from off-site regeneration of spent GAC, as opposed to using GAC on a throw-away basis. The cut-off point between throw-away and off-site regeneration being most economical, and the estimated savings from the latter mode, are based on data presented by Zanitsch and Stenzel (1978). The rough estimate of off-site regeneration costs is sufficient for this study, since only the very largest plants considered for the case of one-year breakthrough time are above the cut-off point.

Figure G5-10 plots operating and maintenance costs parametrically as a function of plant capacity, operating flow rate, and contact time, for the case of a one-year breakthrough time. Figure G5-11 is a similar plot for the case of equilibrium breakthrough time. The cost curves in both of these figures were derived from the costs presented in Tables G5-11 and 12. The operating and maintenance cost curves for the equilibrium breakthrough case show minimum annual costs for a given flow rate, independent of contact time or plant capacity. This minimum cost corresponds to any case where the carbon bed size is such that equilibrium breakthrough occurrs in 10 years or less (compare

TABLE G5-12

CARBON REPLACEMENT COSTS FOR GRANULAR ACTIVATED CARBON TREATMENT

Plant Capacity, Gallons per Minute	Empty Bed Contact Time, Minutes	Bed Carbon Capacity, Pound[a]	Carbon Replacement Cost, $/Year[b]	
			1-Year Breakthrough	10-Year Breakthrough
1000	7.5	25,000	20,000	2,000
1000	15	50,000	40,000	4,000
1000	30	100,000	80,000	8,000
3000	7.5	75,000	60,000	6,000
3000	15	150,000	120,000	12,000
3000	30	300,000	192,000[c]	24,000
5000	7.5	125,000	100,000	10,000
5000	15	250,000	172,000[c]	20,000
5000	30	500,000	272,000[c]	40,000

Notes:
(a) Based on 25 pounds per cubic foot bed density.
(b) Based on 80¢ per pound for virgin GAC (Chalmers 1983).
(c) Based on 40¢ per pound net cost for GAC requirements beyond 180,000 pounds per year, as an approximation of savings resulting from offsite regeneration. (Zanitsch and Stenzel 1978).

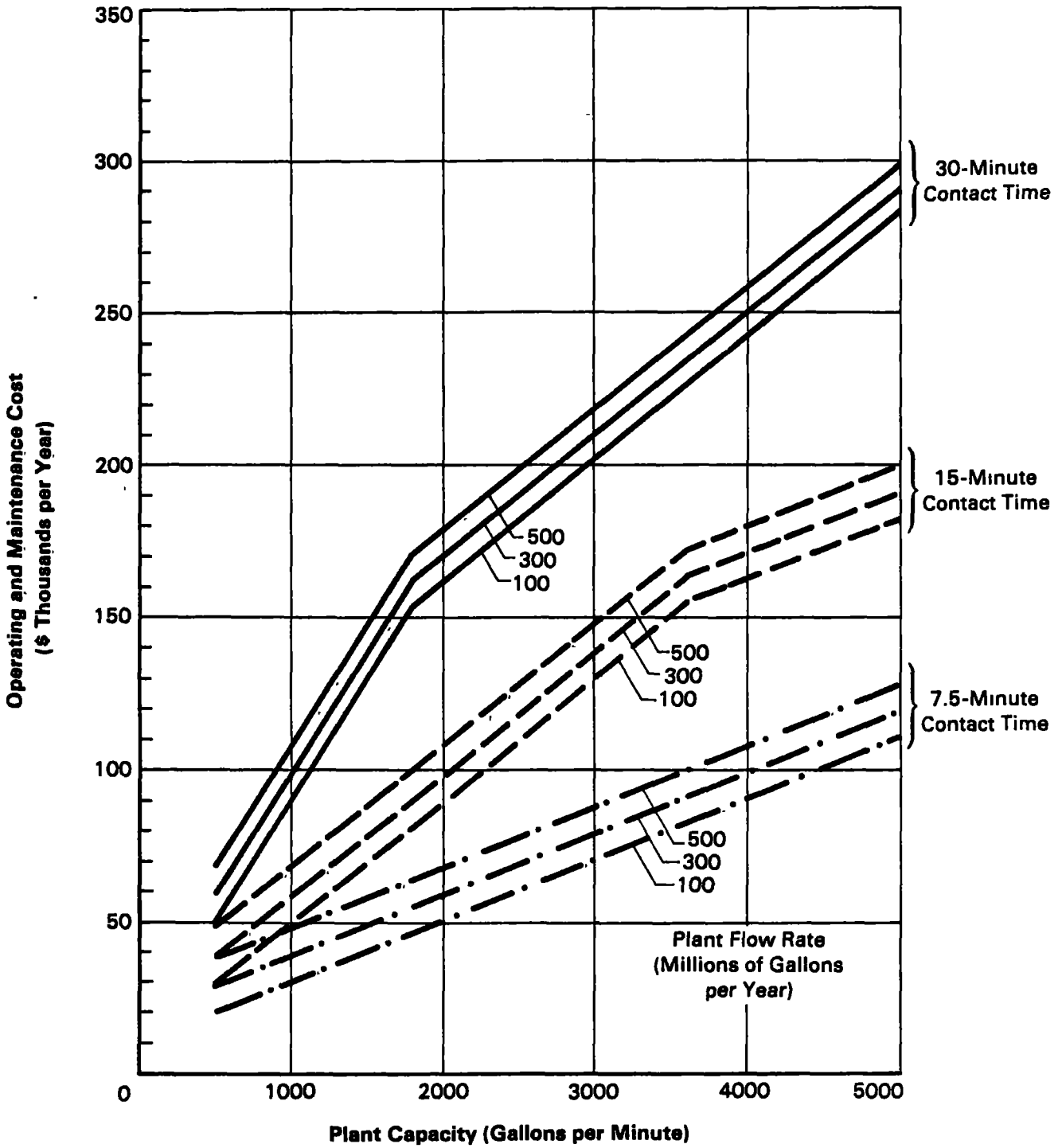

Figure G5-10 Operating and Maintenance Costs for Granular Activated Carbon Treatment for a One-Year Breakthrough Time (Derived from Tables G5-11 and G5-12)

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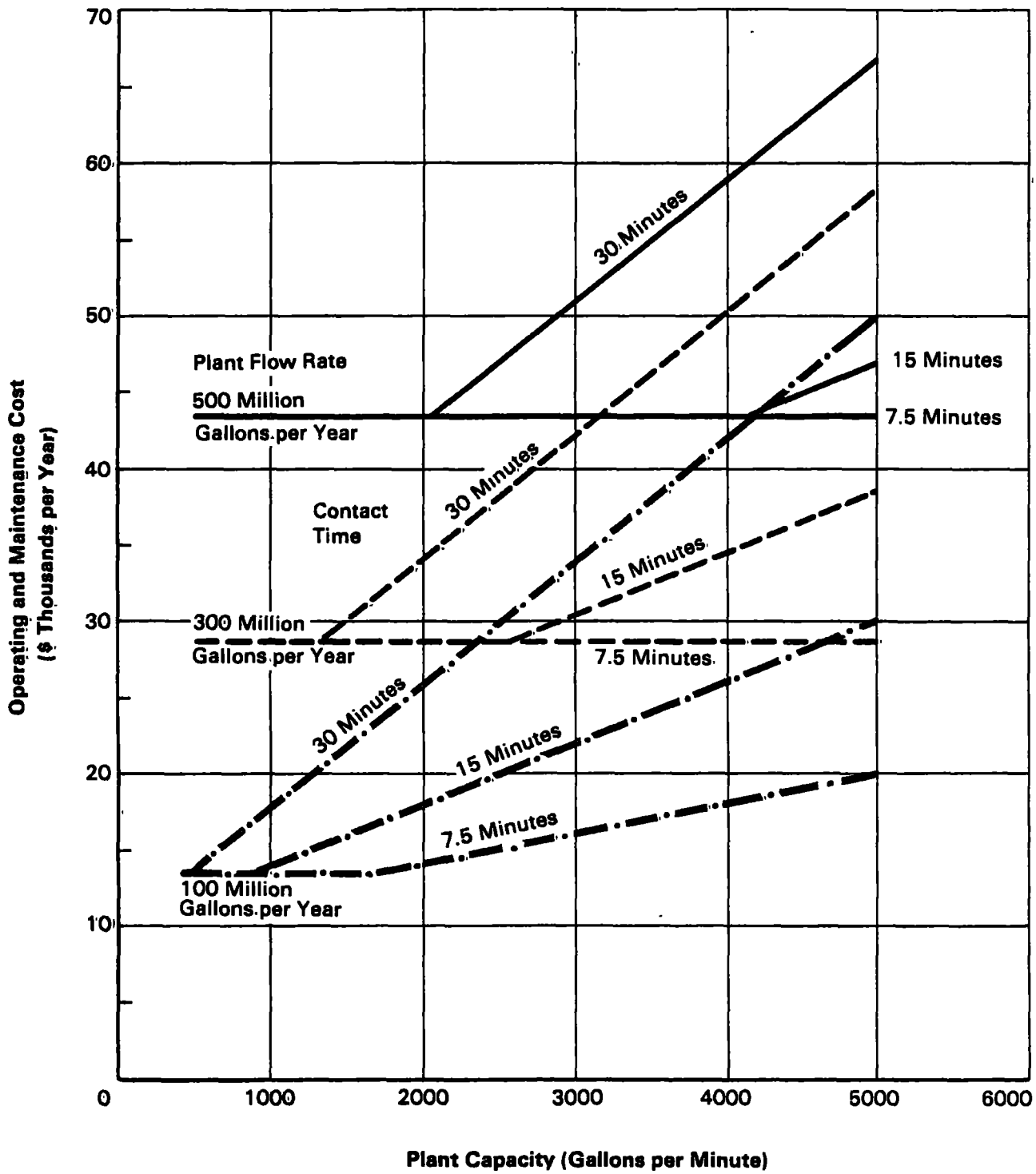

Figure G5-11 Operating and Maintenance Costs for Granular Activated Carbon Treatment for Equilibrium Breakthrough Times (With a maximum breakthrough time of 10 years) (Derived from Tables G5-11 and G5-12 and Figures G5-7 and G5-8)

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Figures G5-7 and 8). In such a case, carbon is replaced at the equilibrium exhausation rate, which is constant for a given flow rate (parametrically varied), inlet concentration (10 micrograms per liter total PAH), and equilibrium adsorption capacity (2 pounds carbon per 1000 pounds PAH). Cost curves lying above these minimums correspond to cases where equilibrium breakthrough occurs in more than 10 years, yet the carbon is assumed to be replaced on a 10-year cycle nonetheless.

G5.4 Plant Performance Monitoring

It is necessary to have an accurate and reliable technique for monitoring the performance of any drinking water treatment technology in removing PAH in order to ensure that the treatment system is operating properly and achieving the necessary removal efficiencies. In order to satisfy this objective, there are special requirements for sampling and analysis associated with plant performance monitoring, as opposed to compliance monitoring, which is discussed in Appendix J. First, the time between sampling and data return for performance monitoring must be short to allow as close to real-time control as possible. Second, performance monitoring data should be concise and uncomplicated. Ideally, one or two key PAH-related parameters or a measurement that yields a total PAH concentration should be used, allowing for quick interpretation. As more compounds or parameters are included, it becomes more difficult to sort and correlate the data for use in monitoring and controlling the treatment plant's performance. Third, the method for performance monitoring must be cost-effective. Adequate control monitoring is likely to require frequent sampling, so the cost per analysis should be kept as low as possible.

Two basic options exist for a control monitoring technique: field measurements or field sampling for laboratory analysis. With respect to the latter approach, the most comprehensive monitoring technique would be to use the same analytical protocol as used in compliance monitoring (Appendix J). Unfortunately, this approach fails all three requirements of a good control monitoring program. The cost per

sample for a complete PAH analysis as described in Appendix J is $500 to 600. This is a high cost for something like weekly sampling. The extraction and analysis is tedious and time consuming, requiring 2 to 4 week turnaround times. The method generates so much data that several hours would be required to correlate and interpret the results. For that reason, the first assumption is that one or two key parameters or a measurement of total PAH should be used for performance monitoring. There is good statistical and analytical support for this supposition. The history of PAH contamination in groundwater in the St. Louis Park area is well known, and considerable analytical data have been generated. Therefore, a reasonably accurate and consistent estimate of the relevant abundances of various PAH compounds can be made. The chemistry of PAH is well enough understood to allow comparisons to be made between individual PAH. Analytically, the measurement process has been studied for several years, and relative sensitivities of individual PAH can be accurately predicted. Pulling all of this information together, it should be possible to select one or two representative compounds, or a technique which measures total PAH, once a treatment technology has been chosen.

This leaves two basic considerations: cost-effectiveness and data turnaround. Field measurement offers the most immediate data return. However, the levels of total PAH which will have to be measured will certainly be less than 4.0 micrograms per liter, and probably less than 1.0 micrograms per liter. No known measurement device can measure this level of PAH, even as a total measurement, without a pre-concentration step. Once this pre-concentration step is added, the field measurement approach would require a field laboratory for sample preparation. Whether this sample preparation is solvent extraction of a water sample or some collection adsorbent, several problems arise. In order to support this field laboratory, safe storage for solvents and chemicals is needed. Solvents are flammable and several are toxic. This means adding a hood, some form of waste disposal (55 gallon waste drums with regular pickup from a waste disposer), fire proof storage cabinets, appropriate safety signs, etc. There are several OSHA requirements and local codes which have

to be satisfied. The requirements associated with maintaining a field laboratory in a safe, approved, and competant manner, plus the costs associated with these requirements, makes this option unfavorable.

Field sampling and transport of samples to an established analytical laboratory offers the easiest alternative. However, care must be taken to develop a procedure which will offer quick data turnaround, and a laboratory which is competent and responsive to the data turnaround needs. The first option is a measurement of one or two individual PAH as indicator parameters. The cost associated with this analysis should be $150 to 200 per sample. The major problem is that the sample (probably 1 liter) will require extraction and concentration prior to analysis. The minimum turnaround time, even with a regular laboratory arrangement, is on the order of one weeks. Somewhat less time, at the expense of special handling costs might be possible. In spite of the lag-time, this approach offers a good analytical value at a cost much less than the total PAH measurement and with quicker return of less complex data.

Another option is to use a pre-concentration step involving an adsorbent resin, through which a known amount of water is passed at the source. The resin tube would be returned to the laboratory for extraction and analysis. If a small tube can be used, involving small quantities of solvent, the resin might be directly extracted in a small vial and analyzed without the need to concentrate the solvent. If this technique can be developed for this application, the cost per sample could be as low as $50 to 75 per sample. Several variations of each method are also possible, which would indicate performance monitoring costs might be somewhere between those given for each technique ($50 to $200 per sample).

One other possibility is to analyze for total PAH as a single measurement. This could be used for extracts from either of the two techniques described. The extract would be injected onto an HPLC without column separation, for example, and a total fluorescence measurement taken of the extract. Also, a column could be used, but the areas of several pre-selected peaks summed to give a total area.

This approach does not yield specific PAH concentration but requires less data workup and often has application in analyses for treatment control.

Given these various approaches, it has been assumed, for the purpose of estimating drinking water treatment operating costs, that an accurate and reliable control monitoring technique could be developed that would cost on the order of $100 per sample. A range of from $50 to $200 per sample is likely, but $100 per sample has been used for cost estimating. It is further assumed that weekly sampling would be required for modified iron removal plant technologies and that biweekly sampling would suffice for GAC treatment.* This difference in sampling frequencies reflects the fact that GAC treatment is characterized by a good ability to handle fluctuations in inlet water quality or plant upsets, while PAC and ozone injection treatment would be affected more by such variations. It should be noted, however, that rapid and substantial fluctuations in PAH concentrations in wellhead water are not expected in the space of weeks, given the flow characteristics and response times of aquifers in the St. Loius Park area. Frequent (weekly or biweekly) monitoring is therefore specified largely to detect variations or problems in treatment plant performance. After experience with control monitoring results is developed, it may be possible to decrease the required sampling frequency.

The plant performance monitoring discussed here would be performed in addition to regular compliance monitoring, which would follow the procedures outlined in Appendix J and occur on a quarterly basis. The results of compliance monitoring would yield the definitive measure of whether treated water met the recommended PAH criteria. Costs for compliance monitoring are discussed in Chapter 6 and are not included in the cost estimates developed here for drinking water treatment.

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*This yields monitoring costs of $5200 per year for modified iron removal treatment and $2600 per year for GAC treatment. These costs can also be viewed as more or less frequent monitoring at a proportionately lower or higher cost per sample (e.g., $200 per sample for biweekly modified iron removal treatment monitoring and monthly GAC treatment monitoring).

It should be noted that the plant performance monitoring options considered here do not necessarily involve monitoring for carcinogenic PAH per se, but rather monitoring for parameters indicative of total PAH. This assumes that a relationship between carcinogenic and total PAH could be established from the results of compliance monitoring and used to add in the interpretation of performance monitoring data with respect to carcinogenic PAH. Establishing such a relationship seems reasonable based on the large amount of analytical data already available for St. Louis Park area wells.

There will be a distinct cost associated with developing an inexpensive and reliable plant performance monitoring technique. It is assumed that such a study would cost on the order of $100,000 to perform. This seemingly high cost is based on the fact that a large number of detailed and expensive ($500 to $600 per sample) GC/MS analyses and a significant amount of time by an experienced analytical chemist would be required to verify a simple performance monitoring technique. Some equipment might also need to be purchased. The estimated cost of $100,000 corresponds to about 100 GC/MS analyses, 8 weeks of a senior analytical chemist, and about $25,000 for equipment. This cost is included as part of the study cost for implementing any drinking water treatment system and is not apportioned on a plant-by-plant basis. The investment of about $100,000 to develop an inexpensive and reliable plant performance monitoring technique would clearly be cost-effective if drinking water treatment was applied. This is apparent from comparing the present value costs of weekly analyses at $500 per sample versus $100 per sample, which are $516,000 and $103,000, respectively, based on 100 years operation and a 5 percent effective interest rate.

G5.5 Cost Comparisons

This section presents the results of comparing costs of the various drinking water treatment alternatives considered. Costs are compared in two basic ways. First, costs are compared for the general case of a single well or well field with a capacity of from 1000 to the 5000 gallons per minute and an operating flow rate of from 100 to

500 million gallons per year. These are the measures of plant size for which costs were developed parametrically. Second, costs are compared for the case of specific Prairie du Chien-Jordan municipal supply wells that require treatment or are predicted to require treatment within the next 100 years. All cost comparisons in both cases are presented as present value costs based on 100 years of plant operation. This long time-frame reflects the assumption that PAH contaminants are unlikely to be purged out of the Prairie du Chien-Jordan to levels below the recommended PAH criteria within this period.

G5.5.1 Costs for a Single Well

Figures G5-12 through G5-16 present estimated present value costs for iron removal treatment, ozone injection, PAC injection, and granular activated carbon treatment (at equilibrium breakthrough and one year breakthrough times). Costs in each case are presented as a function of plant capacity and operating flow rate, as well as any other key design variables evaluated parametrically (e.g., contact time or injectin rate). The cost of plant monitoring is included in all cases ($5200 per year for modified iron removal treatment and $2600 per year for GAC treatment). All present value costs are based on 100 years operation at an effective interest rate (net after inflation - see Appendix L) of 5.0 percent. Plant replacement after 50 years is included. Present value costs were calculated from the capital and operating and maintenance costs presented in Figures G5-1 through G5-6 and G5-9 through G5-11 using the equation:

$$\text{Present Value Cost} = 1.0872\ (\text{Capital Cost}) + 19.8479\ (\text{Operating and Maintenance Costs})$$

The factors in this equation are readily derived from the time-value of money equations presented in Appendix L.

Careful comparison of Figures G5-13 and G5-14 shows that PAC injection is the least expensive alternative across the entire range of design conditions considered, except at plant capacities above

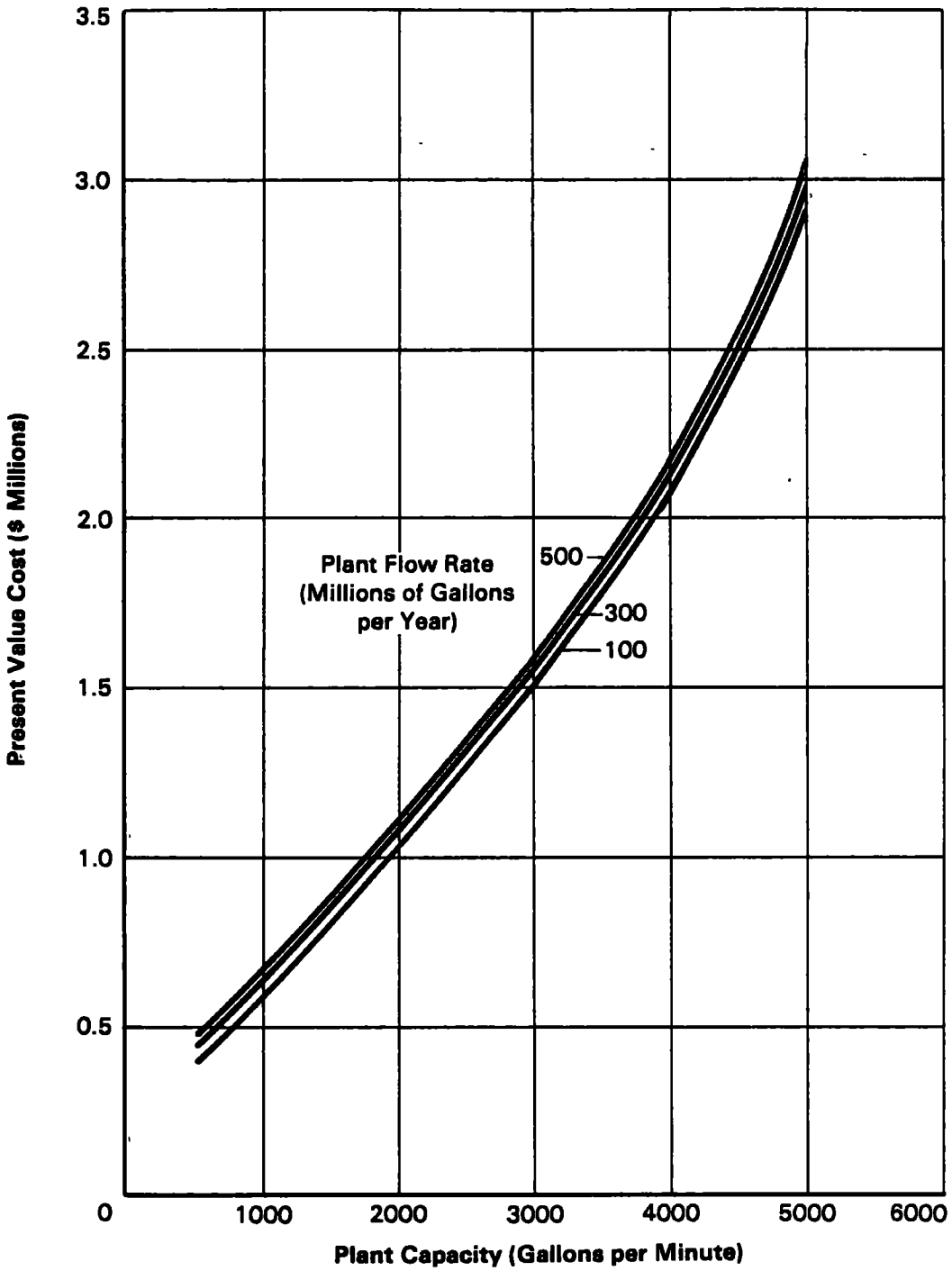

Figure G5-12 Present Value Costs for Iron Removal Treatment Plants (Based on 100 years operation at 5 percent annual effective interest rate) (Excludes plant performance PAH monitoring costs)

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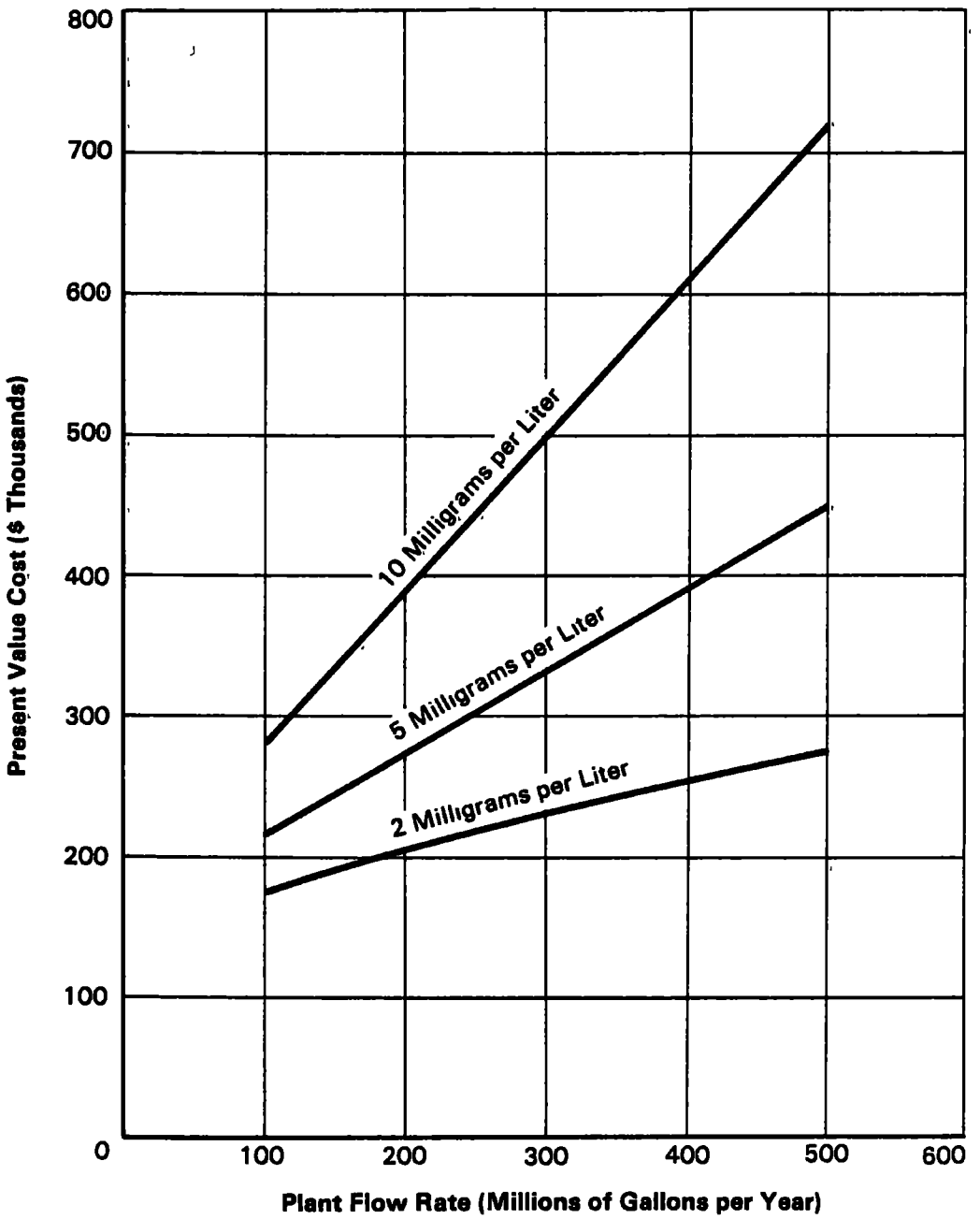

Note: Present value cost is only slightly affected by plant capacity due to low capital costs. Difference in present value costs between 1000 and 5000 gallons per minute capacity plants is only $1,000 to $3,000

Figure G5-13 Present Value Costs for Powdered Activated Carbon Treatment at Wells with Existing Iron Removal Plants (Based on 100 years operation at 5 percent annual effective interest rate)

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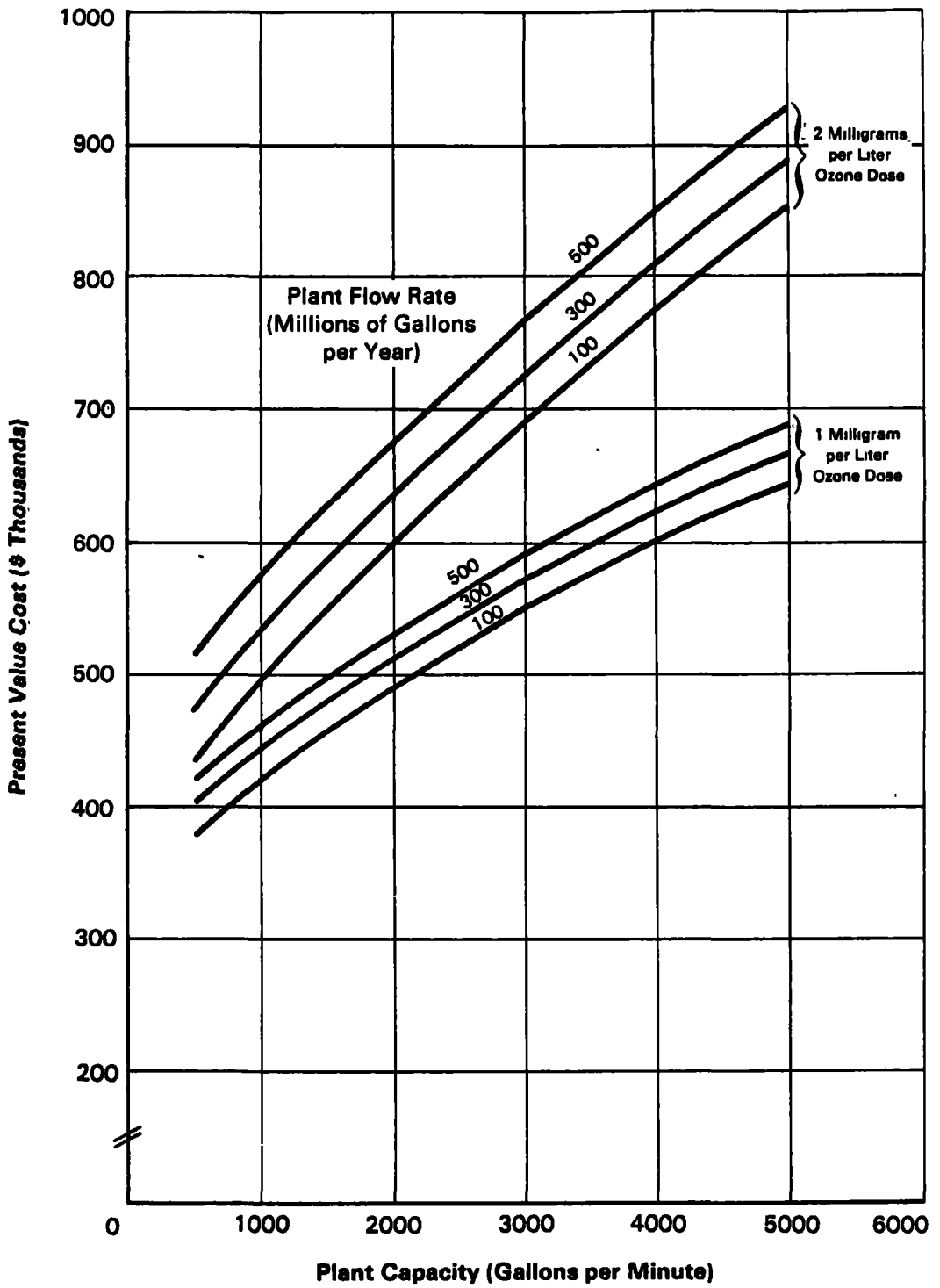

Figure G5-14 Present Value Cost of Ozone Injection Treament at Wells with Existing Iron Removal Treament (Based on 100 years operation at 5 percent annual effective interest rate)

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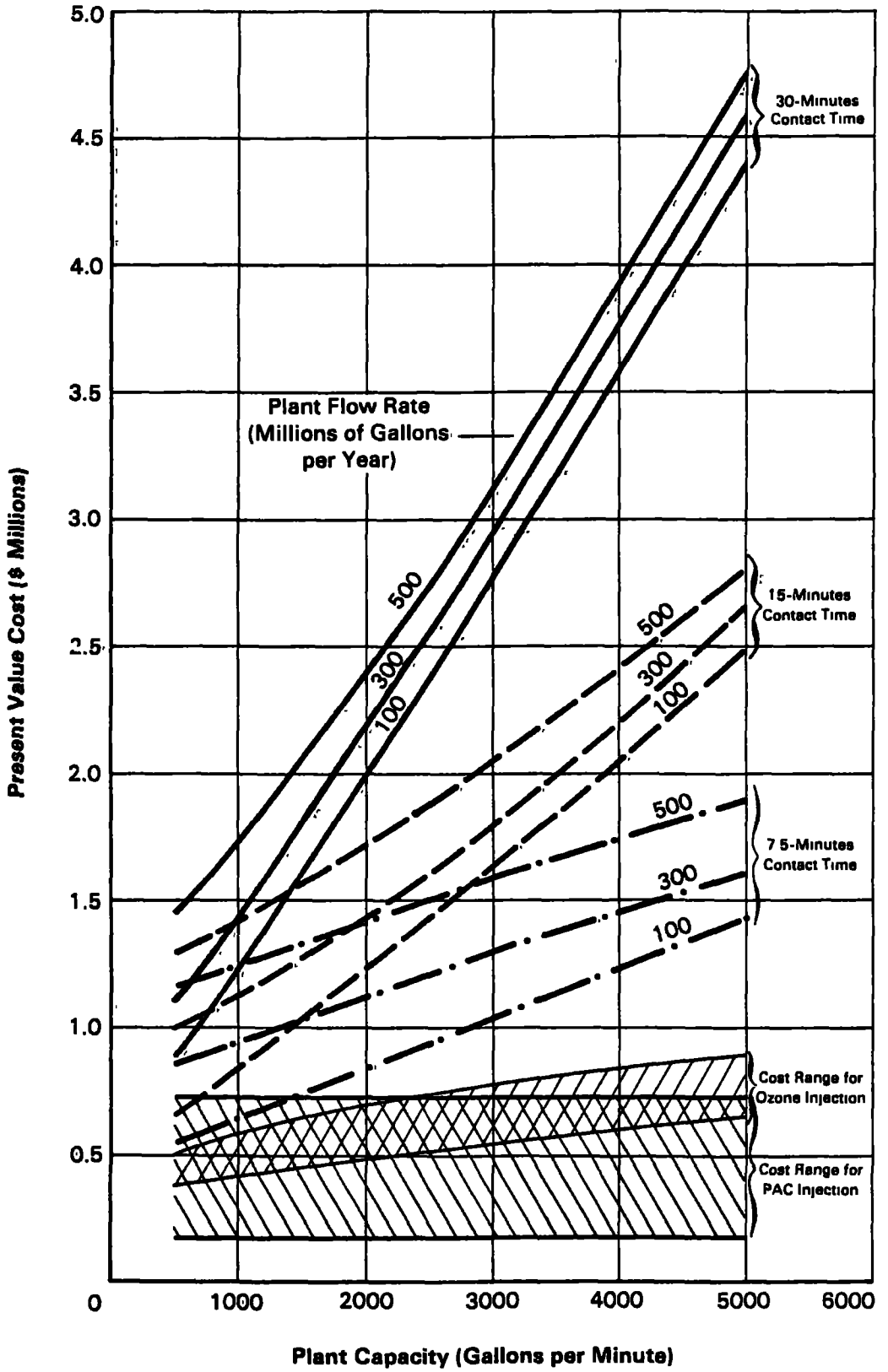

Figure G5-15 Present Value Cost for Granular Activated Carbon Treatment at Equilibrium Breakthrough Time (Based on 100 years operation at 5 percent annual effective interest rate) (For wells with existing iron removal treatment plants)

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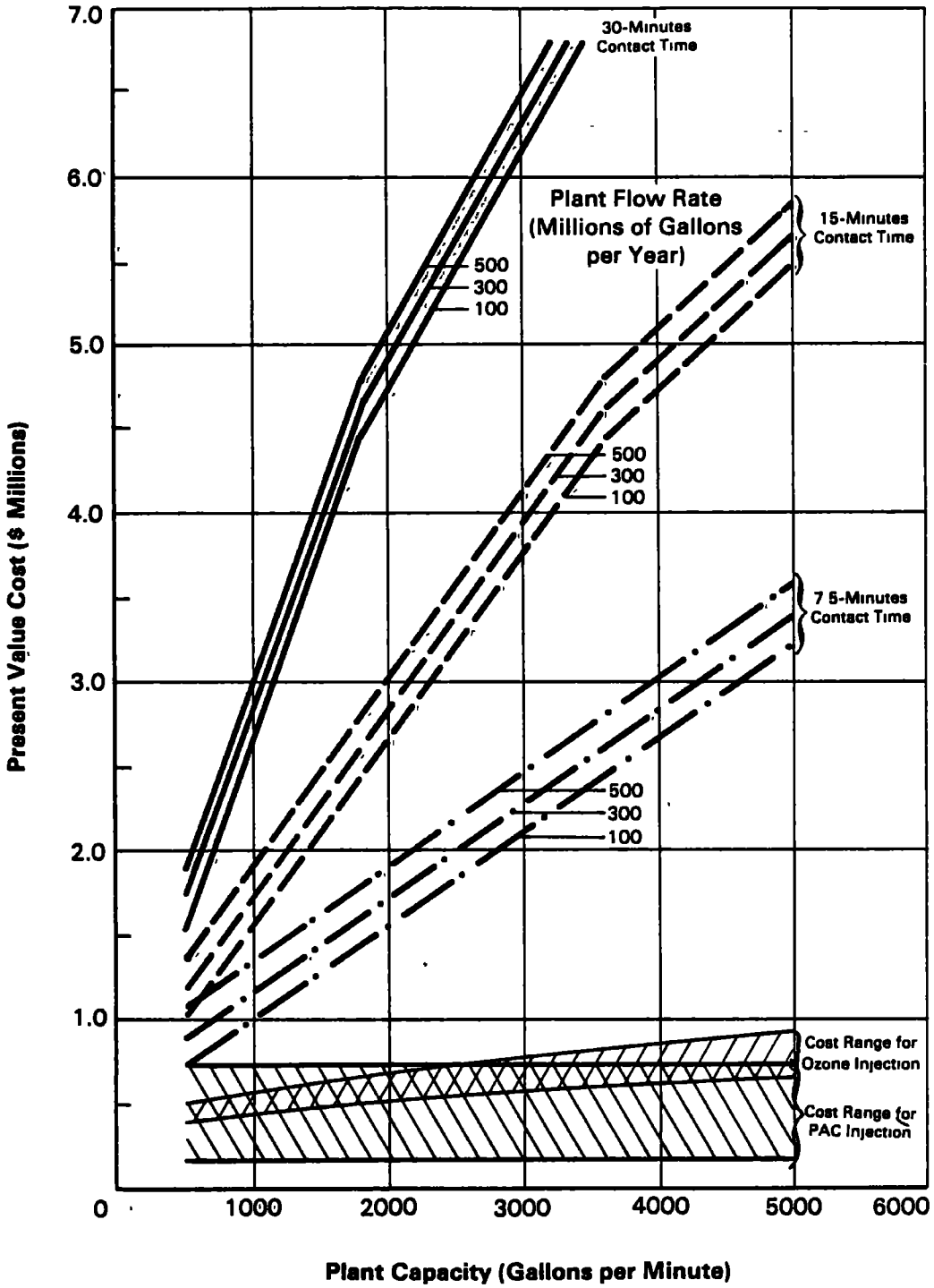

Figure G5-16 Present Value Cost for Granular Activated Carbon Treatment at One-Year Breakthrough Time (Based on 100 year operation at 5 percent annual effective interest rate) (For wells with existing iron removal treatment plants)

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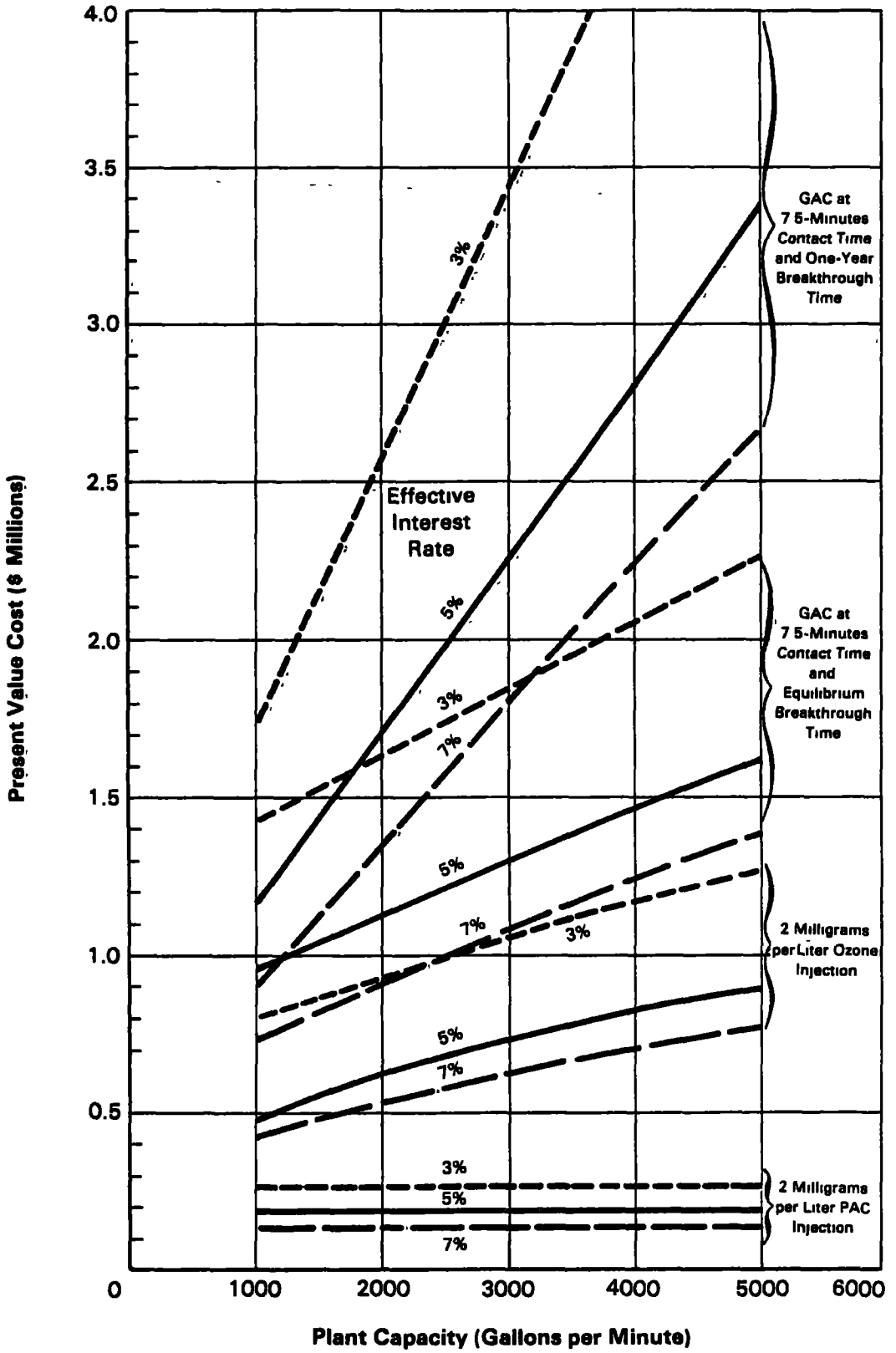
about 4000 gallons per minute at the highest dose considered (10 milligrams per liter), when ozone injection at a low dose (1 milligram per liter) becomes less expensive. Modified iron removal treatment (ozone or PAC injection) under any of the design bases considered is less expensive than any of the granular activated carbon designs considered. The cost range of modified iron removal treatment from Figures G4-13 and G4-14 is indicated on the granular activated carbon plots (Figures G4-15 and G4-16) to help illustrate this point.* For the most optimistic GAC design (7.5 minute contact time and equilibrium breakthrough time), the additional present value cost of GAC treatment ranges from $0.15 to $1.6 million, depending on the plant size (capacity and flow rate) and the ozone or PAC design conditions. For the more realistic GAC design of 7.5 minutes contact time and one-year breakthrough time, the additional present value cost ranges from $0.5 to $3.3 million.

