CAA
58391

08-059-00701

LEYDEN GAS STORAGE
L&U ESTIMATE CALCULATION
10/5/90

Estimated remaining gas in void storage;

8.42 MMCF/psig X 69 psig =	0.58 BCF
Estimated recoverable gas in formation	+ 0.4 BCF
Estimated remaining total recoverable gas in storage	0.98 BCF

A stabilized cavern pressure was not extrapolated, but the 0.4 BCF is assumed to include the gas volume associated with pressure stabilization. This 0.4 BCF is equivalent to a 48 psig increase in cavern pressure (8.42 MMCF/psig x 48 psig = .4 BCF). The 0.4 BCF is probably optimistic, but is a reasonable figure to use with this quick calculation method.

Book remaining vol	1.6 BCF
Calc est remain vol	0.98 BCF
Potential L&U	0.62 BCF

Brad Hulbert

A 26

PSC 039876

3 BCF MAXIMUM STORAGE CAPACITY
(AS REPORTED IN ANNUAL ACA REPORTS)

BUT, AS OF 11/30/90, TOTAL GAS IN STORAGE IS 3.461 BCF (BOOK)

12/12/90 243.3

CAVERN PRESSURE ON 11/30/90 IS 246.1 PSIG & IS FAIRLY STABLE (DROPPING 0.28 #/day IN 5 DAYS AFTER 11/30)

77.72

(250 − 246.1) PSIG × 11.6 MMCF/PSIG = 45.24 MMCF REQUIRED TO GET CAVERN PRESS UP TO 250 #. THIS IS A MINIMUM BECAUSE THE PRESSURE IS DROPPING (NOT STABLE @ 246.1). still not stable @ 243.3

Dec 12 243.3#

3.461 BCF IN STORAGE @ 246.1 # (BOOK VOL)
+ 77.72 + 0.045 BCF REQ. TO GET TO 250 #
= 3.539 3.506 BCF ESTIMATED TOTAL BOOK VOL @ 250 #

3.539 3.506 BCF BOOK VOL
− 3 − 3.0 BCF TOTAL STORAGE CAPACITY
0.54 BCF LEU 0.506 BCF LEU

IF THE MAXIMUM STORAGE CAPACITY IS 3 BCF, THEN 0.5 BCF LEU SHOULD BE WRITTEN OFF.

0.54 THIS IS A MINIMUM

V/P RELATIONSHIP IS 11.6 MMCF/PSIG (ESTIMATED) & IS APPLICABLE FOR VERY LOW FLOW RATES. THIS REFLECTS THE TRUE TOTAL STORAGE VOLUME, WHICH INCLUDES SAND POROSITY, COAL ADSORPTION, & OPEN VOID STORAGE.

11.6 MMCF/PSIG × 250 PSIG = 2900 MMCF = 2.9 BCF
AT 12 MMCF/PSIG, & 250 PSIG ⇒ 3000 MMCF = 3 BCF
THE V/P RELATIONSHIP IS DEPENDENT UPON DRAWDOWN OR INJECTION RATE, STABILIZATION TIME, CAVERN WATER VOLUME, & INJECTION/WITHDRAWAL ACTIVITY.

PSC 039877

A 27

B. HOLLENBAUGH 12/27/90

3 BCF MAX STORAGE CAPACITY (CONTINUED)

THE FASTER YOU INJECT/WITHDRAWAL, THE LOWER THE V/P FOR THAT PERIOD.

THE LONGER THE STABILIZATION TIME (AFTER SHUT IN), THE HIGHER THE V/P FOR THE (INJ/WITHD + STABILIZATION) PERIOD.

JUSTIFICATION FOR V/P = 11.6 MMCF/PSIG

THE 8/26/80 JOHN SHEALY REPORT YIELDS A V/P OF 11.6 MMCF/PSIG FOR STABILIZED CAVERN PRESSURES.

AN EVALUATION OF THE PERIOD BETWEEN 2/14/90 AND 7/10/90 YIELDS A STABILIZED V/P WHICH IS IN EXCESS OF 10.5. THIS PERIOD WAS NOT YET STABLE AS OF 7/10/90, AND V/P WILL BE > 10.5 WHEN STABILITY IS ACHIEVED.

START DRAWDOWN 2/14/90 FROM 244.4 # & VOL CAV = 3427491 MCF
SHUT IN 5/1/90 AT 49.3 # w/ VOL CAV = 1620628 MCF
BUILDUP TO 7/10/90, TO 72 # w/ VOL CAV = 1620628 MCF
NOT YET STABLE AT 72 #

244.4 #	3427491 MCF	⟹	$\frac{1806.863 \text{ MMCF}}{172.4 \text{ PSI}} = 10.5 \frac{\text{MMCF}}{\text{PSIG}}$
− 72 #	− 1620628 MCF		
172.4 #	1806.863 MCF		

IF WE ASSUME 11.6 MMCF/PSI IS VALID WHEN STABLE, THIS GIVES A STABILIZED CAV PRESS OF 88.6 PSIG VS. 72 PSIG. THIS IS A REASONABLE NUMBER, AS CAN BE SEEN BY VISUALLY EXTRAPOLATING THE ATTACHED TWO CURVES.

THE CONCLUSION OF 0.5 TO 0.54 BCF L&U IS CONSERVATIVE ON THE LOW SIDE BECAUSE, (1) CAVERN PRESS IS NOT YET STABLE & STILL DROPPING, & (2) THE ACTUAL MAX STORAGE CAPACITY COULD BE LESS THAN 3 BCF.

B HOLLENBAUGH 12/27/90

A-28

THE ACTUAL MAXIMUM STORAGE CAPACITY IS PROBABLY BETWEEN 2.64 BCF & 3 BCF

LOOKS GOOD *

PER MINE RECORDS; 5941 720 tons = 1.1883×10^{10} lb
DENSITY AT 84.9 #/FT^3
1.1883×10^{10} lb / 84.9 lb/ft^3 = 140×10^6 ft^3
ORIGINAL VOID = 140 MMCF

STOOPING PROCESS & COLLAPSE/UNCONSOLIDATION OF COAL & ROCK WOULD REDUCE THIS VOID, AS WOULD WATER WHICH OCCUPIES IT.

ACTUAL STORAGE SPACE IS INCREASED BY: AVAILABLE PORE SPACE IN SANDS, COAL CLEAT & ADSORPTION SYSTEMS, & DISPLACING WATER OUT OF ADJACENT AQUIFERS.

IT IS VERY UNLIKELY THAT THE MAXIMUM EFFECTIVE AVAILABLE STORAGE CAPACITY EXCEEDS 3 BCF.

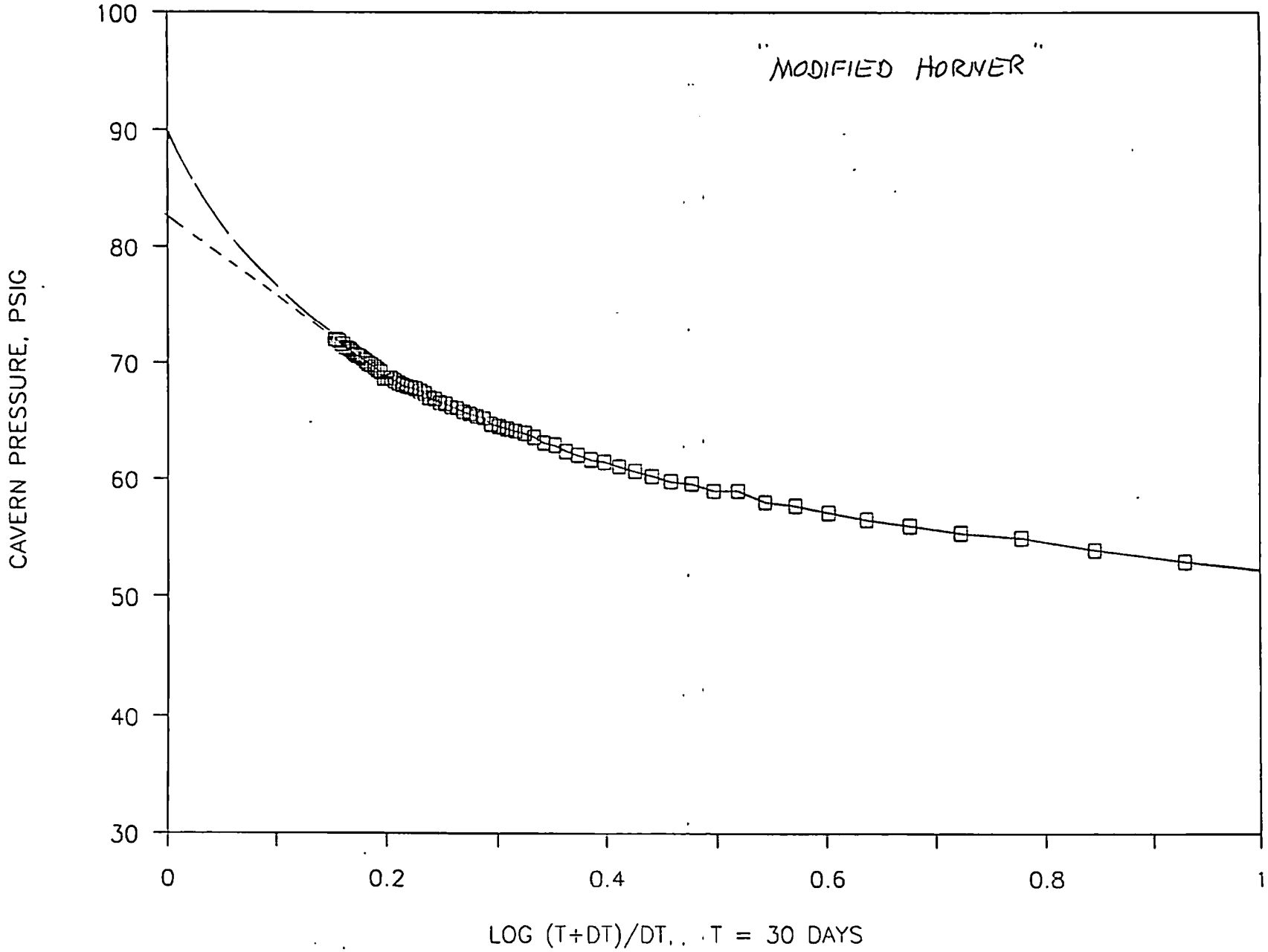
* MAX STORAGE CAPACITY (@ 250 PSIG) IS 3 BCF @ 14.65 PBASE. SEE "STORAGE VOLUME THEORY & CALCULATIONS" DATED 1/17/91 IN THE "PRESSURE-VOLUME RELATIONSHIP" FILE, BH 1/31/91

PSC 039879

B. HOLLENBAUGH 1/2/91

LEYDEN PRESSURE BUILDUP

MAY 1, 1990 TO JULY 10, 1990

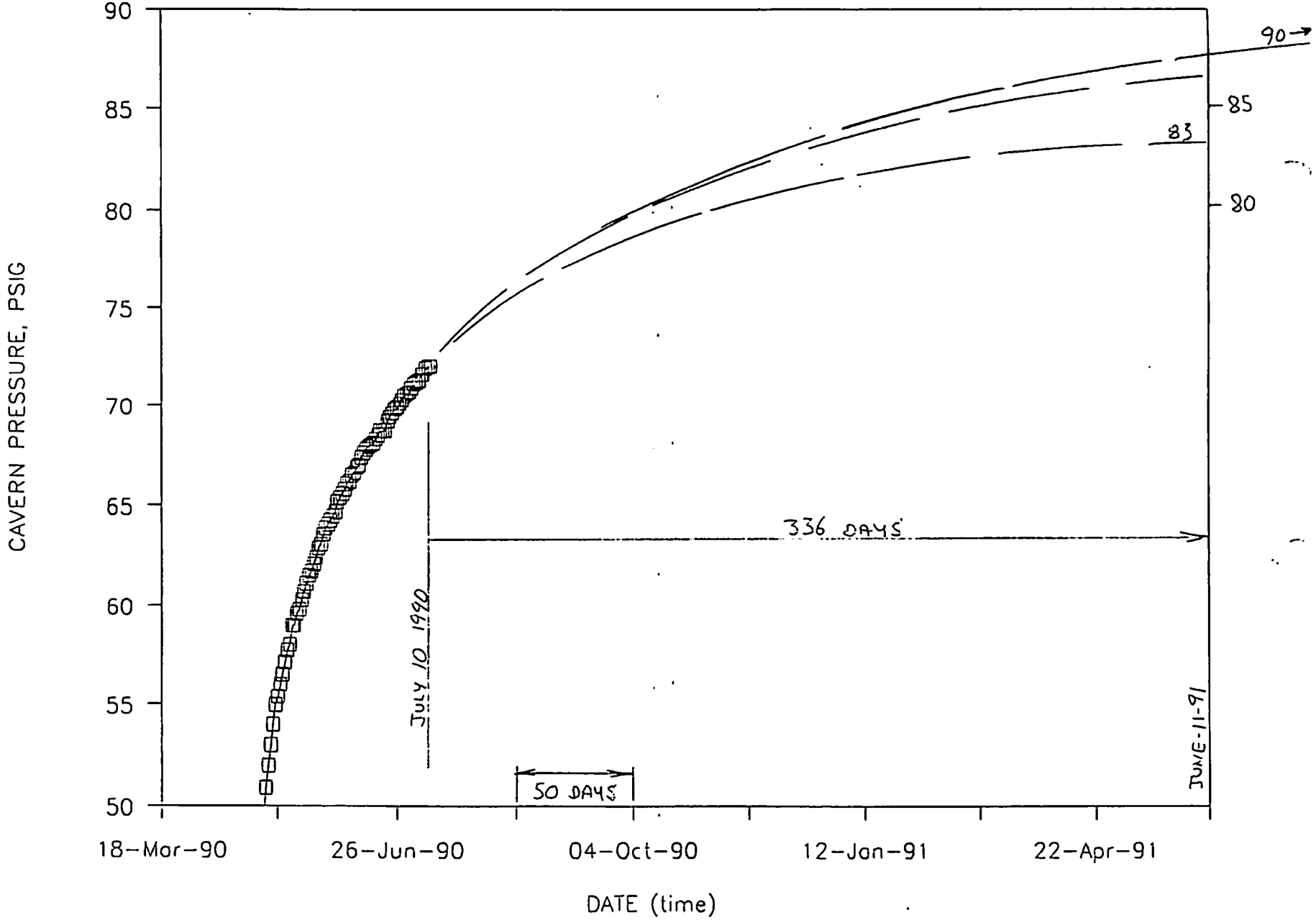


A 30

PSC 039880

LEYDEN PRESSURE BUILDUP

MAY 1, 1990 TO JULY 10, 1990



A 31

B. Hollingsworth
12/28/90

PSC 039881

1b-day BALANCE

THERE IS NO OBVIOUS CORRELATION BETWEEN 1b-day BAL & LEU. 1b-day BAL RECORDS HAVE NOT BEEN DEVELOPED FOR THE PERIODS PRIOR TO 9/1/82, AND THEREFORE NO COMPARISONS CAN BE MADE PRIOR TO 9/1/82.

LEU CALCULATIONS WERE NOT DONE FOR SEVERAL YEARS SINCE 1982, AND THEREFORE COMPARISONS ARE DIFFICULT SINCE 1982.

STABILIZED PRESSURES ARE DIFFICULT TO PREDICT ACCURATELY IN RECENT YEARS DUE TO THE FREQUENT INJECTION & WITHDRAWAL ACTIVITY.

PSC 039882

B. HOLLENBAUGH
12/28/90

IDEN lb x DAY BALANCE SUMMARY

	ANNUAL				CUMULATIVE SINCE 9/1/82			
AQUIFER PRESSUR	192 psi							
PERIOD	ANNUAL LB. DAY ABOVE	ANNUAL LB. DAY BELOW	ANNUAL BALANCE	AQUIFER PRESSUR FOR ANNUAL BALANCE = 0	CUMULATIVE LB. DAY ABOVE	CUMULATIVE LB. DAY BELOW	CUMULATIVE BALANCE	AQUIFER PRESSUR FOR CUMULATIVE BALANCE = 0
01-Sep-82 TO 31-Aug-83	9559.6	19117.8	-9558.2	165.8	9559.6	19117.8	-9558.2	165.8
01-Sep-83 TO 31-Aug-84	7197.6	9098.5	-1900.9	186.8	16757.2	28216.3	-11459.1	176.3
01-Sep-84 TO 31-Aug-85	7782.8	6258.7	1524.1	196.2	24540	34475	-9935	182.9
01-Sep-85 TO 31-Aug-86	6232.5	12569.7	-6337.2	174.6	30772.5	47044.7	-16272.2	180.9
01-Sep-86 TO 31-Aug-87	7015.1	602.6	-6337.2	174.6	37787.6	47647.3	-9859.7	186.6
01-Sep-87 TO 31-Aug-88	7482.6	16882.2	-9399.6	166.2	45270.2	64529.5	-19259.3	183.2
01-Sep-88 TO 31-Aug-89	6574.1	16745.8	-10171.7	164.1	51844.3	81275.3	-29431	180.5
01-Sep-89 TO 31-Aug-90	7238.6	19324.4	-12085.8	158.9	59082.9	100599.7	-41516.8	177.8

ANNUAL

CUMULATIVE

EXAMPLE: FOR 88/89, IF WE WERE USING AN AQUIFER PRESSURE OF 164.1 (INSTEAD OF 192), THE # DAY BAL. FOR THAT YEAR WOULD BE Ø.

FROM 9/82 THRU 8/90, IF WE WERE USING AN AQUIFER PRESSURE OF 177.8 (INSTEAD OF 192), THE # DAY BAL FOR THAT PERIOD WOULD BE Ø.

BRAD HOLLENBAUGH
10/30/90.