A check on the sensitivity of these cost comparisons to the effective interest rate used in calculating present value costs is shown in Figure G5-17. Present value costs are shown in this figure for effective interest rates of 3, 5, and 7 percent per year for the most and least expensive modified iron removal treatment alternatives (2 milligrams per liter ozone injection and 2 milligrams per liter PAC injection, respectively) and for 7.5 minute contact time GAC for equilibrium and one-year breakthrough times. Figure G5-17 shows that the conclusions reached using a 5 percent interest rate are the same if 3 or 7 percent rates are used. This indicates that the relative proportions of capital and operating and maintenance costs are sufficiently similar for these alternative technologies that the effective interest rate, which weights the relative present value cost contribution of capital and annual costs, does not significantly affect cost comparisons.

G5.5.2 Costs for Actual and Predicted Well Closures

As discussed in Appendix E and Chapter 6, computerized ground-water flow modeling was used to predict the migration of PAH contaminants in the Prairie du Chien-Jordan aquifer under the scenario

*Note that cost ranges shown for PAC and ozone injection span various operating flow rates as well as different injection doses.



Note: All costs for a 300 million gallon per year operating flow rate.

Figure G5-17 Sensitivity Analysis of Present Value Cost at Different Effective Interest Rates (All costs based on 100 years operation)

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of using contaminated municipal supply wells in this aquifer with treatment added to meet the recommended PAH criteria. The timing of future well closures was predicted for best and worst-case assumptions regarding contaminant migration. All well closure predictions were based on a criterion for noncarcinogenic PAH near the lower bound of the recommended range (4 micrograms per liter). This subsection presents estimated costs for treating contaminanted wells under the worst-case migration scenario for two basic cases: 1) treating all contaminated wells and 2) only treating wells with existing iron removal plants.

Table G4-13 presents estimated present value costs for treating all municipal supply wells that currently exceed the recommended PAH criteria (based on 4 milligrams per liter for noncarcinogenic PAH) or are predicted to do so within the next 100 years.* The plant capacities and operating flow rates are derived from the data presented in Section G2. Costs are presented for three basic treatment alternatives (PAC injection, ozone injection, GAC columns) for a range of design conditions. Costs of iron removal treatment plants required at wells SLP4 and E3 for PAC or ozone injection are also included.

Table G5-13 shows that the present value cost of treating all contaminated municipal supply wells ranges from $1.7 million to $3.2 million if PAC or ozone injection treatment is used. New iron removal plants at wells SLP4 and E3 account for $0.7 million of this cost.

*Treatment was not considered at wells SLP7 and SLP9, which are currently shut down, because these wells do not exceed the recommended criteria and are not predicted to do so. Treatment was not considered at well SLP5, which is currently shut down and does exceed the recommended criteria, because this well is being replaced by a new, adjacent Mt. Simon-Hinckley well (SLP17). Using this new Mt. Simon-Hinckley well is much more cost-effective than treating well SLP5. For example, the least expensive treatment alternative at SLP5 would be PAC injection at 2 milligrams per liter. This has a present value cost of $860,000 at a flow rate of 100 million gallons per year and $960,000 at 300 million gallons per year, including the cost of a new iron removal plant. In comparison, the incremental present value cost of pumping from the Mt. Simon-Hinckley instead of the Prairie du Chien-Jordan is from $160,000 to $300,000 at 100 million gallons per years and $500,000 to $890,000 at 300 million gallons per year (see Chapter 6).

TABLE G5-13

PRESENT VALUE COST OF TREATING ALL CONTAMINATED MUNICIPAL SUPPLY WELLS[j]

Well	Year Required[i]	Capacity, Gallons per Minute	Flow Rate, Millions of Gallons Per Year	Existing Iron Removal Plant	Present Value Cost, $ Thousands[c]				
					Iron Removal Plant	PAC Injection	Ozone Injection	GAC with Equilibrium Breakthrough	GAC with 1-Year Breakthrough
SLP 10&15	1983	2200	300	Yes	54-109[a]	230-505	525-655	1160-2330	1820-5180
SLP4	1983	1200	100	No	690	175-280	435-515	860-1560[f]	1280-3300[f]
SLP6	1983	1200	300	Yes	NA[b]	230-505	455-555	980-1590	1270-3300
H3	1983	1200	100	Yes	NA	175-280	435-515	680-1380	1100-3120
E2	2013	800	400	Yes	NA	255-610[d]	435-530[d]	1060-1360[d]	1120-2480[d]
E3	2033	500	100	No	400[d]	175-280[d]	375-435[d]	720-1050[d,f]	890-1730[d,f]
Total Present Value Costs[e]						1160-2570[g]	2760-3230[g]	4040-7380[h]	5860-15,730

Notes:

(a) Present value cost of cleaning sand-locked well SLP10 for $50,000 to $100,000.
(b) Not applicable.
(c) From Figures G4-12 through G4-16. Ranges reflect different design bases (injection rates or contact times).
(d) Present value costs at time of installation, not discounted to a current cost basis.
(e) Costs for wells E2 and E3 discounted by 30 and 50 years, respectively, to yield current present value costs.
(f) Includes cost of backwash wastewater settling tank (capital cost only) from Figure G4-9.
(g) Includes cost of iron removal plants at wells SLP4, and E3, and cleaning well SLP10.
(h) Iron removal plants not required, but costs of cleaning well SLP10 are included.
(i) Based on worst-case contaminant migration predictions. See Chapter 6, Table 6-5.
(j) Excluding well SLP-5, which is being replaced by a new adjacent Mt. Simon-Hinckley well (SLP-17).

GAC treatment is considerably more expensive, ranging from $4.0 million to $15.7 million, depending primarily on the breakthrough time assumed. For any treatment alternative, treating wells that operate at relatively low rates (wells SLP6, H3, and E3) contributes significantly to the total cost. However, as discussed in Chapter 6, these smaller wells do not necessarily need to be brought back into service in order to provide St. Louis Park, Hopkins, and Edina with adequate water supply capacity.

Table G5-14 illustrates how annual average demand shortfalls* caused by closures of contaminated wells can be satisfied by only treating selected wells and providing additional supply, if needed, from other, uncontaminated wells. The wells selected for treatment in this case are only wells with existing iron removal plants that are pumped at relatively high rates. Only treating these larger wells (SLP6, SLP10, SLP15 and E2) substantially decreases the total present value cost of drinking water treatment, as shown by Table G5-15. Comparing the present value cost estimates in Tables G5-13 and G5-15 shows that treating only larger wells with existing iron removal plants reduces total costs by $1.1 million to $1.8 million for PAC or ozone injection treatment and by $1.6 million for GAC treatment. The obvious conclusion from these comparisons is that the minimum number of wells adequate to meet municipal water supply requirements should be treated.

One other option that could be considered for reducing the total cost of drinking water treatment is to add piping to allow water from smaller wells without iron removal plants to be treated at larger well stations that have iron removal treatment. The two examples are St. Louis Park wells SLP4 and SLP6 and Edina wells E2 and E3. In both cases, the wells are within 1 mile of each other (see Figures G2-1 and G2-10) and could be interconnected at a cost of about $0.2 million, assuming that existing pumping facilities would be adequate. Table G5-16 shows the estimated present value cost savings that would result

*Adequate capacity for supplying short-term demand variations is discussed in section G2.3.

TABLE G5-14

ALTERNATIVE WELL MANAGEMENT SCENARIOS FOR MEETING MUNICIPAL WATER SUPPLY SHORTFALLS

			Treat all Wells that Are Currently Closed		Treat Selected Wells Sufficient to Meet Supply Shortfalls	
Well	Year of Closure	Supply Shortfall Millions of Gallons per Year[i]	Action	Supply Added Millions of Gallons per Year[j]	Action	Supply Added Shortfall Millions of Gallons per Year[j]
SLP4	1983[b]	40	Treat	100	Abandon[e]	0
SLP5	1983[a]	90	Abandon[f]	0	Abandon[f]	0
SLP6	1983[c]	270	Treat	300	Treat	300
SLP7	1983[h]	25	Use[g]	25	Use[g]	25
SLP9	1983[h]	25	Use[g]	25	Use[g]	25
SLP10	1983[a]	50	Treat	300	Treat	300
SLP15	1983[a]	240	Treat		Treat	
SLP17	(d)	0	Use[g]	100	Use[g]	100
Subtotals		740		850		750
H3	1983[b]	70	Treat	100	Abandon[e]	70
E2	2013[c]	420	Treat	400	Treat	400
E3	2038[c]	30	Treat	100	Abandon[e]	50
Totals		1260		1450		1270

Notes to Table G5-14

(a) Currently out-of-service and exceeds recommended PAH criteria based on a 4 microgram per liter criterion for noncarcinogenic PAH.
(b) Currently out-of-service. Does not exceed recommended PAH criteria, but is predicted to do so if restarted.
(c) Predicted to become contaminated.
(d) New Mt. Simon-Hinckley well due for start-up in 1983.
(e) Supply shortfall caused by closure of less frequently used wells will be made up by other wells in the supply system.
(f) Supply shortfall will be made up by the adjacent new well SLP17.
(g) No treatment is required to use these wells and meet the recommended criteria.
(h) Currently out-of-service, but does not exceed recommended PAH criteria and is not predicted to do so if restarted.
(i) Based on average pumping rate data presented in section G2.
(j) Based on nominal predicted pumping rates, where the minimum flow rate to justify treatment is assumed to be 100 million gallons per year.

TABLE G5-15

PRESENT VALUE COST OF TREATING
SELECTED MUNICIPAL SUPPLY WELLS

Well	Year Required	Capacity, Gallons Per Minute	Flow Rate, Millions of Gallons Per Year	Present Value Cost, $ Thousands[a]			
				PAC Injection	Ozone Injection	GAC with Equilibrium Breakthrough	GAC with One-Year Breakthrough
SLP10 & 15[b]	1983	2200	300	280-610	580-760	1,220-2,460	1,880-5,300
SLP6	1983	1200	300	230-500	460-560	980-1,590	1,280-3,320
E2[c]	2013	800	400	60-140	100-120	260-340	260-580
				570-1,260	1,140-1,440	2,460-4,390	3,420-9,200

Notes:

(a) Costs from Figures G4-12 through G4-16. Ranges reflect different design bases (injection rates or contact time.)

(b) Includes present value cost of $55,000 to $110,000 for cleaning out sand-locked well SLP10.

(c) Costs discounted by 30 years to give current present value cost.

TABLE G5-16

POTENTIAL COST SAVINGS IN COMBINED TREATMENT OF WELLS SLP4 AND SLP6

ITEM	PAC Injection	Ozone Injection	GAC with Equilibrium Breakthrough	GAC with One-Year Breakthrough
	Present Value Costs, $ Thousands[f]			
SLP 4 Treatment	865-970[a]	1,125-1,205[a]	860-1,560[b]	1,280-3,300[b]
SLP 6 Treatment	230-505	455-555	980-1,590	1,270-3,300
	1,100-1,470	1,580-1,760	1,840-3,150	2,350-6,600
Combined Treatment of SLP4 & SLP6	255-610	545-695	1,360-2,580	2,040-5,560
Cost to Connect SLP4 to SLP6 (c)	155-225	155-225	155-225	155-225
Additional Iron Removal Plant Operating Costs at SLP6[d]	20	20	20	20
TOTALS:	430-860	720-940	1,540-2,820	2,220-5,800
Potential Savings, Best Case	670-610	860-820	300-330	130-800
Potential Equipment Modification Costs At SLP6 Iron Plant[e]	400	400	400	400
Potential Savings (Loss), Worst Case	270-210	460-420	(100)-(70)	(270)-400

NOTES:

(a) Includes present value cost of building an iron removal plant at SLP4.

(b) Includes present value cost of operating GAC plant in part as an iron removal plant at SLP4.

(c) Based on 5,200 feet of 10 inch pipe buried 4 to 6 feet deep at an installed cost (December 1982 basis) of $20 per foot (Sanks 1980), plus 10 to 12 road crossings at $5,000 to $10,000 each for repaving. Assumes that no additional pumping equipment is required.

(d) Based on additional operating and maintenance cost of $1,000 per year for increase of 100 million gallons per year (Figure G5-2). Assumes that no equipment modifications are required in increasing the capacity of the iron removal plant at SLP 6 from 1,200 to 2,400 gallons per minute.

(e) Based on capital costs for 1,200 and 2,400 gallon per minute plants shown in Figure G5-1.

(f) From Figures G4-12 through G4-16. Ranges reflect different design bases (injection rates or contact times).

from treating water from SLP4 at the treatment station for wells SLP6 and SLP12. The savings for PAC or ozone injection range from $0.6 million to $0.9 million and are higher than those for GAC treatment because the need for a new iron removal plant at SLP4 is only eliminated in the case of PAC or ozone treatment. These savings are based on the assumption that the existing iron removal plant for wells SLP6 and SLP12 could handle the additional flow from SLP4 without major modifications. Such modifications could cost on the order of $0.4 million, which would substantially reduce the cost savings from combined treatment of wells SLP4 and SLP6. Similar results would be expected from combined treatment of Edina wells E2 and E3.

The potential savings from combined treatment of selected contaminated wells are not as great as those associated with only treating major wells with existing iron removal plants. In addition, combined treatment should not be necessary to meet water supply requirements. Finally, there could be difficulties in the timing of implementing combined treatment. For example, SLP4 is currently contaminated and SLP6 is not. While ground-water modeling results predict that SLP6 could become contaminated within the next 10 years (see Appendix E), it would not be appropriate to connect wells SLP4 and SLP6 until the latter requires treatment, if ever, because of the uncertainties in predicting contaminant migration. In the meantime, there would be the question of what to do about contamination at SLP4. For these reasons, combined treatment of selected contaminated wells (specifically, SLP4 and SLP6, and E2 and E3) was not considered to be a practical or cost-effective alternative.

G6. CONCLUSIONS AND RECOMMENDATIONS

There are a variety of drinking water treatment techniques available that can remove PAH from contaminated municipal supply wells. The selection of the best treatment alternative depends first on establishing criteria for carcinogenic and noncarcinogenic PAH. Once this is done, the selection of a treatment technology, if treatment is indeed required, depends on the relative cost, effectiveness, and reliability of the alternatives that are capable of meeting the criteria. Based on the drinking water treatment studies performed to date in St. Louis Park by Serco, Hickok, CH2M Hill, and ERT (section G4), and the cost analyses presented in section G5, the following conclusions have been established with respect to selection of a drinking water treatment technique.

1) If a criterion for noncarcinogenic PAH is established near the upper end of the recommended range (400 micrograms per liter), then treatment is not required in order for finished water to meet the recommended criteria. As explained in Chapter 4, this is because finished water in none of the St. Louis Park municipal supply wells exceeds the recommended carcinogenic PAH criterion of 28 nanograms per liter or a noncarcinogenic PAH criterion greater than about 10 micrograms per liter (except for well SLP5). While untreated water from SLP15, and presumably SLP10, does exceed the carcinogenic PAH criterion, finished water from St. Louis Park Water Treatment Station No. 1, which includes uncontaminated wells SLP3 and SLP11 in addition to SLP10 and SLP15, should not exceed the carcinogenic PAH criterion if SLP3 and SLP11 are operated whenever SLP15 is pumping.

Further assurance that the carcinogenic PAH criterion would not be exceeded in finished water from Station No. 1 is provided by the fact that the existing iron removal treatment plant is effective at removing higher molecular weight carcinogenic PAH. ERT's tests of the iron removal plant at Station No. 1 showed that benz(a)anthracene and chrysene, both carcinogenic PAH, were removed by about 70 percent to a combined concentration less than the 28 nanogram per liter criterion. ERT's tests also showed that five and six-ring carcinogenic PAH, which

may be present in untreated water from well SLP15 at less than nanogram per liter concentrations, are also removed by the iron removal treatment plant. Removal of higher molecular weight carcinogenic PAH was shown by ERT's tests to result from adsorption in the filter bed.

2) If a criterion for noncarcinogenic PAH is established near the lower end of the recommended range (4 micrograms per liter), then drinking water treatment will be required to meet this criterion in finished water from contaminated supply wells. Testing at well SLP15 by Serco, Hickok and CH2M Hill has shown that there are three alternatives capable of meeting a noncarcinogenic PAH criterion of 4 micrograms per liter and a carcinogenic PAH criterion of 28 nanograms per liter. These alternatives are: 1) powdered activated carbon (PAC) injection, 2) ozonation, and 3) granular activated carbon (GAC) columns.

PAC injection has been shown to be an effective treatment by bench and pilot-scale testing. Such injection would be most effective at the wellhead prior to iron removal treatment. However, the practicality and design of a full-scale application has not been established. The primary concern is the effect of PAC on the performance of the filter beds in an iron removal plant.

Ozone injection has been shown to be an effective treatment by bench-scale testing by CH2M Hill. Again, injection would be most effective at the wellhead upstream of an iron removal plant. While the detailed design of an ozone injecton system has not been established, no technical implementation problems are foreseen. However, ozonation without UV light, which is much less expensive than treatment with UV light, does not completely oxidize PAH and leaves partially oxidized PAH by-products in the water, such as ketones, carboxylic acids and aldehydes. These by-products should be no more toxic than their PAH precursors, but the yield, composition, and toxicity of these by-products has not been established.

Granular activated carbon treatment has been shown to be effective in bench and pilot-scale tests by Hickok and CH2M Hill. This alternative should be practical and effective in full-scale application. However, the effects of ferrous and ferric iron on the design and operation of a GAC treatment plant have not been established.

3) ERT's economic analysis of the PAC, ozone, and GAC treatment alternatives shows that GAC treatment is considerably more expensive than PAC or ozone injection. This conclusion allows for the current uncertainties in the design of any of these alternatives. The economic analysis, when combined with an analysis of water supply capacity requirements, also shows that treatment should not be applied to all contaminated wells, irrespective of the treatment employed. Instead, treatment should only be applied at wells with existing iron removal plants, which generally operate at much greater rates than wells without iron removal treatment. This is not a major constraint, since most of the municipal wells in St. Louis Park and Edina have iron removal treatment.

4) Based on the above conclusions and the data analysis presented in this appendix, it is recommended that any additional testing of drinking water treatment be limited to further studies of PAC or ozone injection. The need for such testing depends first on the criteria established for PAH, particularly for noncarcinogenic PAH, and then on the choice between using new Mt. Simon-Hinckley wells or drinking water treatment to meet the criteria (see Chapter 6). No further study of GAC treatment is required because is is clearly not cost-effective compared to PAC or ozone injection or to the use of new Mt. Simon-Hinckley wells.

G7. REFERENCES

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G8. DATA FOR ERT TESTS

This section contains figures and tables which present all of the laboratory analyses and field measurements data obtained during ERT's tests of the iron removal plant at St. Louis Park Water Treatment Station Number 1. A brief description of the data presented is provided below. Descriptions of the sampling and analysis techniques used are provided in sections G4.43 and G4.5.3.

G8.1 December 1982 Test

Tables G8-1A through G8-1K present the results of Monsanto's SIM GC/MS PAH analyses of water and sand samples from ERT's December 1982 test. Tables G8-2A through G8-2D present the results of Monsanto's analyses of water samples for various inorganic constituents. Tables G8-3A, B, and C present the results of field measurements made by Soil Exploration Company.

Figure G8-1 shows SIM GC/MS chromatograms for all of the water samples analyzed by Monsanto, including some samples that were not quantified and are not reported in Table G8-1. Figures G8-2 and G8-3 show SIM GC/MS chromatograms for sand sample extracts and air sample resin extracts, respectively. Figure G8-4 shows chromatograms for spiking standard and blank samples corresponding to the December 1982 test. All of the chromatograms indicate the concentration of the full-scale peak height. Concentrations of other peaks are roughly proportional to the peak height relative to full-scale, but this is only approximate because of differing response factors for different compounds. The identities of the various peaks can be approximately determined from the response times given in Table G8-4.

Figure G8-5 shows GC/MS chromatograms for volatile organics analyses. Full-scale peak height concentrations are indicated, as are peak identities, when known.

Figures G8-6, 7, and 8 are copies of recording charts for the flow rates of wells SLP3 and SLP15 and of backwash wastewater during the December test.

G8.2 February 1983 Test

Tables G8-5A, B and C present the results of Monsanto's SIM GC/MS PAH analyses for water samples collected during ERT's February 1983 test. Tables G8-6A and B present similar data for sand sample extracts. No SIM GC/MS chromatograms are presented for the February test because all of the samples collected were quantified.

Table G8-7A, B and C present Monsanto's analysis results for various inorganic constituents. Tables G8-8 presents the results of field measurements made by Soil Exploration Company.

Figures G8-9 and G8-10 are copies of recording charts for flow rates of well SLP15 and backwash wastewater during the February test.

G8.3 September 1982 Test

Tables G8-9A, B and C present the results of Monsanto's SIM GC/MS PAH analyses for split samples collected during CH2M Hill's September 15, 1982 test of the iron removal plant at well SLP15. Each sample was collected and analyzed in duplicate. Monsanto then combined the extracts from duplicate samples remaining after analysis and further concentrated them to 0.1 milliliter. This was done in order to lower the detection limits for PAH compounds. The results of SIM GC/MS PAH analyses for these combined and concentrated extracts are given in Table G8-10.

TABLE G8-1A

RESULTS OF SIM ANALYSES FOR PNAs FOR DECEMBER 1982 CW #15 TREATMENT SYSTEM STUDY

Date January 27, 1983 ERT Task 210

Feature Identification (Q Mass)	Feature Number	Feature L O D[a]	Sample Identification: 1D-1-S RTCC-194	1D-2-S RTCC-193	1D-3-P RTCC-190			
			Concentration (ng/L)					
Indene (116)	64	3	89	83	45			
2,3-Dihydroindene (118)	65	5	1.8×10^3	1.8×10^3	1.1×10^3			
Naphthalene (128)	1	2	25	34	32			
2-Methylnaphthalene (141)	2	4	6.6	9.3	9.3			
1-Methylnaphthalene (141)	3	4	100	91	63			
Biphenyl (154)	4	3	740	540	4.4×10^2			
C_2-naphthalene (141) - Total	5-11	4	590	650	3.3×10^2			
Acenaphthylene (152)	12	11	1,000	1,100	680			
Dihydroacenaphthylene (154)	13	0.5	1,900	1,900	1.3×10^3			
Fluorene (166)	15	3	2,200	2,000	1.0×10^3			
Phenanthrene (178)	20	3	99	100	92			
Anthracene (178)	22	3	160	200	97			

Feature Identification (Q Mass)	Feature Number	Feature L O D[a]	Sample Identification: 1D-1-S RTCC-194	1D-2-S RTCC-193	1D-3-P RTCC-190			
			Concentration (ng/L)					
Fluoranthene (202)	31	3	660	710	330			
Pyrene (202)	32	9	480	510	220			
Benzo(a)anthracene (228)	33	1	24	18	45			
Chrysene (228)	34	8	22	16	25			
Benzo(b)fluoranthene (252)	36	24	ND[b]	ND	ND			
Benzo(k)fluoranthene (252)	37	24	ND	ND	ND			
Benzo(e)pyrene (as 39) (252)	38	13	ND	ND	ND			
Benzo(a)pyrene (252)	39	13	ND	ND	ND			
Perylene (as 39) (252)	40	13	ND	ND	ND			
Indeno(1,2,3,cd)pyrene (276)	45	23	ND	ND	ND			
Dibenz(a,h)anthracene (278)	66	19	ND	ND	ND			
Benzo(g,h,i)perylene (276)	46	14	ND	ND	ND			
Acridine (178)	67	29	96	97	65			

Feature Identification (Q Mass)	Feature Number	Feature L O D[a]	Sample Identification: 1D-1-S RTCC-194	1D-2-S RTCC-193	1D-3-P RTCC-190			
			Concentration (ng/L)					
Carbazole (116)	68	19	6.8	21	13			
Anthracene-d_{10} (IS) (188)	21	-	25	25	25			
Surrogate Spiking Compound		Amount added (ng/L)	Recovery (%)					
Naphthalene-d_8 (136)	63	100	43	59	42			
Chrysene-d_{12} (240)	35	100	77	93	95			

[a] L O D = limit of detection

[b] ND = none detected with a detection limit given by the L O D value (in ng/L) for each compound

TABLE G8-1B

RESULTS OF SIM ANALYSES FOR PNAs FOR DECEMBER 1982 CW #15 TREATMENT SYSTEM STUDY

Date January 27, 1983 ERT Task 210

Feature Identification (Q Mass)	Feature Number	Feature L O D[a]	Sample Identification: 1D-9-P RTCC-200	1D-9-P Duplicate RTCC-214	1D-9-F/R-W RTCC-230	1D-9-F/R-W Duplicate RTCC-231	1D-9-F/R-F RTCC-241	1D-9-F/R-F Duplicate RTCC-239
			Concentration (ng/L)					
Indane (116)	64	3	38	46	54	55	ND[b]	4 9
2,3-Dihydroindene (118)	65	5	$9\ 0 \times 10^2$	$8\ 1 \times 10^2$	$9\ 7 \times 10^2$	$7\ 6 \times 10^2$	ND	ND
Naphthalene (128)	1	2	18	23	81	73	12	13
2-Methylnaphthalene (141)	2	4	4.9	6 6	21	21	2 9	1.4
1-Methylnaphthalene (141)	3	4	70	69	90	65	ND	ND
Biphenyl (154)	4	3	$1\ 9 \times 10^2$	$2\ 9 \times 10^2$	$4\ 3 \times 10^2$	$2\ 6 \times 10^2$	0 36	ND
C_2-naphthalene (141) - Total	5-11	4	$2\ 3 \times 10^2$	$3\ 0 \times 10^2$	$5\ 1 \times 10^2$	$4\ 0 \times 10^2$	ND	ND
Acenaphthylene (152)	12	11	323	540	600	630	ND	ND
Dihydroacenaphthylene (154)	13	0 5	868	$1\ 1 \times 10^3$	$1\ 0 \times 10^3$	$1\ 3 \times 10^3$	ND	ND
Fluorene (166)	15	3	570	870	$1\ 0 \times 10^3$	820	0 74	ND
Phenanthrene (178)	20	3	140	120	180	150	26	27
Anthracene (178)	22	3	100	98	120	74	ND	ND

Feature Identification (Q Mass)	Feature Number	Feature L O D[a]	Sample Identification: 1D-9-P RTCC-200	1D-9-P Duplicate RTCC-214	1D-9-F/R-W RTCC-230	1D-9-F/R-W Duplicate RTCC-231	1D-9-F/R-F RTCC-241	1D-9-F/R-F Duplicate RTCC-239
			Concentration (ng/L)					
Fluoranthene (202)	31	3	330	320	470	340	31	51
Pyrene (202)	32	9	270	230	260	240	18	23
Benzo(a)anthracene (228)	33	1	22	12	15	ND	4 6	8 3
Chrysene (228)	34	8	22	13	23	ND	4 6	8 4
Benzo(b)fluoranthene (252)	36	24	ND	ND	ND	ND	ND	ND
Benzo(k)fluoranthene (252)	37	24	ND	ND	ND	ND	ND	ND
Benzo(e)pyrene (as 39) (252)	38	13	ND	ND	ND	ND	ND	ND
Benzo(a)pyrene (252)	39	13	ND	ND	ND	ND	ND	ND
Perylene (as 39) (252)	40	13	ND	ND	ND	ND	ND	ND
Indeno(1,2,3,cd)pyrene (276)	45	23	ND	ND	ND	ND	ND	ND
Dibenz(a,h)anthracene (278)	66	19	ND	ND	ND	ND	ND	ND
Benzo(g,h,i)perylene (276)	46	14	ND	ND	ND	ND	ND	ND
Acridine (178)	67	29	54	37	61	53	ND	ND

Feature Identification (Q Mass)	Feature Number	Feature L O D[a]	Sample Identification: 1D-9-P RTCC-200	1D-9-P Duplicate RTCC-214	1D-9-F/R-W RTCC-230	1D-9-F/R-W Duplicate RTCC-231	1D-9-F/R-F RTCC-241	1D-9-F/R-F Duplicate RTCC-239
			Concentration (ng/L)					
Carbazole (166)	68	19	12	ND	27	24	ND	ND
Anthracene-d_{10} (IS) (188)	21	-	25	25	25	25	25	25
Surrogate Spiking Compound		Amount added (ng/L)	Recovery (%)					
Naphthalene-d_8 (136)	63	100	42	27	61	45	59	49
Chrysene-d_{12} (240)	35	100	68	62	103	59	71	90

[a] L O D = limit of detection

[b] ND = none detected with a detection limit given by the L O.D. value (in ng/L) for each compound

TABLE G8-1C

RESULTS OF SIM ANALYSES FOR PNAs FOR DECEMBER 1982 CW #15 TREATMENT SYSTEM STUDY

Date January 27, 1983 ERT Task 210

Feature Identification (Q Mass)	Feature Number	Feature L O D[a]	Sample Identification: 1D-10-P RTCC-201	1D-10-F/R-W RTCC-232	1D-10-F/R-F RTCC-240	Method Blank RTCC-188		
			Concentration (ng/L)					
Indene (116)	64	3	39	41	1 5	2 3		
2,3-Dihydroindene (118)	65	5	8 5 x 10^2	8-2 x 10^2	ND[b]	ND		
Naphthalene (128)	1	2	20	88	14	21		
2-Methylnaphthalene (141)	2	4	4 6	25	1 4	2 6		
1-Methylnaphthalene (141)	3	4	66	93	ND	ND		
Biphenyl (154)	4	3	3 0 x 10^2	3 4 x 10^2	5 0	6 9		
C_2-naphthalene (141) - Total	5-11	4	2 8 x 10^2	4 8 x 10^2	ND	ND		
Acenaphthylene (152)	12	11	530	890	ND	ND		
Dihydroacenaphthylene (154)	13	0 5	992	1 6 x 10^2	ND	12		
Fluorene (166)	15	3	800	890	17	13		
Phenanthrene (178)	20	3	150	210	27	20		
Anthracene (178)	22	3	110	120	3 6	18		

Feature Identification (Q Mass)	Feature Number	Feature L O D[a]	Sample Identification: 1D-10-P RTCC-201	1D-10-F/R-W RTCC-232	1D-10-F/R-F RTCC-240	Method Blank RTCC-188		
			Concentration (ng/L)					
Fluoranthene (202)	31	3	410	480	52	2 2		
Pyrene (202)	32	9	290	330	18	1 4		
Benzo(a)anthracene (228)	33	1	32	18	6	ND		
Chrysene (228)	34	8	25	11	9	ND		
Benzo(b)fluoranthene (252)	36	24	ND	ND	ND	ND		
Benzo(k)fluoranthene (252)	37	24	ND	ND	ND	ND		
Benzo(e)pyrene (as 39) (252)	38	13	ND	ND	ND	ND		
Benzo(a)pyrene (252)	39	13	ND	ND	ND	ND		
Perylene (as 39) (252)	40	13	ND	ND	ND	ND		
Indeno(1,2,3,cd)pyrene (276)	45	23	ND	ND	ND	ND		
Dibenz(a,h)anthracene (278)	46	19	ND	ND	ND	ND		
Benzo(g,h,i)perylene (276)	46	14	ND	ND	ND	ND		
Acridine (178)	67	29	60	56	ND	ND		

Feature Identification (Q Mass)	Feature Number	Feature L O D[a]	Sample Identification: 1D-10-P RTCC-201	1D-10-F/R-W RTCC-232	1D-10-F/R-F RTCC-240	Method Blank RTCC-188		
			Concentration (ng/L)					
Carbazole (166)	68	19	14	30	ND	ND		
Anthracene-d_{10} (IS) (188)	21	-	25	25	25	25		
Surrogate Spiking Compound		Amount added (ng/L)	Recovery (%)					
Naphthalene-d_8 (136)	63	100	31	72	29	45		
Chrysene-d_{12} (240)	35	100	70	71	87	80		

[a] L O D = limit of detection

[b] ND = none detected with a detection limit given by the L O D value (in ng/L) for each compound

TABLE G8-1D

RESULTS OF SIM ANALYSES FOR PNAs FOR DECEMBER 1982 CW #15 TREATMENT SYSTEM STUDY

Date January 27, 1983 ERT Task 210

Feature Identification (Q Mass)	Feature Number	Feature L O D [a]	Sample Identification: 2-1-P RTCC-185	2-2-P RTCC-202	2-2-F/R-W RTCC-227	2-2-F/R-F RTCC-238	Method Blank RTCC-199	
			Concentration (ng/L)					
Indene (116)	64	3	87	44	43	ND[b]	1 1	
2,3-Dihydroindene (118)	65	5	$1 5 \times 10^3$	$1 0 \times 10^3$	$9 8 \times 10^2$	ND	ND	
Naphthalene (128)	1	2	62	24	62	9 6	7 0	
2-Methylnaphthalene (141)	2	4	15	5 3	12	8 3	3 5	
1-Methylnaphthalene (141)	3	4	75	74	62	ND	4 5	
Biphenyl (154)	4	3	$5 9 \times 10^2$	$3 5 \times 10^2$	$3 6 \times 10^2$	2 3	2 2	
C_2-naphthalene (141) - Total	5-11	4	$5 5 \times 10^2$	$3 6 \times 10^2$	$5 0 \times 10^2$	ND	ND	
Acenaphthylene (152)	12	11	700	610	550	ND	0 36	
Dihydroacenaphthylene (154)	13	0 5	$1 3 \times 10^3$	$1 2 \times 10^3$	$1 3 \times 10^3$	ND	15	
Fluorene (166)	15	3	$1 4 \times 10^3$	890	$1 1 \times 10^3$	1 6	13	
Phenanthrene (178)	20	3	80	150	150	26	260	
Anthracene (178)	22	3	130	120	140	ND	ND	

Feature Identification (Q Mass)	Feature Number	Feature L O D [a]	Sample Identification: 2-1-P RTCC-185	2-2-P RTCC-202	2-2-F/R-W RTCC-227	2-2-F/R-F RTCC-238	Method Blank RTCC-199	
			Concentration (ng/L)					
Fluoranthene (202)	31	3	610	290	390	26	61	
Pyrene (202)	32	9	430	220	280	16	35	
Benzo(a)anthracene (228)	33	1	29	20	20	4 8	1 7	
Chrysene (228)	34	8	35	20	20	4 2	5 4	
Benzo(b)fluoranthene (252)	36	24	ND	ND	ND	ND	24	
Benzo(k)fluoranthene (252)	37	24	ND	ND	ND	ND	ND	
Benzo(e)pyrene (as 39) (252)	38	13	ND	ND	ND	ND	ND	
Benzo(a)pyrene (252)	39	13	ND	ND	ND	ND	ND	
Perylene (as 39) (252)	40	13	ND	ND	ND	ND	ND	
Indeno(1,2,3,cd)pyrene (276)	45	23	ND	ND	ND	ND	ND	
Dibenz(a,h)anthracene (278)	66	19	ND	ND	ND	ND	ND	
Benzo(g,h,i)perylene (276)	46	14	ND	ND	ND	ND	ND	
Acridine (178)	67	29	74	60	65	ND	ND	

Feature Identification (Q Mass)	Feature Number	Feature L O D [a]	Sample Identification: 2-1-P RTCC-185	2-2-P RTCC-202	2-2-F/R-W RTCC-227	2-2-F/R-F RTCC-238	Method Blank RTCC-199	
			Concentration (ng/L)					
Carbazole (166)	68	19	24	24	31	ND	23	
Anthracene-d_{10} (IS) (188)	21	-	25	25	25	25	25	
Surrogate Spiking Compound		Amount added (ng/L)	Recovery (%)					
Naphthalene-d_8 (136)	63	100	63	45	72	11	55	
Chrysene-d_{12} (240)	35	100	88	57	120	78	53	

[a] L O D = limit of detection

[b] ND = none detected with a detection limit given by the L O D value (in ng/L) for each compound

TABLE G8-1E

RESULTS OF SIM ANALYSES FOR PNAs FOR DECEMBER 1982 CW #15 TREATMENT SYSTEM STUDY

Date: January 27, 1983 ERT Task 210

Feature Identification (Q Mass)	Feature Number	Feature L O D.[a]	Sample Identification: 3B-1-P RTCC-192	3B-2-P RTCC-191	3B-3-P RTCC-203	3B-4-P RTCC-204	3B-5-P RTCC-205	
			Concentration (ng/L)					
Indene (116)	64	3	84	76	67	40	5 1	
2,3-Dihydroindene (118)	65	5	$1\ 5 \times 10^3$	$1\ 5 \times 10^3$	$1\ 1 \times 10^3$	$1\ 0 \times 10^3$	$8\ 0 \times 10^2$	
Naphthalene (128)	1	2	39	36	23	21	15	
2-Methylnaphthalene (141)	2	4	9 6	4 2	6 9	7 3	4 0	
1-Methylnaphthalene (141)	3	4	74	68	69	66	32	
Biphenyl (154)	4	3	$6\ 0 \times 10^2$	$5\ 9 \times 10^2$	$4\ 0 \times 10^2$	$2\ 6 \times 10^2$	$2\ 2 \times 10^2$	
C_2-naphthalene (141) - Total	5-11	4	$5\ 0 \times 10^3$	$3\ 1 \times 10^3$	$4\ 1 \times 10^3$	$3\ 9 \times 10^3$	13	
Acenaphthylene (152)	12	11	810	680	660	540	2 8	
Dihydroacenaphthylene (154)	13	0 5	170	$1\ 8 \times 10^3$	$1\ 3 \times 10^3$	970	2 7	
Fluorene (166)	15	3	$1\ 3 \times 10^3$	$1\ 3 \times 10^3$	960	660	780	
Phenanthrene (178)	20	3	72	68	140	140	87	
Anthracene (178)	22	3	91	120	140	60	3 1	

Feature Identification (Q Mass)	Feature Number	Feature L O D.[a]	Sample Identification: 3B-1-P RTCC-192	3B-2-P RTCC-191	3B-3-P RTCC-203	3B-4-P RTCC-204	3B-5-P RTCC-205	
			Concentration (ng/L)					
Fluoranthene (202)	31	3	590	580	490	280	190	
Pyrene (202)	32	9	360	400	350	150	1 6	
Benzo(a)anthracene (228)	33	1	36	38	35	28	11	
Chrysene (228)	34	8	31	30	22	17		
Benzo(b)fluoranthene (252)	36	24	ND[b]	ND	ND	ND	ND	
Benzo(k)fluoranthene (252)	37	24	ND	ND	ND	ND	ND	
Benzo(e)pyrene (as 39) (252)	38	13	ND	ND	ND	ND	ND	
Benzo(a)pyrene (252)	39	13	ND	ND	ND	ND	ND	
Perylene (as 39) (252)	40	13	ND	ND	ND	ND	ND	
Indeno(1,2,3,cd)pyrene (276)	45	23	ND	ND	ND	ND	ND	
Dibenz(a,h)anthracene (278)	66	19	ND	ND	ND	ND	ND	
Benzo(g,h,i)perylene (276)	46	14	ND	ND	ND	ND	ND	
Acridine (178)	67	29	68	71	97	56	20	

Feature Identification (Q Mass)	Feature Number	Feature L O D.[a]	Sample Identification: 3B-1-P RTCC-192	3B-2-P RTCC-191	3B-3-P RTCC-203	3B-4-P RTCC-204	3B-5-P RTCC-205	
			Concentration (ng/L)					
Carbazole (166)	68	19	9 0	9 0	27	ND	ND	
Anthracene-d_{10} (IS) (188)	21	-	25	25	25	25	25	
Surrogate Spiking Compound		Amount added (ng/L)	Recovery (%)					
Naphthalene-d_8 (136)	63	100	52	81	57	38	27	
Chrysene-d_{12} (240)	35	100	88	65	78	62	63	