GAS CHARGING OF ADJACENT SANDS

I. SAND @ 137' GL @ WELL # 27
POTENTIAL FOR CHARGING W/ L & U GAS

1. 20' NET (ESTIMATED PER HLS COMPUTED LITH. LOG)
10 % POROSITY
50 % S_w
ASSUME RADIUS OF NET SAND IS 500'
$A = \pi/4 (500)^2 \text{ ft}^2 = 196{,}350 \text{ ft}^2$
$196\,350 \text{ ft}^2 / 43{,}560 \text{ ft}^2/\text{ACRE} = 4.5$ ACRES
10 PSIG GAS CHARGE PRESSURE

pg 1 of 5

(1) $$B_{gi} = \frac{P_b T_z}{5.615\, p\, T_b Z_b} = \frac{P_b}{5.615\, p}$$ for LOW PRESS OF 10# & DEPTH OF 137'

$$= \frac{14.65}{5.615(10+12)} = 0.11859$$

(2) $$G = 7758\, A\, h\, \phi\, (1 - S_{wi}) \frac{1}{B_{gi}}$$

$$= (7758)(4.5)\text{Acres}(20)\text{ft}(0.1)(1-0.5)\frac{1}{0.11859}$$

$$G = 294{,}384 \text{ scf} = 294 \text{ MCF}$$

PSC 039884

w/ annual L&U @ 0.1BCF, THIS IS $\frac{294 \text{ MCF}}{100{,}000 \text{ MCF}} = 0.3\%$

THIS TYPE OF CHARGING WOULD ACCOUNT FOR 3/10 OF A PERCENT (0.3%) OF THE ANNUAL L & U.

2 ASSUME THIS SAND IS CONTINUOUS THROUGH OUT THE STORAGE FIELD, & ∴ HAS AN AREA OF 1100 ACRES.

$G = 294 \text{ MCF} \times 1100/4.5 = 71\,867$ MCF, OR ABOUT 72% OF THE ANNUAL L & U VOLUME

B. HOLLENBAUGH
1/2/90

3. ASSUME THE SAND HAS A NET THICKNESS OF 2' (VS 20') AND AN AREA OF ABOUT 500 ACRES;

$$G = (294)\ \text{MCF} \times \frac{500\ \text{ACRES}}{4.5\ \text{ACRES}} \times \frac{2'}{20'} = 3267\ \text{MCF}$$

WHICH IS ABOUT 3% OF THE ANNUAL LEU.

A 35

B. HOLLENBAUGH
1/2/90

METER ERROR ? 1983 THRU 1990

FROM 1983 THRU 1990, A NET OF 30,400 MCF OF LEU WAS WRITTEN OFF.

FROM 1983 THRU NOV, 1990: (8 YEAR PERIOD)

TOTAL INJ.	12,049,873 MCF	
TOTAL WITHD	11,373,430 MCF	
	676,443 MCF	NET INJECTION

A +4% METERING ERROR ON INJECTED VOLUMES (ONLY INJECTED VOLUMES) WOULD PRODUCE A + 0.5 BCF ERROR FOR THIS TIME PERIOD.

ACTUAL NET LEU WRITTEN OFF FOR THAT PERIOD WAS 30,400 MCF (0.03 BCF).

TOT INJ	TOT INJ/YEAR	TOT WITHD	WITHD/YEAR	INJ + WITHD TOTAL ACTIVITY	INJ + WITHD ACTIVITY/YEAR
12 050 MMCF	1 506 MMCF	11 373 MMCF	1 422 MMCF	23.423 MMCF	2928 MMCF

$$\frac{0.1 \text{ BCF LEU}}{1.506 \text{ BCF}} = 6.6\%$$

A 37

II. CALC ACRES CHARGED IN 30 YEARS BY L&U.

AS AN EXAMPLE, THE TOTAL FIELD L&U OF 2.3 BCF WOULD OCCUPY ABOUT 990 ACRES IF IT HAS CHARGED A 50' THICK NET SAND AT 20% ϕ & 50% S_w, AND 150 PSIG CHARGE, THE MINE COVERS ABOUT 1100 ACRES.

Pg 3 of 3

THIS IS PER EQN 2, SOLVING FOR A, W/:

$P = 162$ PSIA $\qquad G = 2.3$ BCF
$S_w = 0.5$
$\phi = 0.2$
$Z = 0.989$

$$A = \frac{G B_g}{7758\, h\, \phi\, (1-S_w)} = \frac{2.3\times10^9 \dfrac{(14.65)(85+460)(0.989)}{(5.615)(162)(520)(1)}}{(7758)(50)(0.2)(0.5)}$$

$$= 990 \text{ ACRES}$$

SEE "GEOLOGICAL REPORT ON THE LEYDEN GAS STORAGE FACILITY" BY CHARLES BARROWS, FUELCO, DATED 8/1988 FOR SIMILAR PROJECTIONS.

THIS SAND (OR SUMMATION OF SANDS) WOULD NEED TO BE REMOTE FROM THE STORAGE FORMATION SUCH THAT THE GAS IS NOT ECONOMICALLY/READILY RECOVERABLE. THIS IS NON-RECOVERABLE L&U GAS

PSC 039887

A 36

B. HOLLENBAUGH
1/2/90

LEYDEN GAS BLOWN @ SURFACE — ANNUAL ESTIMATES

a. WELL 12. $\boxed{500 \text{ MCFY}}$ - VENTED & BLOWN TO KEEP GAS BUBBLE FROM FORCING WATER AWAY FROM PUMP.

b. GAS SEPARATOR w/ WELLHEAD PANS! 40" DIA SEP.

$$\left(\frac{40}{12}\right)^2 \pi/4 \times 11' = 96 \text{ ft}^3 \Rightarrow 100 \text{ ft}^3$$
$$+ 30' \text{ OF } 10'' \text{ PIPING} \Rightarrow \left(\frac{10}{12}\right)^2 \pi/4 \times 30 = 16 \text{ ft}^3 \quad \Big\} \; 120 \text{ ft}^3$$

$$120 \text{ ft}^3 \; \frac{240 + 12}{14.65} = 2{,}064 \text{ ft}^3 \text{ gas } (14.65) \text{ @ } 240 \text{ PSIG}$$

= 2 MCF PER BLOWDOWN PER WELL

× 9 WELLS ON LINE

18 MCF PER BLOWDOWN PER FIELD

× 15 BLOWDOWNS PER YEAR - COVERS MAINTENANCE & BLOWING WATER OUT.

270 MCF

$\Longrightarrow$ $\boxed{300 \text{ MCFY}}$

c. LEAKING VALVES - EST TOTAL VALVE LEAKAGE AT ABOUT 1 MCFH (SOME SEP DUMP VALVES LEAK A LOT THROUGHOUT THE YEAR).

1 MCFH × 24 H/D × 365 D/YEAR = $\boxed{8{,}800 \text{ MCFY}}$ ← COULD BE TOO HIGH?

THIS ALSO INCLUDES CONTRIBUTION OF OTHER LEAKING COMPONENTS

d. WORKOVER OPERATIONS

8 5/8 CSG ⇒ 8" ID @ 800' DEPTH

$(8/12)^2 \pi/4 \; 800 = 279 \text{ ft}^3$

$280 \text{ ft}^3 \times \frac{150 + 12}{14.65} = 3096 \text{ ft}^3 = 3 \text{ MCF PER BLOWDOWN}$

EST. 8 BLOWDOWNS PER YEAR = 24 MCFY ⇒ $\boxed{30 \text{ MCFY}}$

e. GAS HEATERS IN SEPARATORS -

EST 6 MONTHS/YEAR, 9 WELLS, 100 CFH LOAD

100 CFH × 24 H/D × 365/2 days/year = 438 000 CFY = 440 MCFY

$\boxed{400 \text{ MCFY}}$

PSC 039888

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B. HOLLENBAUGH
1/3/91

f. STATION BLOWING GAS - PER 1990 FIGURES IN "SUMMARY OF GAS DELIVERED" REPORTS, THERE WAS 220 MCF REPORTED GAS BLOWN. THIS SEEMS LIGHT, ROUND UP TO $\boxed{500 \text{ MCF/Y}}$

g. GATHERING SYSTEM BLOWDOWN

GENERALLY USE COMPRESSION TO PULL GATHERING SYSTEM DOWN TO ≈ 50 PSIG PRIOR TO BLOW DOWN & PIG.

BST GAS TO RUN PIG THRU: X 5 PIG RUNS =

62 PSIA BEFORE BLOW DOWN

KNOCK OUT TANK VOLUME BST @ 1571 ft^3

GATHERING SYSTEM PIPING VOLUME 54 561 ft^3

56 132 ft^3

$$56\,132 \text{ ft}^3 \times \frac{(50+12)\text{ PSIA}}{14.65 \text{ PSIA}} = 237{,}555 \text{ scf}$$

$$= 238 \text{ MCF}$$

AT MAX, AVG OF 2 BLOW DOWNS /YEAR ⟹ 480 MCF

THIS WILL ALSO ACCOUNT FOR GAS USED TO RUN PIGS THRU LINE.

SUMMARY - GAS BLOWN @ SURFACE

a	Well 12	500 MCF/YEAR	
b	BLOWDOWN OF GAS SEPS	300	
c	LEAKING VALVES & COMPONENTS	8,800	CUMMULATIVE
d	WORKOVER OPERATIONS	30	↓
e	GAS HEATERS IN SEPARATORS	400	⇒ 10 030/YEAR
f.	GAS BLOWN AT STATION	500	10 530 MCF/Y
g	GATHERING SYSTEM BLOWDOWN	480	
		11 010 MCF/YEAR	

99 526 ft^3
6 miles 24" @ 150#
⟹ 1,100 MCF

$$\frac{0.011}{0.1} = 11\%$$

⟹ 11 000 MCF/YEAR
= 11 MMCF/Y
= 0.011 BCF/Y

B. HOLLENBACK
1/3/91

A 40

LEYDEN INJECTION AND WITHDRAWAL
MCF @ 14.65 psi

YEAR	INJECTION	WITHDRAWAL	MAX VOL	DATE MAX V
1963	1221265	466096		
1964	2555422	2367484		
1965	4240333	3965501		
1966	2793165	2904758		
1967	2492612	2874759		
1968	2513328	2345001		
1969	3372195	2886755		
1970	2371900	1951494		
1971	1225805	1088610		
1972	2441378	2570220		
1973	1997856	1772579		
1974	2526165	2446193		
1975	3178862	3051250		
1976	2706279	2707792		
1977	3063997	2865967		
1978	3299630	3763276		
1979	3942511	3246330		
1980	915289	818041		
1981	1870500	1685936		
1982	2250854	2250777	2 851 653	1/20/82
1983	2178244	2306530		
1984	1271501	898303		
1985	983561	874220		
1986	1357006	1209532		

* Data is from February 1 to December 31

1987	625 041	461 790	3471 376	12/10/87 249.6
1988	1 629 912	1 936 261	3 471 376	1/3/88
1989	2 121 220	1 862 546	3 401 701	12/28/89
1990				

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LONDON BLOWN GAS AT STATION -

PETR GAS MEAS REPORTS:

~~LONDON MONTHLY BLOW DOWN REPORT~~

NOV	1990	Ø			
10		148 CCF	DEC	89	Ø
9		Ø	11		Ø
8		Ø	10		89 CCF
7		Ø	9		Ø
6		Ø	8		Ø
5		Ø	7		Ø
4		Ø	6		Ø
3		2655 CCF	5		Ø
2		0	4		Ø
1/90		0	3		Ø
		2803 CCF	2		Ø
		= 280 MCF	1/89		Ø

PETR "SUMMARY OF GAS DELIV." REPORTS IN CHART PROCESSING'S FILE

NOTE: I DON'T THINK THESE REPORTED FIGURES ARE EVER SUBTRACTED FROM "TOTAL IN STORAGE" ON GAS MEAS REPORTS

PAGE 3 OF 4

B. HOLLENBAUGH
1/3/91

BROWSE -- T0509.GASSSOUT ---------- LINE 00000161 COL 001 080
COMMAND ===> SCROLL ===> CSR

** SOLUTION TOLERANCES **

FROM STONER MODEL PER PLANNING.

NODE FLOW (UNITS GIVEN ABOVE) 0.0010
UNKNOWN CORRECTION (DIMENSIONLESS) 0.010000
MAXIMUM NUMBER OF ITERATIONS 20
* * * * * * * PIPE SIZE SUMMARY * * * * * * * *

CONVERT TO FT

VOLUME = $\pi/4 (D^2) L$

NOMINAL INCHES	COUNT	TOTAL FEET	ASSUME SCHD 40	
6	1	200.00	6.065" ID	40 ft^3
8	1	1250.00	7.981	434 ft^3
10	5	10729.99	10.020	5876 ft^3
12	5	3580.00	11.938	2783 ft^3
20	2	6799.99	18.812	13318 ft^3
23 24" ?	6	11500.00	22.626	32.110 ft^3
				54 561 ft^3

F1=HELP F2=SPLIT F3=END F4=RETURN F5=RFIND F6=RCHANGE
F7=UP F8=DOWN F9=SWAP F10=LEFT F11=RIGHT F12=RETRIEVE

KNOCK OUT TANK: BST @ 10' DIA & 20' LENGTH ?

$V = \pi/4 (10)^2 (20) = 1571 ft^3$

DETERMINING GATHERING SYSTEM VOLUME

Pg 4 OF 4

BN
1/3/91

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PSC 039892

WATER REMOVAL

WATER WITHDRAWAL DOES NOT HAVE A SIGNIFICANT EFFECT ON LEU CALCULATIONS.

ON OCCASION IN THE PAST, THE CALCULATED LEU WAS REDUCED BY AN AMOUNT OF GAS EQUAL TO THE WATER PRODUCTION FOR THAT PERIOD. THIS PROCEDURE IS ONLY VALID IF THAT PRODUCED WATER IS NEVER REPLACED BY THE AQUIFER.

IN REALITY, THE PRODUCED WATER IS REPLACED BY THE AQUIFER AS THE CAVERN PRESS GETS BELOW THE AQUIFER PRESSURE. THIS IS EVIDENT BY THE WATER INFLUX INTO THE CAVERN WHICH WAS OBSERVED DURING THE 1990 SPRING DRAWDOWN.

PSC 039893

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RH 12/31/90

Gas-storage calculations yield accurate cavern, inventory data

R. G. Mason
Transcontinental Gas Pipeline Corp.
Houston

Determining gas-storage cavern size and inventory variance is now possible with calculations based on shut-in cavern surveys.

The method is the least expensive of three major methods and is quite accurate when recorded over a period of time.

Measurement methods

Several methods exist to determine gas-storage cavern size and inventory variance. Among these are direct measurement by sonar survey, direct measurement by water fill, and volume calculation from data furnished by shut-in surveys.

The method of direct measurement is the most accurate but is also expensive, requiring a sonar log or cavern degasing. Until recently, the cavern had to be filled with water to conduct the sonar survey.

The sonar device, which measures the time of return of sound waves reflected from the cavern wall, can also be used to determine void space behind the casing. This measurement is inaccurate if a cement sheath covers the casing, which is usually the case in wells completed with high-quality techniques.

The cavern size can also be directly measured by the cavern being degased through means of a water fill. This method is not as accurate as the sonar because of a chance of measurement error between the amount of injected water and withdrawn gas.

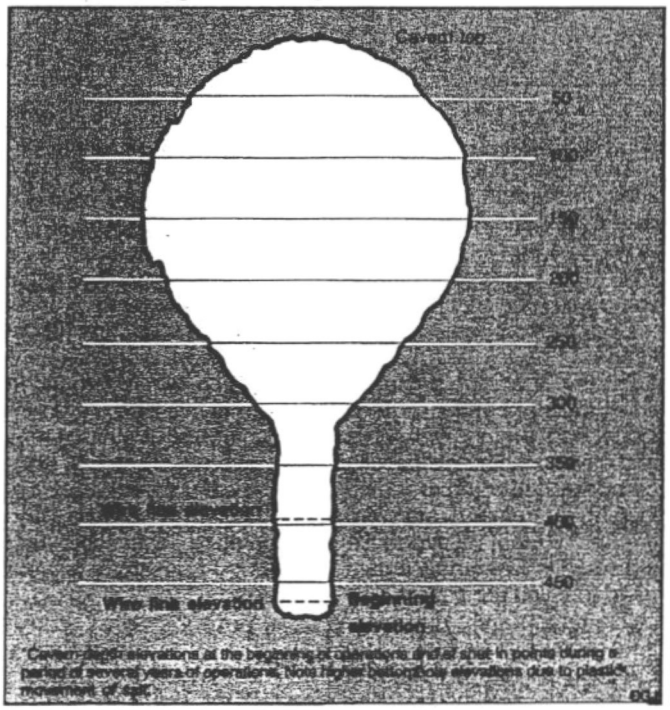
The method may cost $100,000 to $1 million because most gas-storage caverns hold more than 1 million bbl in volume, and water fill may cost $0.10-1.00/bbl. Thus, water fill is usually reserved for well maintenance which can only be achieved by killing the well.

The final method involves the calculation of inventory and cavern size from subsurface data taken during shut-in surveys.

This method is the least expensive, involving a relatively small amount of down time and inexpensive logging costs. And it is quite accurate when recorded over a period of time.

Fig. 1

Salt dome gas-storage cavern*



*Cavern depth elevations at the beginning of operations and at shut-in points during a period of several years of operations. Note higher beginning elevations due to plastic movement of salt.

Inventory variance

Many salt caverns in the U.S. that are used to store natural gas at high pressures experience unaccounted for gas losses (inventory variance) and salt creep (cavern shrinkage).

An inventory variance can be the result of gas migration or poor measurement practices. But, because salt caverns tend to be self-healing at the salt-casing contact as a result of the plasticity of salt at high temperatures and pressures, most inventory variances can be traced to poor measurement practices.