[a] L O D = limit of detection

[b] ND = none detected with a detection limit given by the L O D value (in ng/L) for each compound

TABLE G8-1F

RESULTS OF SIM ANALYSES FOR PNAs FOR DECEMBER 1982 CW #15 TREATMENT SYSTEM STUDY

Date January 27, 1983 SRT Task 210

Feature Identification (Q Mass)	Feature Number	Feature L O D[a]	Sample Identification: 4A-4-P RTCC-209	4A-4-P Duplicate RTCC-215	4A-4-F/R-W RTCC-228	4A-4-F/R-W Duplicate RTCC-234	4A-4-F/R-F RTCC-237	4A-4-F/R-F Duplicate RTCC-243
			Concentration (ng/L)					
Indene (116)	64	3	48	44	60	47	ND[b]	3 1
2,3-Dihydroindene (118)	65	5	8 6 x 10^2	8 2 x 10^2	1 1 x 10^3	7 9 x 10^2	ND	ND
Naphthalene (128)	1	2	27	30	45	48	6 5	11
2-Methylnaphthalene (141)	2	4	6 6	12	8 7	7 6	ND	4 1
1-Methylnaphthalene (141)	3	4	67	72	93	55	ND	ND
Biphenyl (154)	4	3	1 9 x 10^2	3 6 x 10^2	4 5 x 10^2	1 9 x 10^2	1 8	3 1
C_2-naphthalene (141) - Total	5-11	4	3 2 x 10^2	3 3 x 10^2	3 6 x 10^2	2 9 x 10^2	ND	ND
Acenaphthylene (152)	12	11	460	580	650	250	ND	ND
Dihydroacenaphthylene (154)	13	0 5	970	1 2 x 10^3	1 1 x 10^3	740	ND	ND
Fluorene (166)	15	3	800	960	1 5 x 10^3	1 3 x 10^3	ND	ND
Phenanthrene (178)	20	3	160	250	120	120	16	21
Anthracene (178)	22	3	56	95	140	98	ND	ND

Feature Identification (Q Mass)	Feature Number	Feature L O D[a]	Sample Identification: 4A-4-P RTCC-209	4A-4-P Duplicate RTCC-215	4A-4-F/R-W RTCC-228	4A-4-F/R-W Duplicate RTCC-234	4A-4-F/R-F RTCC-237	4A-4-F/R-F Duplicate RTCC-243
			Concentration (ng/L)					
Fluoranthene (202)	31	3	340	310	320	270	18	19
Pyrene (202)	32	9	150	140	170	140	8 0	7 7
Benzo(a)anthracene (228)	33	1	ND	ND	ND	ND	ND	ND
Chrysene (228)	34	8	ND	ND	ND	ND	ND	ND
Benzo(b)fluoranthene (252)	36	24	ND	ND	ND	ND	ND	ND
Benzo(k)fluoranthene (252)	37	24	ND	ND	ND	ND	ND	ND
Benzo(e)pyrene (as 39) (252)	38	13	ND	ND	ND	ND	ND	ND
Benzo(a)pyrene (252)	39	13	ND	ND	ND	ND	ND	ND
Perylene (as 39) (252)	40	13	ND	ND	ND	ND	ND	ND
Indeno(1,2,3,cd)pyrene (276)	45	23	ND	ND	ND	ND	ND	ND
Dibenz(a,h)anthracene (278)	66	19	ND	ND	ND	ND	ND	ND
Benzo(g,h,i)perylene (276)	46	14	ND	ND	ND	ND	ND	ND
Acridine (178)	67	29	56	53,	48	17	ND	ND

Feature Identification (Q Mass)	Feature Number	Feature L O D[a]	Sample Identification: 4A-4-P RTCC-209	4A-4-P Duplicate RTCC-215	4A-4-F/R-W RTCC-228	4A-4-F/R-W Duplicate RTCC-234	4A-4-F/R-F RTCC-237	4A-4-F/R-F Duplicate RTCC-243
			Concentration (ng/L)					
Carbazole (116)	68	19	19	16	21	34	ND	ND
Anthracene-d_{10} (IS) (188)	21	-	25	25	25	25	25	25
Surrogate Spiking Compound		Amount added (ng/L)	Recovery (%)					
Naphthalene-d_8 (136)	63	100	67	5 2	39	38	4 3	41
Chrysene-d_{12} (240)	35	100	67	40	84	47	66	85

[a] L O D = limit of detection

[b] ND = none detected with a detection limit given by the L O D value (in ng/L) for each compound

TABLE G8-1G

RESULTS OF SIM ANALYSES FOR PNAs FOR DECEMBER 1982 CW #15 TREATMENT SYSTEM STUDY

Date January 27, 1983 ERT Task 210

Feature Identification (Q Mass)	Feature Number	Feature L O D[a]	Sample Identification: 4A-5-P RTCC-210	4A-5-F/R-W RTCC-233	4A-5-F/R-F RTCC-242	4A-6-P RTCC-213	Method Blank RTCC-211	
			Concentration (ng/L)					
Indene (116)	64	3	37	31	1 6	36	1 8	
2,3-Dihydroindene (118)	65	5	$1\ 2 \times 10^3$	$1\ 1 \times 10^3$	ND[b]	$8\ 3 \times 10^2$	ND	
Naphthalene (128)	1	2	28	49	12	18	17	
2-Methylnaphthalene (141)	2	4.	9 8	13	7.7	4 2	5 2	
1-Methylnaphthalene (141)	3	4	87	91	ND	58.	7 7	
Biphenyl (154)	4	3	$3\ 9 \times 10^2$	$4\ 4 \times 10^2$	4 4	$2\ 9 \times 10^2$	0 31	
C_2-naphthalene (141) - Total	5-11	4	$3\ 8 \times 10^2$	$4\ 5 \times 10^2$	ND	$2\ 5 \times 10^2$	ND	
Acenaphthylene (152)	12	11	290	150	ND	350	ND	
Dihydroacenaphthylene (154)	13	0 5	$1\ 1 \times 10^3$	$1\ 1 \times 10^3$	ND	890	9 4	
Fluorene (166)	15	3	680	$1\ 1 \times 10^3$	0 51	730	3 5	
Phenanthrene (178)	20	3	130	150	14	52	25	
Anthracene (178)	22	3	23	19	ND	56	ND	

Feature Identification (Q Mass)	Feature Number	Feature L O D[a]	Sample Identification: 4A-5-P RTCC-210	4A-5-F/R-W RTCC-233	4A-5-F/R-F RTCC-242	4A-6-P RTCC-213	Method Blank RTCC-211	
			Concentration (ng/L)					
Fluoranthene (202)	31	3	350	390	25	230	12	
Pyrene (202)	32	9	150	180	13	82	50	
Benzo(a)anthracene (228)	33	1	ND	ND	ND	ND	ND	
Chrysene (228)	34	8	ND	ND	ND	ND	ND	
Benzo(b)fluoranthene (252)	36	24	ND	ND	ND	ND	ND	
Benzo(k)fluoranthene (252)	37	24	ND	ND	ND	ND	ND	
Benzo(e)pyrene (as 39) (252)	38	13	ND	ND	ND	ND	ND	
Benzo(a)pyrene (252)	39	13	ND	ND	ND	ND	ND	
Perylene (as.39) (252)	40	13	ND	ND	ND	ND	ND	
Indeno(1,2,3,cd)pyrene (276)	45	23	ND	ND	ND	ND	ND	
Dibenz(a,h)anthracene (278)	66	19	ND	ND	ND	ND	ND	
Benzo(g,h,i)perylene (276)	46	14	ND	ND	ND	ND	ND	
Acridine (178)	67	29	56	67	ND	54.	ND	

Feature Identification (Q Mass)	Feature Number	Feature L O D[a]	Sample Identification: 4A-5-P RTCC-210	4A-5-F/R-W RTCC-233	4A-5-F/R-F RTCC-242	4A-6-P RTCC-213	Method Blank RTCC-211	
			Concentration (ng/L)					
Carbazole (116)	68	19	35	11	ND	ND	ND	
Anthracene-d_{10} (18) (188)	21		25	25	25	25	25	
Surrogate Spiking Compound		Amount added (ng/L)	Recovery (%)					
Naphthalene-d_8 (136)	63	100	37	59	44	38	69	
Chrysene-d_{12} (240)	35	100	96	94	89	68	115	

[a] L.O D = limit of detection

[b] ND = none detected with a detection limit given by the L O D value (in ng/L) for each compound

TABLE G8-1H

RESULTS OF SIM ANALYSES FOR PNAs FOR DECEMBER 1982 CW #15 TREATMENT SYSTEM STUDY

Date January 27, 1983 ERT Task 210

Feature Identification (Q Mass)	Feature Number	Feature L O D[a]	Sample Identification: 4B-1-P RTCC-187	4B-2-P RTCC-226	4C-1-P RTCC-216	Method Blank RTCC-217		
			Concentration (ng/L)					
Indene (116)	64	3	59	54	85	1 2		
2,3-Dihydroindene (118)	65	5	$9\ 6 \times 10^2$	$7\ 9 \times 10^2$	$1\ 7 \times 10^3$	ND[b]		
Naphthalene (128)	1	2	29	17	52	22		
2-Methylnaphthalene (141)	2	4	4 8	2 4	14	4 2		
1-Methylnaphthalene (141)	3	4	51	34	$1\ 0 \times 10^2$	2 2		
Biphenyl (154)	4	3	$2\ 2 \times 10^2$	66	$6\ 1 \times 10^2$	0 42		
C_2-naphthalene (141) - Total	5-11	4	$2\ 1 \times 10^2$	$2\ 1 \times 10^2$	$6\ 2 \times 10^2$	ND		
Acenaphthylene (152)	12	11	380	330	820	ND		
Dihydroacenaphthylene (154)	13	0 5	840	$1\ 1 \times 10^3$	$1\ 3 \times 10^3$	9 2		
Fluorene (166)	15	3	540	510	$1\ 4 \times 10^3$	8 8		
Phenanthrene (178)	20	3	28	34	140	16		
Anthracene (178)	22	3	18	48	120	ND		

Feature Identification (Q Mass)	Feature Number	Feature L.O D[a]	Sample Identification: 4B-1-P RTCC-187	4B-2-P RTCC-226	4C-1-P RTCC-216	Method Blank RTCC-217		
			Concentration (ng/L)					
Fluoranthene (202)	31	3	13	340	410	0 85		
Pyrene (202)	32	9	5 9	180	210	1 2		
Benzo(a)anthracene (228)	33	1	ND	ND	ND	ND		
Chrysene (228)	34	8	ND	ND	ND	ND		
Benzo(b)fluoranthene (252)	36	24	ND	ND	ND	ND		
Benzo(k)fluoranthene (252)	37	24	ND	ND	ND	ND		
Benzo(e)pyrene (as 39) (252)	38	13	ND	ND	ND	ND		
Benzo(a)pyrene (252)	39	13	ND	ND	ND	ND		
Perylene (as 39) (252)	40	13	ND	ND	ND	ND		
Indeno(1,2,3,cd)pyrene (276)	45	23	ND	ND	ND	ND		
Dibenz(a,h)anthracene (278)	66	19	ND	ND	ND	ND		
Benzo(g,h,i)perylene (276)	46	14	ND	ND	ND	ND		
Acridine (178)	67	29	45	54	68	ND		

Feature Identification (Q Mass)	Feature Number	Feature L O D[a]	Sample Identification: 4B-1-P RTCC-187	4B-2-P RTCC-226	4C-1-P RTCC-216	Method Blank RTCC-217		
			Concentration (ng/L)					
Carbazole (116)	68	19	22	ND	16	ND		
Anthracene-d_{10} (IS) (188)	21	-	25	25	25	25		
Surrogate Spiking Compound		Amount added (ng/L)	Recovery (%)					
Naphthalene-d_8 (136)	63	100	58	42	96	36		
Chrysene-d_{12} (240)	35	100	84	98	110	51		

[a] L O D = limit of detection

[b] ND = none detected with a detection limit given by the L O D value (in ng/L) for each compound

TABLE G8-1I

RESULTS OF SIM ANALYSES FOR PNAs FOR DECEMBER 1982 CW #15 TREATMENT SYSTEM STUDY

Date January 27, 1983 ERT Task 210

Feature Identification (Q Mass)	Feature Number	Feature L O D[a]	Sample Identification 7-5-2-P/C ng/mL	7-5-2-P/C ng/g	7-5-3-P/C ng/mL	7-5-3-P/C ng/g	7-5-9-P/C ng/mL	7-5-9-P/C ng/g
			Concentration					
Indene (116)	64	13	ND[b]	ND	ND	ND	ND	ND
2,3-Dihydroindene (118)	65	18	ND	ND	ND	ND	ND	ND
Naphthalene (128)	1	8	ND	ND	11	8 4	66	66
2-Methylnaphthalene (141)	2	14	ND	ND	ND	ND	ND	ND
1-Methylnaphthalene (141)	3	15	ND	ND	ND	ND	ND	ND
Biphenyl (154)	4	10	ND	ND	8 8	6 6	6 4	6 4
C_2-naphthalene (141) - Total	5-11	15	ND	ND	ND	ND	ND	ND
Acenaphthylene (152)	12	44	ND	ND	ND	ND	120	120
Dihydroacenaphthylene (154)	13	2	ND	ND	ND	ND	77	77
Fluorene (166)	15	12	ND	ND	ND	ND	ND	ND
Phenanthrene (178)	20	12	ND	ND	ND	ND	44	44
Anthracene (178)	22	12	ND	ND	ND	ND	100	100

Feature Identification (Q Mass)	Feature Number	Feature L O D[a]	Sample Identification 7-5-2-P/C ng/mL	7-5-2-P/C ng/g	7-5-3-P/C ng/mL	7-5-3-P/C ng/g	7-5-9-P/C ng/mL	7-5-9-P/C ng/g
			Concentration					
Fluoranthene (202)	31	12	ND	ND	ND	ND	12	12
Pyrene (202)	32	36	ND	ND	ND	ND	20	20
Benzo(a)anthracene (228)	33	4	ND	ND	ND	ND	78	78
Chrysene (228)	34	32	ND	ND	ND	ND	150	150
Benzo(b)fluoranthene (252)	36	96	ND	ND	ND	ND	170	170
Benzo(k)fluoranthene (252)	37	96	ND	ND	ND	ND	170	170
Benzo(e)pyrene (as 39) (252)	38	52	ND	ND	ND	ND	ND	ND
Benzo(a)pyrene (252)	39	52	ND	ND	ND	ND	20	20
Perylene (as 39) (252)	40	52	ND	ND	ND	ND	ND	ND
Indeno(1,2,3,cd)pyrene (276)	45	92	ND	ND	ND	ND	ND	ND
Dibenz(a,h)anthracene (278)	66	76	ND	ND	ND	ND	ND	ND
Benzo(g,h,i)perylene (276)	46	56	ND	ND	ND	ND	ND	ND
Acridine (178)	67	116	ND	ND	ND	ND	ND	ND

Feature Identification (Q Mass)	Feature Number	Feature L O D[a]	Sample Identification 7-5-2-P/C ng/mL	7-5-2-P/C ng/g	7-5-3-P/C ng/mL	7-5-3-P/C ng/g	7-5-9-P/C ng/mL	7-5-9-P/C ng/g
			Concentration					
Carbazole (116)	68	76	ND	ND	ND	ND	ND	ND
Anthracene-d_{10} (IS) (188)	21	-	25	25	25	25	25	25
Surrogate Spiking Compound		Amount added (ng/g)	Recovery (%)					
Naphthalene-d_8 (136)	63	~100	130	130	99	99	123	123
Chrysene-d_{12} (240)	35	~100	67	67	63	63	106	106

[a] L O D = limit of detection

[b] ND = none detected with a detection limit given by the L O D value (in ng/mL) for each compound

TABLE G8-1J

RESULTS OF SIM ANALYSES FOR PNAs FOR DECEMBER 1982 CW #15 TREATMENT SYSTEM STUDY

Date January 27 1983 ERT Task 210

Feature Identification (Q Mass)	Feature Number	Feature L.O.D.[a]	Sample Identification: 8-1-S RTCC-189	8-2-S RTCC-186	8-3-S RTCC-222	8-4-S RTCC-223		
			Concentration (ng/L)					
Indene (116)	64	3	50	42	6.9	12		
2,3-Dihydroindene (118)	65	5	640	660	150	230		
Naphthalene (128)	1	2	36	40	28	16		
2-Methylnaphthalene (141)	2	4	16	9.5	8.7	7.2		
1-Methylnaphthalene (141)	3	4	61	53	11	21		
Biphenyl (154)	4	3	350	270	43	57		
C_2-naphthalene (141) - Total	5-11	4	350	200	37	76		
Acenaphthylene (152)	12	11	510	330	91	120		
Dihydroacenaphthylene (154)	13	0.5	1,000	690	140	150		
Fluorene (166)	15	3	540	650	170	270		
Phenanthrene (178)	20	3	100	51	46	55		
Anthracene (178)	22	3	68	52	4.4	15		

Feature Identification (Q Mass)	Feature Number	Feature L.O.D.[a]	Sample Identification: 8-1-S RTCC-189	8-2-S RTCC-186	8-3-S RTCC-222	8-4-S RTCC-223		
			Concentration (ng/L)					
Fluoranthene (202)	31	3	430	280	62	96		
Pyrene (202)	32	9	290	160	43	52		
Benzo(a)anthracene (228)	33	1	100	61	13	6.7		
Chrysene (228)	34	8	89	45	20	7.6		
Benzo(b)fluoranthene (252)	36	24	280	130	90	ND[b]		
Benzo(k)fluoranthene (252)	37	24				ND		
Benzo(e)pyrene (as 39) (252)	38	13	56	35	ND	ND		
Benzo(a)pyrene (252)	39	13	55	28	7.2	ND		
Perylene (as 39) (252)	40	13	25	10	5.2	ND		
Indeno(1,2,3,cd)pyrene (276)	45	23	110	31	ND	ND		
Dibenz(a,h)anthracene (278)	66	19	19	ND	ND	ND		
Benzo(g,h,i)perylene (276)	46	14	82	32	ND	ND		
Acridine (178)	67	29	55	53	ND	13		

Feature Identification (Q Mass)	Feature Number	Feature L.O.D.[a]	Sample Identification: 8-1-S RTCC-189	8-2-S RTCC-186	8-3-S RTCC-222	8-4-S RTCC-223		
			Concentration (ng/L)					
Carbazole (116)	68	19	67	32	ND	ND		
Anthracene-d_{10} (IS) (188)	21	-	25	25	25	25		
Surrogate Spiking Compound		Amount added (ng/L)	Recovery (%)					
Naphthalene-d_8 (136)	63	100	49	44	37	46		
Chrysene-d_{12} (240)	35	100	92	82	86	97		

[a] L.O.D. = limit of detection

[b] ND = none detected with a detection limit given by the L.O.D. value (in ng/L) for each compound

TABLE G8-1K

RESULTS OF SIM ANALYSES FOR PNAs FOR DECEMBER 1982 CW #15 TREATMENT SYSTEM STUDY

Date January 27, 1983 ERT Task 210

Feature Identification (Q Mass)	Feature Number	Feature L O D[a]	Sample Identification: Method Blank RTCC-235	Blank-W RTCC-229	Blank-F RTCC-236			
			Concentration (ng/L)					
Indene (116)	64	3	6 3	1 7	ND[b]			
2,3-Dihydroindene (118)	65	5	ND	ND	ND			
Naphthalene (128)	1	2	33	42	7 6			
2-Methylnaphthalene (141)	2	4	5 9	7 8	7 7			
1-Methylnaphthalene (141)	3	4	2 6	6 4	ND			
Biphenyl (154)	4	3	1 5	8 3	1 6			
C_2-naphthalene (141) - Total	5-11	4	ND	ND	ND			
Acenaphthylene (152)	12	11	ND	ND	ND			
Dihydroacenaphthylene (154)	13	0 5	10	8 7	ND			
Fluorene (166)	15	3	6 7	5 2	ND			
Phenanthrene (178)	20	3	47	42	29			
Anthracene (178)	22	3	ND	ND	ND			

Feature Identification (Q Mass)	Feature Number	Feature L O D[a]	Sample Identification: Method Blank RTCC-235	Blank-W RTCC-229	Blank-F RTCC-236			
			Concentration (ng/L)					
Fluoranthene (202)	31	3	12	12	13			
Pyrene (202)	32	9	4 1	7 4	5 0			
Benzo(a)anthracene (228)	33	1	ND	ND	ND			
Chrysene (228)	34	8	ND	ND	ND			
Benzo(b)fluoranthene (252)	36	24	ND	ND	ND			
Benzo(k)fluoranthene (252)	37	24	ND	ND	ND			
Benzo(e)pyrene (as 39) (252)	38	13	ND	ND	ND			
Benzo(a)pyrene (252)	39	13	ND	ND	ND			
Perylene (as 39) (252)	40	13	ND	ND	ND			
Indeno(1,2,3,cd)pyrene (276)	45	23	ND	ND	ND			
Dibenz(a,h)anthracene (278)	66	19	ND	ND	ND			
Benzo(g,h,i)perylene (276)	46	14	ND	ND	ND			
Acridine (178)	67	29	ND	ND	ND			

Feature Identification (Q Mass)	Feature Number	Feature L O D[a]	Sample Identification: Method Blank RTCC-235	Blank-W RTCC-229	Blank-F RTCC-236			
			Concentration (ng/L)					
Carbazole (116)	68	19	ND	ND	ND			
Anthracene-d_{10} (IS) (188)	21	-	25	25	25			
Surrogate Spiking Compound		Amount added (ng/L)	Recovery (%)					
Naphthalene-d_8 (136)	63	100	65	53	6			
Chrysene-d_{12} (240)	35	100	85	98	107			

[a] L O D = limit of detection

[b] ND = none detected with a detection limit given by the L O D value (in ng/L) for each compound

TABLE G8-2A

INORGANIC ANALYSES FOR DECEMBER 1982 CW #15 WATER TREATMENT STUDY

January 21, 1983 ERT Task: 210

Feature Identification	Feature Analytical Method	Feature L.O.D.[a]	Sample Identification					
			2-1-0	2-2-0	8-1-0	8-2-0	8-3-0	8-4-0
			Concentration (mg/L)					
Non purgeable TOC	EPA-415.1	0.5	2.9	2.9	2.7	2.5	2.8	2.9
Fe	EPA-200.7	0.025	0.829	0.771	3.89	8.47	4.66	6.17
Mn	EPA-200.7	0.003	0.099	0.102	0.121	0.117	0.128	0.124
Alkalinity ($CaCO_3$)	EPA-403	20	304	310	294	292	272	280
Hardness (mg eq $CaCO_3$/L)	EPA-200.7	1	324	331	315	308	287	287
Dissolved Fe	EPA-200.7	0.025	0.761	0.719				

[a]L.O.D. = limit of detection in mg/L.

TABLE G8-2B

INORGANIC ANALYSES FOR DECEMBER 1982 CW #15 WATER TREATMENT STUDY

January 21, 1983 ERT Task: 210

Feature Identification	Feature Analytical Method	Feature L.O.D.[a]	Sample Identification					
			3B-1-0	3B-2-0	3B-3-0	3B-4-0	3B-5-0	
			Concentration (mg/L)					
Non purgeable TOC	EPA-415.1	0.5	3.4	2.8	2.5	2.6	2.5	
Fe	EPA-200.7	0.025	0.749	0.798	0.768	0.758	0.767	
Mn	EPA-200.7	0.003	0.098	0.099	0.098	0.097	0.102	
Alkalinity ($CaCO_3$)	EPA-403	20	306	308	309	309	300	
Hardness (mg eq $CaCO_3$/L)	EPA-200.7	1	322	329	320	311	333	
Dissolved Fe	EPA-200.7	0.025	0.375	0.728	0.249			

[a]L.O.D. = limit of detection in mg/L.

TABLE G8-2C

INORGANIC ANALYSES FOR DECEMBER 1982 CW #15 WATER TREATMENT STUDY

January 21, 1983 ERT Task: 210

Feature Identification	Feature Analytical Method	Feature L.O.D.[a]	Sample Identification					
			4A-4-0	4A-4-0 Duplicate	4A-6-0	1D-9-0	1D-9-0 Duplicate	
			Concentration (mg/L)					
Non purgeable TOC	EPA-415.1	0.5	2.3	2.3	2.8	2.5	2.4	
Fe	EPA-200.7	0.025	0.065	0.125	0.049	0.769	0.776	
Mn	EPA-200.7	0.003	0.093	0.095	0.089	0.102	0.103	
Alkalinity ($CaCO_3$)	EPA-403	20	308	308	306	306	312	
Hardness (mg eq $CaCO_3$/L)	EPA-200.7	1	329	338	323	330	335	

[a]L.O.D. = limit of detection in mg/L.

TABLE G8-2D

INORGANIC ANALYSES FOR DECEMBER 1982 CW #15 WATER TREATMENT STUDY

January 21, 1983 ERT Task: 210

Feature Identification	Feature Analytical Method	Feature L.O.D.[a]	Sample Identification					
			4B-1-0	4B-2-0	4C-1-0	Field Blank 12071320	Field Blank 12071130	4A-2-0
			Concentration (mg/L)					
Non purgeable TOC	EPA-415.1	0.5	2.2	3.9	3.1	0.5	0.5	
Fe	EPA-200.7	0.025	1.51	3.61	0.100	0.026	ND[b]	
Mn	EPA-200.7	0.003	0.092	0.086	0.084	0.004	ND	
Alkalinity ($CaCO_3$)	EPA-403	20	296	308	308	ND[b]	ND	
Hardness (mg eq $CaCO_3$/L)	EPA-200.7	1	318	322	327	ND	ND	
Dissolved Fe	EPA-200.7	0.025						0.068

[a]L.O.D. = limit of detection in mg/L.

[b]ND = none detected with a detection limit given by the L.O.D. value for each feature.

TABLE G8-3A

FIELD MEASUREMENTS MADE ON DECEMBER 6,1982
DURING ERT'S TEST AT ST. LOUIS PARK STATION
NO. 1 (REPRODUCED FROM SEC 1982)

Sample[1] Location	Time	Temperature °C	pH	S. Conductance umhos/cm	Dissolved Oxygen, mg/l	Iron mg/l	Turbidity NTU	Chlorine mg/l
4B-1	11:14	10.5	6.3	560	-[2]	2.7	24	-
8-1	11:20	10	6.7	540	-	5.0	22	-
8-2	11:23	10	6.8	520	-	11.2	22	-
8-3	11:30	10	6.7	505	-	8.4	17	-
2-1	14:30	9.8	6.9	585	0.25	0.95	0.8	0
3B-1	15:03	9.8	7.1	590	0.20	1.20	1.75	0.32
3B-2	15:26	9.8	7.1	545	0.35	1.05	1.1	0
4E[3]	16:02	9.9	-	590	2.1	0.6	2.6	0
3B	16:05	-	-	-	-	-	-	1.28
4C[3]	16:10	-	-	-	-	-	-	0
4D[3]	16:27	-	-	-	-	0.55	-	-
4B[3]	16:32	-	-	-	-	1.3	-	-
4B	16:42	-	-	-	-	0.5	-	-
4C	16:34	-	-	-	-	0.45	-	-
4C	16.38	-	-	-	2.3	-	-	-
4C	16:44	-	-	-	-	0.4	-	-
4A	16:35	-	-	-	-	1.2	-	-
4A	16:48	-	-	-	-	0.55	-	-
3B	16:55	9.8	7.2	-	0.7	-	-	0.61

See Footnotes at the end of tables

soil exploration

TABLE G8-3B

FIELD MEASUREMENTS MADE ON DECEMBER 7, 1982
DURING ERT'S TEST AT ST. LOUIS PARK STATION
NO.1 (REPRODUCED FROM SEC 1982)

Sample Location[1]	Time	Temperature °C	pH	S. Conductance umhos/cm	Dissolved Oxygen, mg/l	Iron mg/l	Turbidity NTU	Chlorine mg/l
3B-3	9:12	9.8	6.6	600	1.4	1.0	-	0
4D[3]	9:45	-	-	-	0.4	-	-	-
4D	9:51	-	-	-	0.4	-	-	-
4D	10:00	-	-	-	0.4	-	-	-
4B[3]	10:03	-	-	-	0.2	-	-	-
4B	10:05	-	-	-	0.2	-	-	-
4B	10:09	-	-	-	0.2	-	-	-
4B	10:11	-	-	-	-	-	-	0
4B	10:34	-	-	-	0.2	-	-	-
4B	12:50	-	-	-	0.3	-	-	-
4E[3]	10:46	9.8	7.1	605	3.3[4]	0.4	1.0	-
4E	11:00	-	-	-	2.8	-	-	-
4E	11:18	-	-	-	1.8	-	-	-
4E	11:36	-	-	-	1.6	-	-	-
4E	12:03	-	-	-	3.1	-	-	0
4E	12:25	-	-	-	2.65	-	-	-
4E	12:29	-	-	-	2.6	0.3	-	-
4E	13:07	-	-	-	1.8	-	-	-
4C[3]	11:13	(9.5)[5]	-	-	0.3	-	-	-
4C	11:30	(9.5)	-	-	0.2	0.3	-	-

See Footnotes at end of tables

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TALBE G8-3B (continued)

Sample Location[1]	Time	Temperature °C	pH	S. Conductance umhos/cm	Dissolved Oxygen, mg/l	Iron mg/l	Turbidity NTU	Chlorine mg/l
4C[3]	12:38	-	-	-	-	0.3	-	-
4D[3]	11:23	(9.5)	-	-	0.3	-	-	-
4D	12:01	-	-	-	-	-	-	0
4D	12:06	-	-	-	-	-	-	0
4D	12:13	-	-	-	2.8	-	-	0
4D	12:16	-	-	-	-	-	-	0
4D	12:17	-	-	-	-	-	-	0
4D	12:22	-	-	-	-	-	-	0
4D	12:28	-	-	-	-	-	-	0
4D	13:10	-	-	-	1.8	-	-	-
4D	13:20	-	-	-	1.8	-	-	-
2	11:48	(9.5)	-	-	0.1	-	-	-
3B	11:57	-	-	-	-	-	-	0.36
3B	12:08	-	-	-	-	-	-	0.22
3B	12:20	-	-	-	-	-	-	0.20
3B	13:03	-	-	-	-	-	-	0.34
4A[3]	12:41	-	-	-	-	0.3	-	-
3B	13:52	(9.5)	7.2	605	2.4	0.95	-	0.13
1D	13:53	9	7.4	610	-	0.95	-	0
4E[3]	13:57	9.8	7.3	610	3.1	0.3	-	0

See Footnotes at end of tables

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TABLE G8-3B (continued)

Sample[1] Location	Time	Temperature °C	pH	S. Conductance umhos/cm	Dissolved Oxygen, mg/l	Iron mg/l	Turbidity NTU	Chlorine mg/l
4E[3]	15:17	9.5	7.2	610	-	0.25	1.3	0.08
4E	16:13	-	-	-	-	-	-	0.13
2	15:18	9.8	7.2	590	-	1.05	1.2	0
3B	15:23	9.8	7.2	600	-	1.05	1.8	0.70
3B	15:33	-	-	-	-	-	-	0.62
1D	15:55	9.5	7.3	610	-	0.9	1.5	0
4E	16:06	9.8	7.2	605	0.3	0.3	1.5	0.14
4C[3]	16:08	-	-	-	-	-	-	0
3B	16:08	(10)	7.2	595	0.55	1.0	1.7	0.29
4A[3]	16:17	9.8	-	-	1.6	-	-	0
2	17:04	9.5	7.2	600	0.2	1.05	1.4	0
1D	17:10	9.8	7.2	590	-	1.05	1.3	0
4E	18:32	-	-	-	0.3	-	-	-
4E	18:45	-	-	-	0.4	-	-	-
4E	18:47	-	-	-	-	-	-	0.20
4E	18:50	-	-	-	0.4	-	-	-
4E	18:51	-	-	-	-	-	-	0.25
3B	18:36	-	-	-	-	-	-	5.73
3B	18:42	9.8	-	-	1.1	-	-	-
3B	18:50	-	-	-	-	-	-	5.06
3B	19:01	(9.8)	-	-	0.8	-	-	-

See Footnotes at end of tables

TABLE G8-3C

FIELD MEASUREMENTS MADE ON DECEMBER 8, 1982
DURING ERT'S TEST AT ST. LOUIS PARK STATION
NO. 1 (REPRODUCED FROM SEC 1982)

Sample[1] Location	Time	Temperature °C	pH	S. Conductance umhos/cm	Dissolved Oxygen, mg/l	Iron mg/l	Turbidity NTU	Chlorine mg/l
2	9:59	9.7	-	-	-	-	-	-
2	10:48	(9.8)	-	-	0.1	-	-	-
8	9:47	(10)	7.2	540	-	4.4	8.7	-
8	9:58	9.9	7.2	520	-	4.9	4.8	-
8	10:03	9.8	7.3	540	-	4.45	4.1	-
8	10:09	9.7	7.2	510	-	4.35	3.1	-
8	10:16	9.5	7.3	540	-	>5[6]	6.9	-
8	10:21	9.7	7.3	520	-	4.55	3.7	-
8	10:34	(10.5)	7.3	505	-	4.25	2.5	-
4B[3]	10:34	(10)	7.2	580	-	3.05	7.9	-
8	10:41	(10)	7.3	505	-	6.0	4.9	-

See Footnotes at end of tables.

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FOOTNOTES TO TABLES G8-3A,B AND C
(REPRODUCED FROM SEC 1982)

[1]Sample location is identified by the sample number when the tests were run in conjunction with a sample. If tests were not run along with a sampling event, then measurements are identified by location number (see original proposal by ERT, Document No. B690-210A, 11-23-82) and time taken. If only one or two tests were run at a location, then these tests are identified by the exact time that the reading was taken. If more than two tests were run at a location, then the measurements have been identified by the time that these measurements were initiated. See Appendix A, sampling information forms, for the exact times that readings were taken within a set of measurements. Series of tests at one location were grouped together rather than trying to maintain chronological order.

[2]A dash instead of an entry means that that test was not run at that time.

[3]Spigots on the tank of filter beds have been renumbered from the original proposal, so that they are now in reverse order of the original sequence. The spigot closest to the aerator is now 4E, not 4A.

[4]Dissolved oxygen readings for the afternoon of December 7 seemed rather high, but the DO meter appeared to be operating properly. The meter was recalibrated after the high readings began, but only a very slight adjustment was necessary. As a second test of the meters operation, a portion of sample water was treated with sodium sulfite to remove all dissolved oxygen, and this resulted in a DO reading very close to zero (about 0.05 mg/l).

[5]Parentheses denote that the temperature reading was taken from the DO or conductivity meters. While agreement between the temperatures given by these meters and by the thermometer is usually quite good (within 0.3°C), the meter readings are still not considered as accurate.

[6]Insufficient time was available to dilute and retest iron content for this sample.

TABLE G8-4

RETENTION TIMES FOR SIM PAH ANALYSES BY MRC ON SAMPLES COLLECTED DURING ERT'S DECEMBER 6-8, 1982 TEST AT ST. LOUIS PARK STATION NO. 1

Compound	Approximate Retention Times, Minutes
2,3-Dihydroindene	6.9
Indene	7.1
Naphthalene	10.2
2-Methylnaphthalene	12.4
1-Methylnaphthalene	12.7
Biphenyl	13.9
C_2-Naphthalenes	14.9
Acenaphthylene	15.1
Dihydroacenaphthylene	15.6
Fluorene	17.2
Phenanthrene	20.0
Anthracene	20.2
Acridine	20.3
Carbazole	20.8
Fluoranthene	23.6
Pyrene	24.2
Benzo(a)anthracene	27.9
Chrysene	28.1
Benzo(b)fluoranthene	31.0
Benzo(k)fluoranthene	31.1
Benzo(e)pyrene	31.7
Benzo(a)pyrene	31.8
Perylene	32.0
Indeno(1,2,3-cd)pyrene	34.5
Dibenz(a,h)anthracene	34.7
Benzo(g,h,i)perylene	35.0

TABLE G8-5A

RESULTS OF SIM ANALYSES FOR PNAs FOR THE FEBRUARY 1983 CW #15 TREATMENT SYSTEM STUDY

Date February 16, 1983 ERT Task 210

Feature Identification (Q Mass)	Feature Number	Feature L O D[a]	Sample Identification: 1D-20-P RTCC-236	1D-21-P RTCC-246	2-20-P RTCC-244	2-20-P Duplicate RTCC-249	3B-20-P RTCC-241	E4A-20-P RTCC-247
			Concentration (ng/L)					
Indene (116)	64	3	41	53	58	39	48	24
2,3-Dihydroindene (118)	65	5	660	890	970	700	1.1×10^3	680
Naphthalene (128)	1	2	18	31	29	22	26	20
2-Methylnaphthalene (141)	2	4	5 8	6 9	12	5 3	6 6	5 0
1-Methylnaphthalene (141)	3	4	90	110	160	67	140	100
Biphenyl (154)	4	3	180	200	330	170	260	220
C_2-naphthalene (141) - Total	5-11	4	420	440	610	380	570	340
Acenaphthylene (152)	12	11	400	520	620	390	390	190
Dihydroacenaphthylene (154)	13	0 5	$1 0 \times 10^3$	700	$1 0 \times 10^3$	660	850	630
Fluorene (166)	15	3	490	660	700	560	720	540
Phenanthrene (178)	20	3	360	650	880	620	760	760
Anthracene (178)	22	3	180	260	270	260	150	44

Feature Identification (Q Mass)	Feature Number	Feature L O D[a]	Sample Identification: 1D-20-P RTCC-236	1D-21-P RTCC-246	2-20-P RTCC-244	2-20-P Duplicate RTCC-249	3B-20-P RTCC-241	E4A-20-P RTCC-247
			Concentration (ng/L)					
Fluoranthene (202)	31	3	320	270	550	430	450	390
Pyrene (202)	32	9	220	190	360	330	210	190
Benzo(a)anthracene (228)	33	1	31	27	37	42	ND[b]	14
Chrysene (228)	34	8	12	17	34	35	ND	20
Benzo(b)fluoranthene (252)	36	24	ND	ND	ND	ND	ND	ND
Benzo(k)fluoranthene (252)	37	24	ND	ND	ND	ND	ND	ND
Benzo(e)pyrene (as 39) (252)	38	13	ND	ND	ND	ND	ND	ND
Benzo(a)pyrene (252)	39	13	ND	ND	ND	ND	ND	ND
Perylene (as 39) (252)	40	13	ND	ND	ND	ND	ND	ND
Indeno(1,2,3,cd)pyrene (276)	45	23	ND	ND	ND	ND	ND	ND
Dibenz(a,h)anthracene (278)	66	19	ND	ND	ND	ND	ND	ND
Benzo(g,h,i)perylene (276)	46	14	ND	ND	ND	ND	ND	ND
Acridine (178)	67	29	16	6 1	19	18	21	ND

Feature Identification (Q Mass)	Feature Number	Feature L O D[a]	Sample Identification: 1D-20-P RTCC-236	1D-21-P RTCC-246	2-20-P RTCC-244	2-20-P Duplicate RTCC-249	3B-20-P RTCC-241	E4A-20-P RTCC-247
			Concentration (ng/L)					
Carbazole (166)	68	19	12	8 7	25	16	11	16
Anthracene-d_{10} (IS) (188)	21							
Surrogate Spiking Compound		Amount added (ng/L)	Recovery (%)					
Naphthalene-d_8 (136)	63	100	54	65	79	52	80	48
Chrysene-d_{12} (240)	35	100	64	71	88	98	89	75

[a] L O D = limit of detection.

[b] ND = none detected with a detection limit given by the L O D value (in ng/L) for each compound

TABLE G8-5B

RESULTS OF SIM ANALYSES FOR PNAs FOR THE FEBRUARY 1983 CW #15 TREATMENT SYSTEM STUDY

Date February 16, 1983 KRT Task 210

Feature Identification (Q Mass)	Feature Number	Feature L.O.D.[a]	Sample Identification: E11-20-P RTCC-243	E11-20-P Duplicate RTCC-248	W-12-20-P RTCC-239			
			Concentration (ng/L)					
Indane (116)	64	3	43	34	45			
2,3-Dihydroindene (118)	65	5	800	940	980			
Naphthalene (128)	1	2	28	27	24			
2-Methylnaphthalene (141)	2	4	7 6	7 2	5 9			
1-Methylnaphthalene (141)	3	4	150	130	98			
Biphenyl (154)	4	3	280	250	230			
C_2-naphthalene (141) - Total	5-11	4	490	380	440			
Acenaphthylene (152)	12	11	360	200	410			
Dihydroacenaphthylene (154)	13	0 5	980	710	660			
Fluorene (166)	15	3	780	720	630			
Phenanthrene (178)	20	3	790	670	670			
Anthracene (178)	22	3	68	65	130			

Feature Identification (Q Mass)	Feature Number	Feature L.O.D.[a]	Sample Identification: E11-20-P RTCC-243	E11-20-P Duplicate RTCC-248	W-12-20-P RTCC-239			
			Concentration (ng/L)					
Fluoranthene (202)	31	3	390	450	350			
Pyrene (202)	32	9	230	270	220			
Benzo(a)anthracene (228)	33	1	<55	ND[b]	17			
Chrysene (228)	34	8	<55	ND	16			
Benzo(b)fluoranthene (252)	36	24	ND	ND	ND			
Benzo(k)fluoranthene (252)	37	24	ND	ND	ND			
Benzo(e)pyrene (as 39) (252)	38	13	ND	ND	ND			
Benzo(a)pyrene (252)	39	13	ND	ND	ND			
Perylene (as 39) (252)	40	13	ND	ND	ND			
Indeno(1,2,3,cd)pyrene (276)	45	23	ND	ND	ND			
Dibenz(a,h)anthracene (278)	66	19	ND	ND	ND			
Benzo(g,h,i)perylene (276)	46	14	ND	ND	ND			
Acridine (178)	67	29	ND	ND	ND			

Feature Identification (Q Mass)	Feature Number	Feature L.O.D.[a]	Sample Identification: E11-20-P RTCC-243	E11-20-P Duplicate RTCC-248	W-12-20-P RTCC-239			
			Concentration (ng/L)					
Carbazole (166)	68	19	7 9	16	11			
Anthracene-d_{10} (IS) (188)	21							
Surrogate Spiking Compound		Amount added (ng/L)	Recovery (%)					
Naphthalene-d_8 (136)	63	100[c]	47	54	53			
Chrysene-d_{12} (240)	35	100[c]	42	82	44			

[a] L.O.D. = limit of detection.

[b] ND = none detected with a detection limit given by the L.O.D. value (in ng/L) for each compound

[c] 200 ng/L added to W-12-20-P (RTCC-239)

TABLE G8-5C

RESULTS OF SIM ANALYSES FOR PNAs FOR THE FEBRUARY 1983 CW #15 TREATMENT SYSTEM STUDY

Date February 16, 1983 ERT Task 210

Feature Identification (Q Mass)	Feature Number	Feature L O D[a]	Sample Identification: E4C-20-P RTCC-245	8-02-P RTCC-2401	8-21-P RTCC-242	Field Blank RTCC-238	Method Blank RTCC-237	Method Blank RTCC-250
			Concentration (ng/L)					
Indene (116)	64	3	53	2 2	41	1 5	ND[b]	ND
2,3-Dihydroindene (118)	65	5	920	96	690	ND	ND	ND
Naphthalene (128)	1	2	25	18	37	64	8 9	15
2-Methylnaphthalene (141)	2	4	4 5	1.1	3 8	23	1 9	2 1
1-Methylnaphthalene (141)	3	4	92	13	75	15	1 6	ND
Biphenyl (154) -	4	3	260	33	200	7 3	3 9	2 5
C_2-naphthalene (141) - Total	5-11	4	470	96	420	52	ND	ND
Acenaphthylene (152)	12	11	520	52	360	ND	ND	ND
Dihydroacenaphthylene (154)	13	0 5	920	100	600	ND	ND	ND
Fluorene (166)	15	3	700	91	490	ND	9 3	12
Phenanthrene (178)	20	3	660	150	440	ND	27	24
Anthracene (178)	22	3	160	88	130	ND	1 5	ND

Feature Identification (Q Mass)	Feature Number	Feature L O D[a]	Sample Identification: E4C-20-P RTCC-245	8-02-P RTCC-2401	8-21-P RTCC-242	Field Blank RTCC-238	Method Blank RTCC-237	Method Blank RTCC-250
			Concentration (ng/L)					
Fluoranthene (202)	31	3	340	54	290	ND	1 5	ND
Pyrene (202)	32	9	180	36	180	ND	0.88	ND
Benzo(a)anthracene (228)	33	1	16	ND	11	ND	ND	ND
Chrysene (228)	34	8	15	ND	10	ND	ND	ND
Benzo(b)fluoranthene (252)	36	24	ND	ND	ND	ND	ND	ND
Benzo(k)fluoranthene (252)	37	24	ND	ND	ND	ND	ND	ND
Benzo(e)pyrene (as 39) (252)	38	13	ND	ND	ND	ND	ND	ND
Benzo(a)pyrene (252)	39	13	ND	ND	ND	ND	ND	ND
Perylene (as 39) (252)	40	13	ND	ND	ND	ND	ND	ND
Indeno(1,2,3,cd)pyrene (276)	45	23	ND	ND	ND	ND	ND	ND
Dibenz(a,h)anthracene (278)	66	19	ND	ND	ND	ND	ND	ND
Benzo(g,h,i)perylene (276)	46	14	ND	ND	ND	ND	ND	ND
Acridine (178)	67	29	8 6	ND	5 7	ND	ND	ND

Feature Identification (Q Mass)	Feature Number	Feature L O D[a]	Sample Identification: E4C-20-P RTCC-245	8-02-P RTCC-2401	8-21-P RTCC-242	Field Blank RTCC-238	Method Blank RTCC-237	Method Blank RTCC-250
			Concentration (ng/L)					
Carbazole (166)	68	19	0 97	ND	ND	ND	ND	ND
Anthracene-d_{10} (IS) (188)	21							
Surrogate Spiking Compound		Amount added (ng/L)	Recovery (%)					
Naphthalene-d_8 (136)	63	100[c]	75	69	86	72	68	41
Chrysene-d_{12} (240)	35	100[c]	72	78	86	57	73	103

[a] L.O.D = limit of detection

[b] ND = none detected with a detection limit given by the L O D value (in ng/L) for each compound

[c] 200 ng/L added to Field Blank (RTCC-238)

TABLE G8-6A

RESULTS OF SIM ANALYSES FOR PNAs FOR SAND SAMPLES FROM THE FEBRUARY 1983 CW #15 TREATMENT SYSTEM STUDY

Date February 23, 1983 ERT Task 210

Feature Identification (Q Mass)	Feature Number	Feature L O D[a]	Sample Identification: E7A-21	E7E-21	Reagent Blank			
			ng/g	ng/g	ng/mL			
Indene (116)	64	0 2, 8	ND[b]	0 60	9 1			
2,3-Dihydroindene (118)	65	0 2, 12	ND	5 5	ND			
Naphthalene (128)	1	0 1, 5	0 24	53	27			
2-Methylnaphthalene (141)	2	0 1, 7	13	4 7	ND			
1-Methylnaphthalene (141)	3	0 1, 7	ND	3 3	ND			
Biphenyl (154)	4	0 1, 6	0 24	5 1	30			
C_2-naphthalene (141) - Total	5-11	0.1, 7	0.27	16	ND			
Acenaphthylene (152)	12	0 1, 6	0 093	6 7	ND			
Dihydroacenaphthylene (154)	13	0 1, 7	0 23	3 3	ND			
Fluorene (166)	15	0 1, 6	0 67	4 0	ND			
Phenanthrene (178)	20	0 3, 16	3 5	5 7	ND			
Anthracene (178)	22	0 2, 12	3 8	2 4	ND			

Feature Identification (Q Mass)	Feature Number	Feature L O D[a]	Sample Identification: E7A-21	E7E-21	Reagent Blank			
			ng/g	ng/g	ng/mL			
Fluoranthene (202)	31	0 1, 6	3 4	4 4	4 6			
Pyrene (202)	32	0 1, 6	3 3	3 0	5 1			
Benzo(a)anthracene (228)	33	0 8, 40	3 2	3 6	ND			
Chrysene (228)	34	0 7 40	3 2	4 8	ND			
Benzo(b)fluoranthene (252)	36	0 6, 30	1 0	13	22			
Benzo(k)fluoranthene (252)	37							
Benzo(e)pyrene (as 39) (252)	38	0 4, 20	0 33	2 9	ND			
Benzo(a)pyrene (252)	39	0 4, 20	0 21	2 5	ND			
Perylene (as 39) (252)	40	0.4, 20	ND	0 69	ND			
Indeno(1,2,3,cd)pyrene (276)	45	0 8, 40	ND	4 0	ND			
Dibenz(a,h)anthracene (278)	66	0 6, 30	ND	ND	ND			
Benzo(g,h,i)perylene (276)	46	0 6, 30	ND	3 7	ND			
Acridine (178)	67	0 7, 40	ND	ND	ND			

Feature Identification (Q Mass)	Feature Number	Feature L O D[a]	Sample Identification: E7A-21	E7E-21	Reagent Blank			
			ng/g	ng/g	ng/mL			
Carbazole (166)	68	0 8, 40	ND	ND	ND			
Anthracene-d_{10} (IS) (188)	21							
Surrogate Spiking Compound		Amount added (ng/g)	Recovery (%)					
Naphthalene-d_8 (136)	63	4	32	10	63			
Chrysene-d_{12} (240)	35	4	76	63	110			

[a] L O D = limit of detection in ng/g for sand extraction and ng/mL for reagent blank

[b] ND = none detected with a detection limit given by the L O D value for each compound

TABLE G8-6B

RESULTS OF SIM ANALYSES FOR PNAs FOR SAND SAMPLES FROM THE FEBRUARY 1983 CW #15 TREATMENT SYSTEM STUDY

Date February 23, 1983 ERT Task 210

Feature Identification (Q Mass)	Feature Number	Feature L O D[a]	Sample Identification: E7A-21 Duplicate	E7E-21 Duplicate	E7A-20	E7E-20	E7A-22	E7L-22
			Concentration (ng/g)					
Indene (116)	64	0 2	ND[b]	0 18	ND	ND	ND	0 20
2,3-Dihydroindene (118)	65	0 2	ND	5 5	ND	0 87	0 31	2 9
Naphthalene (128)	1	0 1	0 43	43	0 88	1 7	12	21
2-Methylnaphthalene (141)	2	0 1	2 0	3 1	3 7	4 5	5 7	9 8
1-Methylnaphthalene (141)	3	0 1	ND	2 3	0 30	ND	2 6	5 7
Biphenyl (154)	4	0.1	0 30	6 1	0 32	0 58	3 4	4 8
C_2-naphthalene (141) - Total	5-11	0.1	0.26	13	0.95	0.57	22	29
Acenaphthylene (152)	12	0 1	0 073	6 0	0 11	0 20	0 36	2 4
Dihydroacenaphthylene (154)	13	0 1	0 24	4 2	0 27	0 13	0 36	1 9
Fluorene (166)	15	0 1	0 57	5 9	0 60	0 21	1 0	2 7
Phenanthrene (178)	20	0 3	3 7	5 7	1 2	1 1	5 1	6 1
Anthracene (178)	22	0 2	3 1	5 0	0 48	0 12	0 83	1 6

Feature Identification (Q Mass)	Feature Number	Feature L O D[a]	Sample Identification: E7A-21 Duplicate	E7E-21 Duplicate	E7A-20	E7E-20	E7A-22	E7L-22
			Concentration (ng/g)					
Fluoranthene (202)	31	0 1	5 8	6 7	1 8	0 47	3 7	2 3
Pyrene (202)	32	0 1	4 8	5 4	1 4	0 48	3 4	1 5
Benzo(a)anthracene (228)	33	0 8	3 8	3 2	2 1	0 46	2 1	0 74
Chrysene (228)	34	0 7	3 6	4 0	2 0	0 61	2 2	0 94
Benzo(b)fluoranthene (252)	36	0 6	2 4	0 98	ND	0 40	0 31	0 20
Benzo(k)fluoranthene (252)	37				ND			
Benzo(e)pyrene (as 39) (252)	38	0 4	0 22	0 21	ND	ND	ND	ND
Benzo(a)pyrene (252)	39	0 4	0 43	ND	ND	ND	ND	ND
Perylene (as 39) (252)	40	0 4	ND	ND	ND	ND	ND	ND
Indeno(1,2,3,cd)pyrene (276)	45	0 8	ND	ND	ND	ND	ND	ND
Dibenz(a,h)anthracene (278)	66	0 6	ND	ND	ND	ND	ND	ND
Benzo(g,h,i)perylene (276)	46	0 6	ND	ND	ND	ND	ND	ND
Acridine (178)	67	0 7	ND	ND	ND	ND	ND	0 38

Feature Identification (Q Mass)	Feature Number	Feature L.O D[a]	Sample Identification: E7A-21 Duplicate	E7E-21 Duplicate	E7A-20	E7E-20	E7A-20	E7E-20
			Concentration (ng/g)					
Carbazole (166)	68	0 7	ND	0 37	ND	ND	1 8	1 3
Anthracene-d_{10} (IS) (188)	21							
Surrogate Spiking Compound		Amount added (ng/g)	Recovery (%)					
Naphthalene-d_8 (136)	63	4	53	13	73	57	110	94
Chrysene-d_{12} (240)	35	4	89	78	100	100	91	62

[a] L O D = limit of detection in ng/g

[b] ND = none detected with a detection limit given by the L O D value (in ng/g) for each compound

TABLE G8-7A

INORGANIC ANALYSES FOR THE FEBRUARY 1983 TEST
AT ST. LOUIS PARK STATION NO. 1

Feature Identification	Feature Analytical Method	Feature L.O.D.[a]	Sample Identification					
			1D-20-0	1D-21-0	2-20-0	2-20-0 Duplicate	3B-20-0	E4A-20-0
			Concentration (mg/L)					
Non purgeable TOC	EPA-415.1	0.5	2.1	1.9	2.0	2.9	1.9	2.2
Fe	EPA-200.7	0.025	NA[b]	0.65	0.68	0.65	0.73	0.046
Mn	EPA-200.7	0.003	NA	0.10	0.10	0.10	0.10	0.087
Alkalinity ($CaCO_3$)	EPA-403	20	NA	NA	NA	NA	NA	NA
Hardness (mg eq $CaCO_3$/L)	EPA-200.7	1	NA	310	314	313	313	309
Dissolved Fe	EPA-200.7	0.025	NA	0.52	0.58	0.59	0.23	0.03

[a]L.O.D. = limit of detection in mg/L.

[b]NA = not analyzed.

TABLE G8-7B

INORGANIC ANALYSES FOR THE FEBRUARY 1983 TEST
AT ST. LOUIS PARK STATION NO. 1

Feature Identification	Feature Analytical Method	Feature L.O.D.[a]	Sample Identification					
			E11-20-0	E11-20-0 Duplicate	W-12-20-0	1D-21-I		
			Concentration (mg/L)					
Non purgeable TOC	EPA-415.1	0.5	1.9	1.8	2.0	NA[c]		
Fe	EPA-200.7	0.025	0.078	0.083	0.12	0.69		
Mn	EPA-200.7	0.003	0.087	0.089	0.087	0.11		
Alkalinity ($CaCO_3$)	EPA-403	20	NA	NA	NA	314		
Hardness (mg eq $CaCO_3$/L)	EPA-200.7	1	312	314	309	312		
Cl^-	EPA-200.7	0.025	NA	NA	NA	10.8		
$SO_4^=$	EPA-200.7	0.025	NA	NA	NA	19.5		
Ca^{+2}	EPA-200.7	0.025	NA	NA	NA	80.9		
Mg^{+2}	EPA-200.7	0.025	NA	NA	NA	26.6		
Na^+	EPA-200.7	0.025	NA	NA	NA	25.4		
K^+	EPA-200.7	0.025	NA	NA	NA	5.6		
TSS	EPA-209D	5	NA	NA	NA	ND[b]		

TABLE G8-7B (continued)

Feature Identification	Feature Analytical Method	Feature L.O.D.[a]	Sample Identification					
			E11-20-0	E11-20-0 Duplicate	W-12-20-0	1D-21-I		
			Concentration (mg/L)					
TDS	EPA-209C	4	NA	NA	NA	367		
Dissolved Fe	EPA-200.7	0.025	0.037	0.042	0.021	NA		

[a]L.O.D. = limit of detection in mg/L.

[b]ND = none detected with a detection limit given by the L.O.D. value for each feature.

[c]NA = not analyzed.

TABLE G8-7C

INORGANIC ANALYSES FOR THE FEBRUARY 1983 TEST
AT ST. LOUIS PARK STATION NO. 1

Feature Identification	Feature Analytical Method	Feature L.O.D.[a]	Sample Identification					
			E4C-20-0	8-20-0	8-21-0	Field Blank		
			Concentration (mg/L)					
Non purgeable TOC	EPA-415.1	0.5	1.8	3.2	2.5	ND[b]		
Fe	EPA-200.7	0.025	0.50	38.8	85.9	0.017		
Mn	EPA-200.7	0.003	0.085	0.66	0.20	0.007		
Alkalinity ($CaCO_3$)	EPA-403	20	NA[c]	NA	NA	NA		
Hardness (mg eq $CaCO_3$/L)	EPA-200.7	1	309	285	308	ND		
Dissolved Fe	EPA-200.7	0.025	0.18	2.03	0.467			

[a] L.O.D. = limit of detection in mg/L.

[b] ND = none detected with a detection limit given by the L.O.D. value for each feature.

[c] NA = not analyzed.

TABLE G8-8

RESULTS OF FIELD MEASUREMENTS MADE ON FEBRUARY 2, 1983 DURING ERT'S TEST AT ST. LOUIS PARK STATION NO. 1 (Reproduced from SEC. 1983)*

First Grab Sample, 3 Hour Composite: 7:42 AM - 8:21 AM

Sample Identification	Temperature °C	pH	S. Conductance umhos/cm	Iron Content, mg/L	Dissolved Oxygen, mg/L	Turbidity, NTU	Chlorine, mg/L
2	10.3	6.96	550	1.0	1.3	0.18	ND[1]
3B	10.3	7.02	560	0.7	1.3	0.55	0.64
E11	10.6	7.08	595	0.4	4.0	0.24	0.34
E4A	10.6	7.12	600	0.3	3.9	0.21	1.27
W12	10.3	7.24	600	0.3	4.05	0.26	1.38
1D	11[2]	7.29	600	0.9	8[2]	0.8	ND

Second Grab Sample, 3 Hour Composite: 8:38 AM - 9:05 AM

Sample Identification	Temperature °C	pH	S. Conductance umhos/cm	Iron Content, mg/L	Dissolved Oxygen, mg/L	Turbidity, NTU	Chlorine, mg/L
2	10.3	7.30	600	0.90	1.3	0.16	ND
3B	10.3	7.24	600	0.95	1.9	0.60	1.48
E11	10.5	7.24	600	0.30	1.4	0.24	1.26
E4A	10.5	7.24	600	0.30	1.2	0.31	1.27
W12	10.5	7.26	600	0.35	1.0	0.22	1.29
1D	10.3	7.36	590	0.80	2.2	1.3	ND

*See end of table for footnotes.

TABLE G8-8 (continued)

Third Grab Sample, 3 Hour Composite:[3] 9:42 AM - 9:55 AM

Sample Identification	Temperature °C	pH	S. Conductance umhos/cm	Iron Content, mg/L	Dissolved Oxygen, mg/L	Turbidity, NTU	Chlorine, mg/L
2	10.3	7.02	595	0.95	0.3	0.35	ND
3B	10.3	7.07	600	0.80	0.4	0.62	1.50
E11	10.3	7.04	600	0.4	0.5	0.38	1.25
E4A	10.3	7.03	600	0.35	0.5	0.24	1.24
W12	10.5	7.08	600	0.35	0.5	0.27	1.26
1D	10.4	7.20	600	0.80	0.9	2.0	ND

Fourth Grab Sample, 3 Hour Composite: 10:31 AM - 10:58 AM

Sample Identification	Temperature °C	pH	S. Conductance umhos/cm	Iron Content, mg/L	Dissolved Oxygen, mg/L	Turbidity, NTU	Chlorine, mg/L
2	10.3	7.16	590	0.85	0.3	0.40	ND
3B	10.3	7.09	600	0.80	0.4	0.95	0.70
E11	10.5	7.11	600	0.35	0.4	0.37	1.37
E4A	10.5	7.11	600	0.35	0.4	0.32	1.30
W12	10.5	7.19	600	0.35	0.5	0.49	1.28
1D	10.4	7.13	600	0.85	0.8	0.33	ND

Sample Identification	Temperature °C	pH	S. Conductance umhos/cm	Iron Content, mg/L	Dissolved Oxygen, mg/L	Turbidity, NTU	Chlorine, mg/L
2 @ 10:50 AM	10.3	-	-	-	0.2	-	-
3B @ 10:50 AM	-	-	-	-	-	-	1.40
3B @ 10:53 AM	-	-	-	-	-	-	1.20
2 @ 10:55 AM	10.3	-	-	-	0.2	-	-

*See end of table for footnotes.

Laboratory No. 2A-0256

twin city testing and engineering laboratory, inc.

TABLE G8-8 (continued)

After Back-Flushing[4]:

Sample Identification	Temperature °C	pH	S. Conductance umhos/cm	Iron Content, mg/L	Dissolved Oxygen, mg/L	Turbidity, NTU	Chlorine, mg/L
8-20/21 @12:49 PM	10.8	6.95	540	24	0.6	34	ND
E4C @12:53 PM	10.7	7.12	550	0.4	1.5	0.44	ND

1 - ND = not detected.

2 - Measurements taken one hour after sample collection.

3 - Membrane for D.O. meter replaced. D.O. meter and pH meter re-calibrated before these measurements.

4 - D.O. meter re-calibrated before these measurements.

TABLE G8-9A

RESULTS OF SIM ANALYSES FOR PNAs FOR CITY WELL #15 TREATMENT SYSTEM

November 1, 1982 ERT Task. 210

Feature Identification	Feature Number	Feature L O D [a]	Feature RT (min)	Feature Mass	Sample Identification: Method Blank RTCC-105	Method Blank RTCC-109	Glass Blank RTCC-102
					Concentration[c] (ng/L)		
Naphthalene	1	1 3	11 42	128	21	27	26
Methyl naphthalene (M1)	2	2 1	13 60	141	6 9	7 4	7 1
" " (M2)	3	2 1	13 90	"	3 8	3 7	3 8
Biphenyl	4	6 1	15 13	152	4 0	5 3	5 9
Me_2-naphthalene (M1)	5			141			
" (M2)	6	3 4	15 43	"	4 7	5 2	4 0
" (M3)	7	3 4	15 82	"	2.9	ND[b]	8 4
" (M4)	8	3 4	16 17	"	6 2	6 2	6 2
" (M5)	9	3 4	16 43	"	5 0	4 9	3 0
" (M6)	10	3 4	16 93	"	ND	ND	ND
" (M7)	11	3 4		"	ND	ND	ND
Acenaphthylene	12	1 1	16 32	152	ND	ND	0 74

Feature Identification	Feature Number	Feature L O D [a]	Feature RT (min)	Feature Mass	Sample Identification: Method Blank RTCC-105	Method Blank RTCC-109	Glass Blank RTCC-102
					Concentration[c] (ng/L)		
Acenaphthene	13	4 7	16 90	152	3 6	3 7	4 1
Dibenzofuran	14	1.4	17 42	168	5 6	5.4	6 8
Fluorene	15	2 2	18 48	166	3 2	2 9	3 7
Me-acenaphthene (M1)	16	2 7	18.78	168	ND	ND	ND
" (M2)	17	2 7	18 88	"	ND	ND	ND
Me-dibenzofuran (M1)	18	2 2	19 07	182	1 2	1 3	1 2
" (M2)	19	2 2	19 27	"	1 4	1 1	1 4
Phenanthrene	20	1 7	21 35	178	17 3	15 4	21 2
Anthracene	22	1 7	21 48	"	ND	ND	ND
Me-phenanthrene (M1)	23	2 6	22 90	192	0 70	0 37	0 76
" (M2)	24	2 6	22 98	"	ND	ND	ND
" (M3)	25	2 6	23 23	"	0 62	ND	0 51
" (M4)	26	2 6	23 30	"	ND	ND	ND

Feature Identification	Feature Number	Feature L O D [a]	Feature RT (min)	Feature Mass	Sample Identification: Method Blank RTCC-105	Method Blank RTCC-109	Glass Blank RTCC-102
					Concentration[c] (ng/L)		
Me-phenanthrene (M5)	27	2 6	23 30	192	ND	ND	ND
Phenyl naphthalene	28	2 5	23 90	204	0 98	0 80	1 3
MW = 188	29		23 18	188	ND	ND	ND
Fluoranthene	31	2 0	25 02	202	4 1	3 4	5 4
Pyrene	32	2 0	25.65	"	2 8	2 6	3 9
Benzo(a)anthracene	33	5 3	29 38	228	ND	ND	ND
Chrysene	34	5 3	29 52	"	ND	ND	2 2
MW = 252 (M1)	36	6 8	32 50	252	ND	ND	ND
" (M2)	37	6 8	32 80	"	ND	ND	ND
" (M3)	38	6 8	33 20	"	ND	ND	ND
Benzo(a)pyrene	39	6 8	33 30	"	ND	ND	ND
MW = 252 (M4)-perylene	40	6 8	33 60	"	ND	ND	ND
MW = 228 (M1)-Benzo(c)-phenanthrene	41	5 3	28 8	228	ND	ND	ND

Feature Identification	Feature Number	Feature L.O D [a]	Feature RT (min)	Feature Mass	Sample Identification: Method Blank RTCC-105	Method Blank RTCC-109	Glass Blank RTCC-102
					Concentration[c] (ng/L)		
MW = 228 (M2)	42	5 3	29 73	228	ND	ND	ND
MW = 202	43	4 1	25 32	202	ND	ND	ND
MW = 276 (M1)	44	10	35 90	276	ND	ND	ND
Indeno(1,2,3,cd)pyrene	45	10	36 21	"	ND	ND	ND
Benzo(g,h,i)perylene	46	10	36 82	"	ND	ND	ND
MW = 276 (M2)	47	10	37 20	"	ND	ND	ND
Dibenzothiophene	62	1 7	20 97	184	ND	ND	ND
Anthracene-d_{10} (IS)	21	1 7	21 43	188	25	25	25
Surrogate Spiking Compound		Amount added (ng/L)			Recovery (%)		
Naphthalene-d_8	63	100	11 42	136	47	45	60
Chrysene-d_{12}	35	100	29 42	240	89	65	84

[a] L O D = limit of detection in ng/L

[b] ND = none detected with a detection limit given by the L O D value for each feature

[c] Not corrected for surrogate spiking compound recoveries

TABLE G8-9B

RESULTS OF SIM ANALYSES FOR PNAs FOR CITY WELL #15 TREATMENT SYSTEM

November 1, 1982 EBT Task 210

Feature Identification	Feature Number	Feature L O D [a]	Feature RT (min)	Feature Mass	Sample Identification: At Well Head RTCC-108	At Well Head RTCC-110	After Aeration RTCC-111	After Aeration RTCC-114[c]
					Concentration[d] (ng/L)			
Naphthalene	1	1 3	11 42	128	27	29	170	190
Methyl naphthalene (81)	2	2 1	13 60	141	7 7	7 6	9.5	15
" " (82)	3	2 1	13 90	"	41	33	12	13
Biphenyl	4	6 1	15 13	152	230	180	44	39
Me_2-naphthalene (81)	5			141				
" (82)	6	3 4	15 43	"	65	43	9 3	12
" (83)	7	3 4	15 82	"	110	97	16	27
" (84)	8	3 4	16 17	"	130	200	21	21
" (85)	9	3 4	16 43	"	79	68	8 6	13
" (86)	10	3 4	16 93	"	ND[b]	ND	ND	ND
" (87)	11	3 4		"	ND	ND	ND	ND
Acenaphthylene	12	1 1	16 32	152	350	340	43	37

Feature Identification	Feature Number	Feature L O D [a]	Feature RT (min)	Feature Mass	Sample Identification: At Well Head RTCC-108	At Well Head RTCC-110	After Aeration RTCC-111	After Aeration RTCC-114[c]
					Concentration[d] (ng/L)			
Acenaphthene	13	4 7	16 90	152	830	890	130	121
Dibenzofuran	14	1 4	17 42	168	490	520	46	53
Fluorene	15	2 2	18 48	166	740	790	68	67
Me-acenaphthene (81)	16	2 7	18 78	168	110	88	11	10
" (82)	17	2 7	18 88	"	70	69	8 1	8 5
Me-dibenzofuran (81)	18	2 2	19 07	182	70	76	5 4	5 7
" (82)	19	2 2	19 27	"	82	91	4 7	6.1
Phenanthrene	20	1 7	21 35	178	58	45	12	17
Anthracene	22	1 7	21 48	"	60	60	2 5	3 6
Me-phenanthrene (81)	23	2 6	22 90	192	87	73	3.5	5 3
" (82)	24	2 6	22 98	"	ND	ND	ND	ND
" (83)	25	2 6	23 23	"	ND	ND	2 7	4 7
" (84)	26	2 6	23 30	"	ND	ND	ND	ND

Feature Identification	Feature Number	Feature L.O D [a]	Feature RT (min)	Feature Mass	Sample Identification: At Well Head RTCC-108	At Well Head RTCC-110	After Aeration RTCC-111	After Aeration RTCC-114[c]
					Concentration[d] (ng/L)			
Me-phenanthrene (85)	27	2 6	23 30	192	ND	ND	ND	ND
Phenyl naphthalene	28	2 5	23 90	204	24	24	2 1	1 7
MW = 188	29		23 18	188	2 6	3 0	ND	ND
Fluoranthene	31	2 0	25 02	202	250	280	5 3	9 2
Pyrene	32	2 0	25 65	"	210	230	4 6	7 7
Benzo(a)anthracene	33	5 3	29 38	228	6 6	7 1	ND	ND
Chrysene	34	5 3	29 52	"	5 6	6 5	ND	2 9
MW = 252 (81)	36	6 8	32 50	252	ND	ND	ND	ND
" (82)	37	6 8	32 80	"	ND	ND	ND	ND
" (83)	38	6.8	33 20	"	ND	ND	ND	ND
Benzo(a)pyrene	39	6 8	33 30	"	ND	ND	ND	ND
MW = 252 (84)-perylene	40	6 8	33 60	"	ND	ND	ND	ND
MW = 228 (81)-Benzo(c)-phenanthrene	41	5 3	28 8	228	2 2	2 5	ND	ND

Feature Identification	Feature Number	Feature L O D [a]	Feature RT (min)	Feature Mass	Sample Identification: At Well Head RTCC-108	At Well Head RTCC-110	After Aeration RTCC-111	After Aeration RTCC-114[c]
					Concentration[d] (ng/L)			
MW = 228 (82)	42	5 3	29 73	228	ND	ND	ND	ND
MW = 202	43	4 1	25 32	202	11	12	ND	ND
MW = 276 (81)	44	10	35 90	276	ND	ND	ND	ND
Indeno(1,2,3,cd)pyrene	45	10	36 21	"	ND	ND	ND	ND
Benzo(g,h,i)perylene	46	10	36 82	"	ND	ND	ND	ND
MW = 276 (82)	47	10	37 20	"	ND	ND	ND	ND
Dibenzothiophene	62	1.7	20 97	184	68	67	4 3	5 9
Anthracene-d_{10} (IS)	21	1 7	21 43	188	25	5	25	25
Surrogate Spiking Compound		Amount added (ng/L)			Recovery (%)			
Naphthalene-d_8	63	100	11 42	136	37	44	48	52
Chrysene-d_{12}	35	100	29 42	240	59	66	60	72

[a] L O D = limit of detection in ng/L

[b] ND = none detected with a detection limit given by the L O D value for each feature

[c] Extract of a 3-liter water sample

[d] Not corrected for surrogate spiking compound recoveries

TABLE G8-9C

RESULTS OF SIM ANALYSES FOR PNAs FOR CITY WELL #15 TREATMENT SYSTEM

November 1, 1982 EMT Task: 210

Feature Identification	Feature Number	Feature L O D [a]	Feature RT (min)	Feature Mass	Sample Identification: After Chlor RTCC-106	After Chlor RTCC-112	After Filtra RTCC-107	After Filtra. RTCC-113
					Concentration[c] (ng/L)			
Naphthalene	1	1 3	11 42	128	630	480	83	90
Methyl naphthalene (#1)	2	2 1	13 60	141	15	13	7 2	8 3
" " (#2)	3	2 1	13 90	"	39	25	15	13
Biphenyl	4	6.1	15 13	152	200	120	33	25
Me_2-naphthalene (#1)	5			141				
" (#2)	6	3 4	15.43	"	52	34	18	16
" (#3)	7	3 4	15 82	"	83	50	24	24
" (#4)	8	3 4	16 17	"	130	57	29	27
" (#5)	9	3 4	16 43	"	50	29	17	13
" (#6)	10	3 4	16 93	"	ND[b]	ND	4 1	3 9
" (#7)	11	3 4		"	ND	ND	ND	ND
Acenaphthylene	12	1 1	16 32	152	200	120	66	55

Feature Identification	Feature Number	Feature L O D [a]	Feature RT (min)	Feature Mass	Sample Identification: After Chlor RTCC-106	After Chlor RTCC-112	After Filtra. RTCC-107	After Filtra. RTCC-113
					Concentration[c] (ng/L)			
Acenaphthene	13	4.7	16 90	152	500	330	180	160
Dibenzofuran	14	1 4	17 42	168	260	160	19	34
Fluorene	15	2 2	18 48	166	390	230	69	58
Me-acenaphthene (#1)	16	2 7	18 78	168	60	40	14	12
" (#2)	17	2 7	18 88	"	48	30	9 8	8 2
Me-dibenzofuran (#1)	18	2 2	19 07	182	33	21	5 9	4 6
" (#2)	19	2.2	19 27	"	35	22	4.7	3 7
Phenanthrene	20	1 7	21 35	178	22	17	12	9 5
Anthracene	22	1 7	21 48	"	13	8 6	3 0	2 3
Me-phenanthrene (#1)	23	2 6	22 90	192	14	9 4	3 3	3 4
" (#2)	24	2 6	22 98	"	ND	ND	ND	ND
" (#3)	25	2 6	23 23	"	11	7 7	3 1	2 1
" (#4)	26	2 6	23 30	"	ND	ND	ND	ND

Feature Identification	Feature Number	Feature L O D [a]	Feature RT (min)	Feature Mass	Sample Identification: After Chlor RTCC-106	After Chlor RTCC-112	After Filtra RTCC-107	After Filtra RTCC-113
					Concentration[c] (ng/L)			
Me-phenanthrene (#5)	27	2 6	23 30	192	ND	ND	ND	ND
Phenyl naphthalene	28	2 5	23 90	204	2 9	2 0	1 1	1 0
MW = 188	29		23 18	188				
Fluoranthene	31	2 0	25 02	202	16	13	5 9	5 4
Pyrene	32	2 0	25 65	"	11	9 3	4 3	3 9
Benzo(a)anthracene	33	5 3	29 38	228	ND	ND	ND	ND
Chrysene	34	5 3	29 52	"	ND	ND	ND	ND
MW = 252 (#1)	36	6 8	32 50	252	ND	ND	ND	ND
" (#2)	37	6 8	32 80	"	ND	ND	ND	ND
" (#3)	38	6 8	33 20	"	ND	ND	ND	ND
Benzo(a)pyrene	39	6 8	33 30	"	ND	ND	ND	ND
MW = 252 (#4)-perylene	40	6 8	33 60	"	ND	ND	ND	ND
MW = 228 (#1)-Benzo(c)-phenanthrene	41	5 3	28 8	228	ND	ND	ND	ND

Feature Identification	Feature Number	Feature L O D [a]	Feature RT (min)	Feature Mass	Sample Identification: After Chlor RTCC-106	After Chlor RTCC-112	After Filtra RTCC-107	After Filtra RTCC-113
					Concentration[c] (ng/L)			
MW = 228 (#2)	42	5 3	29 73	228	ND	ND	ND	ND
MW = 202	43	4 1	25 32	202	1 0	0 90	ND	ND
MW = 276 (#1)	44	10	35 90	276	ND	ND	ND	ND
Indeno(1,2,3,cd)pyrene	45	10	36 21	"	ND	ND	ND	ND
Benzo(g,h,i)perylene	46	10	36 82	"	ND	ND	ND	ND
MW = 276 (#2)	47	10	37 20	"	ND	ND	ND	ND
Dibenzothiophene	62	1 7	20.97	184	22	16	4 0	3 6
Anthracene-d_{10} (IS)	21	1 7	21 43	188	25	25	25	25
Surrogate Spiking Compound	-	Amount added (ng/L)			Recovery (%)			
Naphthalene-d_8	63	100	11 42	136	61	50	52	55
Chrysene-d_{12}	35	100	29 42	240	38	48	65	50

[a] L O D = limit of detection in ng/L

[b] ND = none detected with a detection limit given by the L O D value for each feature

[c] Not corrected for surrogate spiking compound recoveries

TABLE G8-10

RESULTS OF SIM ANALYSES FOR PNAs FOR CITY WELL #15 TREATMENT SYSTEM

November 1, 1982 ERT Task 210

Feature Identification	Feature Number	Feature L O D [a]	Feature RT (min)	Feature Mass	Sample Identification: Method Blank 105+109	After Filtra. 107+113	After Chlor 106+112	At Well Head 108+110
					Concentration [d] (ng/L)			
Naphthalene	1	0 07	11 42	128	14	37	Sat [c]	10
Methyl naphthalene (M1)	2	0 07	13 60	141	3 7	3 1	8 1	2 4
" " (M2)	3	0 07	13 90	"	2 0	6 7	23	14
Biphenyl	4	0 14	15 13	152	1 4	14	123	79
Me_2-naphthalene (M1)	5			141	ND [b]	ND	ND	ND
" (M2)	6	0.14	15 43	"	0 6	7 4	33	23
" (M3)	7	0 14	15 82	"	0 9	11	49	47
" (M4)	8	0 14	16 17	"	1 3	14	56	61
" (M5)	9	0 14	16 43	"	0 4	6.6	31	33
" (M6)	10	0 14	16 93	"	ND	ND	ND	ND
" (M7)	11	0 14		"	ND	ND	ND	ND
Acenaphthylene	12	0 07	16 32	152	0 09	34	Sat	Sat

Feature Identification	Feature Number	Feature L O D [a]	Feature RT (min)	Feature Mass	Sample Identification: Method Blank 105+109	After Filtra 107+113	After Chlor 106+112	At Well Head 108+110
					Concentration [d] (ng/L)			
Acenaphthene	13	0 14	16 90	152	2 1	107	Sat	Sat
Dibenzofuran	14	0 07	17 42	168	2 4	20	Sat	Sat
Fluorene	15	0 07	18 48	166	1 7	41	Sat	Sat
Me-acenaphthene (M1)	16	0 07	18 78	168	0 13	6 9	36	53
" (M2)	17	0 07	18 88	"	0 14	5 7	27	36
Me-dibenzofuran (M1)	18	0 07	19 07	182	0 30	3.0	20	40
" (M2)	19	0 07	19 27	"	0 60	2 6	20	56
Phenanthrene	20	0 07	21 35	178	9 9	6 6	16	33
Anthracene	22	0 07	21 48	"	0 47	1 6	8 7	39
Me-phenanthrene (M1)	23	0 07	22 90	192	0 54	1 7	8 1	49
" (M2)	24	0 07	22 98	"	0 67	0 26	4 6	24
" (M3)	25	0 07	23 23	"	0 59	1 3	2 6	17
" (M4)	26	0 07	23 30	"	0 37	0 33	ND	ND

Feature Identification	Feature Number	Feature L O D [a]	Feature RT (min)	Feature Mass	Sample Identification: Method Blank 105+109	After Filtra. 107+113	After Chlor 106+112	At Well Head 108+110
					Concentration [d] (ng/L)			
Me-phenanthrene (M5)	27	0 07	23 30	192	ND	ND	ND	ND
Phenyl naphthalene	28	0 07	23 90	204	0 37	0 47	1.6	15
MW = 188	29	0 07	23 18	188	ND	ND	0 20	0 91
Fluoranthene	31	0 07	25 02	202	1 7	3 1	11	Sat
Pyrene	32	0.07	25 65	"	0 46	1 7	7 4	Sat
Benzo(a)anthracene	33	0 07	29 38	228	0.19	0 17	0 20	4 6
Chrysene	34	0 07	29 52	"	0 19	0 17	0 20	3 6
MW = 252 (M1)	36	0 14	32 50	252	ND	ND	0 20	0 27
" (M2)	37	0 14	32 80	"	0 24	ND	ND	ND
" (M3)	38	0 14	33 20	"	ND	ND	ND	ND
Benzo(e)pyrene	39	0 14	33 30	"	ND	ND	ND	ND
MW = 252 (M4)-perylene	40	0 14	33 60	"	ND	ND	ND	ND
MW = 228 (M1)-Benzo(c)-phenanthrene	41	0 14	28.8	228	ND	ND	0 14	1 7

Feature Identification	Feature Number	Feature L O D [a]	Feature RT (min)	Feature Mass	Sample Identification: Method Blank 105+109	After Filtra 107+113	After Chlor 106+112	At Well Head 108+110
					Concentration [d] (ng/L)			
MW = 228 (M2)	42	0 14	29 73	228	ND	ND	0 10	0 39
MW = 202	43	0 07	25 32	202	ND	ND	0 94	8 1
MW = 276 (M1)	44	0 21	35 90	276	ND	ND	ND	ND
Indeno(1,2,3,cd)pyrene	45	0 21	36 21	"	ND	ND	ND	ND
Benzo(g,h,i)perylene	46	0 21	36 82	"	ND	ND	ND	ND
MW = 276 (M2)	47	0 21	37 20	"	ND	ND	ND	ND
Dibenzothiophene	62	0 05	20 97	184	0 57	2 4	16	47
Anthracene-d_{10} (IS)	21	0 50	21 43	188				
Surrogate Spiking Compound		Amount added (ng/L)			Recovery (%)			
Naphthalene-d_8	63	100	11 42	136	43	34	52	26
Chrysene-d_{12}	35	100	29 42	240	83	63	63	71

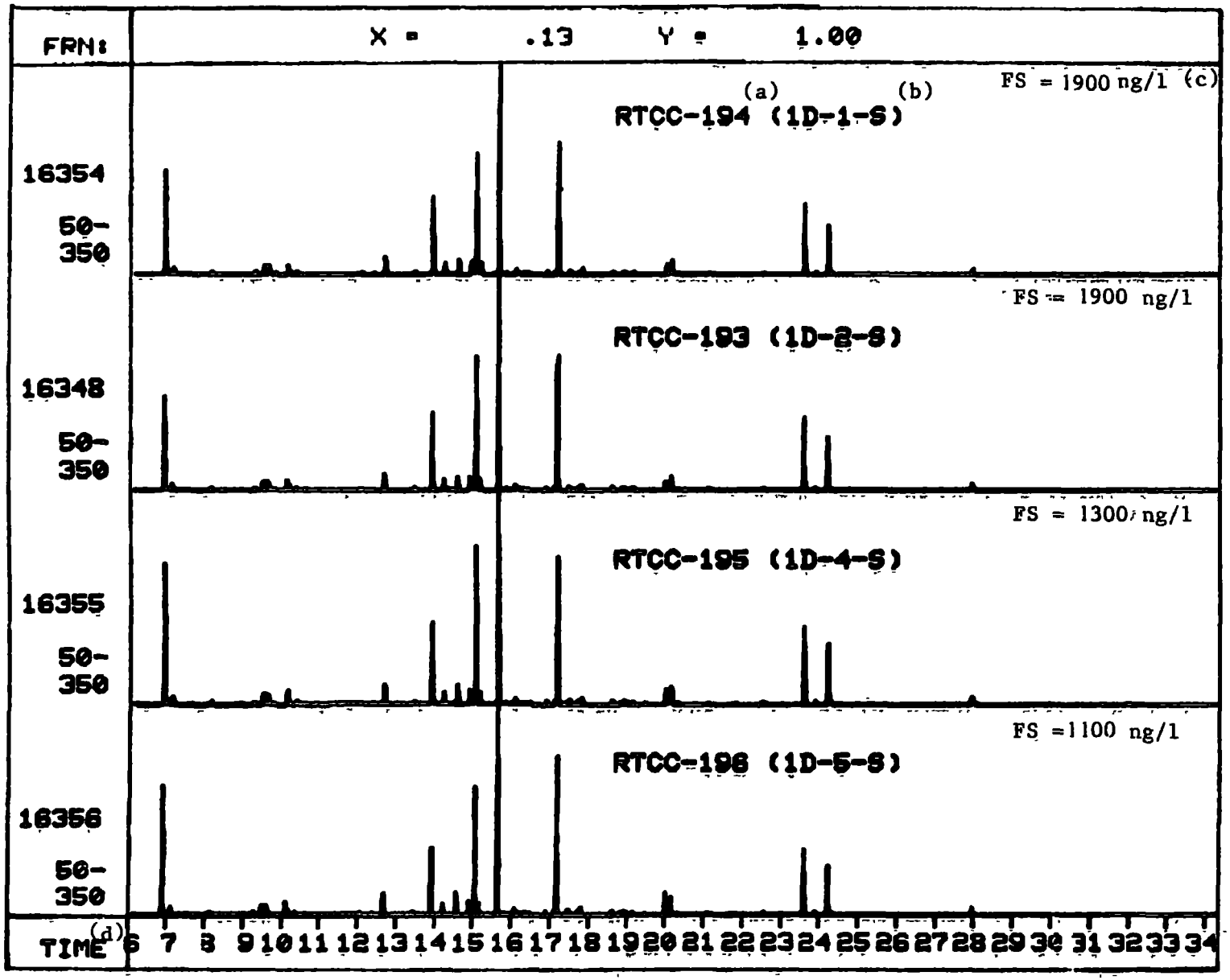
[a] L O D = limit of detection in ng/L

[b] ND = none detected with a detection limit given by the L O D value for each feature

[c] Sat = indicates instrument saturation

[d] Not corrected for surrogate spiking compound recoveries

FIGURE G8-1
PAH SIM CHROMATOGRAMS FOR WATER SAMPLES
COLLECTED DURING ERT'S DECEMBER 6-8, 1982 TEST AT ST. LOUIS PARK STATION NO.1



NOTES:
(a) MRC sample number.
(b) ERT sample number per Table G4-5.
(c) Concentration of full-scale peak in nanograms per liter.
(d) Retention time in minutes.