It should be noted, however, that gas migration caused by leaking tubulars above the salt stock has also been documented. This phenomenon occurs when the cement sheath is of poor quality and the sealing integrity of the collars has been compromised. Gas leaking in this manner may migrate to shallow low-pressure sands or escape at the surface.

Cavern shrinkage is a phenomenon caused by the plastic motion of the salt stock (Fig. 1). Such shrinkage is at a minimum when cavern pressure is at a maximum. Historical operating data have shown, however, that caverns can and will shrink at high storage pressures and, to a lesser degree, when filled with water.

The shrinkage occurs when the cavern pressure is less than that of the lithostatic pressures, the pressure caused by the weight of the salt and rock above the cavern and measured as slightly less than 1 psi/ft.

Cavern shrinkage can be monitored and to some extent limited by sound operating practices. General storage operations will cause cavern shrinkage due to the lower pressures associated with withdrawal activities. The maintenance of high cavern pressures, however, combined with shallow leaching depths and retention of cavern shape are factors used to limit shrinkage.

PSC 039894

Fig. 2

Pressure survey

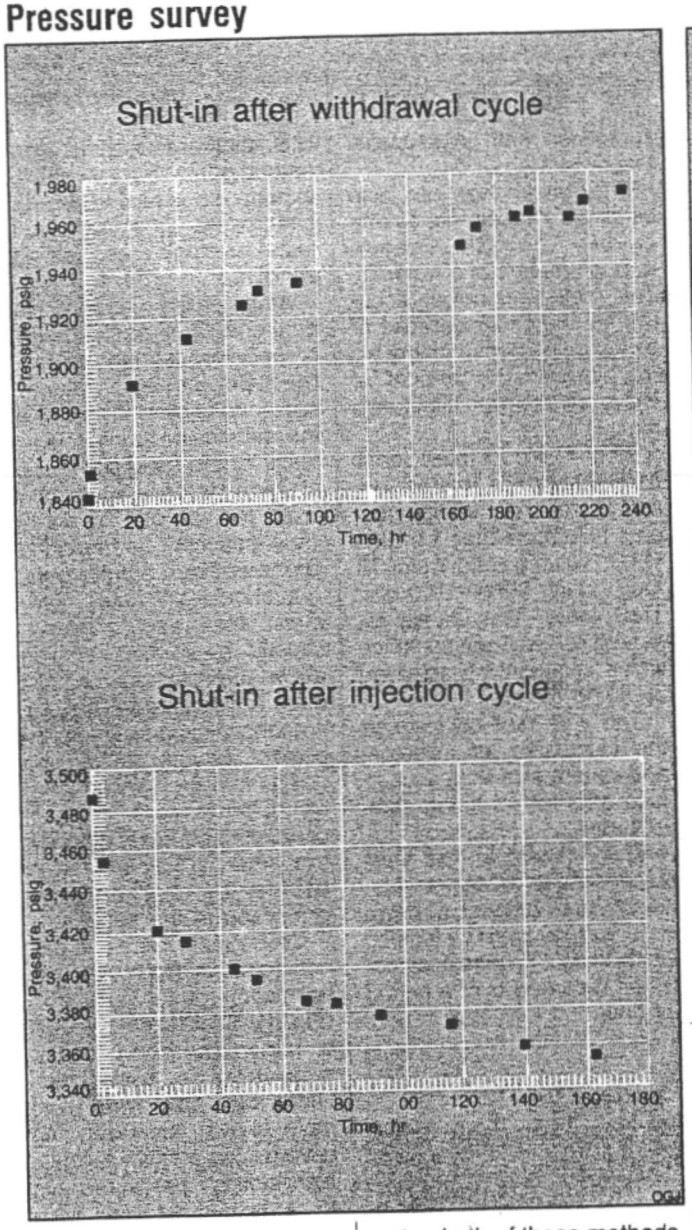
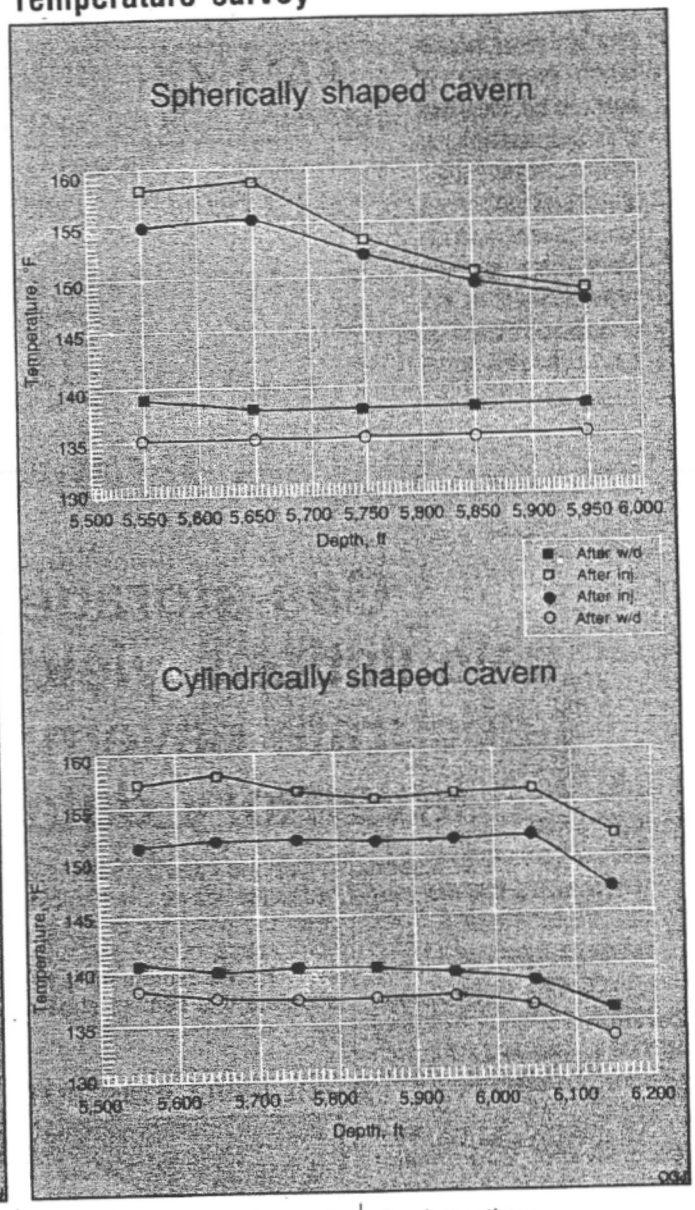


Fig. 3

Temperature survey



Cavern survey

Calculations for shrinkage and inventory, as demonstrated here, are arrived at in much the same manner as inventory verification in a porous reservoir. In addition, the same general shut-in procedure and material balance calculations are applied.

Cavern-sizing surveys are basic studies which produce information used to determine the volume of space in a salt cavern.

As previously noted, there are three methods used to discover cavern volume. Direct measurement requires the use of sonars introduced into the cavern by electric wire line, while degasing requires filling the cavern with water; both of these methods are expensive.

The third method, using subsurface data to calculate cavern volume, is the least expensive and very accurate when used with valid reservoir-engineering techniques.

Compilations and comparisons of survey results will allow the operating company time to make sound decisions concerning well bore and cavern maintenance with comparatively inexpensive logging instruments and wire line equipment. Cavern-sizing surveys that produce data used to calculate cavern size utilize temperature and pressure bombs introduced into the cavern on a slickline. These data and the resulting calculations are used to estimate inventory variance and cavern creep.

Cavern-sizing surveys involve two shut-ins and an injection or withdrawal of a finite volume of gas. The initial and final temperatures, pressures, Z factors, and injected/withdrawn volumes are data, which, when introduced into a material balance equation, produce a reasonable estimation of cavern size. This measurement and accompanying pressure and temperature data are then employed to estimate cavern inventory.

Procedure

Essential to the subsurface method are consistent procedural practices.

This procedure compares results of calculations from data obtained during sizing surveys.

A condition for comparison is analogous data. Therefore, the shut-in survey should always follow the same operating cycle, injection or withdrawal.

In this way, the procedure will generate data which produce a reliable trend with reproducible results when each survey is graphed over an extended period of time.

Another consideration for consistent practices is the amount of shut-in time before the down-hole surveys are conducted. A certain amount

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Fig. 4

Water contact

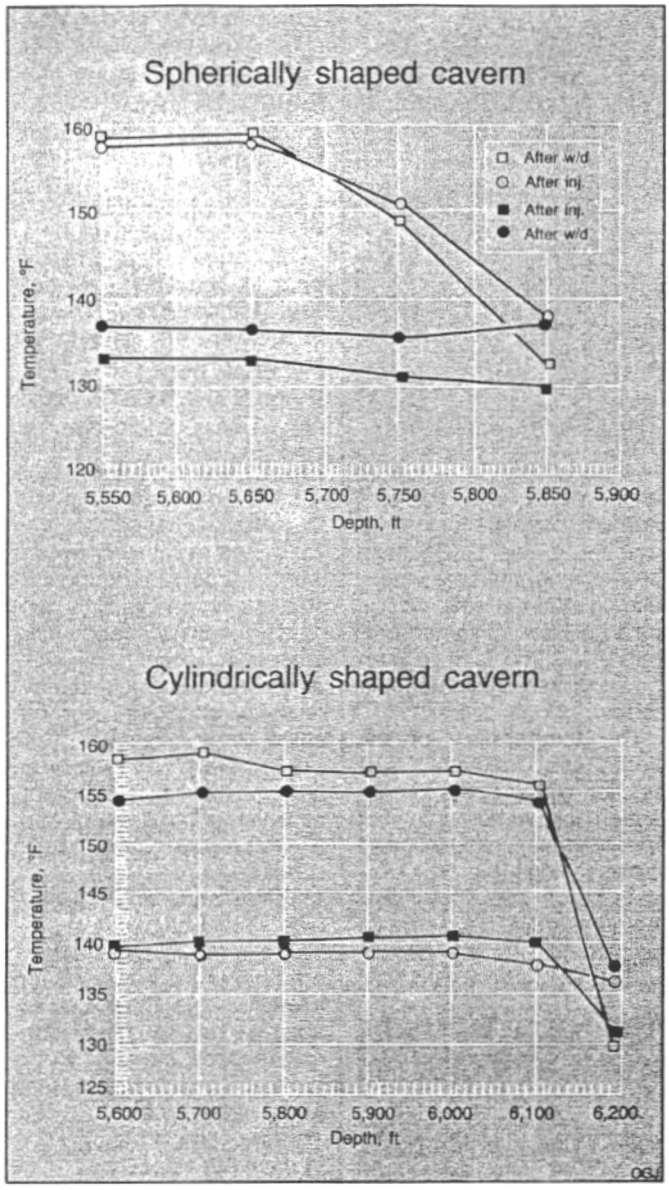


Fig. 5

Measured gas inventory*

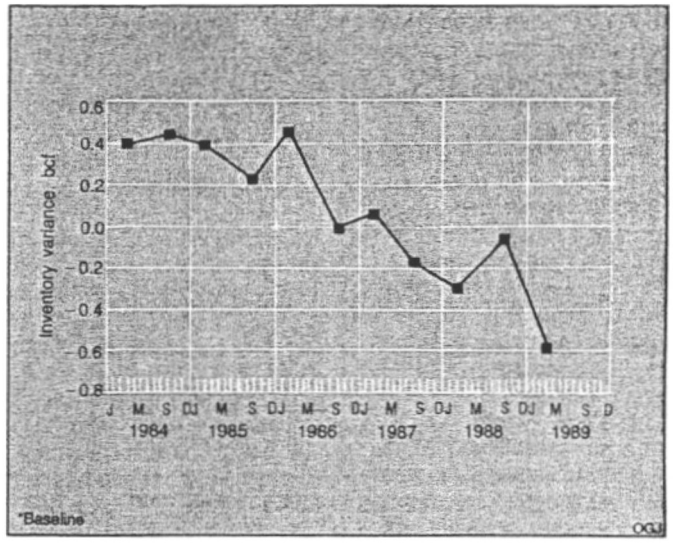
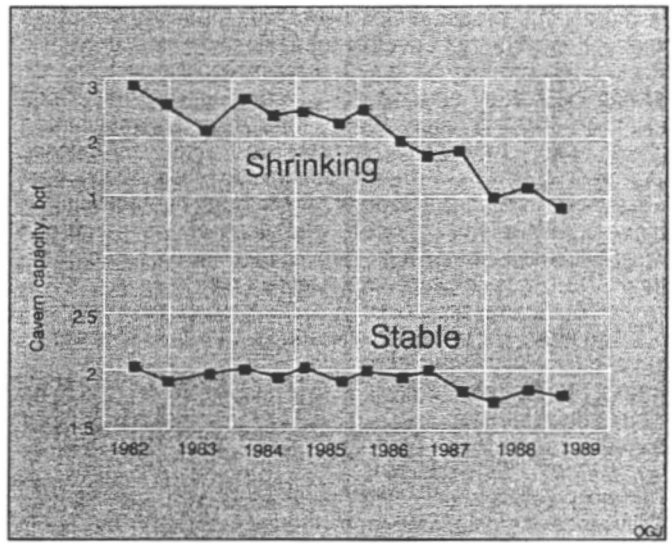


Fig. 6

Cavern capacity



of time must be allotted for the cavern pressure to stabilize.

The stabilization period varies due to the size, shape, and depth of the caverns. Generally, the time required to allow the cavern pressure to stabilize may be predicted by a graph of the daily wellhead pressures and observation of an asymptotic curve trend.

Fig. 2 shows examples of near stabilized shut-in periods. It is worth noting, however, that the cavern is usually shut-in for a period of time that depends upon pipeline operating conditions. An urgent need for gas may dictate an early end to field shut-in time.

As with all surveys utilizing measured quantities from use of mechanical instruments, some measurement error will exist. Errors introduced into the formula due to data gathering will not allow direct comparisons with measured volumes.

The data will always have some margin of error due to the operating conditions of the caverns, with the greatest data errors doubtlessly existing in the temperature recordings. With the best of log data, the accuracy of the calculations will be no better than approximately 5% and with obvious errors in data, the inaccuracy will range to 100% or more. This range of error percentage produces clear evidence that sound engineering procedures must be practiced.

Application

Preplanning is essential for a successful shut-in survey because cooperation from gas control, field operations, and storage engineering departments is integral. Operations must be coordinated to prepare the caverns for shut-in.

The cavern may then be shut-in and allowed to stabilize before downhole temperature and pressure surveys are conducted. This is necessary to obtain the most accurate data possible.

Gas is then injected or withdrawn, depending on the inventory status. It is not necessary completely to withdraw to base gas or fill the cavern. An injection or withdrawal of a volume of gas approximately equal to 15% of the total cavern volume is, however, suggested to produce acceptable results.

The cavern is then shut-in a second time and allowed to stabilize.

A final bottomhole survey must now be conducted to obtain the final data necessary for inclusion in the material balance equation. The result yielded by the equation is the pore volume of the cavern.

Some manipulation of the material balance equation is involved to obtain cavern size

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and inventory. It is helpful to point out that the caverns are not identical in size at every survey because some shrinkage always occurs. Pore volume must, therefore, always be recalculated for each shut-in period.

This is slightly different from a depleted gas-storage field, with no water drive or other externally induced drive force, in that pore volume of the depleted field may be assumed constant. The initial calculation as discussed will reestablish pore volume for every survey.

Inventory verification may then be established at current conditions for comparison with measured volumes to estimate possible variance. For estimation of cavern shrinkage, cavern volume must be established at original maximum operating temperature and pressure for comparison with past cavern sizes. Each formula as discussed will determine the necessary criteria successfully to complete the sizing surveys.

The pore volume obtained from the calculations may be utilized to calculate an estimate of the gas in place at current operating conditions to reveal inventory variance and at original maximum conditions to reveal cavern shrinkage.

Data gathering

Primary data are collected at time zero or initial shut-in. Wellhead pressure is recorded at regular time intervals to ascertain cavern stabilization because wellhead pressures depend on cavern pressures and respond to downhole stabilization. Wellhead temperatures, on the other hand, follow ambient surface temperatures and tend to respond to weather patterns.

Stabilization time for cavern temperature is much longer than that for cavern pressure. Due to the volume of the cavern envelope and relatively small amount of contact area at the cavern walls, the temperature of the gas may take several months to reach that of the surrounding rock.

Hence, bottomhole temperature data cannot be calculated with surface readings. Since cavern temperature at a given depth does not parallel gradients, surface readings prove inaccurate. As such, calculations with gradient equations and which use surface readings are useless.

Consider a comparison with a depleted gas-storage reservoir. The gas touches an infinite area of the host rock through contact with the interstices of the sandstone or vugular spaces of carbonate reservoirs.

The contact area tends to reduce the time necessary for the gas to reach a temperature corresponding to a regional gradient. Because there are no interstices' contact points in a salt cavern, the stabilization time for temperature is too long to conform to a reasonable shut-in period.

The temperature of the stored gas, therefore, is a function of the operation, injection or withdrawal, not time intervals functionally tied to the geology (Fig. 3). Operating history has shown that temperature is a separate function for the injection or withdrawal operation at "near-time" intervals and is directly related to the ongoing or recently completed storage operation.

Temperatures following an injection cycle are warmer, and temperatures following a withdrawal cycle are cooler than gradient temperatures. These temperatures will stabilize to gradient temperature after a long period of time, much longer than practical for a shut-in survey. Therefore, temperature data for calculations are said to be "near-time" dependent, governed by the storage operation.

Cavern shape functionally affects the temperature of the gas in the cavern (Fig. 3). Spherically shaped caverns yield temperatures which tend to cool as depths increase after an injection period. Cylindrically shaped caverns, on the other hand, yield temperatures which remain relatively constant over the entire depth interval.

All cavern temperatures tend to remain constant, however, after a withdrawal exercise over the entire depth range.