FIGURE G8-1 (continued)

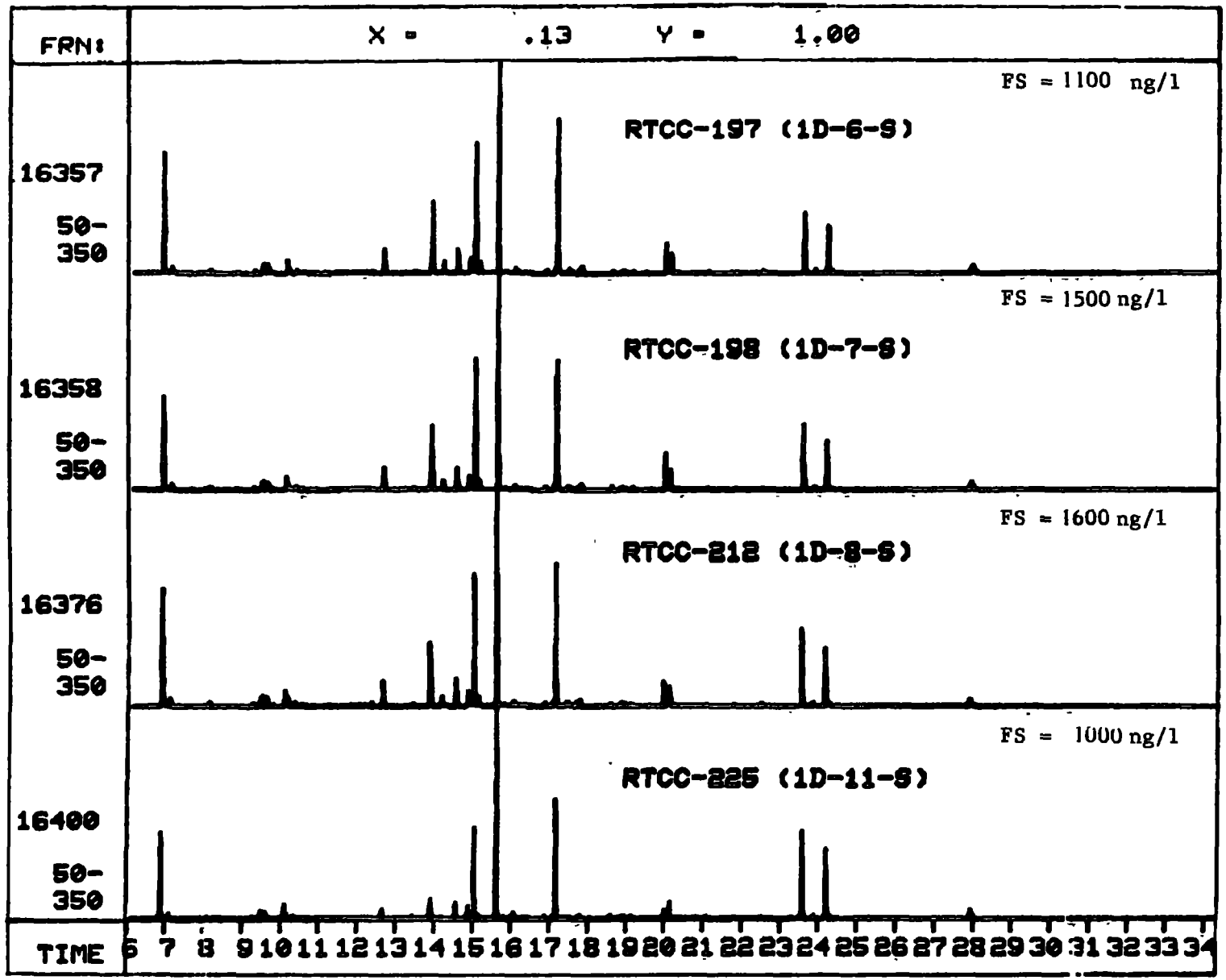


FIGURE G8-1 (continued)

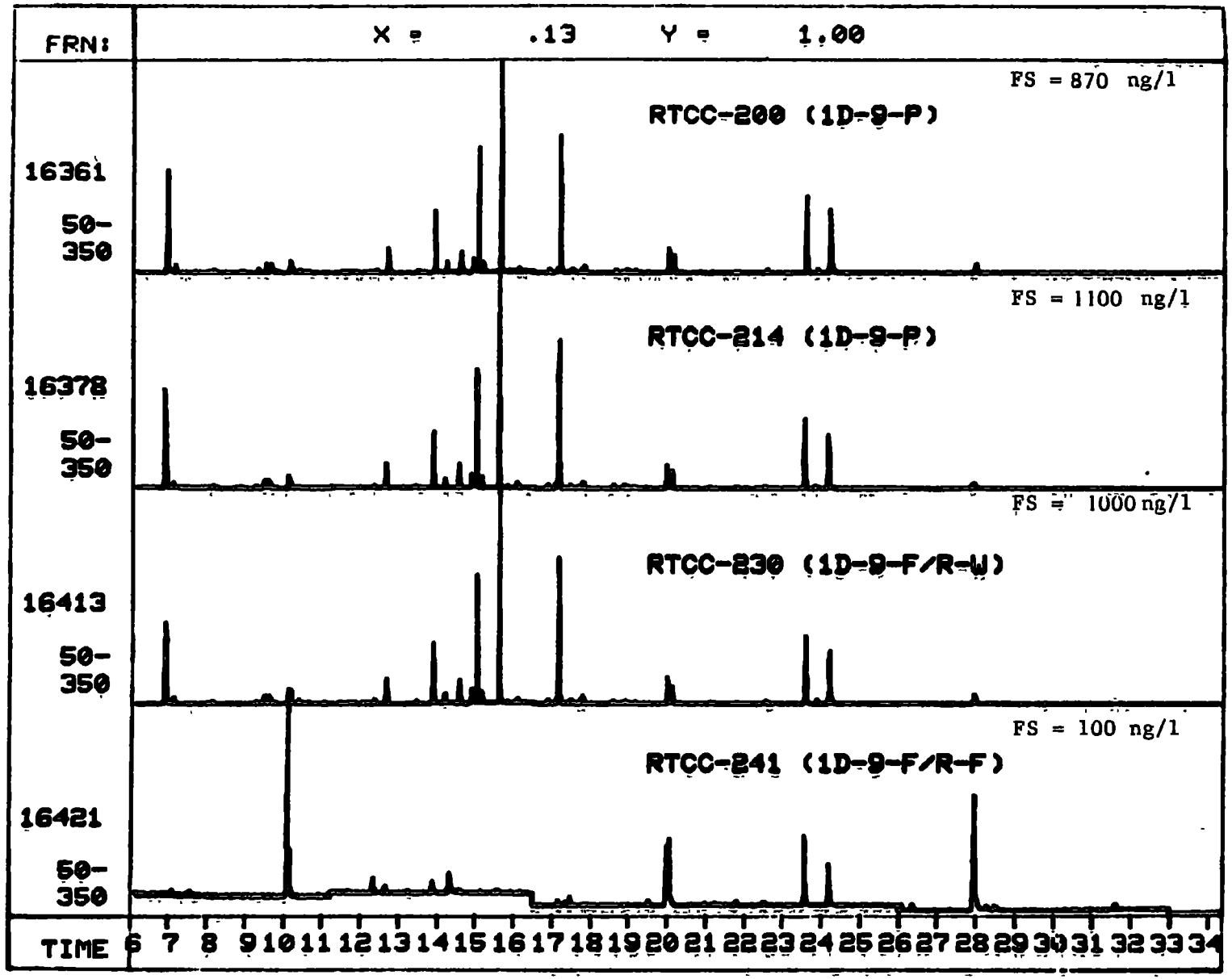


FIGURE G8-1 (continued)

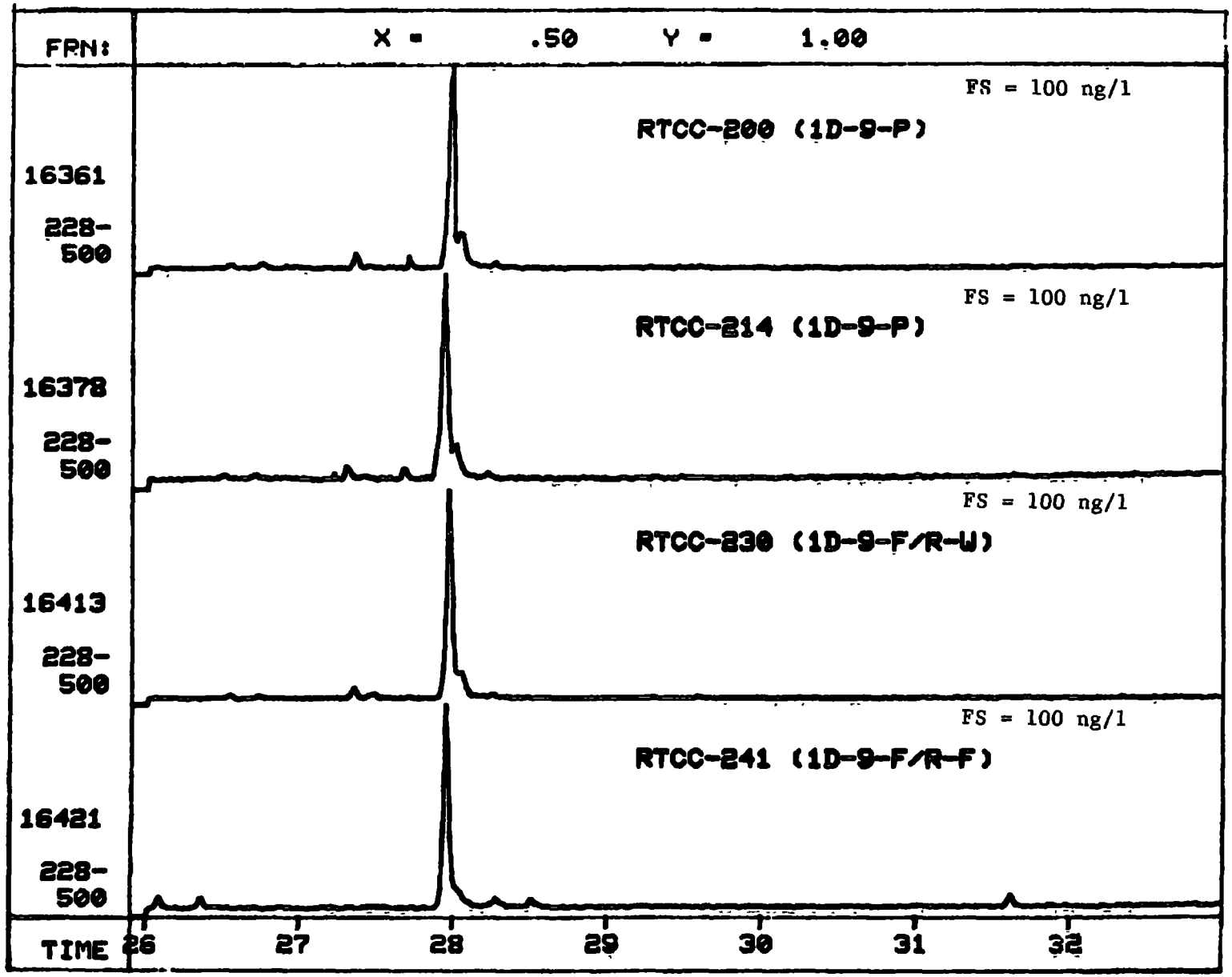


FIGURE G8-1 (continued)

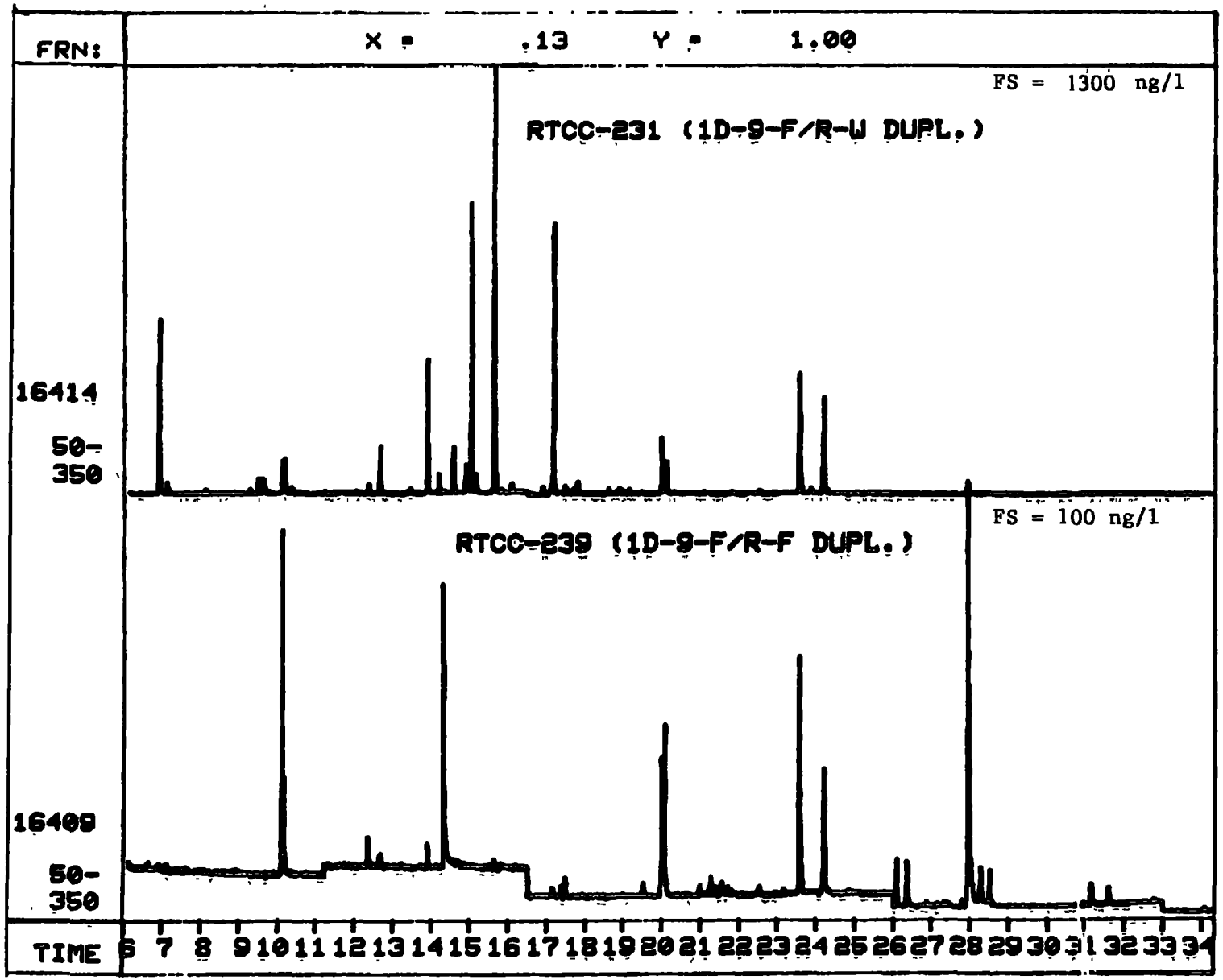


FIGURE G 8-1 (continued)

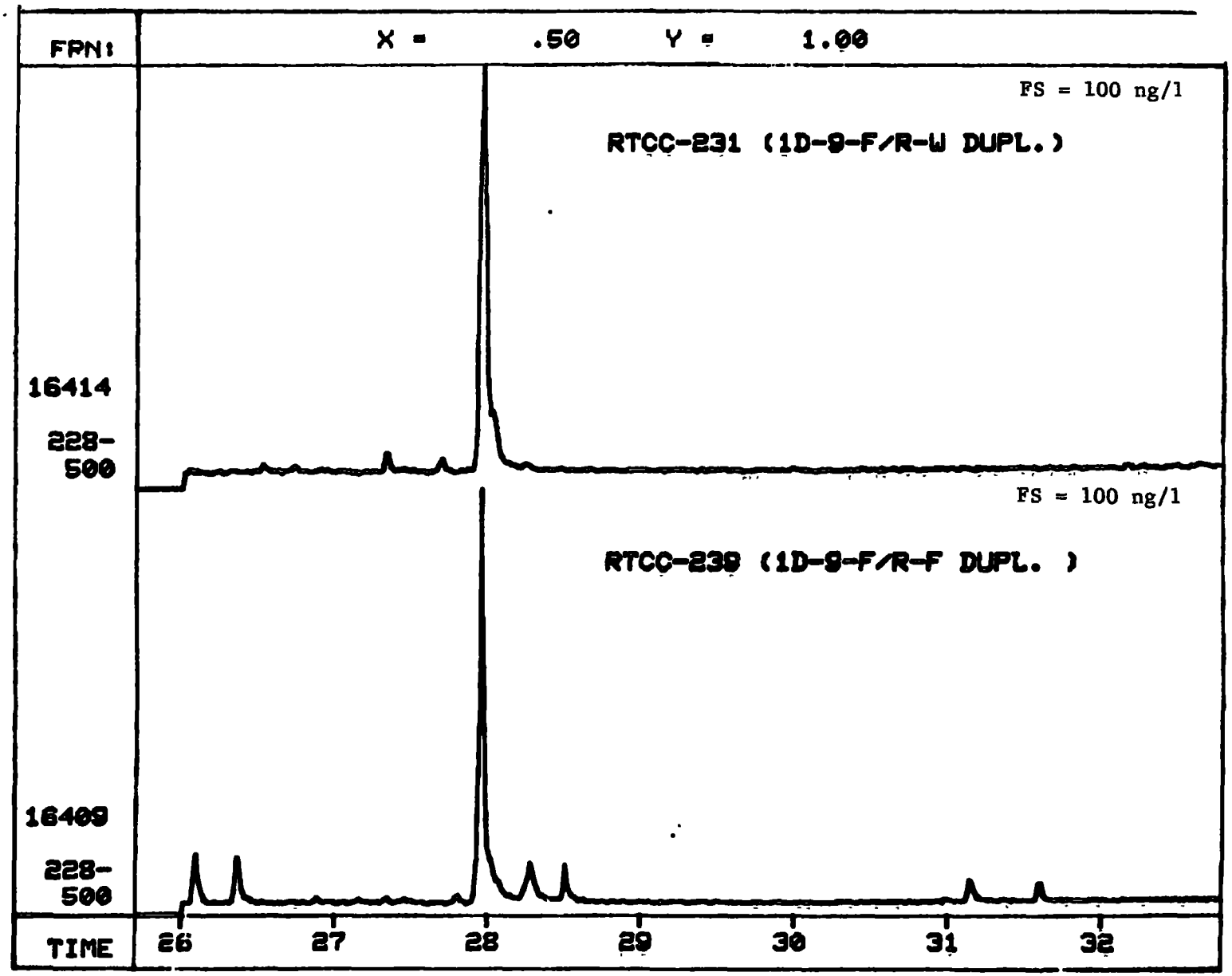


FIGURE G8-1 (continued)

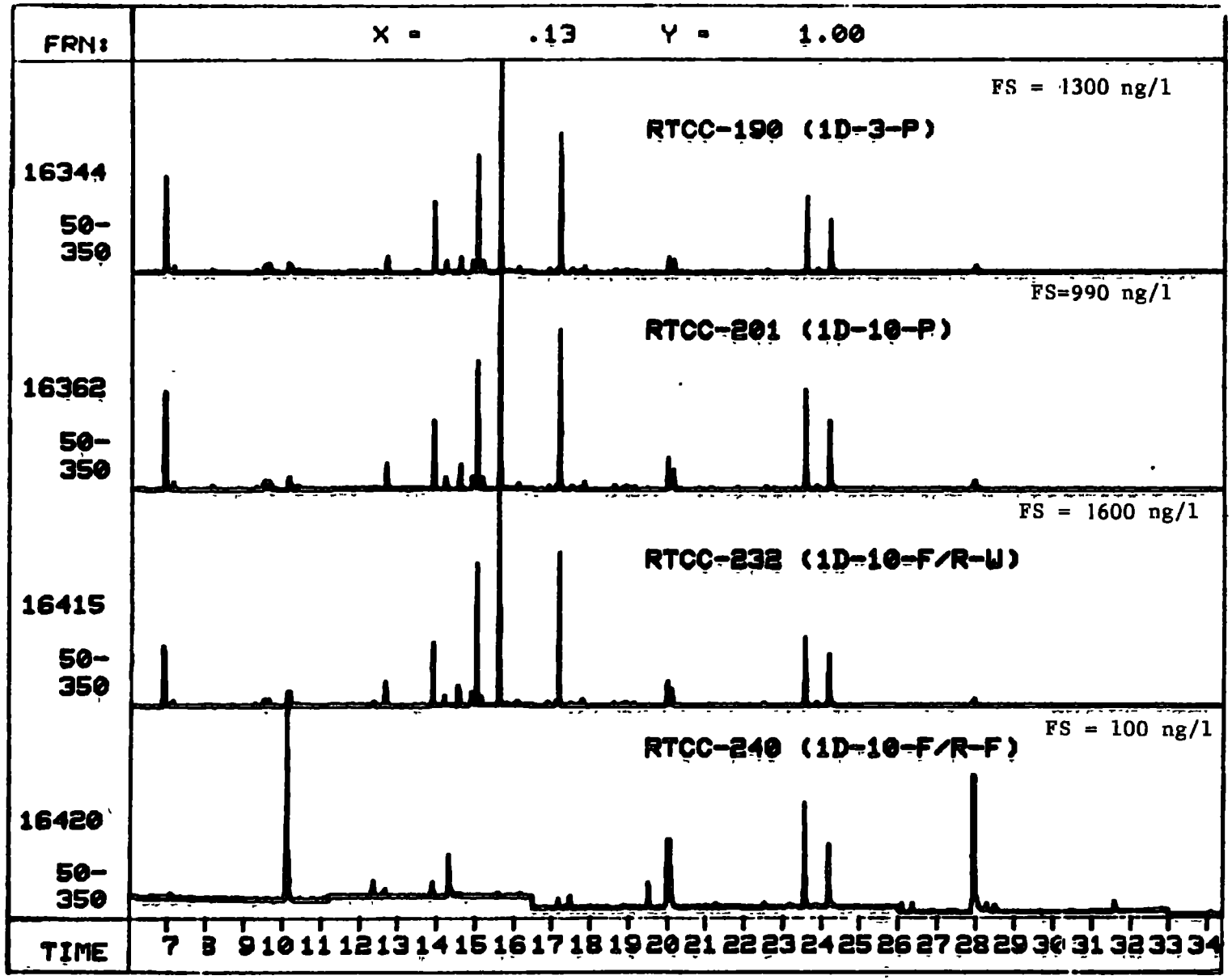


FIGURE G8-1 (continued)

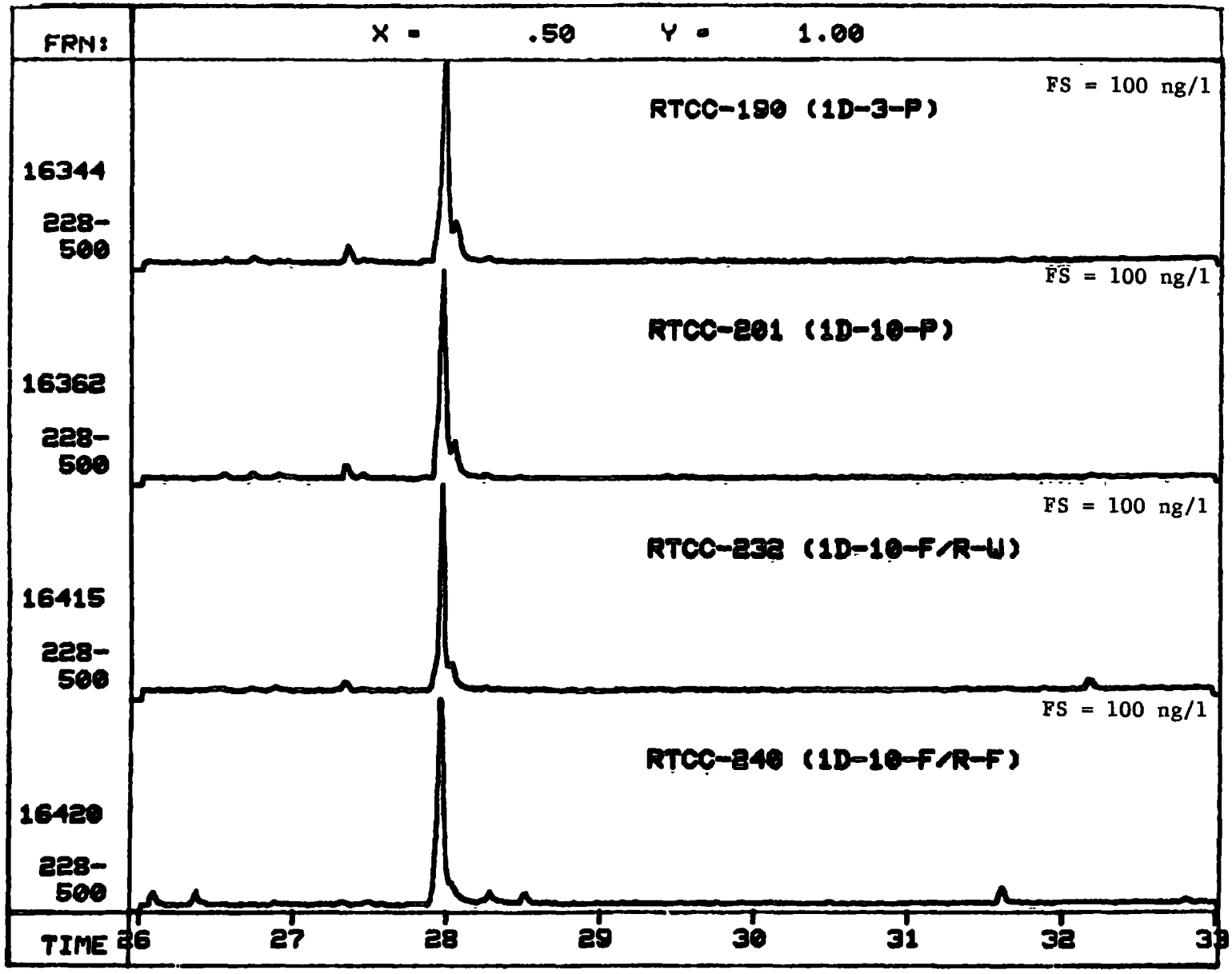


FIGURE G8-1 (continued)

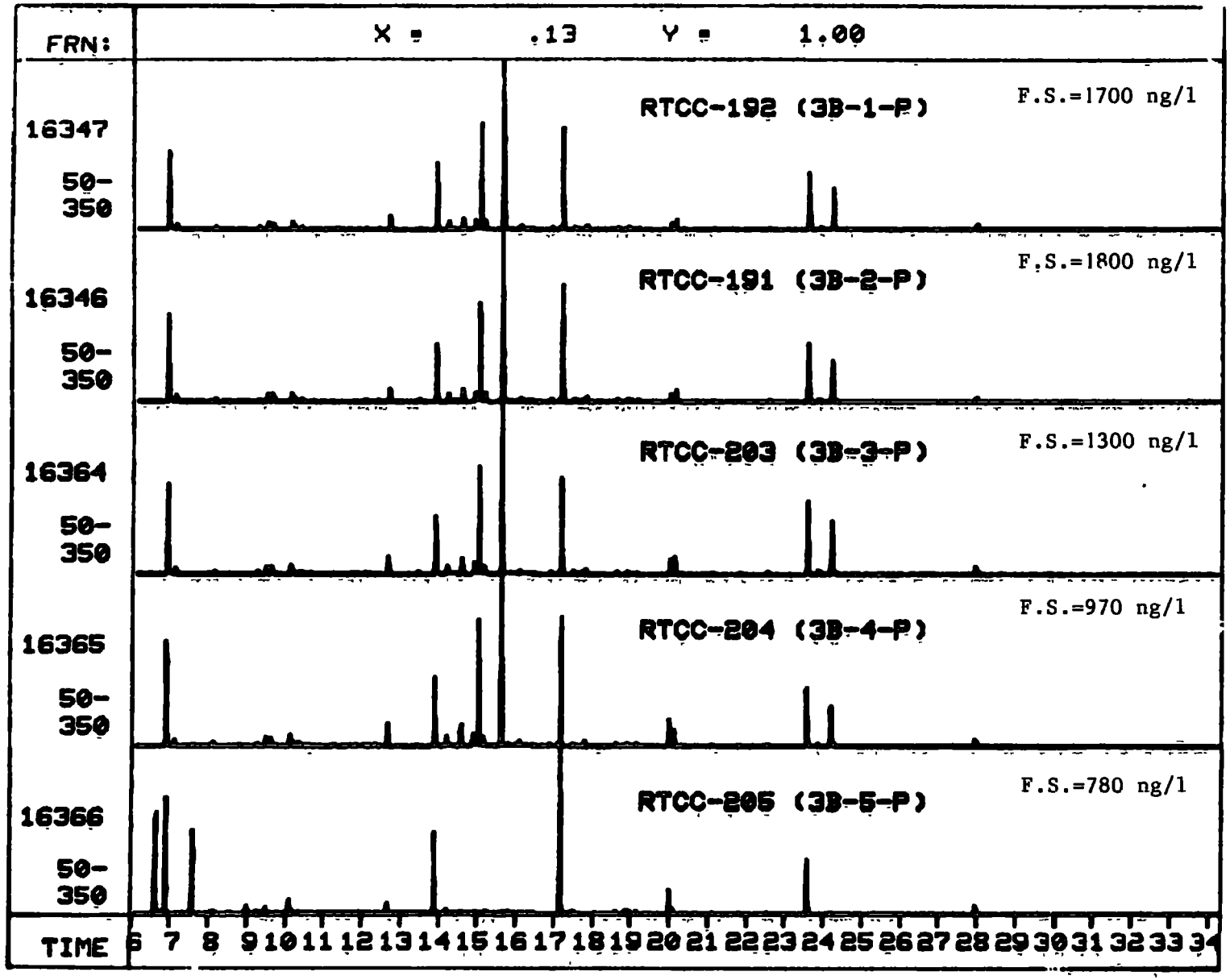


FIGURE G8-1 (continued)

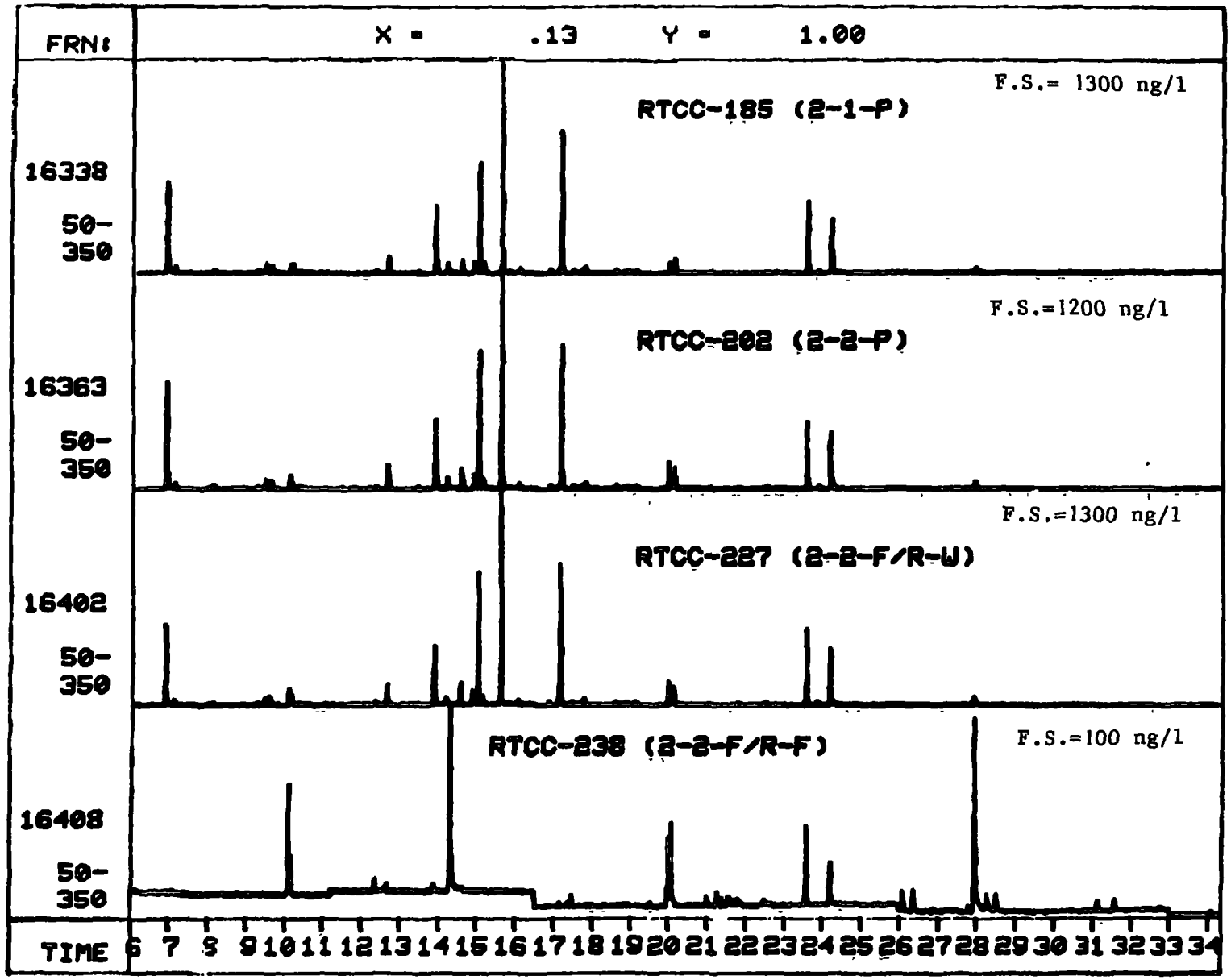


FIGURE G8-1 (continued)

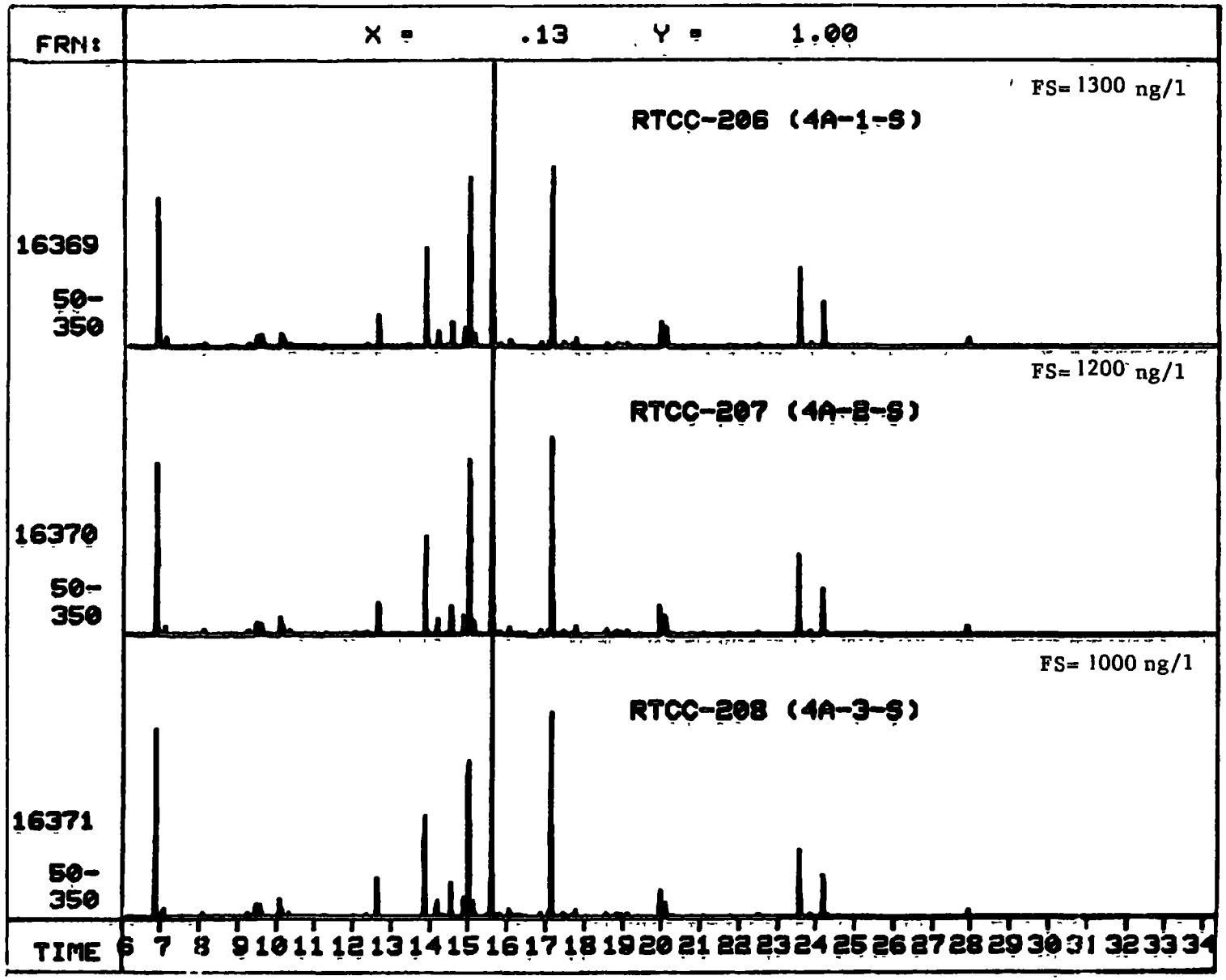


FIGURE G 8-1 (continued)