Temperature and pressure data should be taken at several intervals to obtain an average over the entire cavern interval. An arithmetic average may be used for cylindrically shaped caverns. But a geometrical average is used for spherically shaped caverns because of the changes in diameter.

An interesting condition exists near the bottom of all caverns surveyed. The remaining water pool at the cavern bottom has a temperature which is usually cooler than the gas temperature. As shown in Fig. 4, the temperature drop begins below 5,750 ft for spherically shaped caverns and below 6,100 ft for cylindrically shaped caverns.

Continued recordings of temperature and pressure while the instruments are in contact with the water will affect the average temperature and pressure of the cavern. Thus, the operator must not use temperature and pressure data obtained while the instruments are in contact with the water.

Table 1

Data from bottomhole surveys

Beginning pressure	3,142 psia
Beginning temperature	598.5° R.
Beginning Z-factor	0.8933
Gas volume injected	196,529 Mcf
Ending pressure	3,909 psia
Ending temperature	617.6° R.
Ending Z-factor	0.9427
Original gas formation volume factor	1.379 Mcf/bbl

Table 2

Calculations' results

Pore volume	6,649,592 cu ft 1,184,339 bbl
Indicated gas-in-place	1,576,087,995 cu ft
Maximum volume	1,633,203 Mcf

Equations

$$\frac{Vm}{\frac{T_b}{P_b}\left(\frac{P_1}{T_1 \cdot Z_1} - \frac{P_2}{T_2 \cdot Z_2}\right)} = Vp \qquad (1)$$

where:

Vm = Volume of gas injected/withdrawn, cu ft
Vp = Pore volume of reservoir, cu ft
T_b = Base temperature, °R.
P_b = Base pressure, psia
P_1 = Initial pressure, psia
T_1 = Initial temperature, °R.
Z_1 = Z-factor at initial conditions
P_2 = Final pressure, psia
T_2 = Final temperature, °R.
Z_2 = Z-factor at final conditions

$$(Vp) \cdot \left(\frac{T_b}{P_b}\right) \cdot \left(\frac{P}{T \cdot Z}\right) = Vc \qquad (2)$$

where:

Vc = Capacity at desired condition, cu ft
P = Pressure at desired condition, psia
T = Temperature at desired condition, °R.
Z = Z-factor at desired condition

$$Vp \cdot Bg = Vm \qquad (3)$$

Vp = Port volume of reservoir, bbl
Bg = Gas formation volume factor @ original maximum conditions, Mcf/bbl
Vm = Maximum volume, Mcf

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This situation is avoidable because the interface can be identified by the sudden temperature change.

Survey data; calculations

The equations presented calculate the gas in place (GIP) for inventory verification and the maximum volume to determine cavern shrinkage. The data obtained in the cavern surveys are given in Table 1; the results of the calculations are presented in Table 2.

These results (Figs. 5 and 6) indicate the trend in inventory and cavern size necessary to determine variance and shrinkage.

Graphical results depict surveys which have been conducted over a period of several years. As seen in Fig. 5, the results do not produce a smooth line graph because of changing cavern conditions.

Several states can affect the results of the shut-in survey, including salt spalling from the cavern roof, beginning and ending shut-in pressures and temperatures, cavern shrinkage, and gas migration.

Salt spalling is a serious condition which can have deleterious effects on the cavern. Certainly one problem is damage to the well tubulars. Minor damage to the well bore casing may prevent the introduction of temperature and pressure tools to the cavern, while major damage may restrict or prevent gas flow into and out of the cavern.

Beginning and ending pressures generally have the most effect on the appearance of the graphs. Data errors caused by a short stabilization period cause a severe sawtooth-shaped graph.

This shape is the reason several surveys are graphed and comparisons made. The graph can be "smoothed" over a period of time, for instance, by a least-squares fit of the curve.

Major discrepancies in the graph caused by shrinkage and migration are the focus of the studies. The curves tend to decline with time, indicating shrinkage and variance. This decline is used to develop conclusions concerning the caverns.

Obviously, a severe declination would indicate that immediate remedial action be taken to correct an existing problem. In most cases, however, concerning inventory variance, a periodic write-off of a small amount of gas may be all that is necessary (Fig. 5).

A small amount of declination can be expected in observations of cavern-shrinkage graphs (Fig. 6). A management decision must be made when caverns have become too small and releaching is required.

Care must be taken to exercise patience when evaluating a new leaching program because shrinkage is far worse during initial operation. Older caverns tend to shrink less, probably due to the drying effect of the gas on the walls of the cavern.

Reducing the water content of the salt may induce some brittleness. Consequently, the plasticity of the salt may be reduced, but this does not mean that salt creep will be completely arrested. The oldest salt-dome caverns in the U.S. continue to shrink, although at a slower pace.

Data presented in Table 1 and the resulting calculated information depict a typical cavern-sizing survey. The cavern was shut-in after a withdrawal operation and allowed to stabilize. Every other survey was conducted in this same manner (i.e., the initial shut-in followed a withdrawal operation).

Bottomhole pressure and temperature data were recorded, and the cavern was filled with gas. The cavern was again shut-in and allowed to stabilize (Fig. 2). Subsurface readings were again taken, and the resulting data were used to calculate volumes according to the material-balance equations (Equations 1, 2, and 3 in accompanying equations box).

The form of the material-balance equation used to calculate the cavern pore volume is shown in Equation 1. The equation is modified to obtain GIP (Equation 2).

Further modification yields maximum possible GIP for cavern-shrinkage estimates (Equation 3).

Initial calculations from Equation 1 produce a pore volume in cubic feet occupied by the cavern; barrels of space available are calculated by simple conversion.

Cavern shrinkage can be estimated from this result. For reporting purposes, however, barrels of space are converted to maximum possible gas in place and depicted in cubic feet. The volume of natural gas stored should be reported in cubic feet.

It is important to remember, however, that the result of the calculation of the material-balance equation does not compare exactly with measured volumes of inventory or capacity. Data errors will cause alarming dissimilarities.

As previously mentioned, however, the errors tend to smooth when graphed trends are developed (Fig. 5). Inventory variance and cavern shrinkage may be estimated by use of these graphical trends. Precise adherence to a sound procedure and the use of quality tools for measurement should yield data which in turn produce results with an acceptable margin of error. ▪

The author...

Mason

Robert G. Mason is senior storage engineer for Transcontinental Gas Pipe Line Corp., Houston, where he is responsible for Transco's underground-storage projects which include depleted reservoir and salt-dome storage fields. He is a contributing author for the AGA's gas engineering and operating practices handbook, "Underground Storage of Natural Gas." Mason holds a BS in engineering technology from Texas Tech University, Lubbock.

Extensive analysis critical for horizontal well tie-in

Arild Wilson
Carl Hartmann
Norsk Hydro a.s.
Oslo, Norway

The design of the tie-in of the Gamma North field's horizontal well to the Oseberg field complex required extensive analysis of the physical properties, hydrate evaluation, material studies, and multiphase flow.

The physical property generation was based on in-house procedures that to a large extent are applications of the Gas Processors Association (GPA) developed techniques and method.

Experimental verifications have confirmed the need for these predictions.

Oseberg development

The Oseberg field, located about 125 km (78 miles) west of Bergen, was discovered in 1979 (Fig. 1). The first well drilled revealed a large gas cap. However, the next well penetrated a substantial underlying oil zone. This turned Oseberg into one of the larger oil fields on the Norwegian shelf.

A field development plan was filed with the authorities late in 1983. Two phases of development were described:

Phase 1 would be on stream in 1988. It was to consist of a process and quarters platform (A) connected by a bridge to the drilling platform (B). This constitutes the field center (FC).

Phase 2 was planned to consist of a drilling, quarters, and water-injection platform. First stage separated oil and gas would be routed to the

Based on a paper presented at the Gas Processors Association 69th annual convention, Phoenix, Mar. 12-18.

PSC 039898

LEYDEN L&U REPORT
JANUARY 3, 1991

SUMMARY

1. 0.7 BCF (14.65) should be written off as L&U as of year end 1990. This covers the period from 1983 through 1990.

2. 2.3 BCF of gas has been written off as L&U in the 30 years of storage operations. The L&U rate averages 0.077 BCF/year (77 MMCF/year) for the 30 year period. This includes the 0.7 BCF recommended as L&U through 1990.

3. The current gas loss rate (L&U) is about 0.1 BCF/year, which is consistent with the L&U rate observed since 1972. This annual L&U represents about 3.5% of the total storage volume. 0.1 BCF is 4.7% of the 1989 injected volume, or 2.5% of the 1989 total activity (injection and withdrawal volume).

4. The annual L&U is not increasing over time. The L&U rate may possibly decrease in the future due to casing damage repairs done the summer of 1990. The gas loss rate from the damaged casing was probably not very high, and therefore the decrease in L&U associated with the repairs is not expected to be very high.

5. The L&U is currently at an acceptable economic level. At 0.1 BCF/year (100,000 MCF/year) and a current CG rate of about $2.70/MCF, the annual cost of lost gas is $270,000.

INTRODUCTION

This report is the result of a detailed investigation into "Lost & Unaccounted For" (L&U) gas for the Leyden gas storage field. Several methods were used to determine L&U gas for recent years.

The L&U gas is a combination of the following; (1) gas which migrates into the formation (sand, coal, fractures, aquifers) and is not recoverable, (2) gas which is blown to the atmosphere during wellhead operations, workovers, blowing of separators, pigging of the surface piping system, etc., and (3) gas measurement errors.

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METHODS OF DETERMINING L&U, & RESULTS

The recommended L&U of 0.7 BCF is a compromise between the results of the four methods used. The methods are as follows, and the data and calculations can be found in the attachment material to this report;

Method A - BOOK VOLUME COMPARISON

Per this method, 0.8 BCF should be written off as L&U. This is a comparison of book volumes for two different days, where the cavern was near full and shut in time was sufficient to predict a stabilized cavern pressure. This is the most accurate method, especially if the stabilized cavern pressures are about the same for both days. The dates for comparison were 3/14/83 and 2/12/88.

Method B - HISTORIC TREND

Per this method, 0.7 BCF should be written off as L&U. This method is expected to yield a fairly accurate result. No major changes have occurred that are expected to substantially change the L&U.

Method C - PREDICT REMAINING VOLUME AT LOW CAVERN PRESSURE

Per this method, 0.65 BCF should be written off as L&U. This method is not expected to be as accurate as Method A, but should yield reasonable results.

Method D - VOLUME COMPARED TO 3 BCF MAX STORAGE CAPACITY

Per this method, the minimum L&U that should be written off is 0.54 BCF. This is the least accurate of the four methods, but is conservative in that the predicted L&U will be lower than the expected value.

LB X DAY BALANCE

There is no obvious correlation between lb-day balance and L&U. The lb-day balance records have not been developed for the seasons prior to 9/1/82, and therefore no comparison can be made for these earlier seasons.

L&U calculations were not done for several years since 1982, and therefore annual comparisons are not possible. L&U calculations are based on stabilized cavern pressures. Because of frequent injection and withdrawal activity in recent years, accurate stabilized cavern pressures are difficult to obtain.

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The current design aquifer pressure used for lb x day balance is assumed to be 192 psi. The actual operating lb x day median pressure is 177.8 psi for the period from 9/1/82 to present. The actual average lb x day balance is below the design lb x day balance, and therefore the L&U influenced by lb x day balance should be at a minimum.

However, the actual aquifer pressure may be less than 192 psi, and it may even be less than 177.8 psi. If this is so, it may be possible to reduce the L&U by reducing the operating lb x day balance. More investigation should be done in this area to verify or redefine the actual current aquifer pressure.

STABILIZED CAVERN PRESSURE

It is difficult to accurately predict L&U from one year to the next without an adequate shut in period following injection or withdrawal activity. The shut in period is necessary to allow the accurate extrapolation of a stabilized cavern pressure.

The Modified Horner Plot is a good method to use for predicting stabilized cavern pressures. This is "Modified" in that the plot is done on a standard X-Y plot. The Log of (T+DT)/DT is plotted on the X axis. As the Log of (T+DT)/DT approaches zero, the cavern pressure approaches stabilization.

A minimum of 50 to 70 shut in days are required to predict the stabilized cavern pressure for a pressure buildup analysis (shut in after withdrawal). A minimum of 60 to 80 shut in days are required to predict the stabilized cavern pressure for a pressure decline (shut in after injection). These minimums are based on the data evaluated for this report and may vary from one situation to the next. Extrapolation can be done with less shut in than suggested, but the accuracy of the result goes down.

An area that needs further development is the application of "type curves" or other methods of determining stabilized cavern pressures.

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CAUSES OF L&U

1. LOST UNDERGROUND TO SURROUNDING FORMATIONS

Permeable formations (sands and coals), fractures, bore holes, and aquifers that are in communication with the storage zone can transmit gas away from the storage zone. Gas which travels far enough becomes L&U as it is not recoverable.

Two examples follow which demonstrate the extent of formation gas charging as related to L&U.

A. Well 27 was drilled to investigate a gas charged sand at a depth of 137'. This sand is estimated to have had a 2' net charged thickness, 10% porosity, 50% water saturation, and a 10 psig gas charge. Assuming a gas charged area of 500 acres (about 1/2 the area of the mine), the gas in place would be 3,300 MCF (14.65). This is only about 3% of the annual L&U.

B. The total field L&U of 2.3 BCF over 30 years would cover 990 acres if charging a 50' net thick sand at 20% porosity, 50% water saturation, and 150 psig gas charged pressure. The area of the mine is about 1100 acres.

Only a portion of the 0.1 BCF annual L&U is lost underground to surrounding formations. The remainder is due to surface losses and metering errors. It is probable that part the L&U lost underground eventually makes it's way to the surface. The gas can follow the up dip in the formation to the surface, and can follow old well bores or casing annulus paths to the surface.

2. SURFACE LOSSES

Surface losses occur from various sources, such as piping or compressor station system blowdown, leaking valves, blowing down separators to remove water, workover operations, and gas usage in separator heaters. The combined surface loss is estimated at 11,000 MCF/year. This amounts to 11% of the annual L&U.

3. METERING ERRORS

Metering errors could account for a significant amount of L&U. The same meter run and flow direction are used for injection mode and withdrawal mode, but there could be an error associated with one mode and not the other.

Meter error is often a function of flow rate, and injection rates are often much different than withdrawal rates. This could account for a substantial error on one mode and a minimal error on the other.

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It is possible that metering error will cancel itself out. If the metering is 3% in error while injecting, it may also be 3% in error while on withdrawal.

The average injection for the 8 year period from 1983 through 1990 was 1.506 BCF/year of gas. A positive metering error of 6.64% on this injected volume would produce the current L&U of 0.1 BCF per year.

The average withdrawal volume for the same period was 1.4 BCF/year. A negative metering error of 7.1% on this withdrawal volume would produce the current L&U of 0.1 BCF/year.

The average total activity (injection + withdrawal) for the 8 year period was 2.9 BCF/year. A positive 3.45% injection error combined with a negative 3.45% withdrawal error would produce the current L&U of 0.1 BCF/year.

Brad Hollenbaugh
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WestGas 1/3/91

PSC 039850

COMPARE VOLUME ON 3/14/83 TO VOLUME ON 2/12/88

BASED ON A COMPARISON OF STORAGE VOLUME ON 3/14/83 TO STORAGE VOLUME ON 2/12/88, 0.8 BCF OF GAS SHOULD BE WRITTEN OFF AS L&U. THIS IS PER 0.1 BCF/YEAR FROM 1983 THRU 1990.

PROCEDURE FOR COMPARISON:

CALC 1

3/14/83 - BOOK VOL = 2,814,914 MCF (14.65) PER GAS MGMT REPORTS

PRESS = 236.2 PSIG

PLOTTED P_{STAB} = 234 PSIG (@ MODIFIED HORNER PLOT)

(FOR EXPLANATION OF MODIFIED HORNER PLOT - SEE Pg A21)

2/12/88 BOOK VOL = 3,463,732 MCF (14.65) PER GAS MGMT REPORT

PRESS = 243.6 PSIG

PLOTTED P_{STAB} = 241 PSIG (@ MODIFIED HORNER PLOT)

CONVERT THIS BOOK VOL TO V_{B2} = VOLUME AT A PRESSURE OF 234 PSIG: 241 - 234 = 7 PSIG

V_{B2} = 3,463.732 MMCF − 11.6 MMCF/PSIG × 7 PSIG

= 3,463.732 MMCF − 81.2 MMCF

V_{B2} = 3,382.532 MMCF

IF ON 2/12/88 THE PRESSURE WERE STABILIZED AT 234 PSIG, THE BOOK VOLUME WOULD BE 3,382.532 MMCF

NOW A COMPARISON CAN BE MADE WITH BOOK

12/31/90 EH

1 OF 4

VOLUME ON 3/14/83 & BOOK VOLUME OF 2/12/88, BECAUSE THEY ARE BOTH AT THE SAME STAB. PRESSURE.

AT P_{STAB} = 2321 PSIG;

2/12/88 BOOK VOL = 3,382,532 MMCF
3/14/83 BOOK VOL = 2,814,914 MMCF
L&U = DIFFERENCE = 567,618 MMCF

OR 0.57 BCF
÷ 5 YEARS = 0.114 BCF/YEAR

FOR THIS 5 YEAR PERIOD, A NET OF 8,400 MCF OF L&U WAS WRITTEN OFF & WOULD APPLY OVER & ABOVE THE L&U AMOUNT CALCULATION ABOVE. THIS WOULD BOOST THE 5 YEAR L&U TO 576.018 MMCF, OR 0.115 BCF/YEAR

APPLYING THE 0.114 BCF/YEAR OVER THE 8 YEAR PERIOD TO COVER 1983 THRU 1990, 0.912 BCF SHOULD BE WRITTEN OFF.

PG 2 OF 4

PSC 039852

CALC 2 WILL BE DONE NEXT TO CHECK THE SENSITIVITY OF P_{STAB} FOR 3/14/83 ON THE L&U.