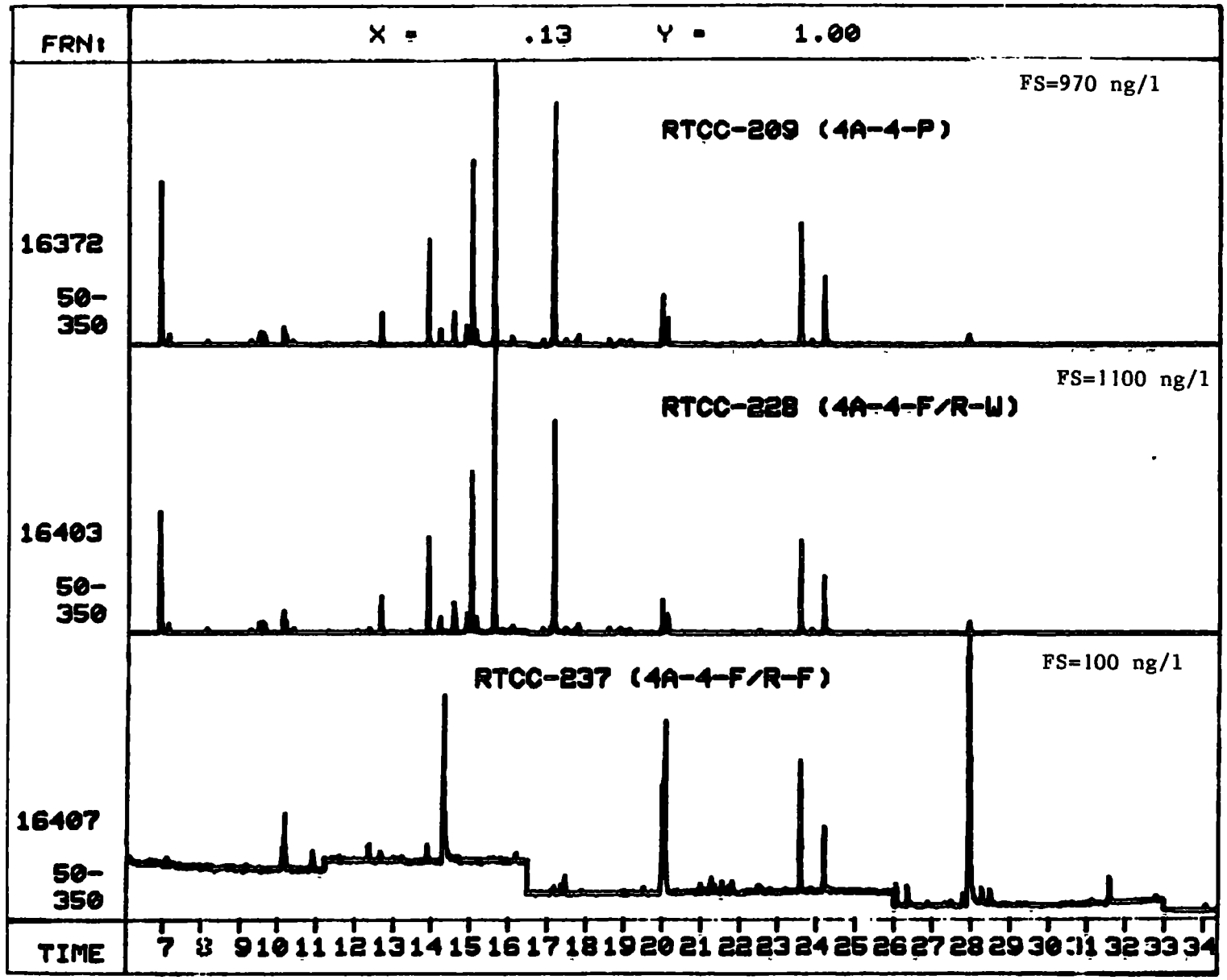


FIGURE G8-1 (continued)

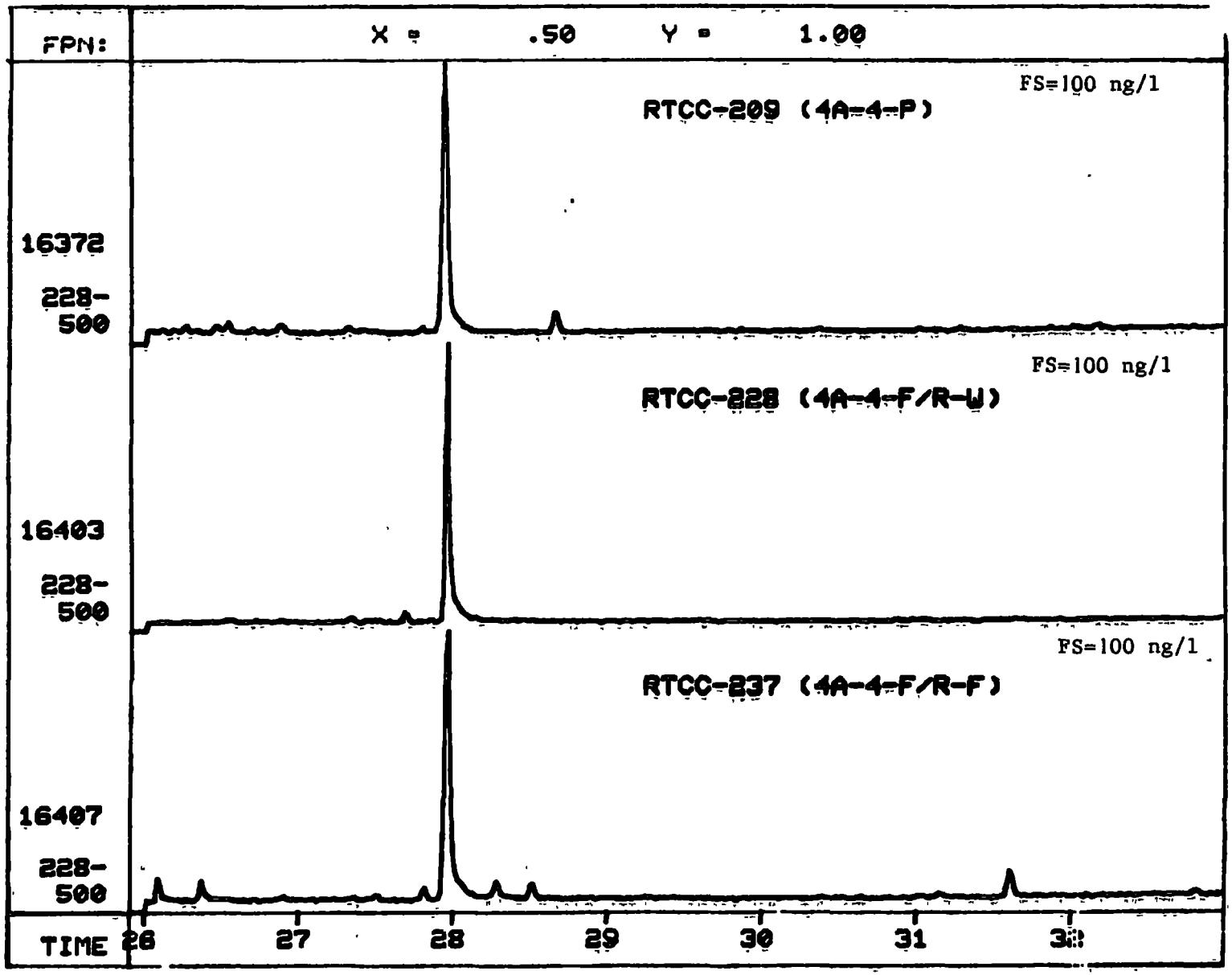


FIGURE G8-1 (continued)

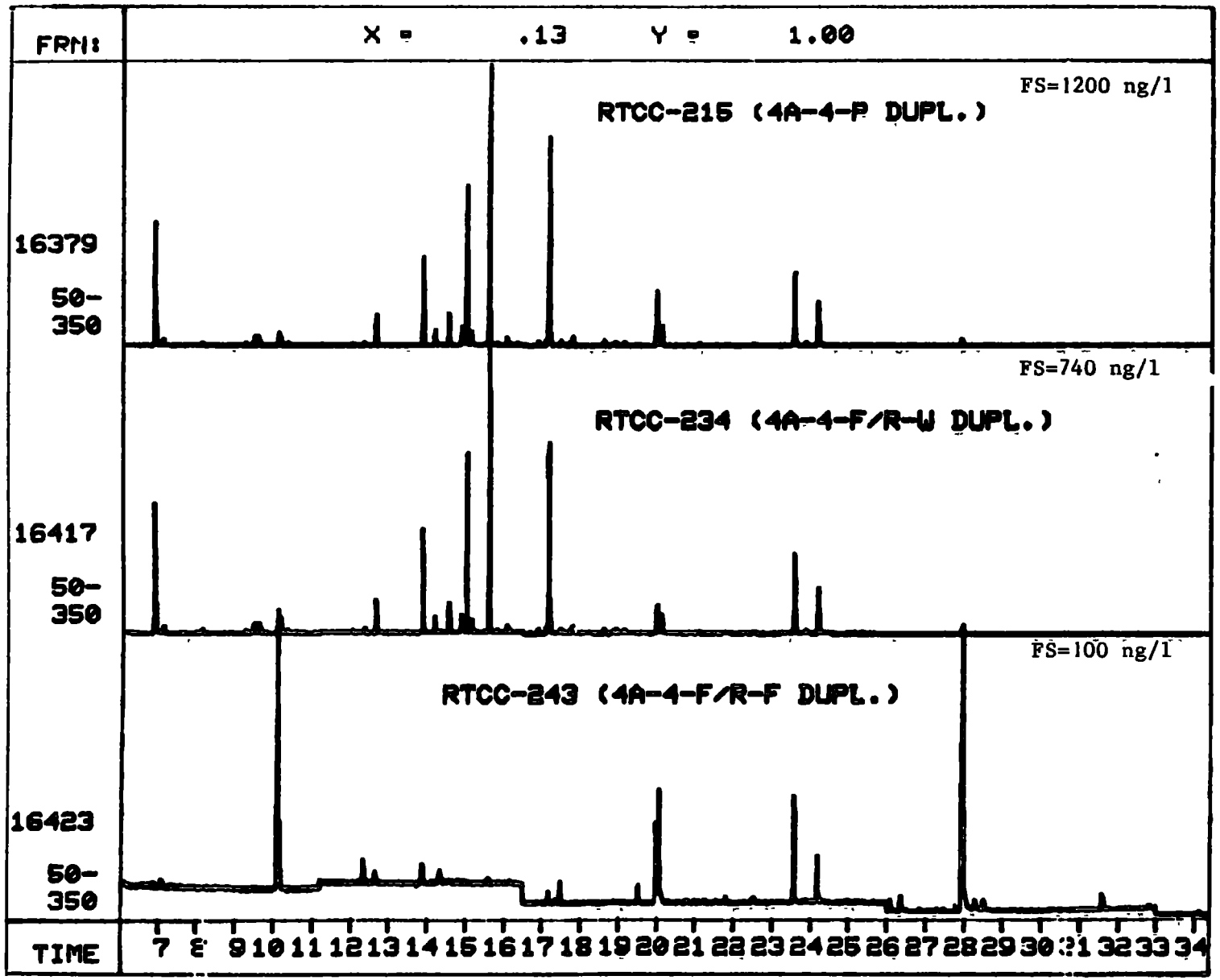


FIGURE G8-1 (continued)

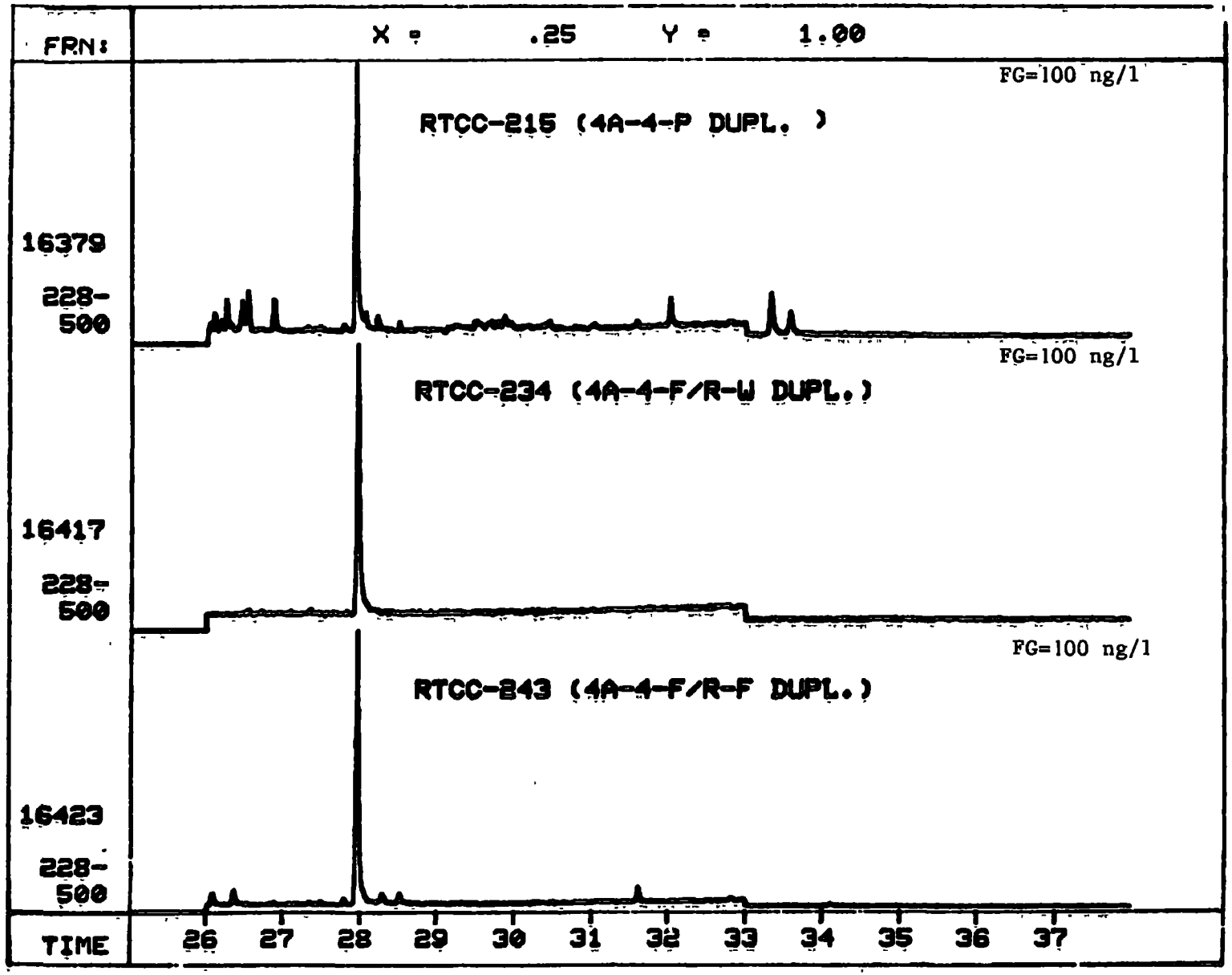


FIGURE G8-1 (continued)

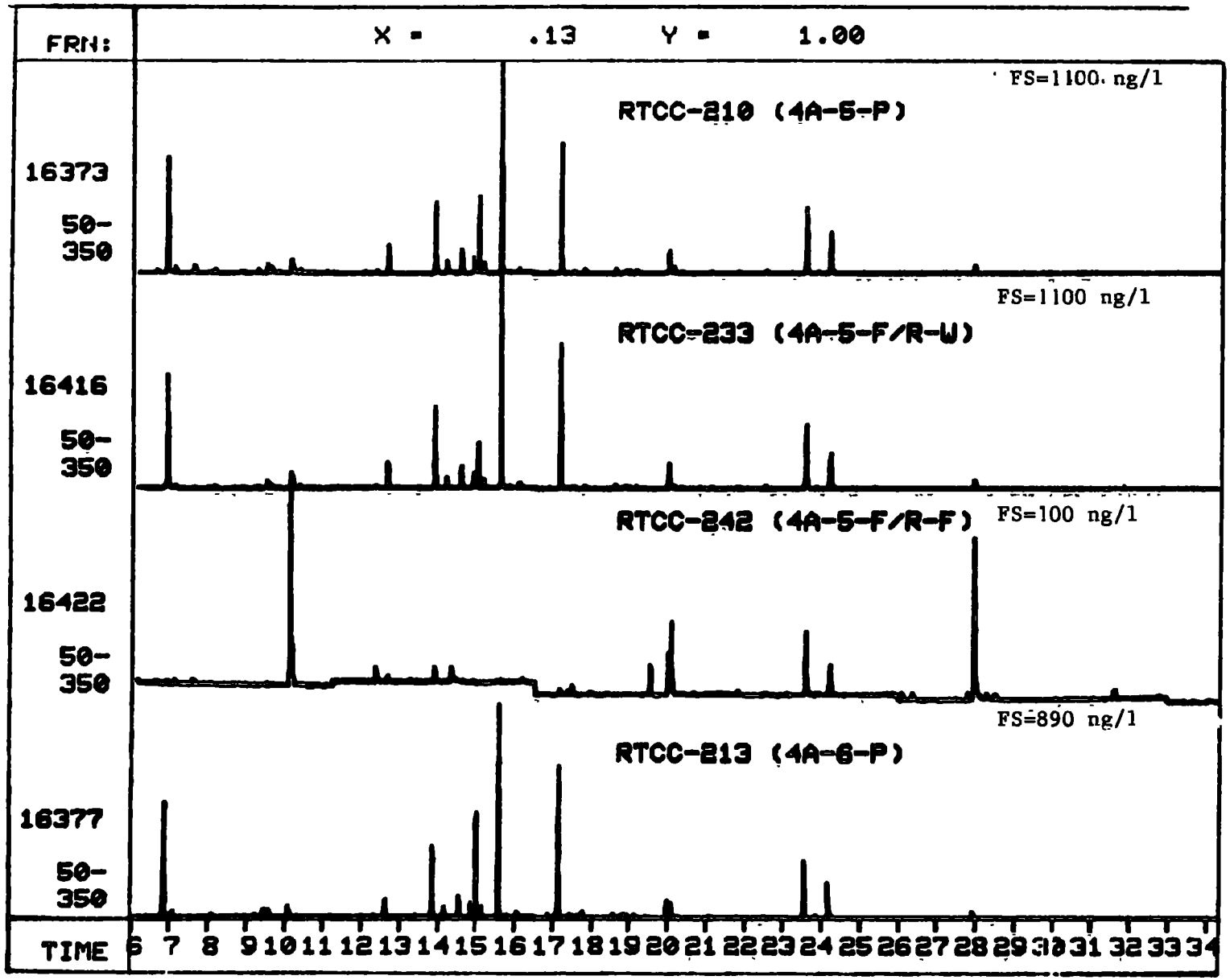


FIGURE G8-1 (continued)

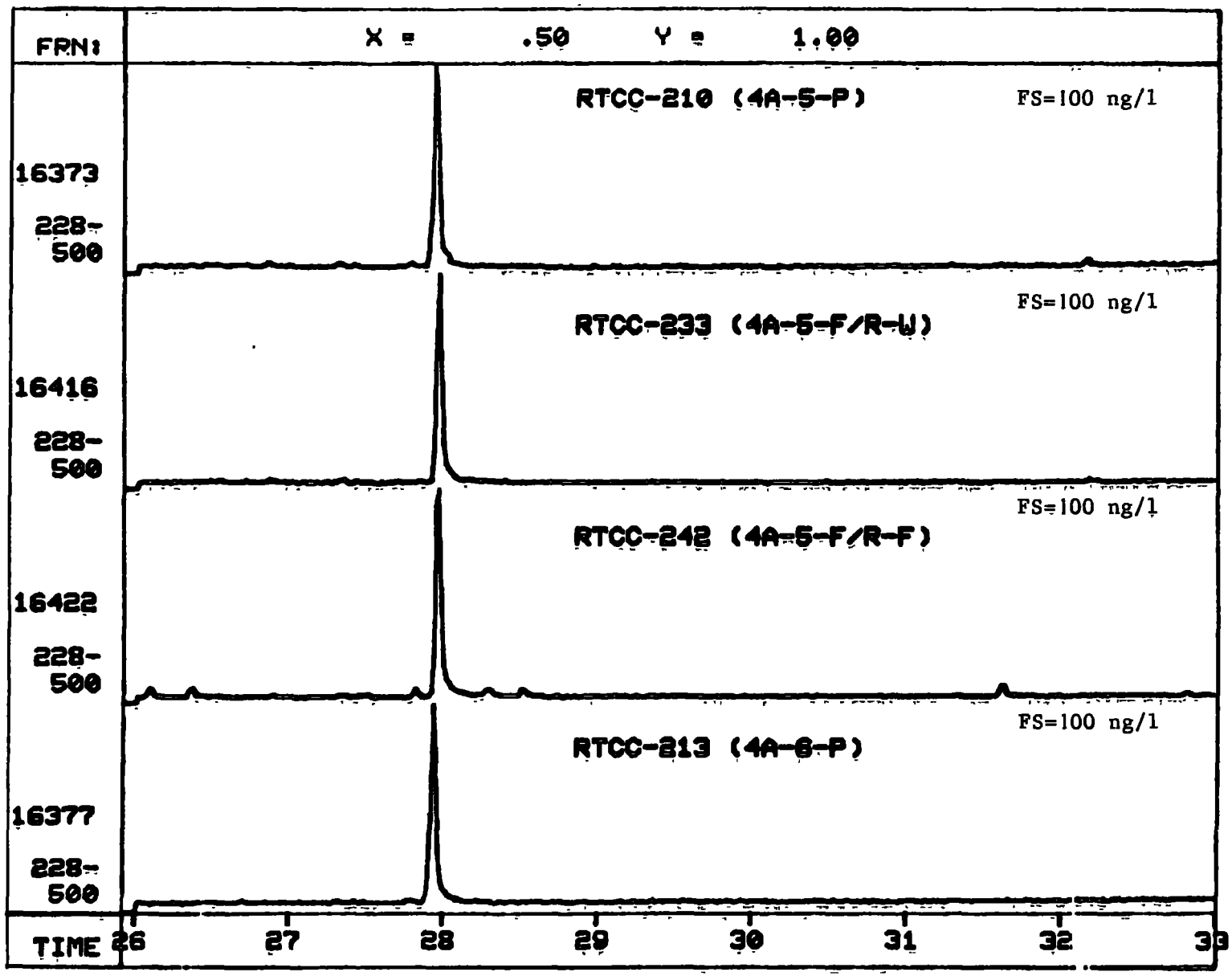


FIGURE G8-1 (continued)

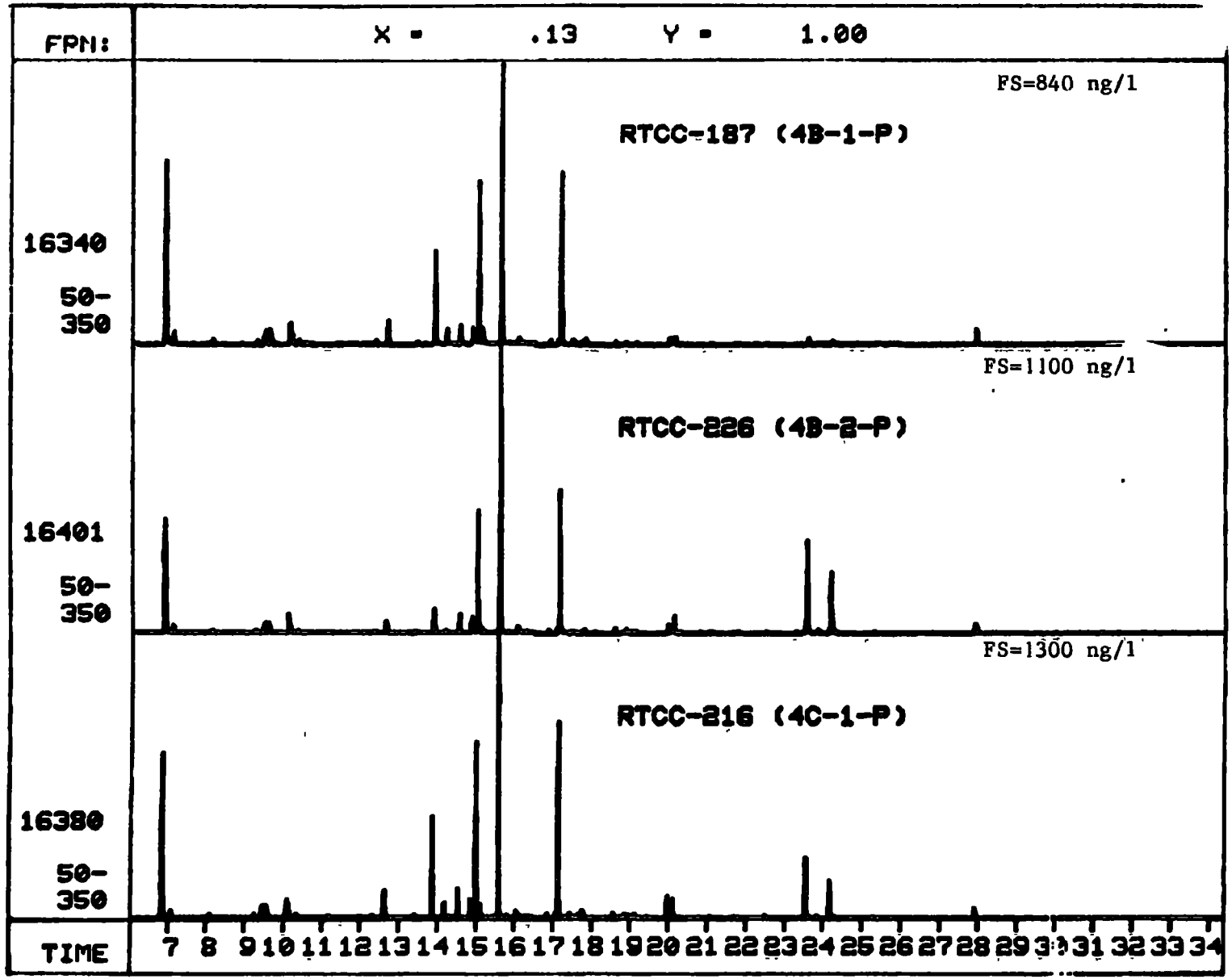


FIGURE G8-1 (continued)

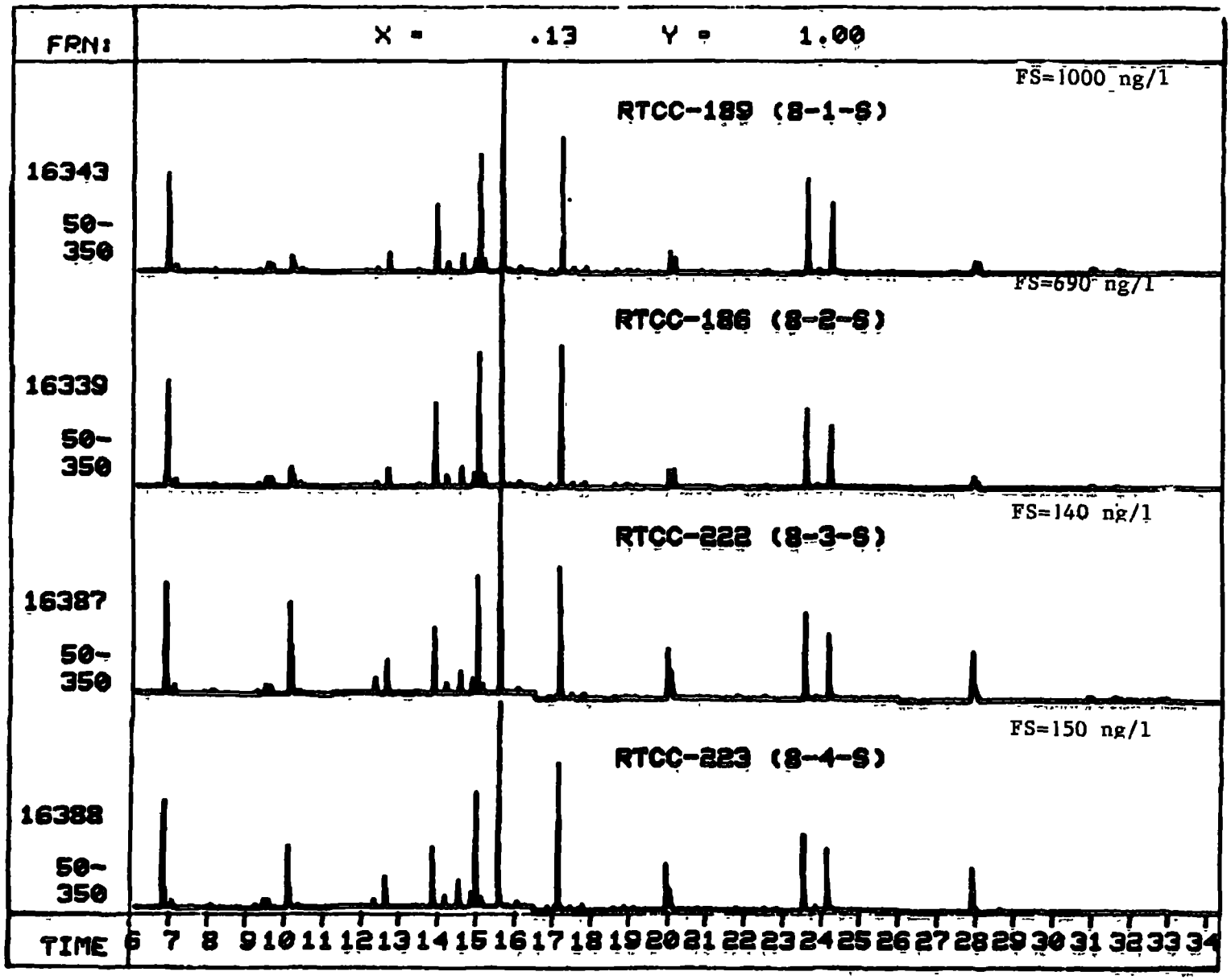


FIGURE G8-1 (continued)

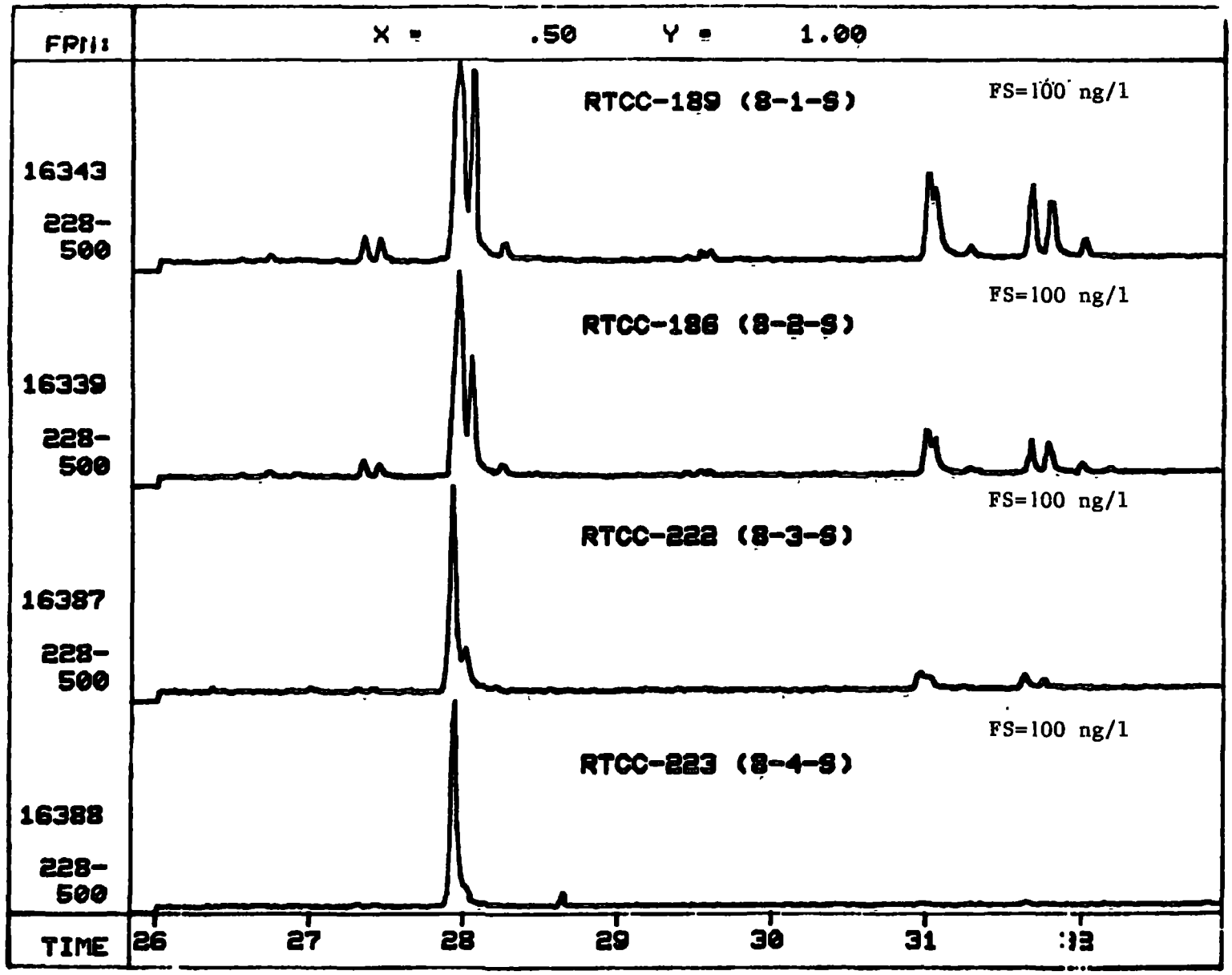


FIGURE G8-1 (continued)

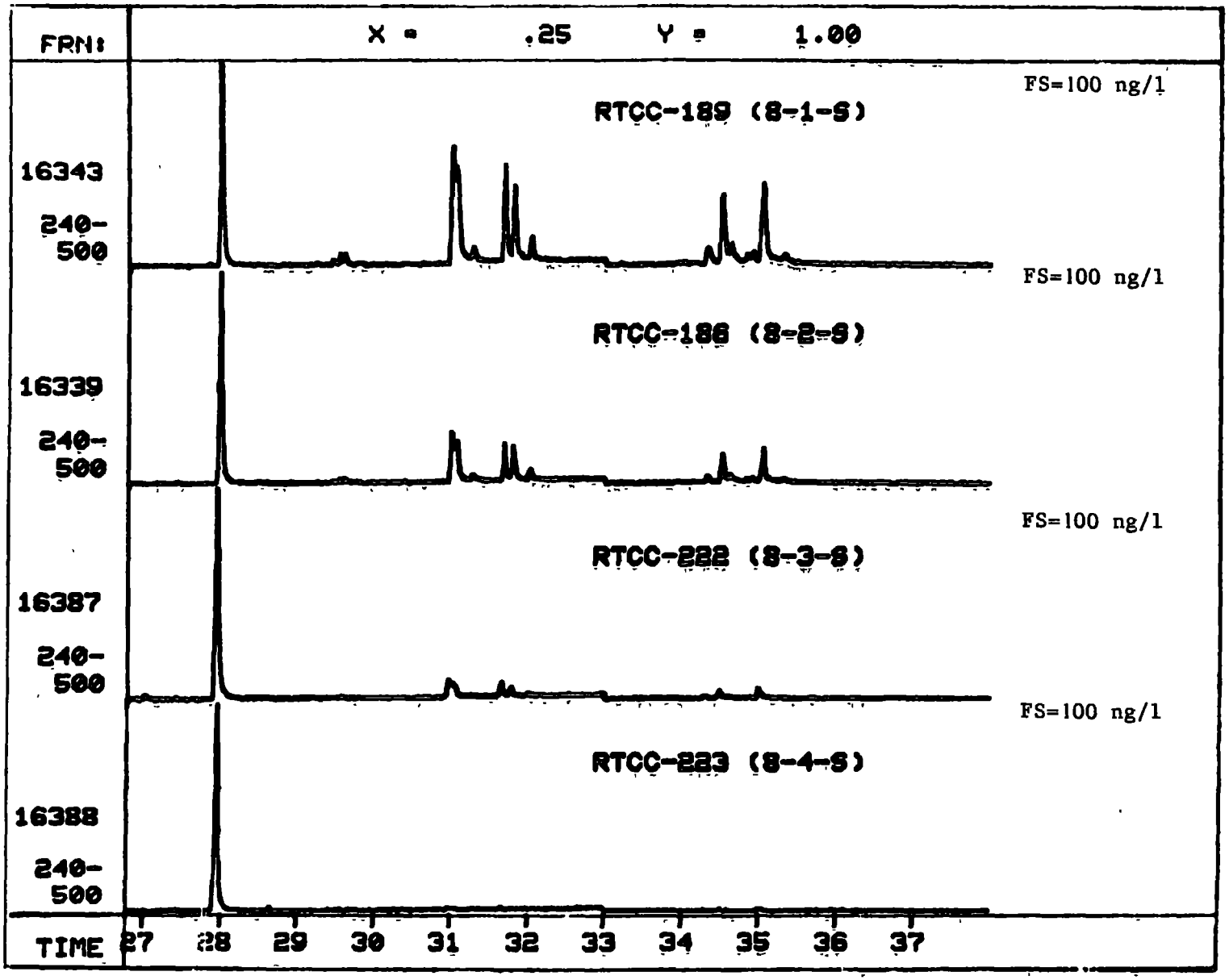
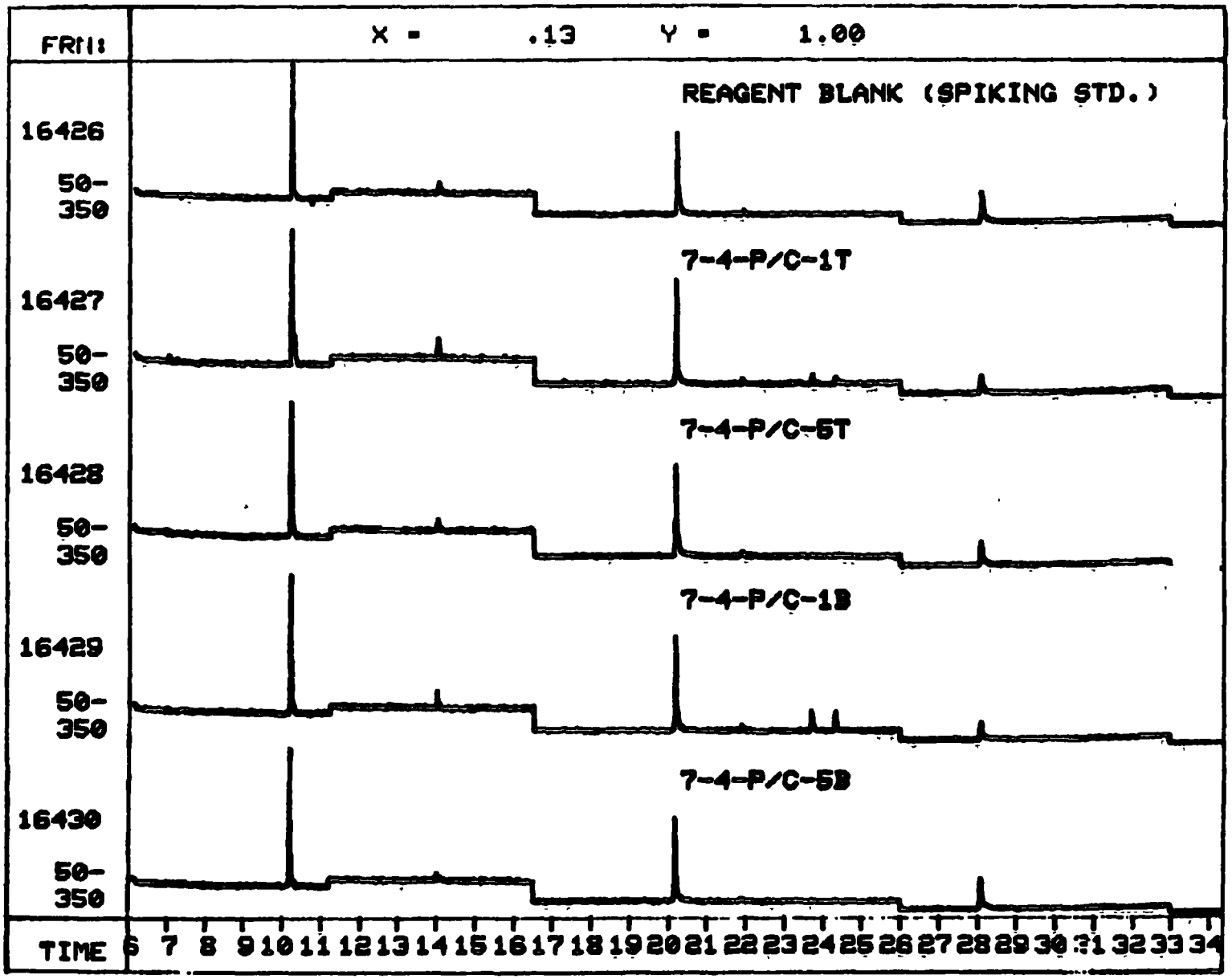


FIGURE G8-2

PAH SIM CHROMATOGRAMS FOR SAND AND SLIME SAMPLES
COLLECTED DURING ERT'S DECEMBER 6-8, 1982 TEST AT ST. LOUIS PARK STATION NO. 1 [a]



(a) Full-scale peak height concentration is 200
ngr pe li f ach om am

FIGURE G8-2 (continued)