12/31/90 BH

A2

CALC 2

3/14/83 BOOK VOL = 2,814,914 MCF

PRESS = 236.2 PSIG

PLOTTED P_{STAR} = 230 PSIG (f/ ⓑ MODIFIED HORNER PLOT)

2/12/88 V_{BOOK} = 3,463,732 MMCF

P = 243.6 #

PLOTTED P_{STAR} = 241 PSIG (f/ MODIFIED HORNER PLOT)

CONVERT TO V_{B2} = VOL @ PRESS OF 230 PSIG

241 − 230 = 11 PSIG

V_{B2} = 3,463,732 MMCF − 11.6 MMCF/PSIG × 11 PSIG

= 3,463,732 − 127.60 MMCF

= 3,336.132 MMCF

@ P_{STAR} = 230 PSIG ;

2/12/88 V_{BOOK} = 3,463,732 MMCF

3/14/83 V_{BOOK} 2,814,914 MMCF

648,818 MMCF

= 0.65 BCF

÷ 5 YEARS = 0.13 BCF/YEAR

648,818 MMCF + 8,400 (already written off) = 657,218 MMCF

÷ 5 years = 0.131 BCF/year

APPLYING THE 0.131 BCF/YEAR OVER THE 8 YEAR PERIOD TO COVER 1983 THRU 1990, 1 BCF SHOULD BE WRITTEN OFF.

PSC 039853

A3

12/31/90 BN

Pg 3 of 4

CALC 1 RESULTS ARE PROBABLY MORE VALID THAN CALC 2 RESULTS. CALC 1 RESULTS ARE BASED ON EXTRAPOLATION OF 64 DAYS OF DATA FOR BOTH DECLINE CURVE PERIODS. IT IS LIKELY THAT THE 12/11/87 TO 2/12/88 HORNER PLOT WILL FALL OFF SIMILAR TO THE 11/14/82 TO 3/24/83 HORNER PLOT IF YOU HAD ABOUT 116 DAYS OF DATA TO PLOT.

CONCLUSION

USING CALC 1 & ROUNDING OFF TO THE NEAREST 1/10th, 0.1 BCF/YEAR IS APPLICABLE FOR THE 5 YEAR PERIOD STUDIED, & COULD ALSO BE APPLIED TO THE REMAINING 3 YEARS. 0.1 BCF/YEAR x 8 YEARS = 0.8 BCF.

Pg 4 of 4

PSC 039854

B. HOLLENSBUCH.

A4

12/31/90

ACCOUNT FOR BOTTOM HOLE PRESSURE & Z

$P_{STAB_1} = 234$ PSIG
$= 246.14$ PSIA

$P_{STAB\ BH} = 251$ PSIA
$Z_{BH} = 0.969$ } 820', 0.65, 65°F → 85°F PER COMPUTER PROGRAM - BHPC 250.91 PSIA

$P_{STAB_2} = 241$ PSIG $= 253.14$ PSIA

$P_{STAB\ BH} = 258$ PSIA
$Z_{BH} = 0.967$ } PER COMPUTER PROGRAM - BHPCS & GASWORK 258.05 PSIA

$P_{STAB\ BH_2} - P_{STAB\ BH_1} = 258$ PSIA $- 251$ PSIA $= 7$ PSI

THIS IS THE SAME ΔP THAT WAS CALCULATED FROM USING SURFACE GAUGE PRESSURES

$$P_{STAB\ 1\ BH}/Z_1 = \frac{251}{0.969} = 259.03 \text{ PSIA}$$

$$P_{STAB\ 2\ BH}/Z_2 = \frac{258}{0.967} = 266.8 \text{ PSIA}$$

$$P_2 - P_1 = 266.8 - 259.03 = 7.77 \text{ PSI}$$

$V_{B2} = 3{,}463{,}732 - 11.6$ MMCF/PSI $\times 7.77$ PSI
$= 3{,}463{,}732 - 90{,}13$ MMCF
$V_{B2} = 3373.6$ MMCF

LEU $= 3373.6 - 2814.914 = 558.69$ MMCF $= 0.56$ BCF
VS LEU OF 567.618 MMCF W/OUT ACCOUNTING FOR Z
% ERROR $= ((567.618 - 558.69)/558.69) \times 100 = 1.6$ % error (negligible)

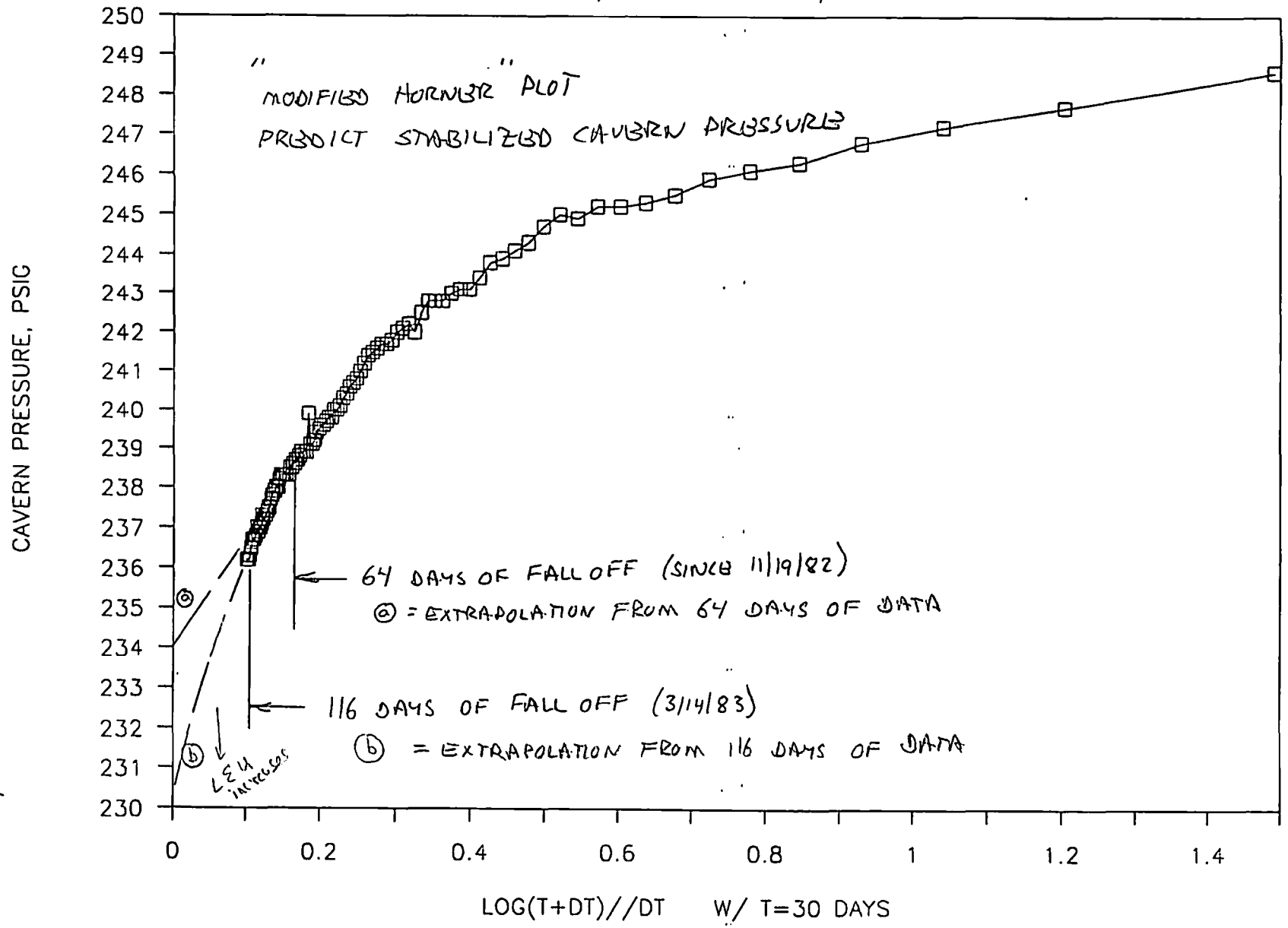
THIS ERROR IS NEGLIGIBLE (1.6% OR 0.77 PSI) COMPARED TO THE ERROR ASSOCIATED WITH EXTRAPOLATION OF STABILIZED CAVERN PRESS.

B. HOLLENBAUGH 1/2/91

PSC 039855

LEYDEN PRESSURE FALL OFF

NOV 19, 82 TO MARCH 14, 83



A6

RH 12/31/90

PSC 039856

LEYDEN GAS STORAGE

ld82-83

PRESSURE DECLINE PERIOD: 11/19/82 TO 3/14/83

SHUT IN WAS 11/19/82 W/ NO ACTIVITY UNTIL 3/15/83

PG 1 OF 4

DATE	PRESSUR	DAY	(T+DT)/DT =TF	'LOG TF
15-Nov-82	237.7			
16-Nov-82	237.5			
17-Nov-82	244.2			
18-Nov-82	250			
19-Nov-82	248.6	1	31	1.491361
20-Nov-82	247.7	2	16	1.204119
21-Nov-82	247.2	3	11	1.041392
22-Nov-82	246.8	4	8.5	0.929418
23-Nov-82	246.3	5	7	0.845098
24-Nov-82	246.1	6	6	0.778151
25-Nov-82	245.9	7	5.285714	0.723103
26-Nov-82	245.5	8	4.75	0.676693
27-Nov-82	245.3	9	4.333333	0.636822
28-Nov-82	245.2	10	4	0.602059
29-Nov-82	245.2	11	3.727272	0.571391
30-Nov-82	244.9	12	3.5	0.544068
01-Dec-82	245	13	3.307692	0.519525
02-Dec-82	244.7	14	3.142857	0.497324
03-Dec-82	244.3	15	3	0.477121
04-Dec-82	244.1	16	2.875	0.458637
05-Dec-82	243.9	17	2.764705	0.441648
06-Dec-82	243.8	18	2.666666	0.425968
07-Dec-82	243.4	19	2.578947	0.411442
08-Dec-82	243.1	20	2.5	0.397940
09-Dec-82	243.1	21	2.428571	0.385350
10-Dec-82	243	22	2.363636	0.373580
11-Dec-82	242.8	23	2.304347	0.362548

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PSC 039857

12-Dec-82	242.8	24	2.25	0.352182
13-Dec-82	242.8	25	2.2	0.342422
14-Dec-82	242.5	26	2.153846	0.333214
15-Dec-82	242	27	2.111111	0.324511
16-Dec-82	242.2	28	2.071428	0.316269
17-Dec-82	242.1	29	2.034482	0.308454
18-Dec-82	242	30	2	0.301029
19-Dec-82	241.8	31	1.967741	0.293968
20-Dec-82	241.7	32	1.9375	0.287241
21-Dec-82	241.7	33	1.909090	0.280826
22-Dec-82	241.6	34	1.882352	0.274701
23-Dec-82	241.5	35	1.857142	0.268845
24-Dec-82	241.4	36	1.833333	0.263241
25-Dec-82	241.2	37	1.810810	0.257873
26-Dec-82	241	38	1.789473	0.252725
27-Dec-82	240.8	39	1.769230	0.247784
28-Dec-82	240.7	40	1.75	0.243038
29-Dec-82	240.6	41	1.731707	0.238474
30-Dec-82	240.4	42	1.714285	0.234083
31-Dec-82	240.3	43	1.697674	0.229854
01-Jan-83	240.1	44	1.681818	0.225779
02-Jan-83	240	45	1.666666	0.221848
03-Jan-83	240	46	1.652173	0.218055
04-Jan-83	239.8	47	1.638297	0.214392
05-Jan-83	239.8	48	1.625	0.210853
06-Jan-83	239.7	49	1.612244	0.207431
07-Jan-83	239.6	50	1.6	0.204119
08-Jan-83	239.6	51	1.588235	0.200914
09-Jan-83	239.5	52	1.576923	0.197810
10-Jan-83	239.4	53	1.566037	0.194802
11-Jan-83	239.2	54	1.555555	0.191885
12-Jan-83	239.1	55	1.545454	0.189056
13-Jan-83	239.1	56	1.535714	0.186310
14-Jan-83	239.9	57	1.526315	0.183644

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15-Jan-83	238.9	58	1.517241	0.181054
16-Jan-83	238.9	59	1.508474	0.178537
17-Jan-83	238.9	60	1.5	0.176091
18-Jan-83	238.9	61	1.491803	0.173711
19-Jan-83	238.8	62	1.483870	0.171396
20-Jan-83	238.7	63	1.476190	0.169142
21-Jan-83	238.7	64	1.46875	0.166947
22-Jan-83	238.6	65	1.461538	0.164810
23-Jan-83	238.6	66	1.454545	0.162727
24-Jan-83	238.5	67	1.447761	0.160696
25-Jan-83	238.5	68	1.441176	0.158717
26-Jan-83	238.3	69	1.434782	0.156786
27-Jan-83	238.3	70	1.428571	0.154901
28-Jan-83	238.3	71	1.422535	0.153063
29-Jan-83	238.3	72	1.416666	0.151267
30-Jan-83	238.3	73	1.410958	0.149514
31-Jan-83	238.3	74	1.405405	0.147801
01-Feb-83	238.3	75	1.4	0.146128
02-Feb-83	238.2	76	1.394736	0.144492
03-Feb-83	238	77	1.389610	0.142893
04-Feb-83	238	78	1.384615	0.141329
05-Feb-83	238	79	1.379746	0.139799
06-Feb-83	237.9	80	1.375	0.138302
07-Feb-83	237.9	81	1.370370	0.136837
08-Feb-83	237.8	82	1.365853	0.135404
09-Feb-83	237.8	83	1.361445	0.134000
10-Feb-83	237.7	84	1.357142	0.132625
11-Feb-83	237.5	85	1.352941	0.131278
12-Feb-83	237.5	86	1.348837	0.129959
13-Feb-83	237.4	87	1.344827	0.128666
14-Feb-83	237.4	88	1.340909	0.127399
15-Feb-83	237.3	89	1.337078	0.126156
16-Feb-83	237.3	90	1.333333	0.124938
17-Feb-83	237.2	91	1.329670	0.123743

18-Feb-83	237.2	92	1.326086	0.122572
19-Feb-83	237.3	93	1.322580	0.121422
20-Feb-83	237.1	94	1.319148	0.120293
21-Feb-83	237	95	1.315789	0.119186
22-Feb-83	237	96	1.3125	0.118099
23-Feb-83	237	97	1.309278	0.117031
24-Feb-83	236.9	98	1.306122	0.115983
25-Feb-83	236.9	99	1.303030	0.114954
26-Feb-83	237	100	1.3	0.113943
27-Feb-83	236.8	101	1.297029	0.112949
28-Feb-83	236.8	102	1.294117	0.111973
01-Mar-83	236.7	103	1.291262	0.111014
02-Mar-83	236.7	104	1.288461	0.110071
03-Mar-83	236.7	105	1.285714	0.109144
04-Mar-83	236.7	106	1.283018	0.108233
05-Mar-83	236.7	107	1.280373	0.107336
06-Mar-83	236.5	108	1.277777	0.106455
07-Mar-83	236.5	109	1.275229	0.105588
08-Mar-83	236.3	110	1.272727	0.104735
09-Mar-83	236.2	111	1.270270	0.103896
10-Mar-83	236.2	112	1.267857	0.103070
11-Mar-83	236.2	113	1.265486	0.102257
12-Mar-83	236.2	114	1.263157	0.101457
13-Mar-83	236.2	115	1.260869	0.100670
14-Mar-83	236.2	116	1.258620	0.099894

A10

LAST 10 DAYS OF DECLINE

236.7 PSIG
- 236.2 PSIG
0.5 PSIG ÷ 10 DAYS = 0.05 PSIG/DAY DECLINE

0.05 PSIG/DAY DECLINE

GAS LOSS (LEU) RATE COULD BE AFFECTING THE PLOT SIGNIFICANTLY NEAR THE END OF THE DECLINE PERIOD.

A GAS LOSS RATE (LEU) OF 0.1 BCF/YEAR WOULD PRODUCE A PRESSURE DECLINE OF 0.024 PSIG/DAY. THIS IS ABOUT HALF OF THE DECLINE OBSERVED ABOVE FOR LAST 10 DAYS

B. HOLLENBAUGH 12/31/90

LEU @ 0.1 BCF/YEAR

0.1 BCF/year = 100 MMCF/Y ÷ 365 days/year
= 0.274 MMCF/Day

$$\frac{0.274 \text{ MMCF/DAY}}{11.6 \text{ MMCF/PSIG}} = 0.024 \text{ PSIG/DAY}$$

AN LEU OF 0.1 BCF/YEAR EQUATES TO A PRESSURE DROP OF 0.024 PSIG PER DAY

ASSUMING; V/P = 11.6 MMCF/PSIG @ VERY LOW FLOW RATES

LEU IS PROBABLY A FUNCTION OF CAVERN PRESSURE, THE HIGHER THE P_{AV}, THE HIGHER THE LEU.

IF 0.1 BCF/Y IS THE ANNUAL LOSS, THEN THE 0.024 PSIG/DAY WOULD BE THE ANNUAL AVERAGE PRESS LOSS CAUSED BY LOST GAS.