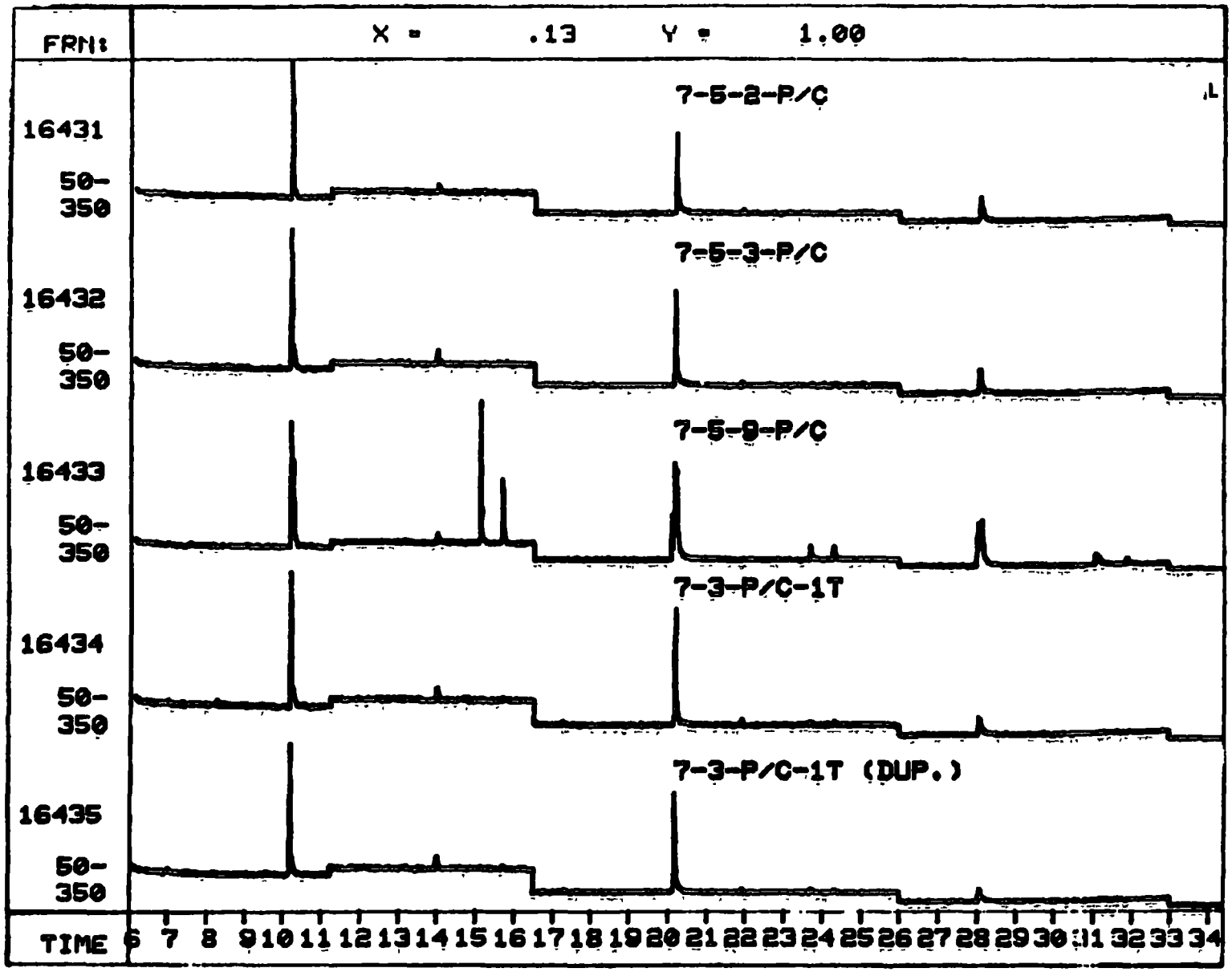


FIGURE G8-2 (continued)

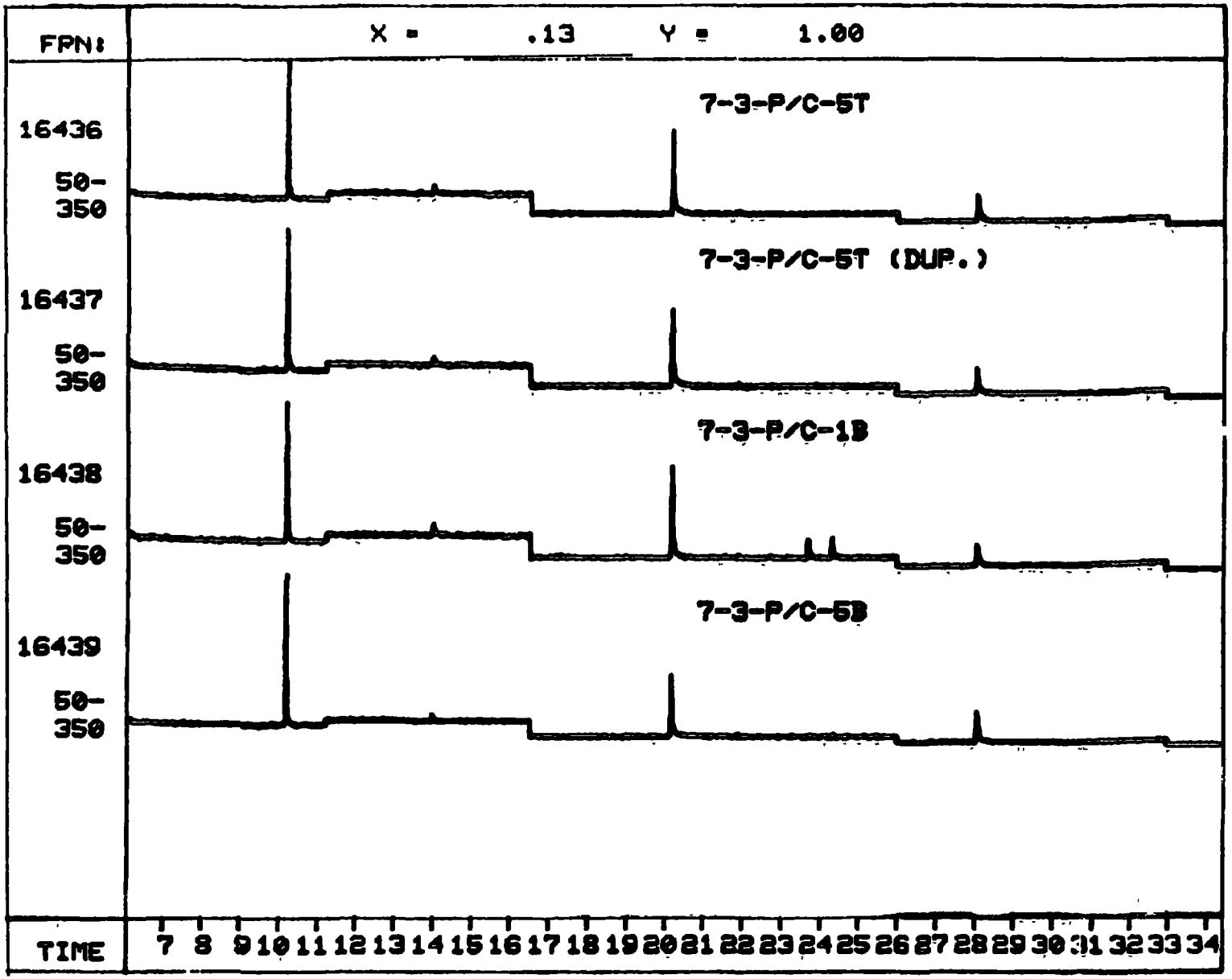
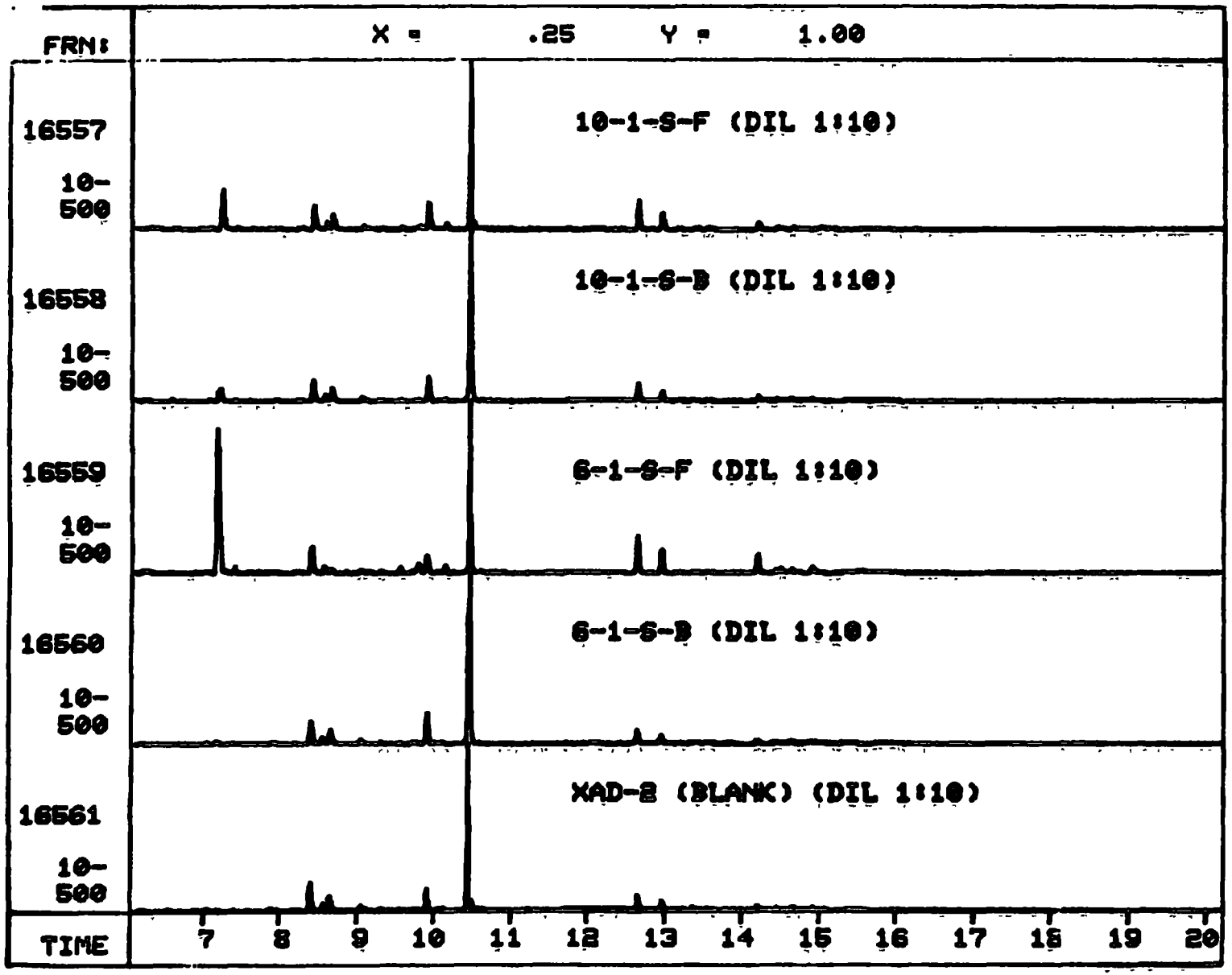


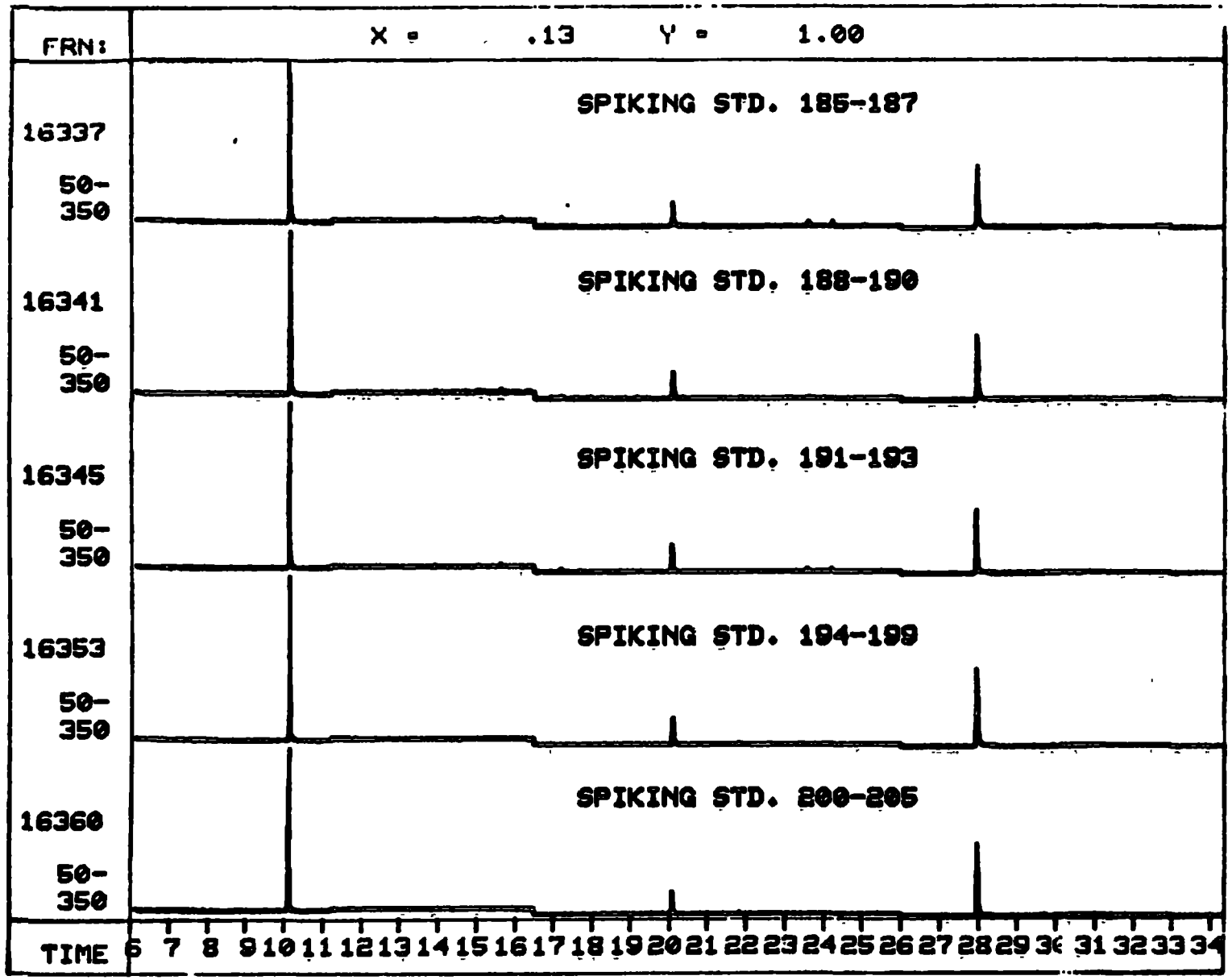
FIGURE G8-3

PAH SIM CHROMATOGRAMS FOR AIR SAMPLE XAD RESIN EXTRACTS
COLLECTED DURING ERT'S DECEMBER 6-8, 1982 TEST AT ST. LOUIS PARK STATION NO.1



Note: Full scale peak height concentrations are unknown due to large quantities of naphthalene from degradation of the XAD-2 resin masking naphthalene-d_8 peaks.

FIGURE G 8-4
PAH SIM CHROMATOGRAMS FOR SPIKING STANDARDS AND
METHOD BLANKS CORRESPONDING TO SAMPLES COLLECTED DURING
ERT'S DECEMBER 6-8, 1982 TEST AT ST. LOUIS PARK STATION NO. 1 [a]



(a) Full-scale height concentration is 100 nanograms per liter for all chromatograms.

FIGURE G8-4 (continued)

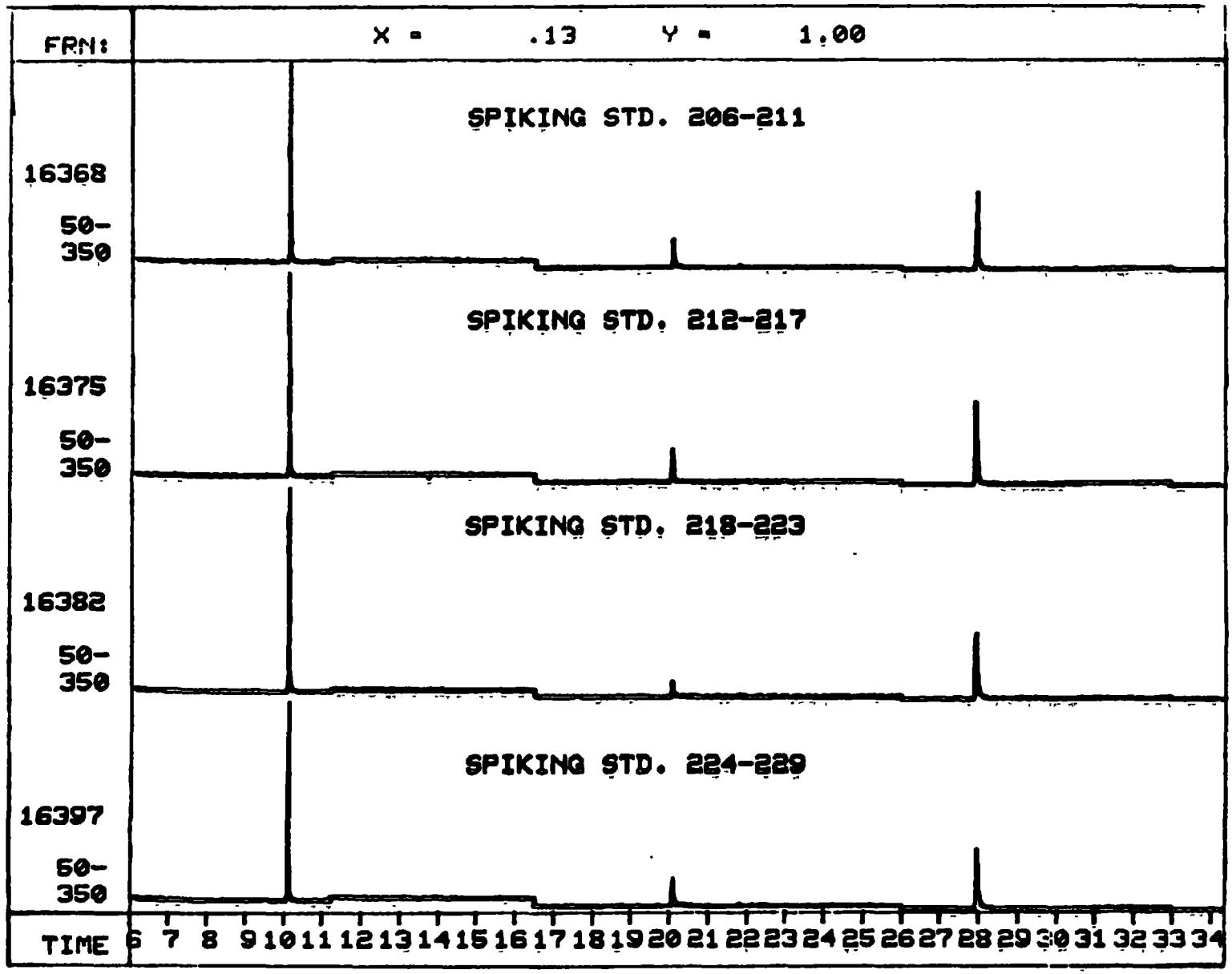


FIGURE G8-4 (continued)

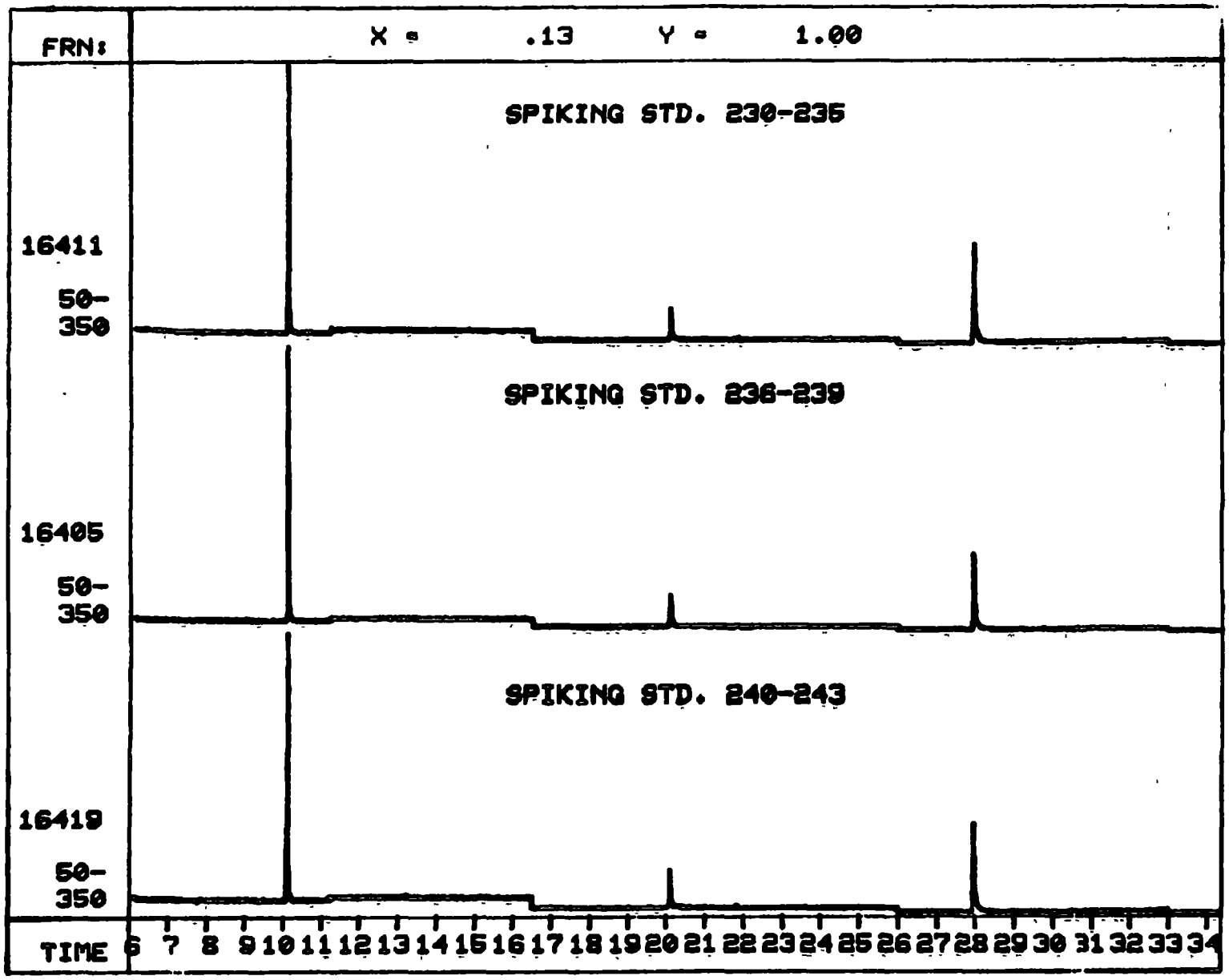


FIGURE G 8-4 (continued)

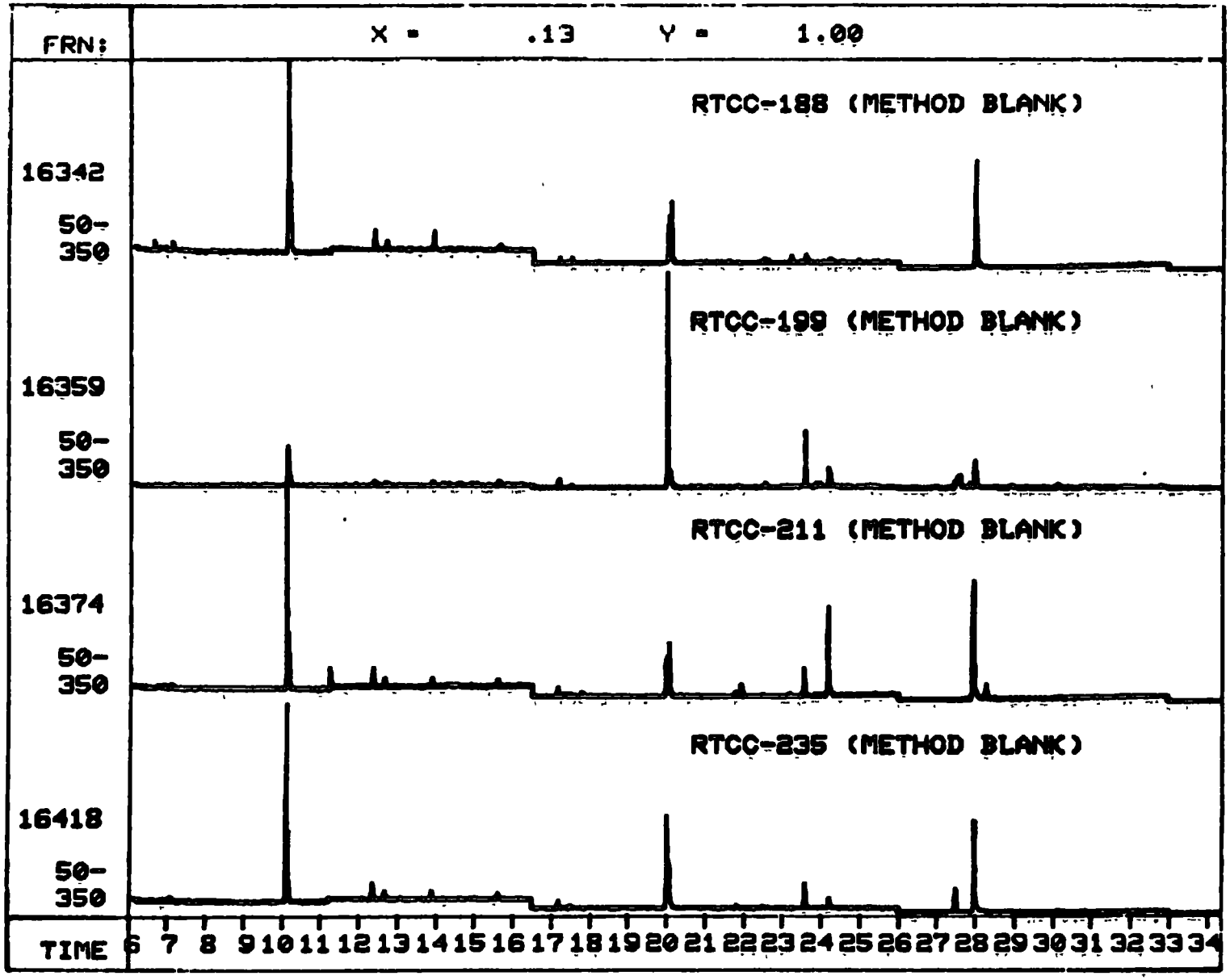
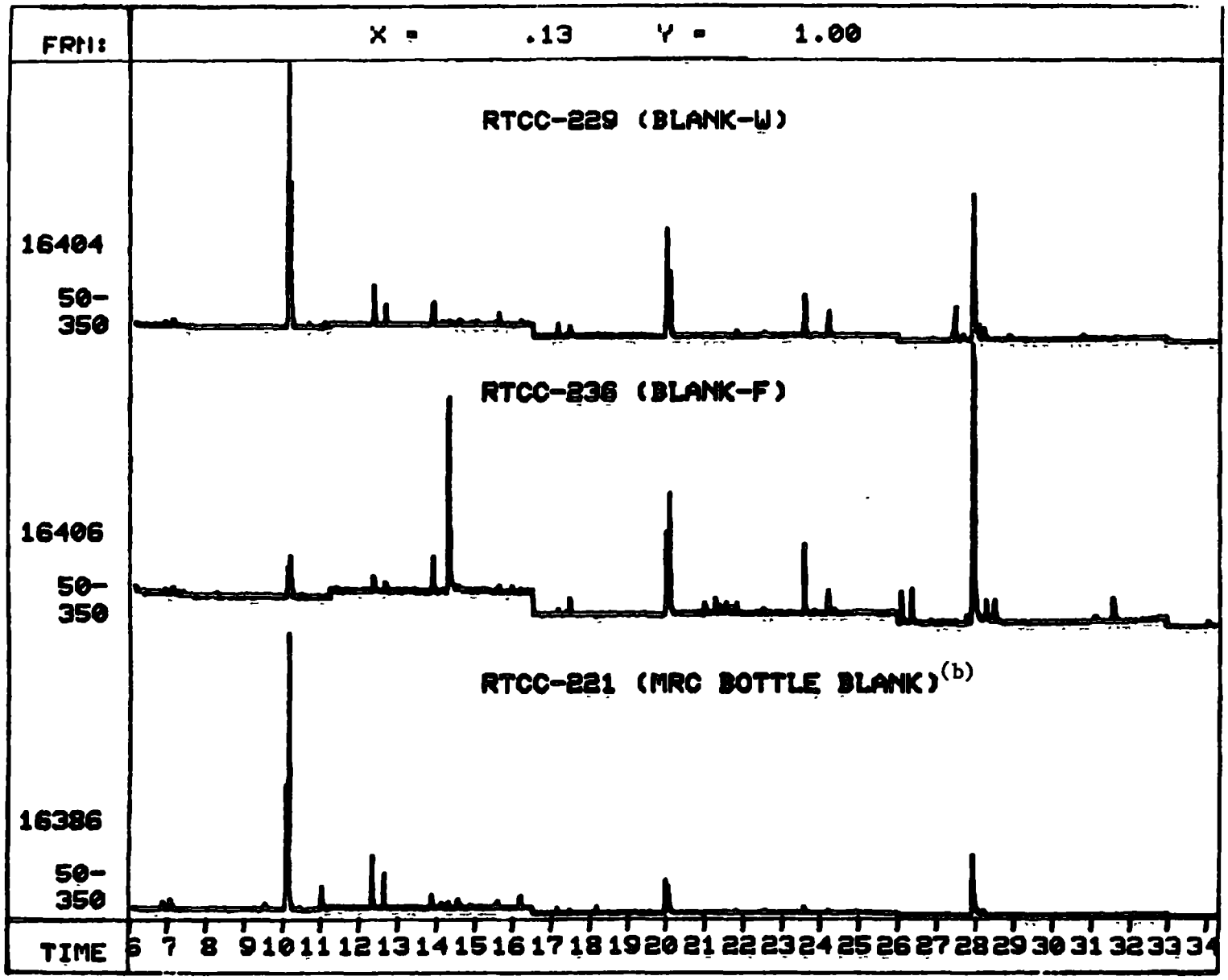


FIGURE G8-4 (continued)



(b) Full-scale height concentration is 200 nanograms per liter.

FIGURE G 8-4 (continued)

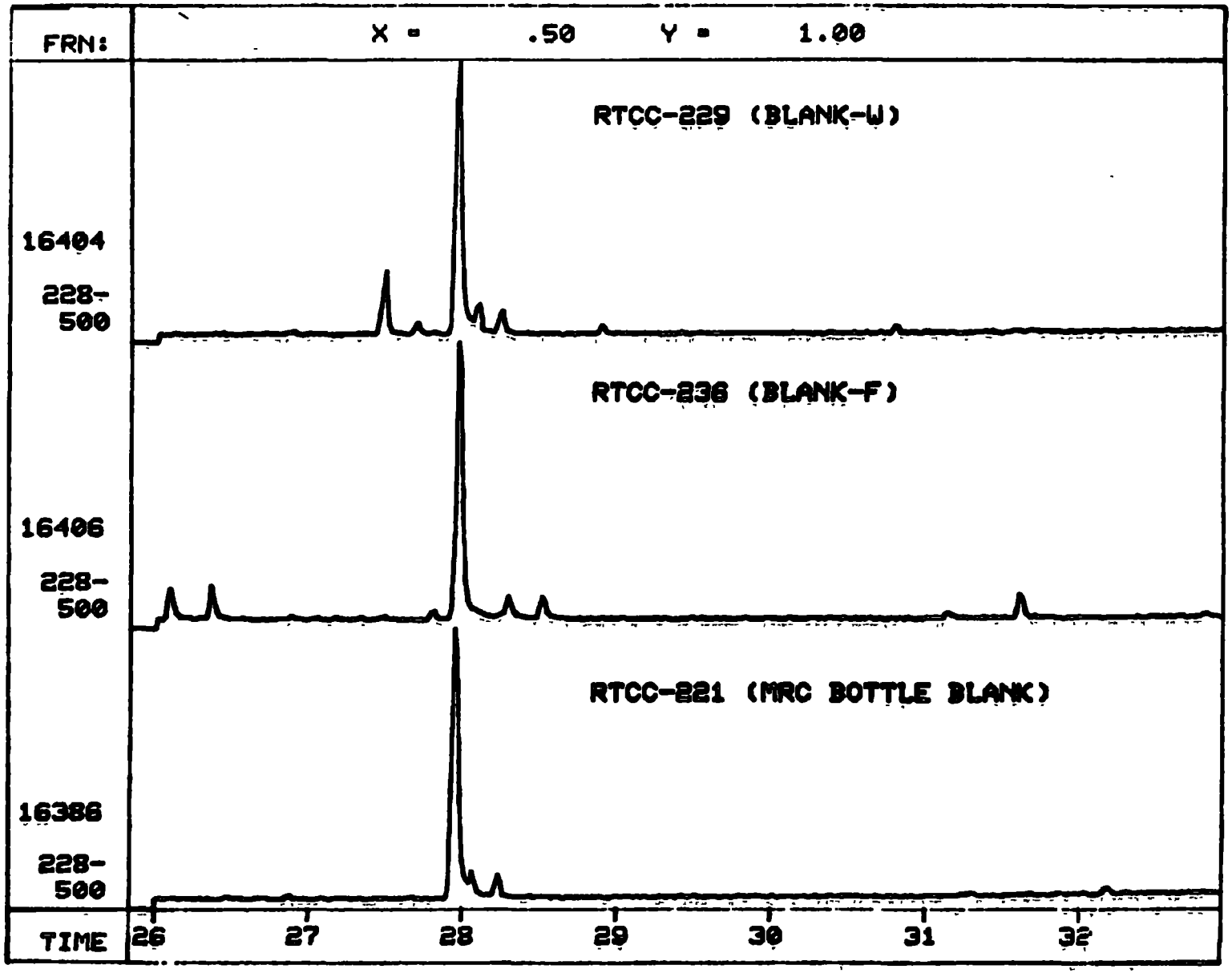
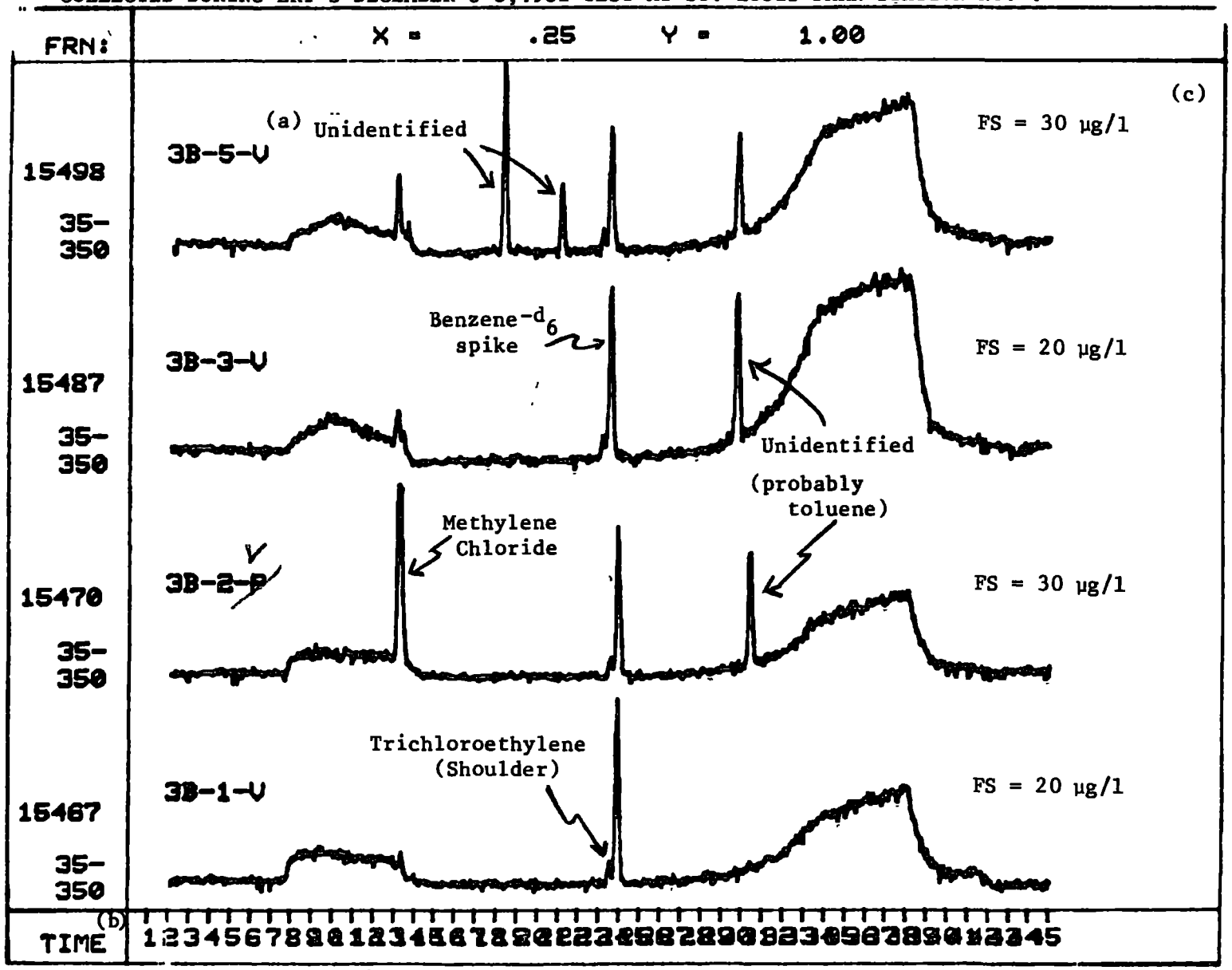


FIGURE G8-5

VOLATILE ORGANICS ANALYSIS CHROMATOGRAMS FOR SAMPLES COLLECTED DURING ERT'S DECEMBER 6-8, 1982 TEST AT ST. LOUIS PARK STATION NO. 1



NOTES:

(a) ERT sample number.

(b) Retention time in minutes.

(c) Concentration of full-scale peak in micrograms per liter.

FIGURE G8-5 (continued)

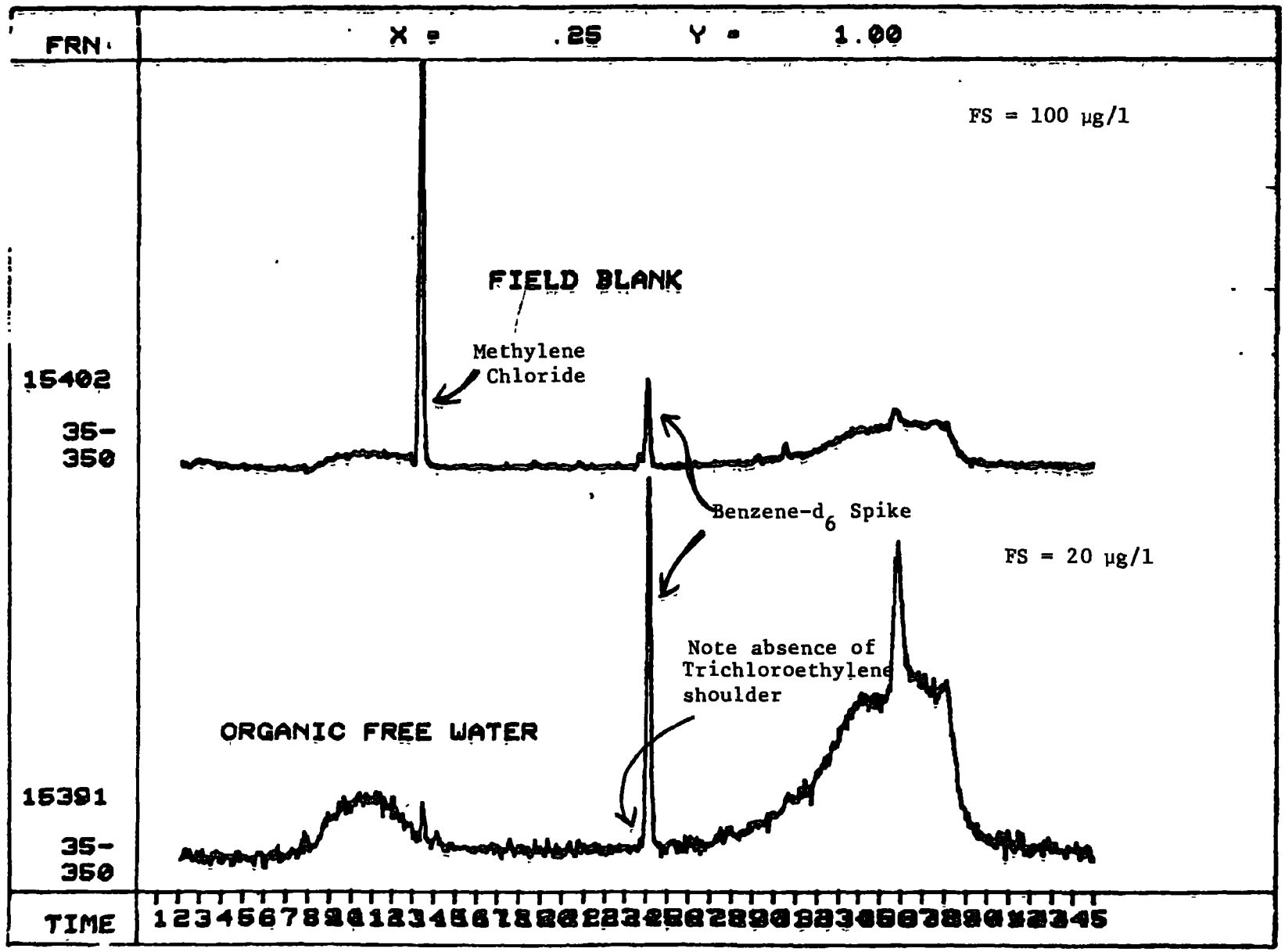


FIGURE G 8-5 (continued)

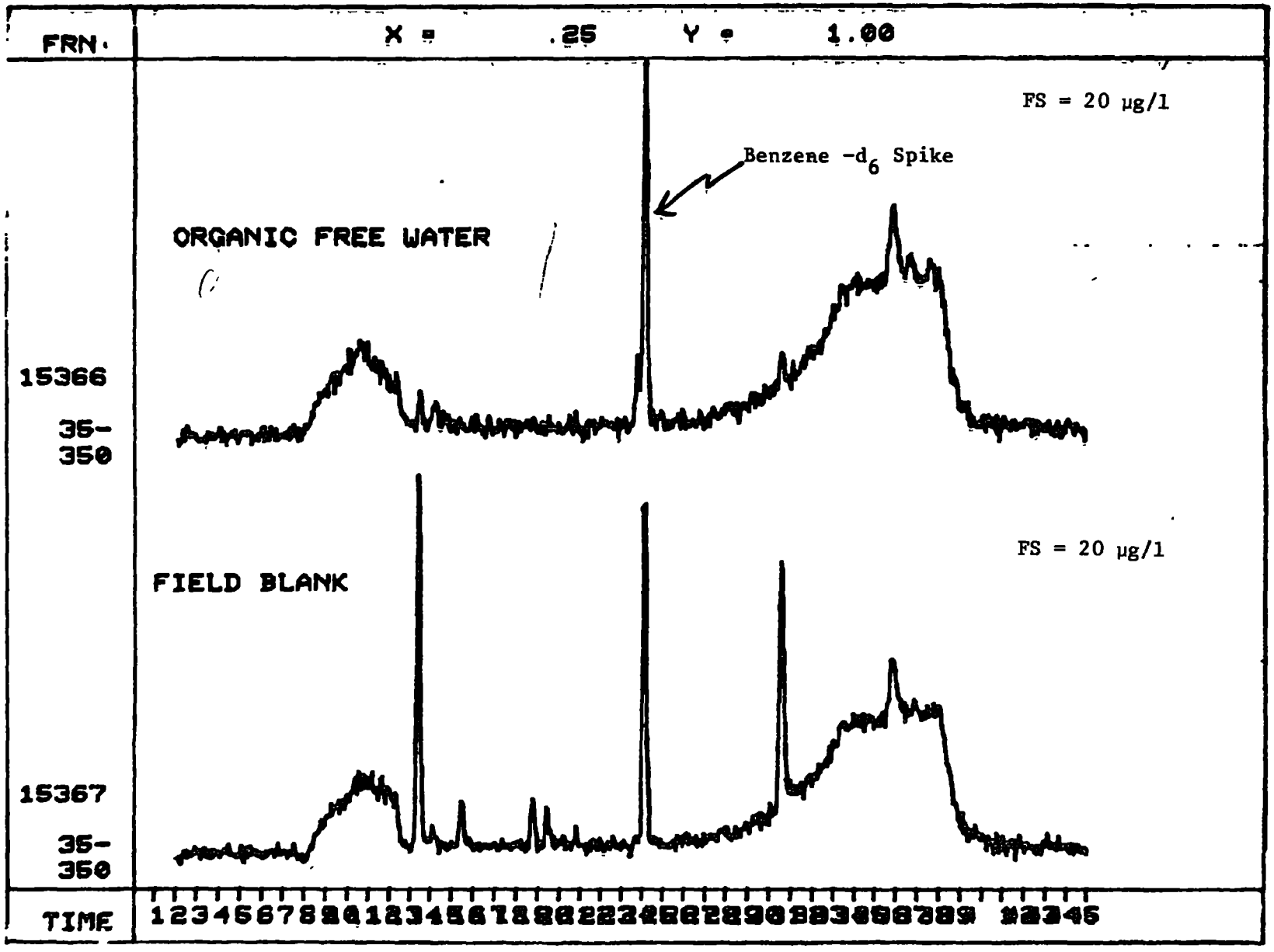


FIGURE G8-5 (continued)

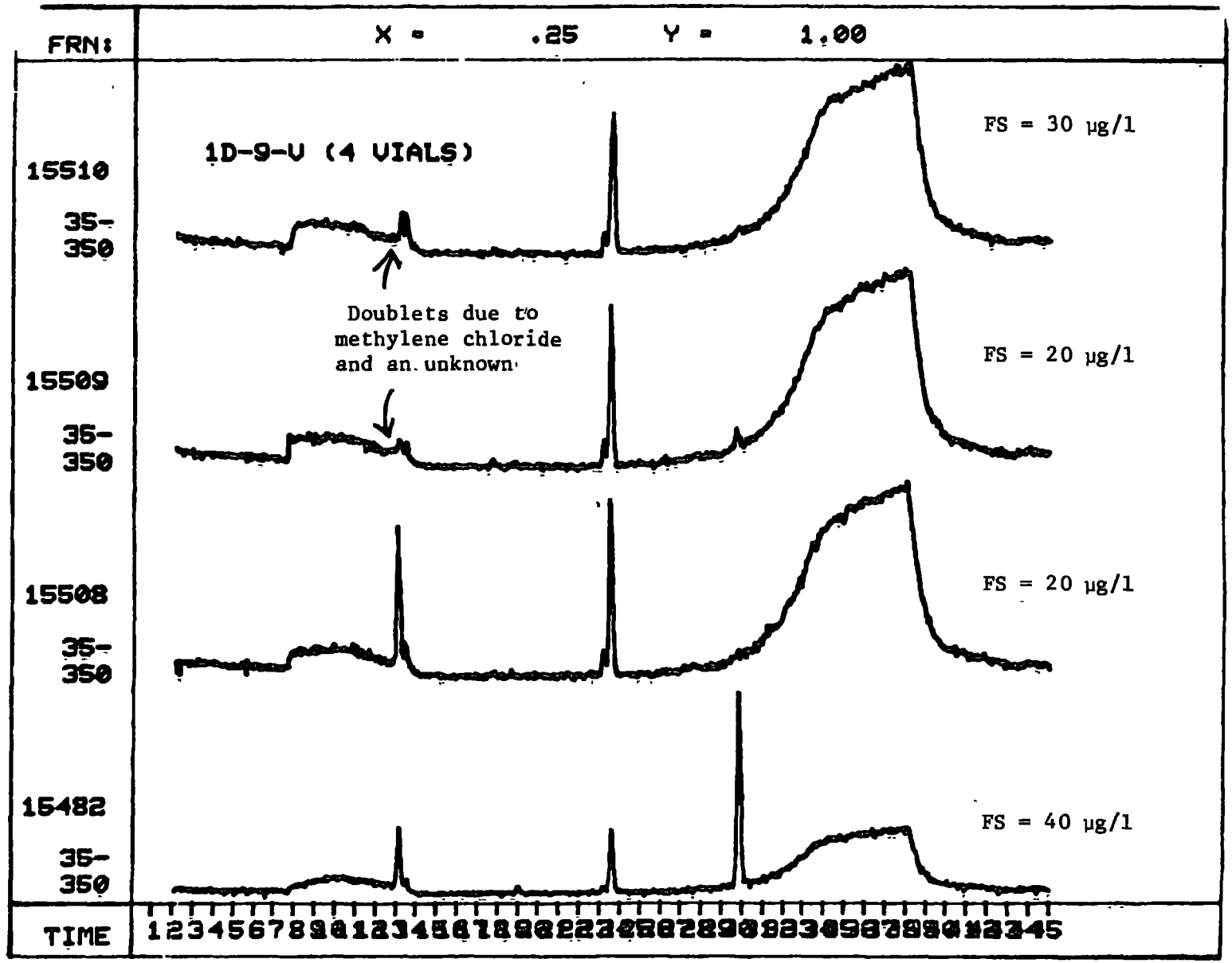


FIGURE G8-5 (continued)

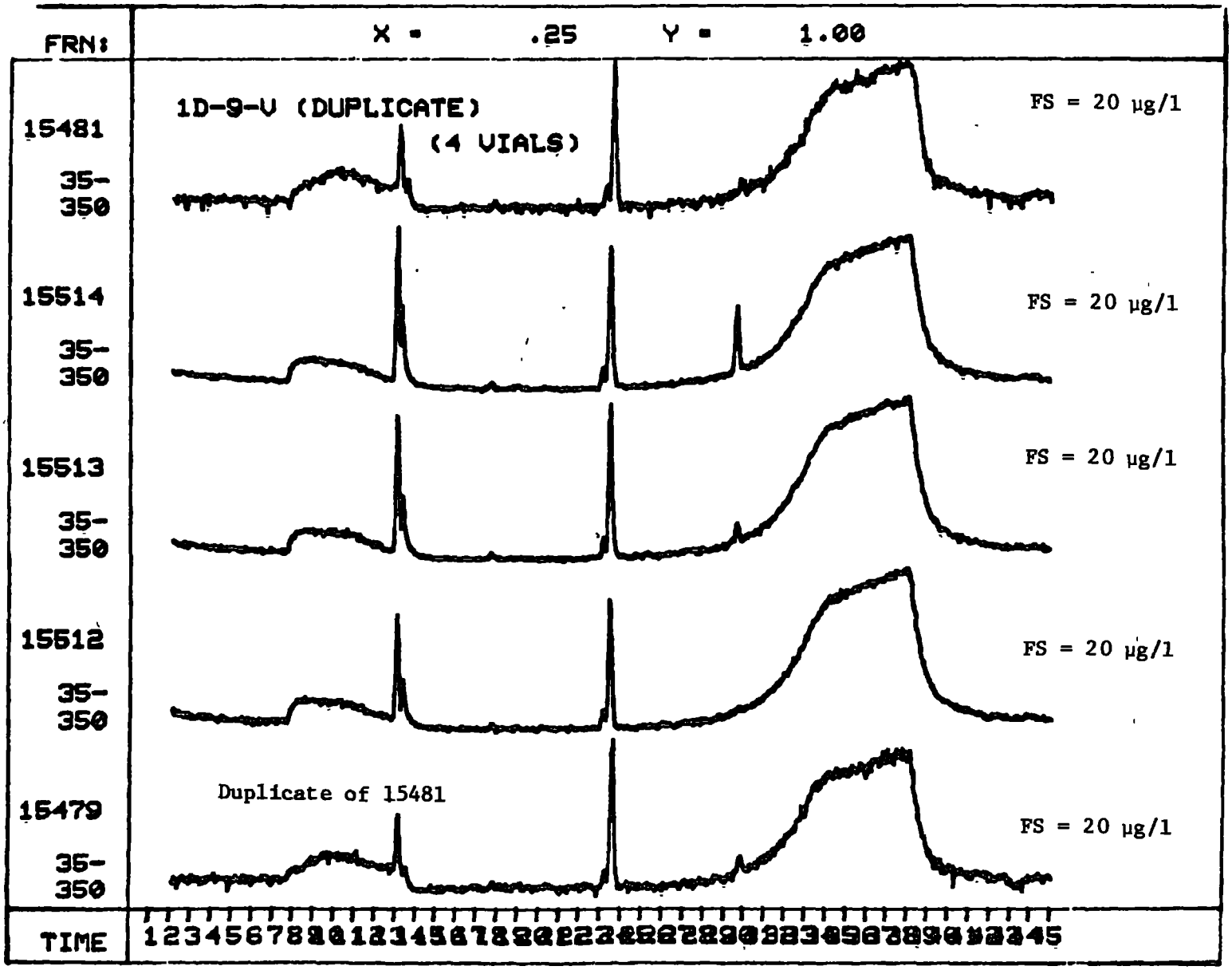


FIGURE G8-5 (continued)

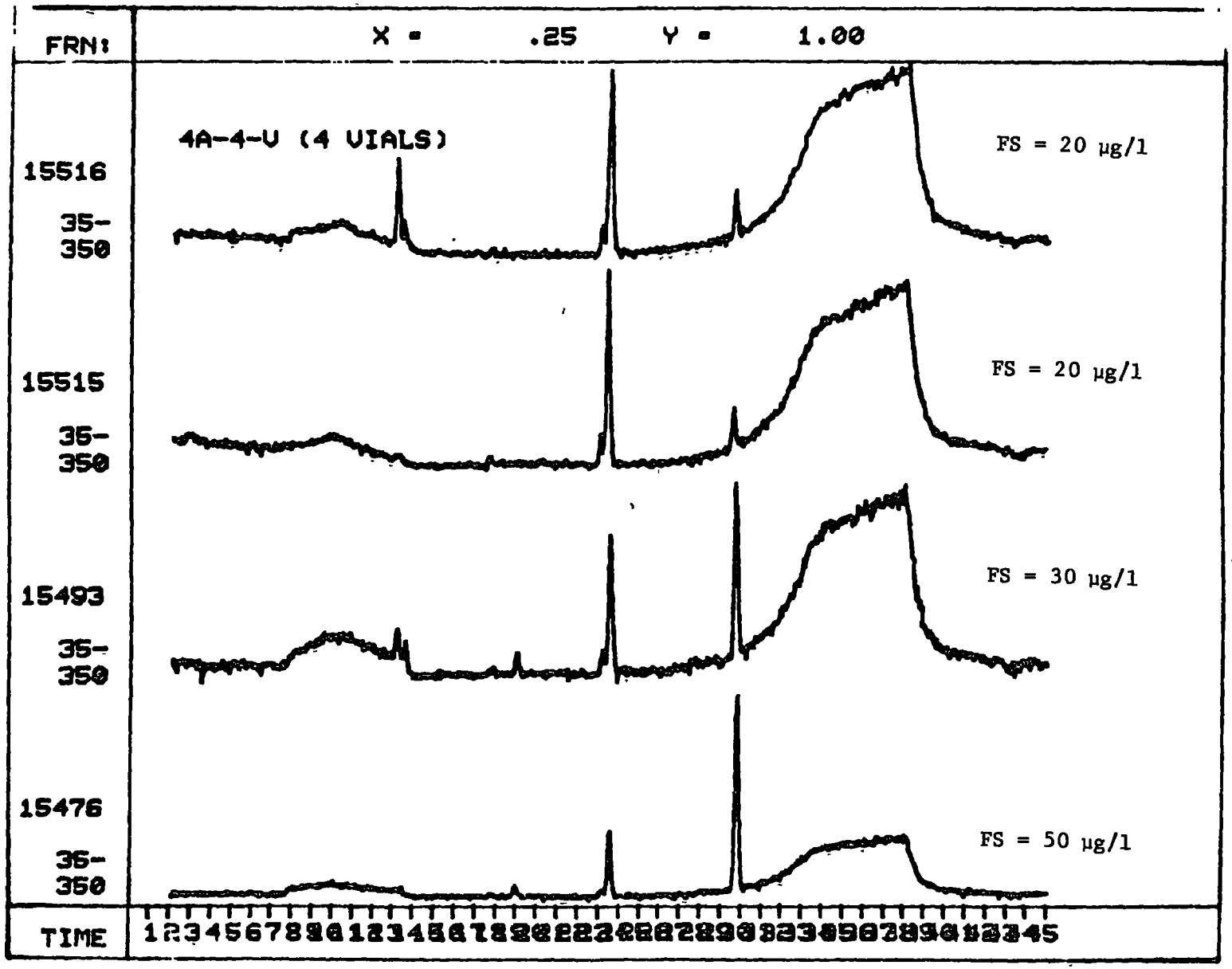


FIGURE G8-5 (continued)

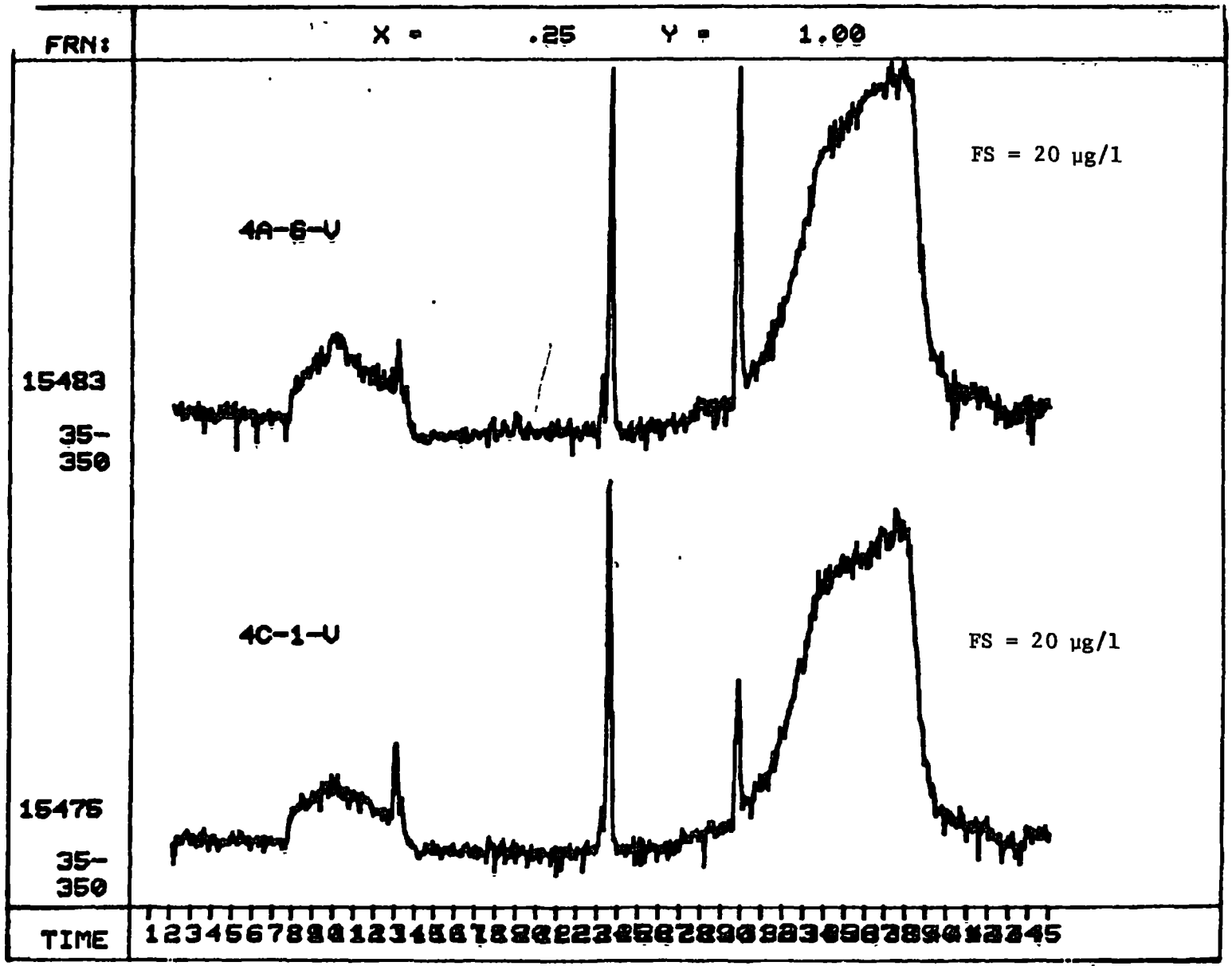
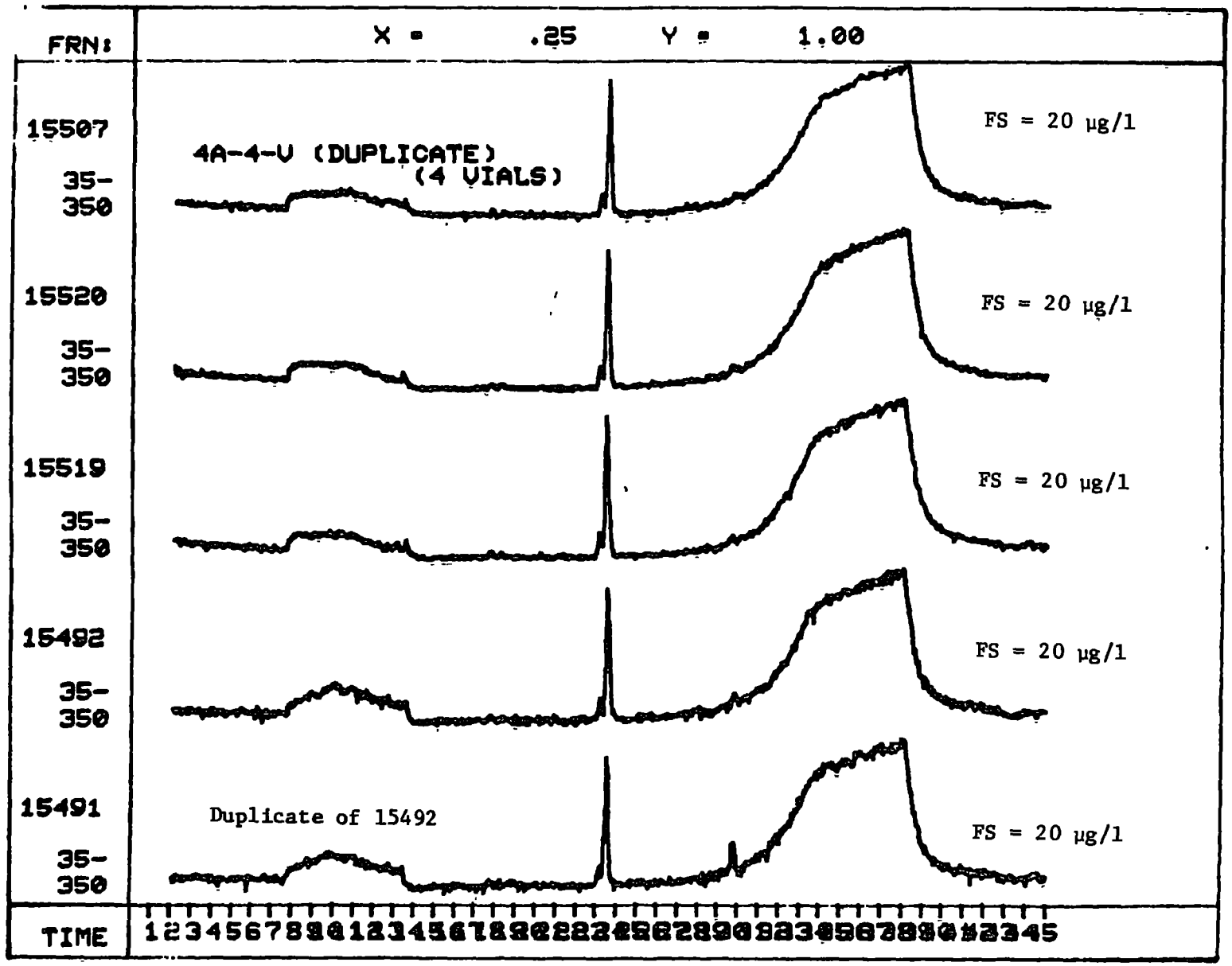


FIGURE G8-5 (continued)



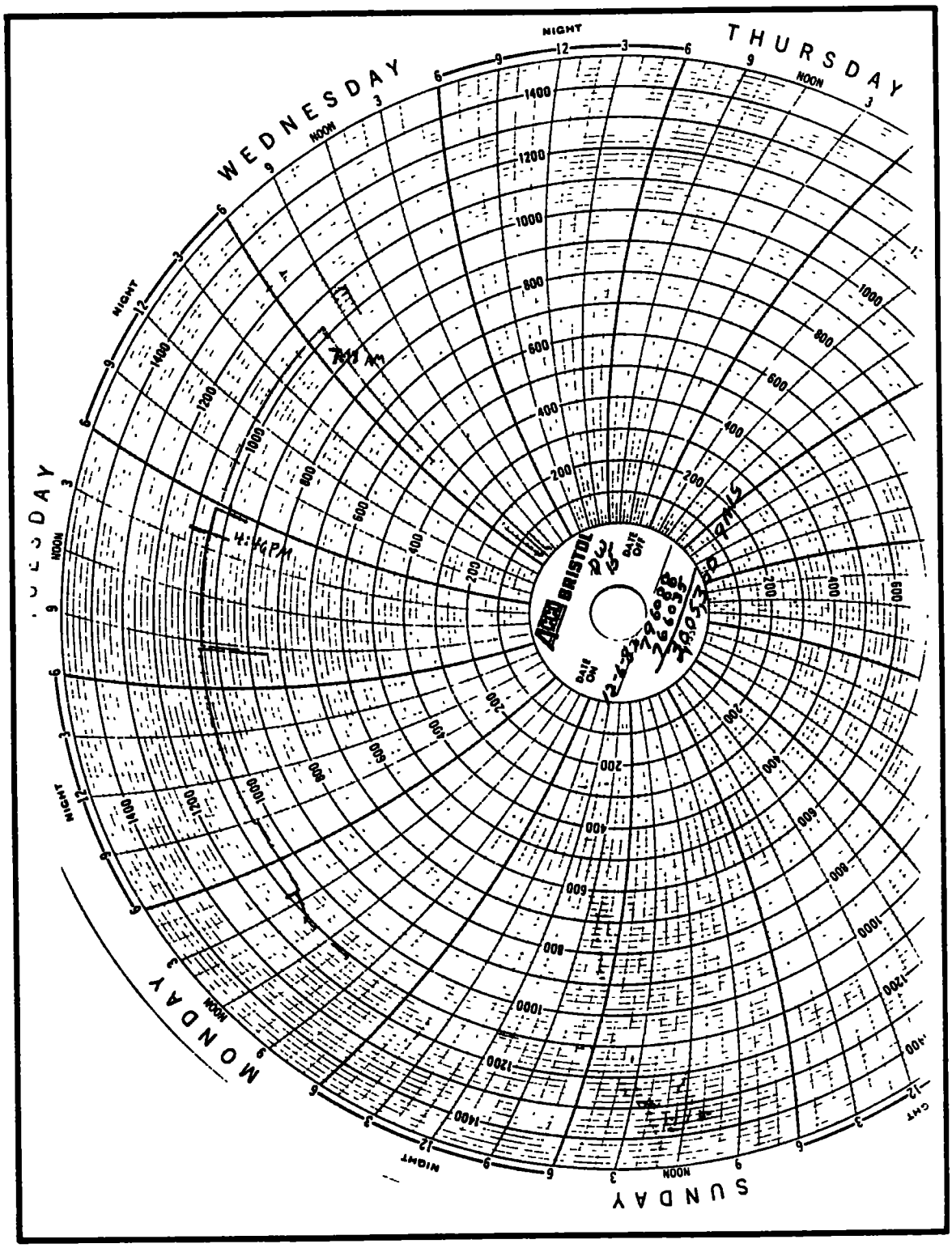


Figure G8-6 Recording Chart for St. Louis Park Well SLP15 Flowrate During ERT's December 6-8, 1982 Test (Units are gallons per minute)

8303042

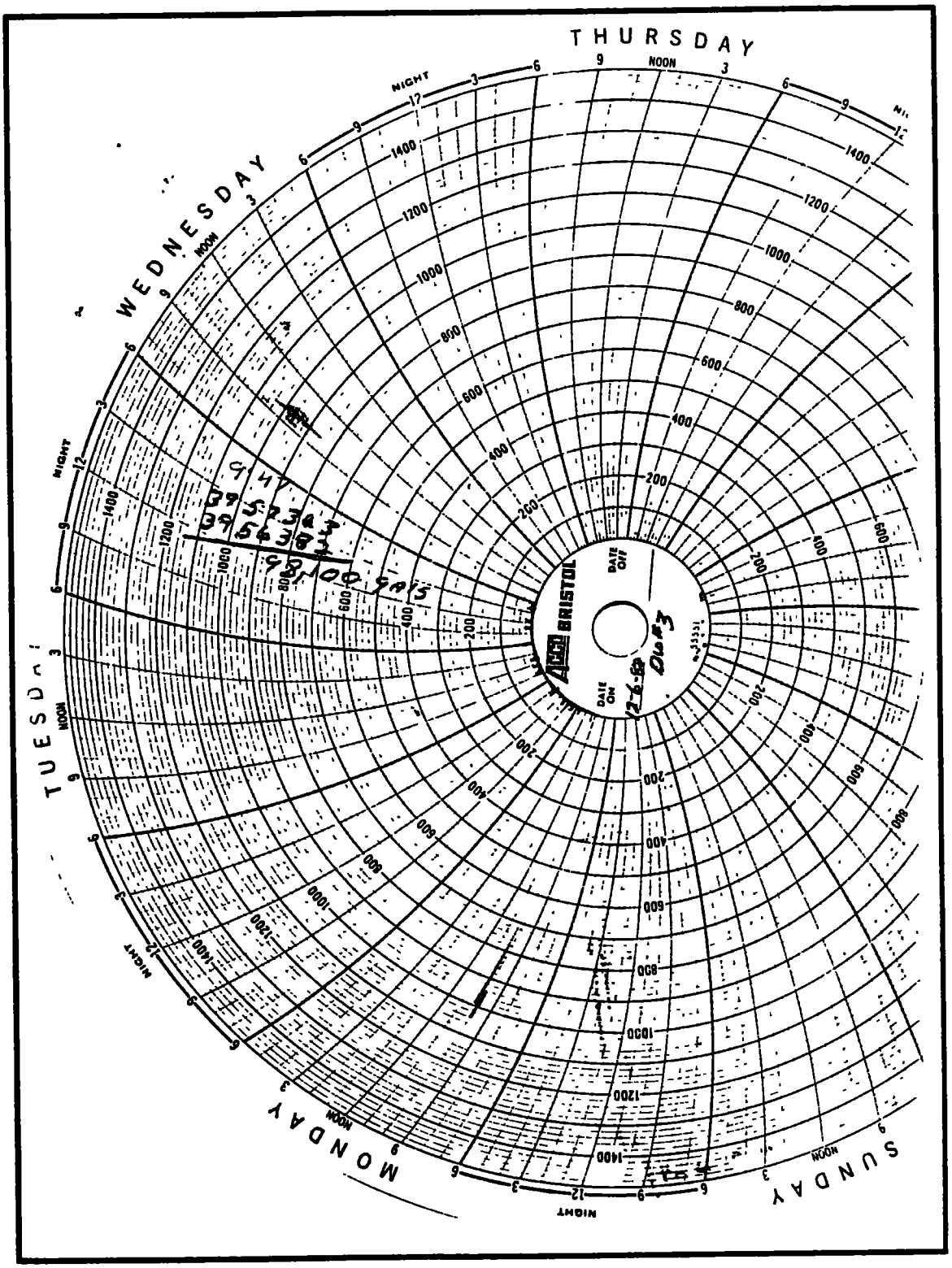


Figure G8-7 Recording Chart for St. Louis Park Well SLP15 Flowrate During ERT's December 6-8, 1982 Test (Units are gallons per minute)

8303043

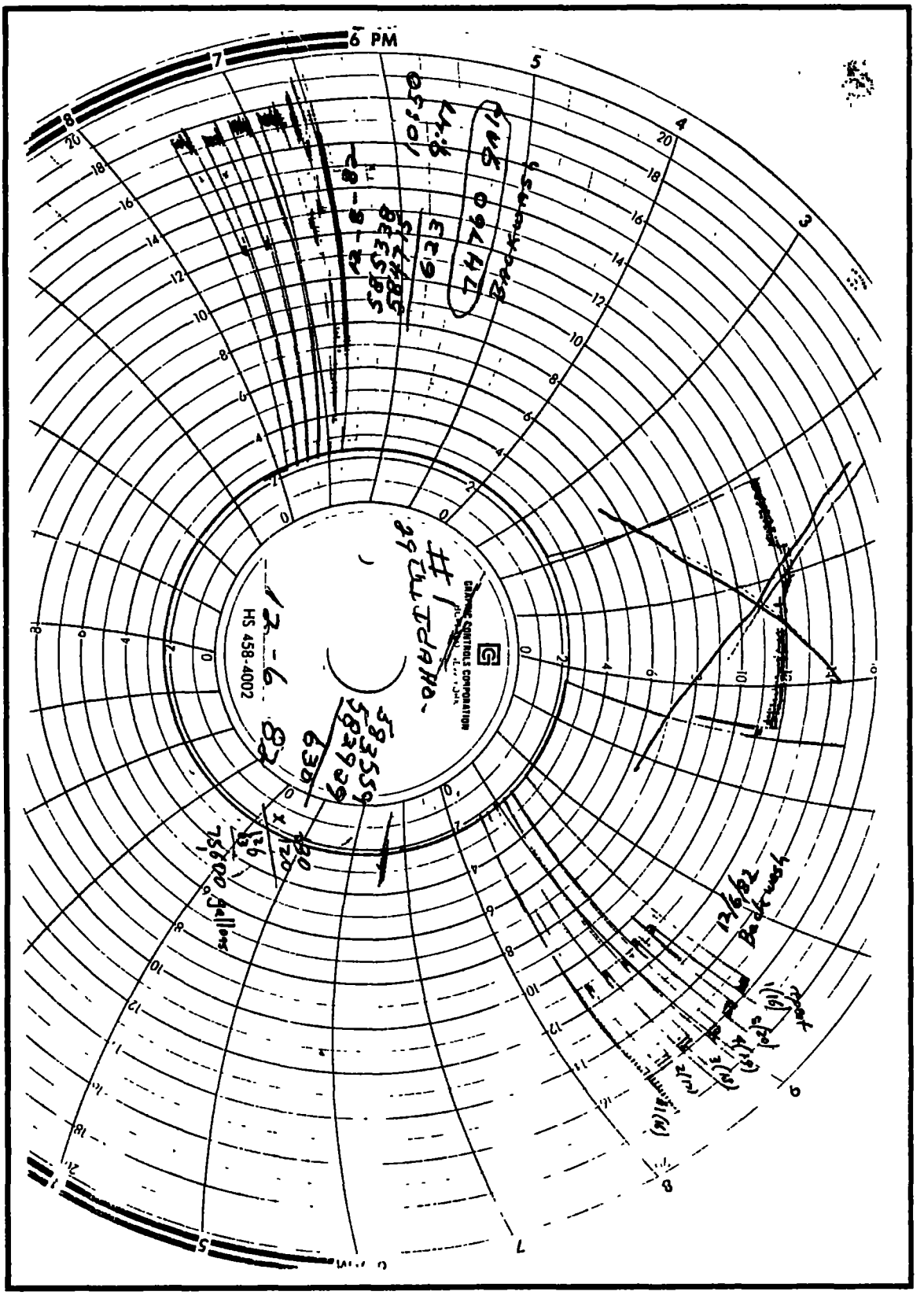


Figure G8-8 Recording Chart for Backwash Controller During ERT's December 6-8, 1982 Test (Units are hundreds of gallons per minute)

8303044

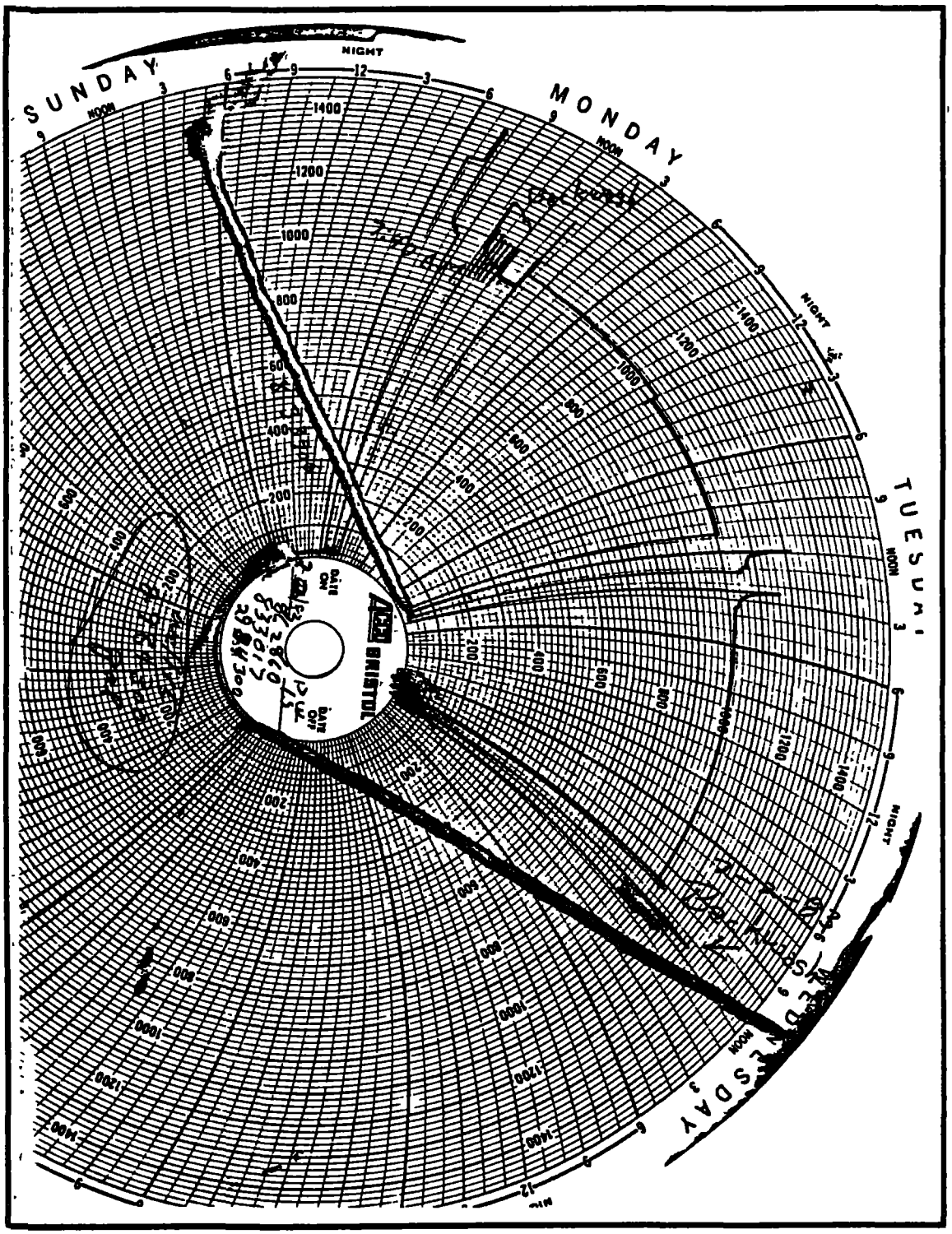


Figure G8-9 Recording Chart for St. Louis Park Well SLP15 Flowrate During ERT's February 1-2, 1983 Test (Units are gallons per minute)

8303046

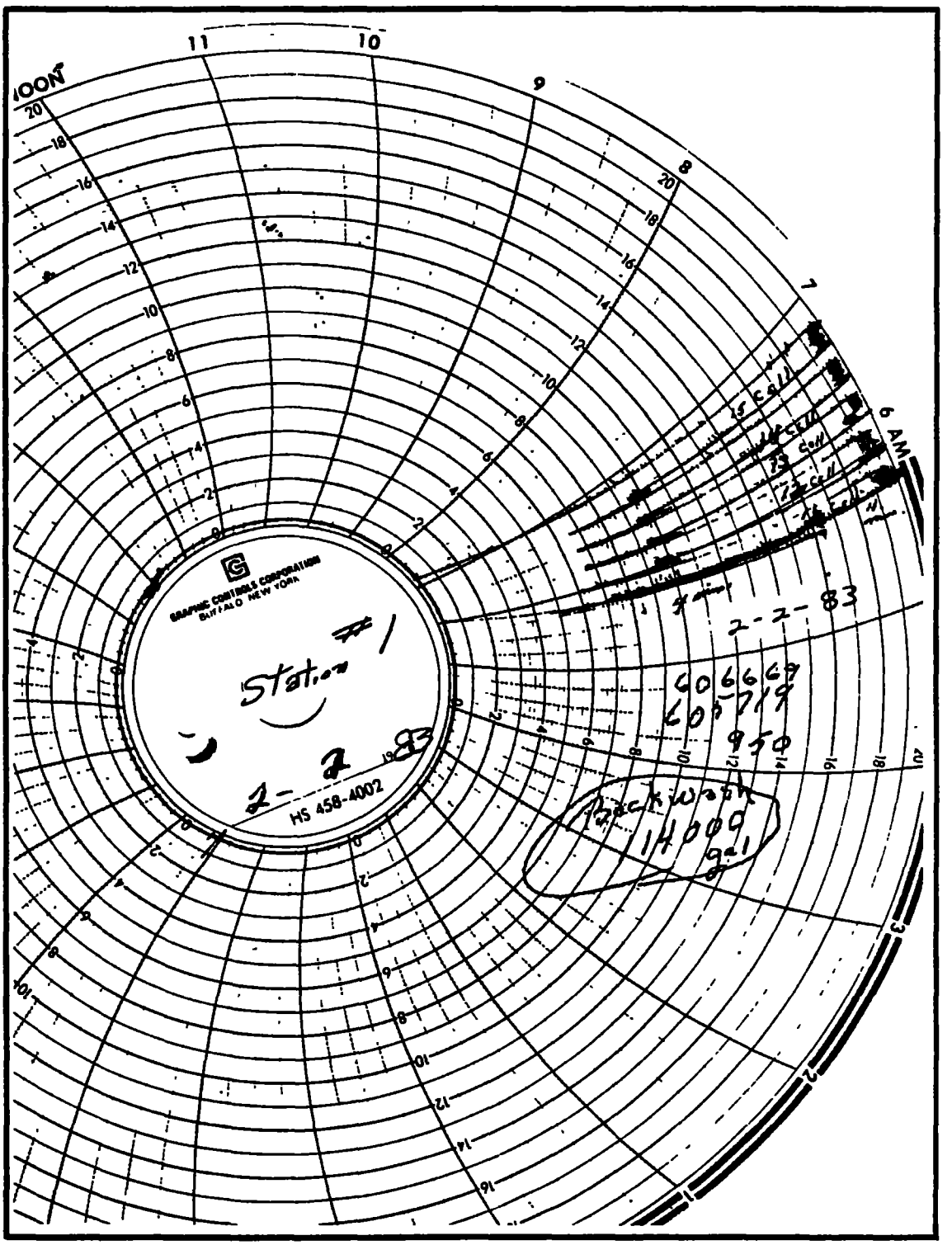


Figure G8-10 Recording Chart for Backwash Controller During ERT's February 1-2, 1983 Test (Units are hundreds of gallons per minute)

8303046

ERT
A COMSAT COMPANY
ENVIRONMENTAL RESEARCH & TECHNOLOGY, INC.
696 VIRGINIA ROAD, CONCORD, MASSACHUSETTS 01742, USA

CONCORD, MA (617) 369-8910 **FORT COLLINS, CO** (303) 493-8878
PITTSBURGH (412) 261-2910 **WASHINGTON, DC** (202) 887-0790
HOUSTON (713) 977-6611 **LOS ANGELES** (213) 889-5313
ATLANTA (404) 955-3121 **CHICAGO** (312) 620-5900
DENVER (303) 779-6940