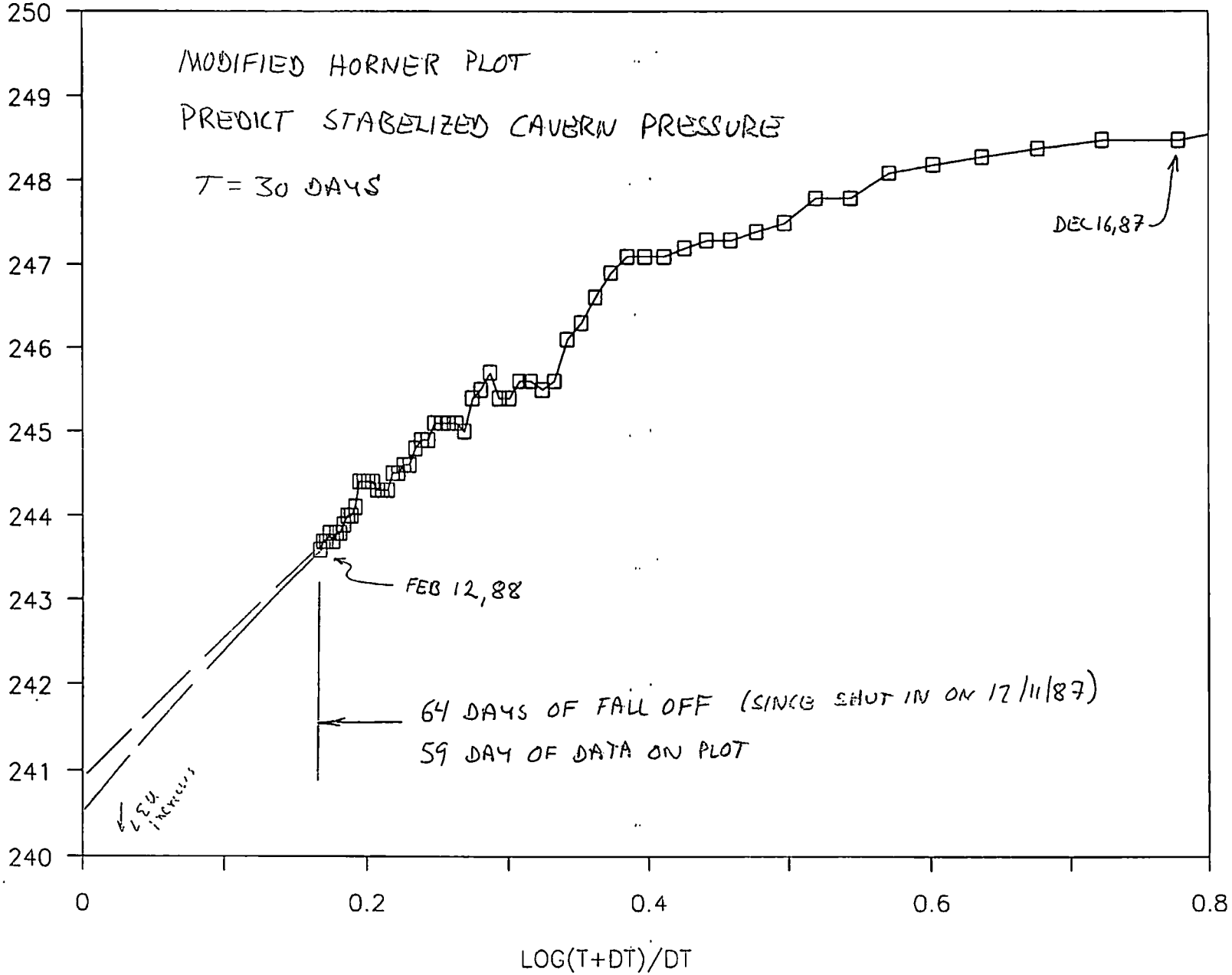
PSC 039861

B. HOLLENBAUGH

A11 12/31/90

LEYDEN PRESSURE FALL OFF

DEC 11, 1987 TO FEB 12, 1988



A 12

PSC 039862

BH 12/28/90

LEYLEUI

MODIFIED HORNER PLOT

DATE	PRESSURE PSIG	DAY	(T+DT)/DT	LOG (T+DT)/DT
11-Dec-87	250	1	31	1.4913616938
12-Dec-87	249.5	2	16	1.2041199827
13-Dec-87	249.1	3	11	1.0413926852
14-Dec-87	248.7	4	8.5	0.9294189257
15-Dec-87	248.7	5	7	0.84509804
16-Dec-87	248.5	6	6	0.7781512504
17-Dec-87	248.5	7	5.2857142857	0.7231036841
18-Dec-87	248.4	8	4.75	0.6766936096
19-Dec-87	248.3	9	4.3333333333	0.6368220976
20-Dec-87	248.2	10	4	0.6020599913
21-Dec-87	248.1	11	3.7272727273	0.5713911716
22-Dec-87	247.8	12	3.5	0.5440680444
23-Dec-87	247.8	13	3.3076923077	0.5195251033
24-Dec-87	247.5	14	3.1428571429	0.4973246408
25-Dec-87	247.4	15	3	0.4771212547
26-Dec-87	247.3	16	2.875	0.458637849
27-Dec-87	247.3	17	2.7647058824	0.4416489366
28-Dec-87	247.2	18	2.6666666667	0.4259687323
29-Dec-87	247.1	19	2.5789473684	0.4114424791
30-Dec-87	247.1	20	2.5	0.3979400087
31-Dec-87	247.1	21	2.4285714286	0.3853508814
01-Jan-88	246.9	22	2.3636363636	0.3735806628
02-Jan-88	246.6	23	2.3043478261	0.3625480336
03-Jan-88	246.3	24	2.25	0.3521825181
04-Jan-88	246.1	25	2.2	0.3424226808
05-Jan-88	245.6	26	2.1538461538	0.333214679
06-Jan-88	245.5	27	2.1111111111	0.3245110915
07-Jan-88	245.6	28	2.0714285714	0.3162699622
08-Jan-88	245.6	29	2.0344827586	0.3084540137
09-Jan-88	245.4	30	2	0.3010299957
10-Jan-88	245.4	31	1.9677419355	0.2939681412

THIS METHOD WOULD NOT WORK WELL WITHOUT A SUFFICIENT SHUT IN PERIOD FOR DECLINE. NEED ENOUGH DATA POINTS AT "NEAR STABILIZED" CONDITIONS TO ESTABLISH A TREND.

IMAGINE TRYING TO EXTRAPOLATE WITH ONLY THE RIGHT 15 TO 24 DATA POINTS.

BH 12/28/90

A-13

PSC 039863

11-Jan-88	245.7	32	1.9375	0.2872417112
12-Jan-88	245.5	33	1.9090909091	0.2808266096
13-Jan-88	245.4	34	1.8823529412	0.2747010569
14-Jan-88	245	35	1.8571428571	0.2688453123
15-Jan-88	245.1	36	1.8333333333	0.2632414348
16-Jan-88	245.1	37	1.8108108108	0.2578730786
17-Jan-88	245.1	38	1.7894736842	0.2527253161
18-Jan-88	245.1	39	1.7692307692	0.2477844837
19-Jan-88	244.9	40	1.75	0.2430380487
20-Jan-88	244.9	41	1.7317073171	0.238474492
21-Jan-88	244.8	42	1.7142857143	0.234083206
22-Jan-88	244.6	43	1.6976744186	0.2298544045
23-Jan-88	244.6	44	1.6818181818	0.2257790432
24-Jan-88	244.5	45	1.6666666667	0.2218487496
25-Jan-88	244.5	46	1.652173913	0.2180557606
26-Jan-88	244.3	47	1.6382978723	0.2143928672
27-Jan-88	244.3	48	1.625	0.2108533653
28-Jan-88	244.3	49	1.612244898	0.2074310113
29-Jan-88	244.4	50	1.6	0.2041199827
30-Jan-88	244.4	51	1.5882352941	0.2009148428
31-Jan-88	244.4	52	1.5769230769	0.1978105087
01-Feb-88	244.4	53	1.5660377358	0.1948022228
02-Feb-88	244.1	54	1.5555555556	0.1918855262
03-Feb-88	244	55	1.5454545455	0.1890562362
04-Feb-88	244	56	1.5357142857	0.1863104242
05-Feb-88	243.9	57	1.5263157895	0.1836443969
06-Feb-88	243.8	58	1.5172413793	0.1810546786
07-Feb-88	243.8	59	1.5084745763	0.178537995
08-Feb-88	243.7	60	1.5	0.1760912591
09-Feb-88	243.8	61	1.4918032787	0.1737115573
10-Feb-88	243.7	62	1.4838709677	0.1713961378
11-Feb-88	243.7	63	1.4761904762	0.1691423991
12-Feb-88	243.6	64	1.46875	0.1669478796

CAN NOT ACCURATELY PREDICT A STABILIZED CAVERN PRESSURE FROM DECLINE DATA UNLESS ABOUT 6% OR MORE DAYS OF SHUT IN DATA ARE AVAILABLE.

THE MODIFIED HORNER PLOT MAY BE MORE ACCURATELY APPLIED TO PRESSURE BUILDUP THAN IT IS TO DECLINE.

A14

HISTORIC LEU REPORTED

BASED ON HISTORICAL LEU TRENDS, WE SHOULD CURRENTLY WRITE OFF BETWEEN 0.5 & 0.8 BCF OF LEU GAS. THE AVG IS 0.69 BCF/YEAR, 1965 TO 1982.

AVG = 0.7 BCF

THIS IS A REVIEW OF THE LEU WRITTEN OFF (SUBTRACTED FROM THE BOOK (OR MEASUREMENT) VOLUME.

1965 TO 1971, 7 YEARS	495 MMCF,	OR 70.7 MMCF/YEAR	OR 0.07 BCF/YEAR
1972 TO 1982, 11 YEARS	1,093.78 MMCF,	OR 99.4 MMCF/YEAR	OR 0.1 BCF/YEAR
SUMMARY, 1965 TO 1982, 18 YEARS	1588.78 MMCF,	OR 88.3 MMCF/YEAR	OR 0.09 BCF/YEAR
1983-1990, 8 YEARS	30.4 MMCF,	OR 3.8 MMCF/YEAR	OR 0.004 BCF/YEAR

FOR 1983 TO 1990

PSC 039865

FOR 1983-1990

MODEL YEARS ⇒	ASSUMPTION OF LEU	LEU EXPECTED		LEU WRITTEN OFF		LEU TO WRITE OFF
1965-71	0.07 BCF/Y	0.56 BCF	MINUS	0.03 BCF	=	0.53 BCF
1972-82	0.1 BCF/Y	0.8 BCF	MINUS	0.03 BCF	=	0.77 BCF
1965-82	0.09 BCF/Y	0.72 BCF	MINUS	0.03 BCF	=	0.69 BCF ← AVG

0.7 BCF

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B. HOLLENBAUGH
12/22/90

LEU HISTORY

BASED ON REPORTED LEU IN GAS MEASUREMENT REPORTS. * INDICATES MICRO FICHE RECORDS.

YEAR	LEU MCF 14.65		CUSHION GAS	COMMENTS
1960				
1961 *				
1962 *				
1963 *			834,000	
1964 *				
1965 *	150,000	DEC		
1966 *				
1967 *				
1968 *				← NO LEU, PER PV TESTING, VOL OF GAS HAS REMAINED RELAT. CONST.
1969 *				
1970 *				
1971 *	345,000	JAN 72		← PER 11/18/71 MEMO, FOR 1966 THRU 1971
1972				
1973	122,880	JAN 74		← COMPARED 12/1 WORKING VOL FROM ONE YEAR TO THE NEXT
1974	106,043	NOV		
1975	98,577	DEC		
1976	19,667	DEC		
1977	132,568	DEC		
1978	130,404	DEC		
1979 *	130,404	DEC	537,000	
1980 *	155,530	JAN		
1981 *	66,616	JAN		
↑ 1982 *	131,089	MAR	794,000	
1983				
1984	−50,000			
1985				
1986	58,400			
1987				
1988	22,000			
1989				
1990				

PSC 039866

B. HOLLENBAUGH
12/28/90

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PER FILE REVIEW

FROM 1965 (OR EARLIER) UNTIL 1971, L & U WAS BASED ON COMPARING BOOK VOLUME (GAS MGAS REPORTS) TO THEORETICAL VOLUME. THEORETICAL VOLUME WAS CALC FROM CAV PRESSURE & ESTIMATED CAVERN PHYSICAL VOLUME.

YEAR	CAV VOLUME ORIGINAL VOID	AVAILABLE CAV VOLUME (1)	P/Z (2)	THEORETICAL STOR VOL @250# (3)
1965	140 MMCF	110.5 MMCF	276.68	2.09 BCF
1967	"	118.1	"	2.23 BCF
1970	"	132.75	"	2.51 BCF
1971	" →	140 MMCF	"	2.64 BCF

(2) THIS IS A CURRENT P/Z CALCULATION
w/ P = 250 PSIG = 262.14 PSIA
Z = 0.965
P BOTTOM HOLE = 267 PSIA
P/Z = 276.68 PSIA

(3) BASED ON CURRENT P/Z CALC @ 250#

(1) ASSUMED WATER ENCROACHMENT OCCUPIED PART OF THE ORIGINAL VOID UNTIL 1971.

12/28/90

1/22/91

ANNUAL L&U RATE OF 0.1 BCF/Y IS BASED ON HISTORICAL DATA FROM 1972 TO 1982.

THE PROPOSED 0.7 BCF WRITE OFF (1/3/91 REPORT) IS BASED ON HISTORICAL DATA FROM 1965 TO 1982

1990 DRAWDOWN - REMAINING VOLUME

0.65 BCF SHOULD BE WRITTEN OFF AS L & U BASED ON REMAINING VOLUME CALCULATED GAS VS BOOK VOLUME, ASSUMING 11.4 MMCF/PSIG IS APPLICABLE FOR RECOVERABLE GAS.

STARTED DRAWDOWN 2/14/90 — 244.4 PSIG, V_{BOOK} = 3427491 MCF

SHUT IN 5/1/90 — 49.3 PSIG, V_{BOOK} = 1620628 MCF

BUILD UP TO 7/10/90 — 72 PSIG, V_{BOOK} = 1620628 MCF

NOT YET STABLE AT 72 PSIG. PER EXTRAPOLATION OF ATTACHED TWO GRAPHS, THE STABILIZED CAVERN PRESSURE IS ABOUT 83 TO 90 PSIG.

ASSUMING P_{STAB} = 85 PSIG*, w/ V_{BOOK} = 1,620,628 MCF

$\Delta P = (244.4 - 85) = 159$ PSIG

$\Delta V = (3427,491 \text{ MMCF} - 1620,628 \text{ MMCF}) = 1,806.86$ MMCF

$V/P = 1806.86 \text{ MMCF}/159 \text{ PSIG} = 11.4$ MMCF/PSIG

REMAINING VOL = 11.4 MMCF/PSIG X 85 PSIG = 969 MMCF

BOOK VOL @ 85 PSIG = 1620.63 MMCF
MINS CALC REMAINING VOL @ 85 PSIG = 969.0 MMCF
POTENTIAL L & U ⇒ 651.6 MMCF
= 0.65 BCF

AFFECTS OF Z ARE NEGLIGIBLE @ THIS PRESSURE.

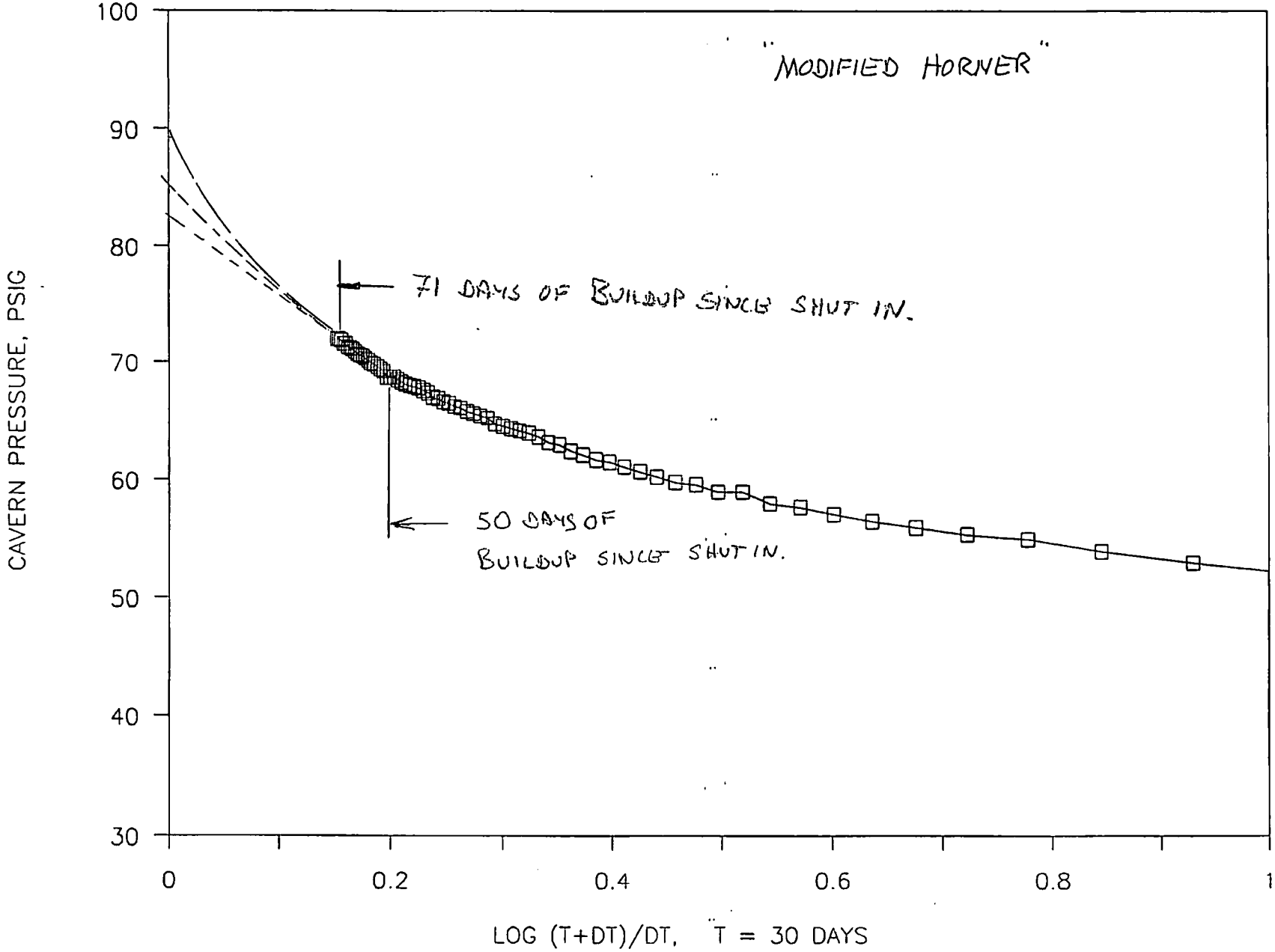
* ASSUMING 11.6 MMCF/PSIG IS VALID, THE PREDICTED STABILIZED PRESSURE IS 88.6 PSIG.

PSC 039868

B. HOLLINGSWORTH
12/28/90

LEYDEN PRESSURE BUILDUP

MAY 1, 1990 TO JULY 10, 1990



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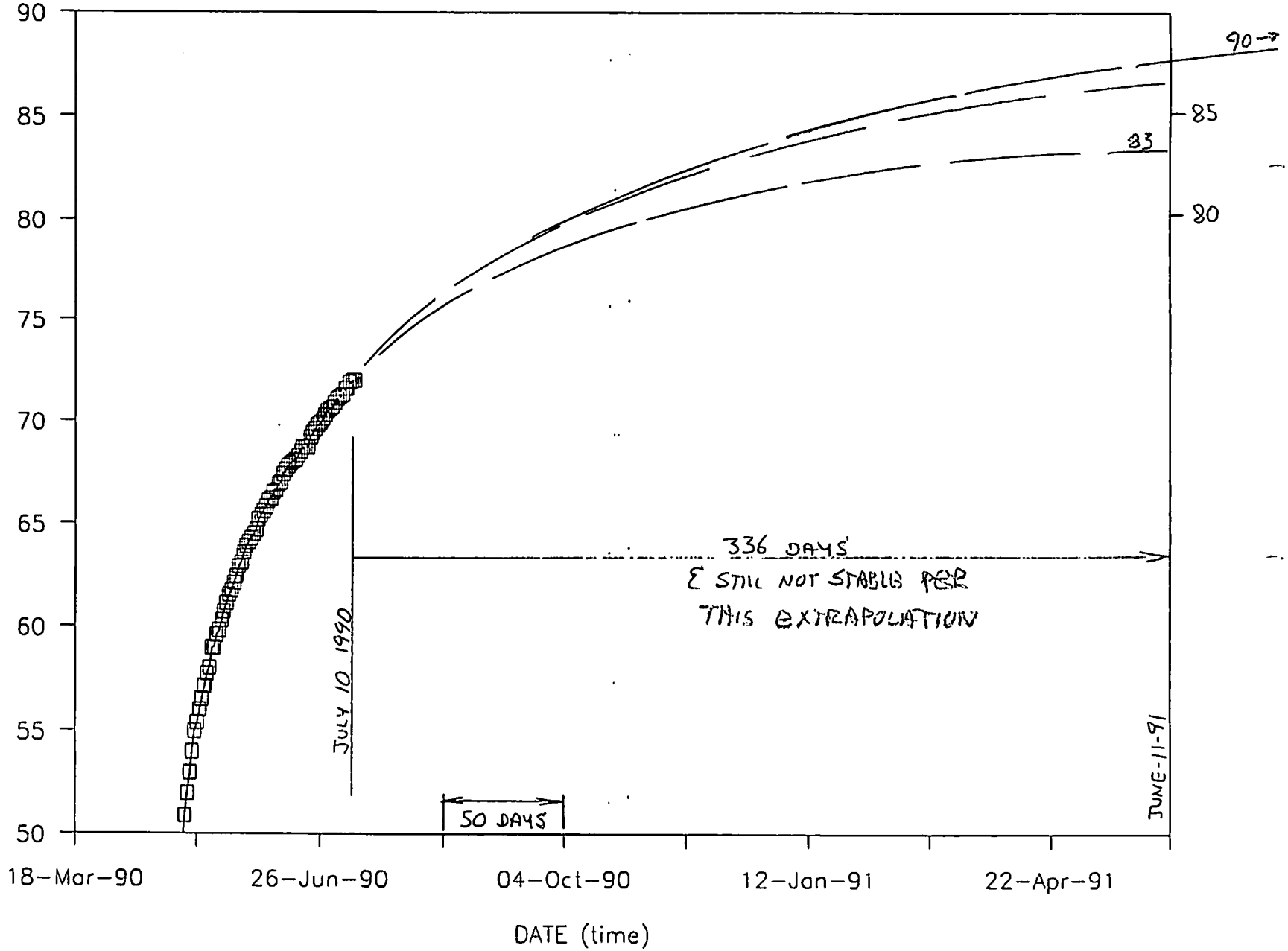
PSC 039869

LEYDEN PRESSURE BUILDUP

MAY 1, 1990 TO JULY 10, 1990



A 20

B. HOLLENBAUGH
12/28/90

PSC 039870

APPLICATION OF HORNER PLOT TO PREDICT STABILIZED CAV. PRESS.

APPLICATION PER SUGGESTION OF BILL YOUNG.

USE LOTUS & A "MODIFIED HORNER" PLOT TO PREDICT WHAT THE STABILIZED CAVERN PRESSURE WILL BE.

FOR STANDARD HORNER PLOT, STABILIZED PRESSURE IS ACHIEVED WHEN $(t+\Delta t)/\Delta t$ REACHES 1 ON REVERSE SEMI-LOG PLOT.

$$P_{STAB} \; @ \; \frac{t+\Delta t}{\Delta t} \Rightarrow 1.0$$

LOTUS CAN'T DO SEMI LOG OR REVERSE SCALE ON X-AXIS.

$\therefore$ PLOT IN LOTUS W/ $\text{LOG}\left[(T+\Delta T)/T\right]$ ON X AXIS.

$$P_{STAB} \; @ \; \text{LOG} \; \frac{T+\Delta T}{\Delta T} \Rightarrow \text{LOG } 1.0$$

$$\text{OR} \; \text{LOG} \left(\frac{T+\Delta T}{\Delta T}\right) \Rightarrow \phi$$

STABLE CAVERN PRESS OCCURS AT ϕ ON X-AXIS.

t = PRODUCTION TIME
Δt = INCRIMENTAL TIME SINCE SHUT IN.

ACTUAL PRODUCTION TIME FOR 1990 DRAWDOWN WAS 60 DAYS, 30 DAYS WAS USED IN MODEL BECAUSE THIS CURVE WAS EASIEST TO EXTRAPOLATE. A SENSITIVITY WAS DONE ON t FROM 10 DAYS TO 160 DAYS. EACH YIELDS ABOUT THE SAME RESULTS.

REF CHAPTER 3, PG 18, "PRESS BUILDUP & FLOW TESTS IN WELLS", SPE MONOGRAPH VOL1, HENRY L. DOHERTY SERIES, 1967.

B HOLLOWAYED
12/28/90

PSC 039871

LEYDEN PRESSURE BUILD UP AFTER SHUT IN ON WITHDRAWAL LD90

MAY 1, 1990 TO JULY 10, 1990 MODIFIED HORNER PLOT

DATE	PRESSURE PSIG	TIME		(T+DT)/DT	LOG OF (T+DT)/DT
01-May-90	49.3		1	$\frac{30+1}{1}$ 31	1.4913616938
02-May-90	50.9	$\frac{30+2}{2}$	2	16	1.2041199827
03-May-90	52		3	$\frac{30+3}{3}$ 11	1.0413926852
04-May-90	53		4	8.5	0.9294189257
05-May-90	54		5	7	0.84509804
06-May-90	55		6	6	0.7781512504
07-May-90	55.4		7	5.2857142857	0.7231036841
08-May-90	56		8	4.75	0.6766936096
09-May-90	56.5		9	4.3333333333	0.6368220976
10-May-90	57.1		10	4	0.6020599913
11-May-90	57.7		11	3.7272727273	0.5713911716
12-May-90	58		12	3.5	0.5440680444
13-May-90	59		13	3.3076923077	0.5195251033
14-May-90	59		14	3.1428571429	0.4973246408
15-May-90	59.6		15	3	0.4771212547
16-May-90	59.8		16	2.875	0.458637849
17-May-90	60.3		17	2.7647058824	0.4416489366
18-May-90	60.7		18	2.6666666667	0.4259687323
19-May-90	61.1		19	2.5789473684	0.4114424791
20-May-90	61.5		20	2.5	0.3979400087
21-May-90	61.7		21	2.4285714286	0.3853508814
22-May-90	62.1		22	2.3636363636	0.3735806628
23-May-90	62.4		23	2.3043478261	0.3625480336
24-May-90	62.9		24	2.25	0.3521825181
25-May-90	63.1		25	2.2	0.3424226808
26-May-90	63.6		26	2.1538461538	0.333214679
27-May-90	63.9		27	2.1111111111	0.3245110915
28-May-90	64.1		28	2.0714285714	0.3162699622

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29-May-90	64.3	29	2.0344827586	0.3084540137
30-May-90	64.5	30	2	0.3010299957
31-May-90	64.7	31	1.9677419355	0.2939681412
01-Jun-90	65.2	32	1.9375	0.2872417112
02-Jun-90	65.4	33	1.9090909091	0.2808266096
03-Jun-90	65.6	34	1.8823529412	0.2747010569
04-Jun-90	65.8	35	1.8571428571	0.2688453123
05-Jun-90	66.1	36	1.8333333333	0.2632414348
06-Jun-90	66.2	37	1.8108108108	0.2578730786
07-Jun-90	66.5	38	1.7894736842	0.2527253161
08-Jun-90	66.6	39	1.7692307692	0.2477844837
09-Jun-90	66.9	40	1.75	0.2430380487
10-Jun-90	67	41	1.7317073171	0.238474492
11-Jun-90	67.4	42	1.7142857143	0.234083206
12-Jun-90	67.6	43	1.6976744186	0.2298544045
13-Jun-90	67.8	44	1.6818181818	0.2257790432
14-Jun-90	67.9	45	1.6666666667	0.2218487496
15-Jun-90	68	46	1.652173913	0.2180557606
16-Jun-90	68.1	47	1.6382978723	0.2143928672
17-Jun-90	68.3	48	1.625	0.2108533653
18-Jun-90	68.5	49	1.612244898	0.2074310113
19-Jun-90	68.7	50	1.6	0.2041199827
20-Jun-90	68.7	51	1.5882352941	0.2009148428
21-Jun-90	68.7	52	1.5769230769	0.1978105087
22-Jun-90	69.2	53	1.5660377358	0.1948022228
23-Jun-90	69.4	54	1.5555555556	0.1918855262
24-Jun-90	69.6	55	1.5454545455	0.1890562362
25-Jun-90	69.8	56	1.5357142857	0.1863104242
26-Jun-90	69.9	57	1.5263157895	0.1836443969
27-Jun-90	70.1	58	1.5172413793	0.1810546786
28-Jun-90	70.3	59	1.5084745763	0.178537995
29-Jun-90	70.5	60	1.5	0.1760912591
30-Jun-90	70.6	61	1.4918032787	0.1737115573
01-Jul-90	70.7	62	1.4838709677	0.1713961378

A 23

02-Jul-90	70.9	63	1.4761904762	0.1691423991
03-Jul-90	71.1	64	1.46875	0.1669478796
04-Jul-90	71.2	65	1.4615384615	0.1648102486
05-Jul-90	71.3	66	1.4545454545	0.1627272975
06-Jul-90	71.6	67	1.447761194	0.1606969316
07-Jul-90	71.6	68	1.4411764706	0.158717163
08-Jul-90	71.9	69	1.4347826087	0.1567861039
09-Jul-90	72	70	1.4285714286	0.15490196
10-Jul-90	72	71	1.4225352113	0.1530630251

A 24

WestGas®
Western Gas Supply Company

Interoffice Memo

10/5/90

To: Bill Uding, Supervisor, Reservoir & Storage Eng.
From: Brad Hollenbaugh, Reservoir Engineer

The attached report on the Leyden 1990 drawdown is FYI & comment. This is just one more small piece of the giant puzzle.

L&U GAS ESTIMATE

Also of interest is the remaining storage volume at the end of the drawdown. There is 1.6 BCF remaining total in storage at 69 psig cavern pressure. This 1.6 BCF is per gas measurement books.

Per a quick calculation, there is about 0.62 BCF which could be written off as L&U gas (see L&U ESTIMATE CALCULATION below). I would like to do a more detailed evaluation of the L&U in order to answer these questions:

1. What is the L&U since the facility was placed in operation?
2. Is annual L&U increasing with time?
3. Is the L&U at an acceptable economic level?
4. Does lowering the pressure to 50 psig increase the L&U?
5. What is the appropriate lb X day balance pressure?
6. Where is the L&U gas going, and is any of it recoverable?

A-25

LEYDEN L&U REPORT
NOVEMBER 27, 1991

SUMMARY

Calculations indicate 0.17 BCF (14.65) less gas in storage than is being carried on the books. An L&U adjustment of 170,000 MCF should be applied to the book volume, by subtracting this amount from same.

Six methods were used to predict the L&U, and method 4 (below) provides significant justification for the 0.17 BCF recommendation. The recommended L&U adjustment is made up of the current year L&U plus some "catch up" L&U. The current year L&U is estimated between 0.1 and 0.14 BCF. The total catch up L&U is estimated at about 0.16 BCF per review of the 1990 L&U report (0.7 - 0.54). About 19% to 44% of this total catch up L&U is accounted for in the recommended 0.17 BCF write-off.

Assumed current year L&U	Catch Up L&U	% of Total Catch Up	Recommended L&U
0.1 BCF (method 6)	0.07	44%	0.17 BCF
0.14 (method 5)	0.03	19%	0.17 BCF

CONCLUSIONS

Six methods were used to estimated L&U. The first four methods calculate the total L&U, which includes any "catch up" L&U. The last two methods only account for the current year L&U, and do not include any catch up volume.

METHOD 1 0.18 BCF Total L&U

Horner plot applied to pressure buildup data (shut in after withdrawal) to determine stabilized cavern pressure (95 psig). Assumes 11.6 MMCF/psig stabilized.

METHOD 2 0.24 BCF Total L&U

Muskat plot applied to pressure buildup data (shut in after withdrawal) to determine stabilized cavern pressure (90 psig). Assumes 11.6 MMCF/psig stabilized.

PSC 039808

METHOD 3 0.24 BCF Total L&U

Stabilized cavern pressure of 90 psig predicted by evaluating pressure buildup data (shut in after withdrawal). Extrapolated pressure from a curve of Pressure vs. buildup time. Assumes 11.6 MMCF/psig stabilized.

METHOD 4 0.17 BCF Total L&U

Analysis of pressure fall off data (shut in after injection) to predict stabilized cavern pressure. This is conservative in that it is the minimum L&U and the actual L&U is probably higher than this. Assumes 11.6 MMCF/psig stabilized.

METHOD 5 0.14 BCF Current Year L&U

Comparison of book volume in 1991 to book volume in 1990 for a similar stabilized pressure condition. Horner plot used for predicting stabilized cavern pressures. Assumes 11.6 MMCF/psig stabilized, but result is not very dependent on this assumption. The current year L&U could be higher than the historic L&U trend of 0.1 BCF/year due to the extreme low pressure drawdown this summer.

METHOD 6 0.1 BCF Current Year L&U

This is based on the historic trend. Documentation can be found in the 1/3/91 L&U Report.

RECOMMENDATIONS

The Horner plot does not appear to be a great tool for predicting the stabilized cavern pressure. The extrapolation is not obvious, and the results do not agree with the Muskat method. The Horner plot may be adequate when comparing a pressure condition from one year to a similar pressure condition of another year (method 5).

The Muskat plot behaves as expected and may be superior to the Horner plot. Further application of the Muskat plot will help evaluate the effectiveness of this tool in predicting the stabilized cavern pressure.

The application of other plots, theories, and type curves should be investigated in future L&U analysis.

Brad Hollenbaugh
Reservoir & Storage Eng.
WestGas 11/27/91

PSC 039809

METHOD 1

RESULTS OF HORNER PLOT (& MODIFIED HORNER PLOT)

ANALYSIS OF 5/2/91 TO 8/13/91 BUILDUP.

STABILIZED CAVERN PRESSURE - PSIG	CALCULATED LEU BCF
92 PSIG	0.21 BCF
* ⟹ 95	0.18
98	0.14
100	0.12

THE HORNER PLOTS SUGGEST A STABILIZED CAVERN PRESSURE OF 95 PSIG, WITH A RESULTING LEU OF 0.18 BCF. THIS LEU IS NOT FOR THE YEAR, BUT IS THAT WHICH THEORETICALLY ACCOUNTS FOR LEU TO DATE.

(1) $LEU = V_{BOOK} - V_{THEORETICAL}$

PSC 039810

(2) $V_{BOOK} = 1\,281\,196$ MCF (14.65 @ END OF DRAWDOWN)

(3) $V_{THEO} = \underbrace{11.6 \frac{MMCF}{PSIG}}_{} \times P_{STAB}\ (PSIG) \times 1000,\ (MCF)$

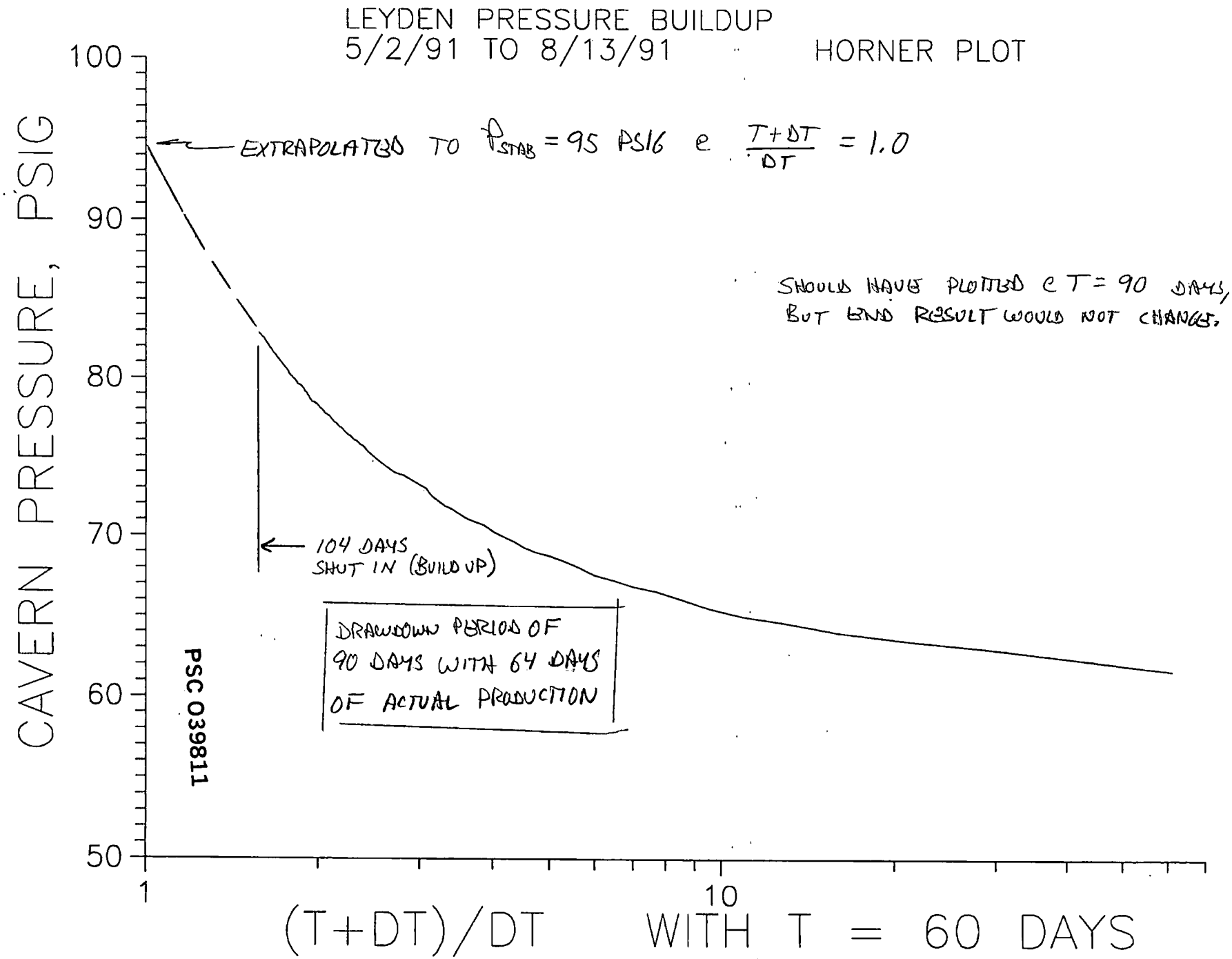
↳ IF WE USED 11.4, THE LEU WOULD INCREASE.

THE HIGHER THE ACTUAL P_{STAB}, THE LOWER THE LEU

- AQUIFER INFLUENCE WILL IMPACT THE BUILDUP.
- THE LEYDEN STORAGE SYSTEM MAY NOT BE SUITED TO THE HORNER PLOT THEORY

A 1.1

11/26/91 B. HOLLENBAUGH



PSC 039811

A1.2

HORNER PLOT ANALYSIS

PLOT P ON Y AXIS

$(T+\Delta T)/\Delta T$ ON X ASIS w/ LOG SCALE

EXTRAPOLATE $\frac{T+\Delta T}{\Delta T}$ TO A VALUE OF 1.0

TO FIND THE STABILIZED (STATIC) CAVERN PRESSURE.

P = BUILDUP PRESSURE AT TIME ΔT
T = TOTAL PRODUCING TIME SINCE WELL COMPLETION
ΔT = TIME ELAPSED SINCE SHUT IN

T & ΔT ARE IN DAYS OR HOURS - BE CONSISTENT

T IS OFTEN APPROXIMATED BY,

PSC 039812

$$T \approx \frac{\text{CUMMULATIVE PRODUCTION}}{\text{PRODUCTION RATE BEFORE SHUT IN}} = \frac{V_{cumm}}{Q}$$

ABOUT 1.8 BCF WAS WITHDRAWN $= V_{cumm}$

@ Q = 10 MMCFD, T = 180 days } ACTUAL NUMBERS
@ Q = 20, T = 90 days } OF DRAWDOWN
@ Q = 40, T = 45 days

ACTUAL T WAS 90 DAYS FOR THE DRAWDOWN PERIOD, WITH ABOUT 64 DAYS OF ACTUAL PRODUCTION,

THE RESULT (PREDICTED P_{STAB}) IS NOT VERY DEPENDENT ON T AS WAS EVIDENT w/ MODIFIED HORNER PLOTS FOR T = 15 days, 30 days, 60 days, 90 days, & 120 days.

11/26/91 B. HOLLENBAUGH

MODIFIED HORNER PLOT

THIS WAS ONLY DONE BECAUSE LOTUS DOES NOT HAVE THE ABILITY TO PLOT W/ LOG SCALE ON X-AXIS. SEE P6 A21 DATED 12/28/90 OF 1/3/91 LEU REPORT FOR APPLICATION OF THE MODIFIED HORNER PLOT.

THE HORNER PLOT IN THIS REPORT WAS DONE WITH THE GRAPHER SOFTWARE. FUTURE PLOTS WILL BE DONE ON LOG SCALE W/ GRAPHER.

THE HORNER PLOT & THE MODIFIED HORNER PLOT PRODUCED THE SAME RESULTS WHEN EXTRAPOLATING FOR STATIC (STABILIZED) CAVERN PRESSURES

HORNER REF: PET ENG HANDBOOK, SPE 1989
PG. 30-9, 35-15, 35-16

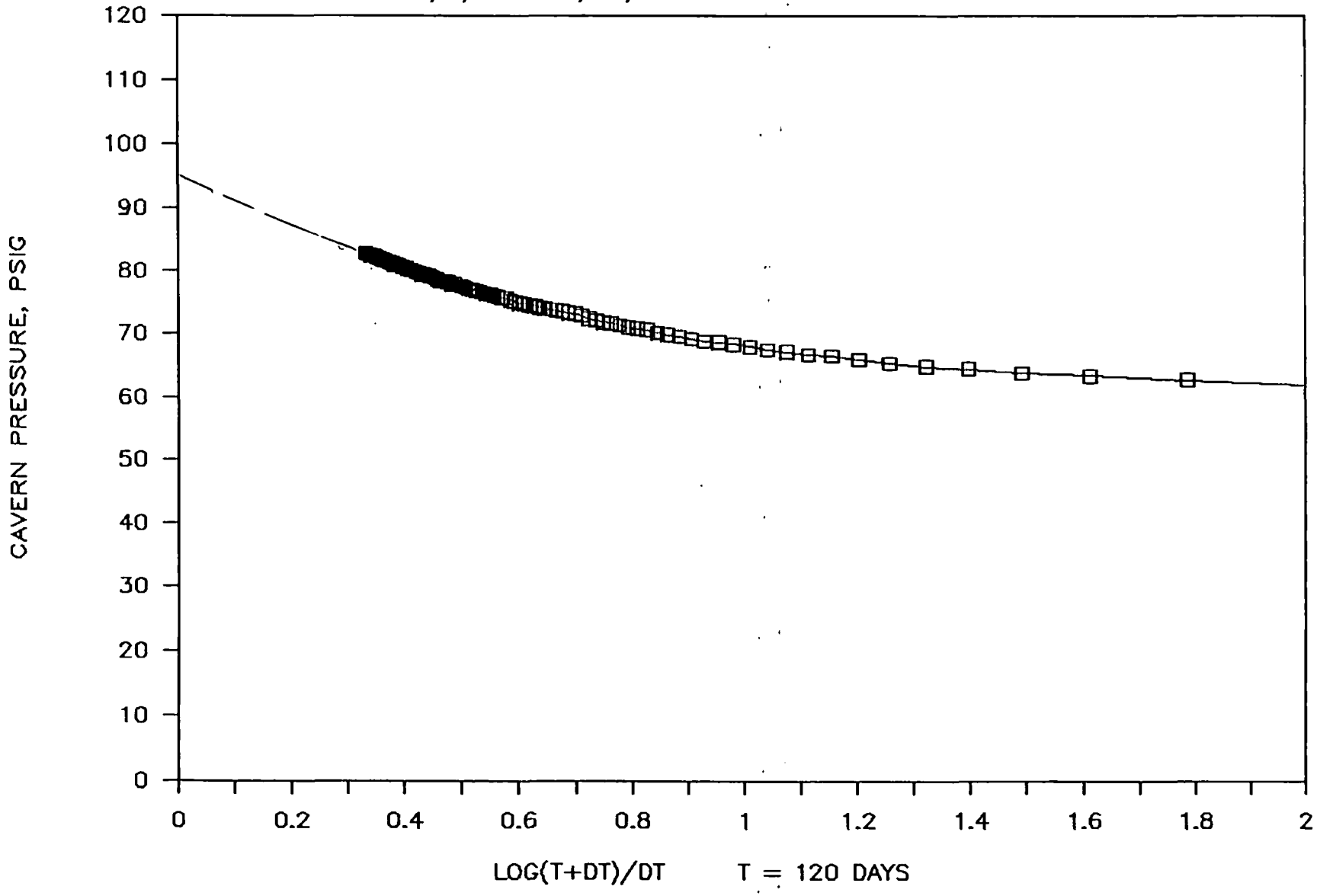
PSC 039813

11/26/91 B. HOLLOWAY

A1.4

LEYDEN PRESSURE BUILDUP

5/2/91 TO 8/13/91 MODIFIED HORNER PLOT

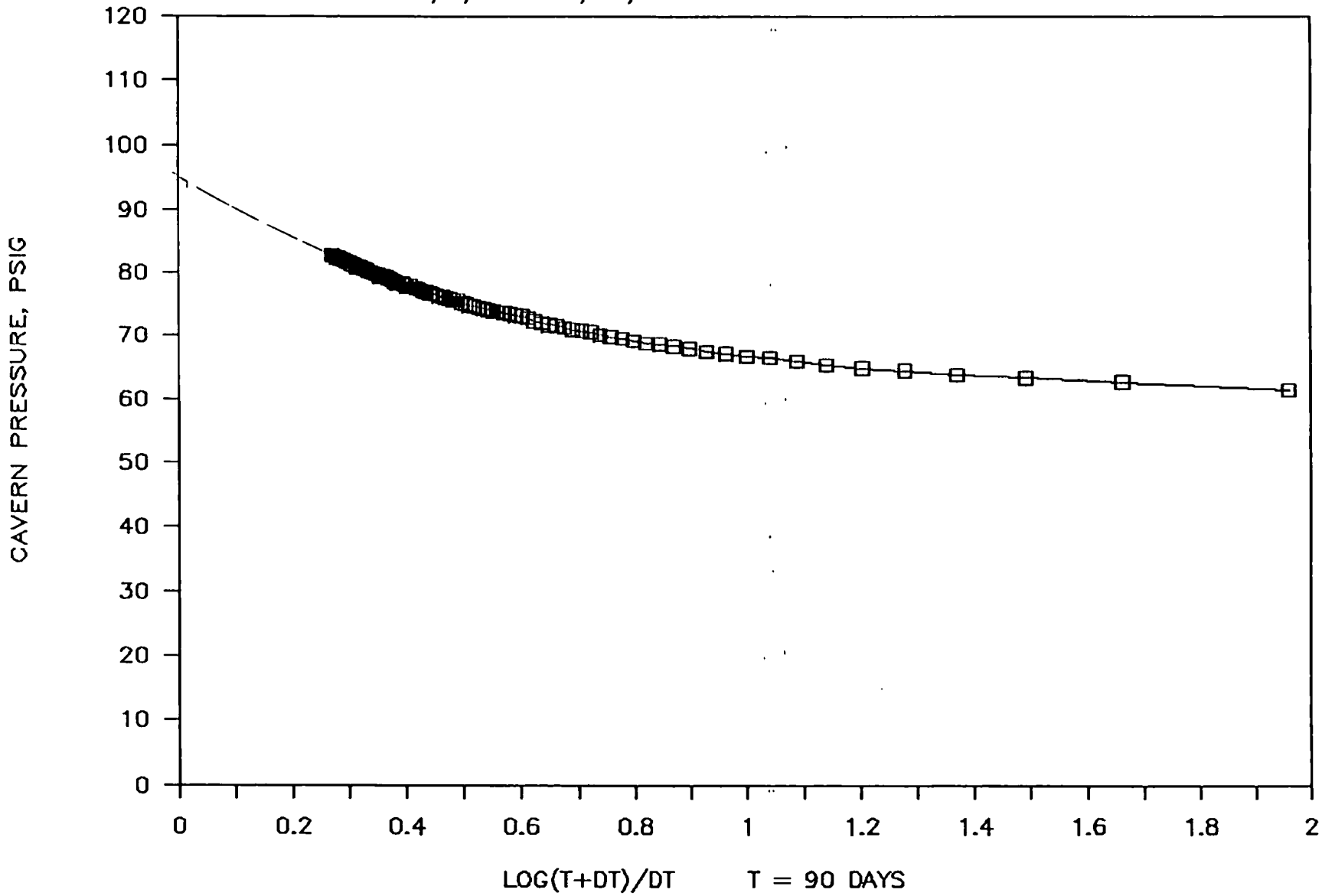


A 1.5

PSC 039814

LEYDEN PRESSURE BUILDUP

5/2/91 TO 8/13/91 MODIFIED HORNER PLOT

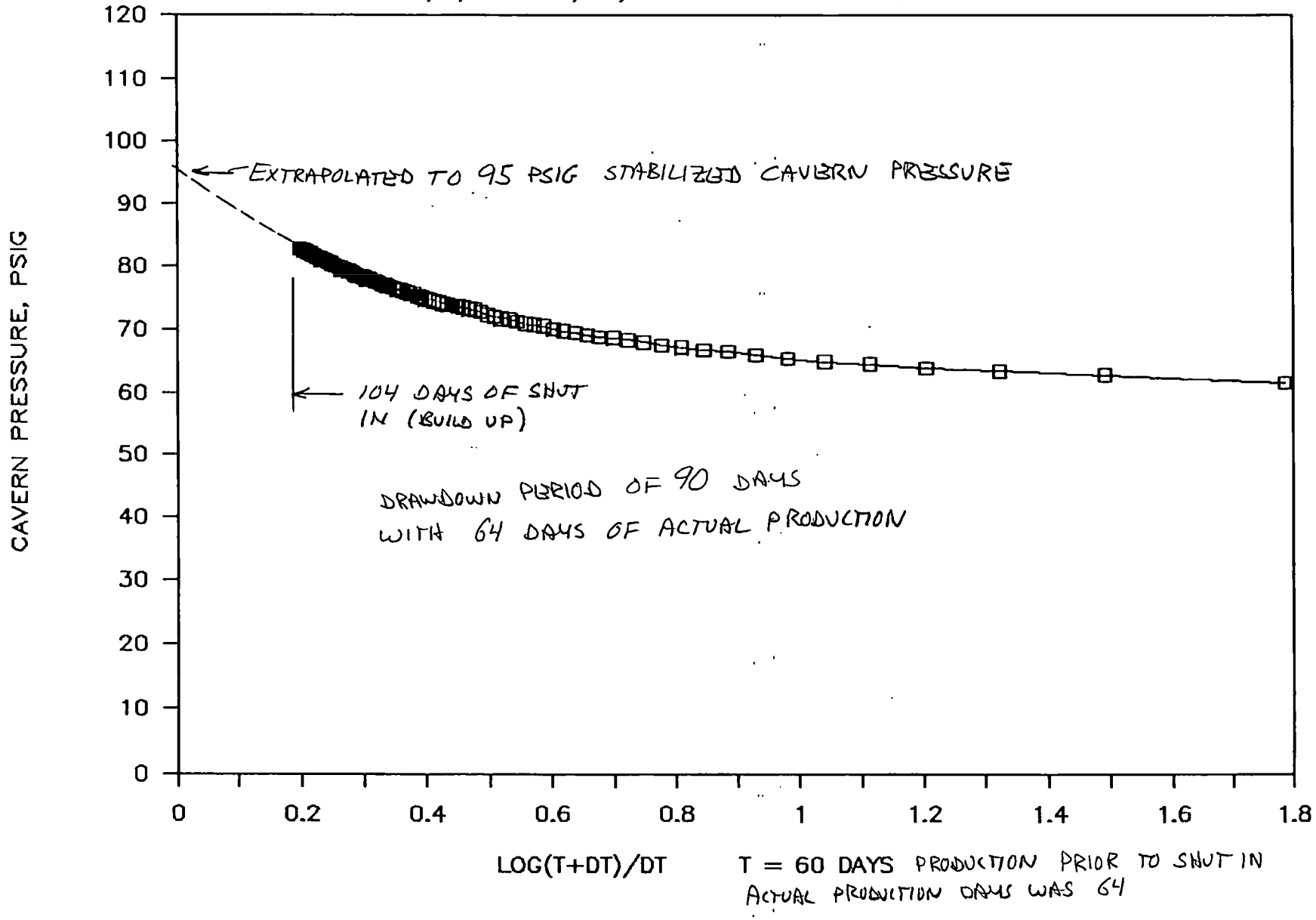


A1.6

PSC 039815

LEYDEN PRESSURE BUILDUP

5/2/91 TO 8/13/91 MODIFIED HORNER PLOT



A1.7

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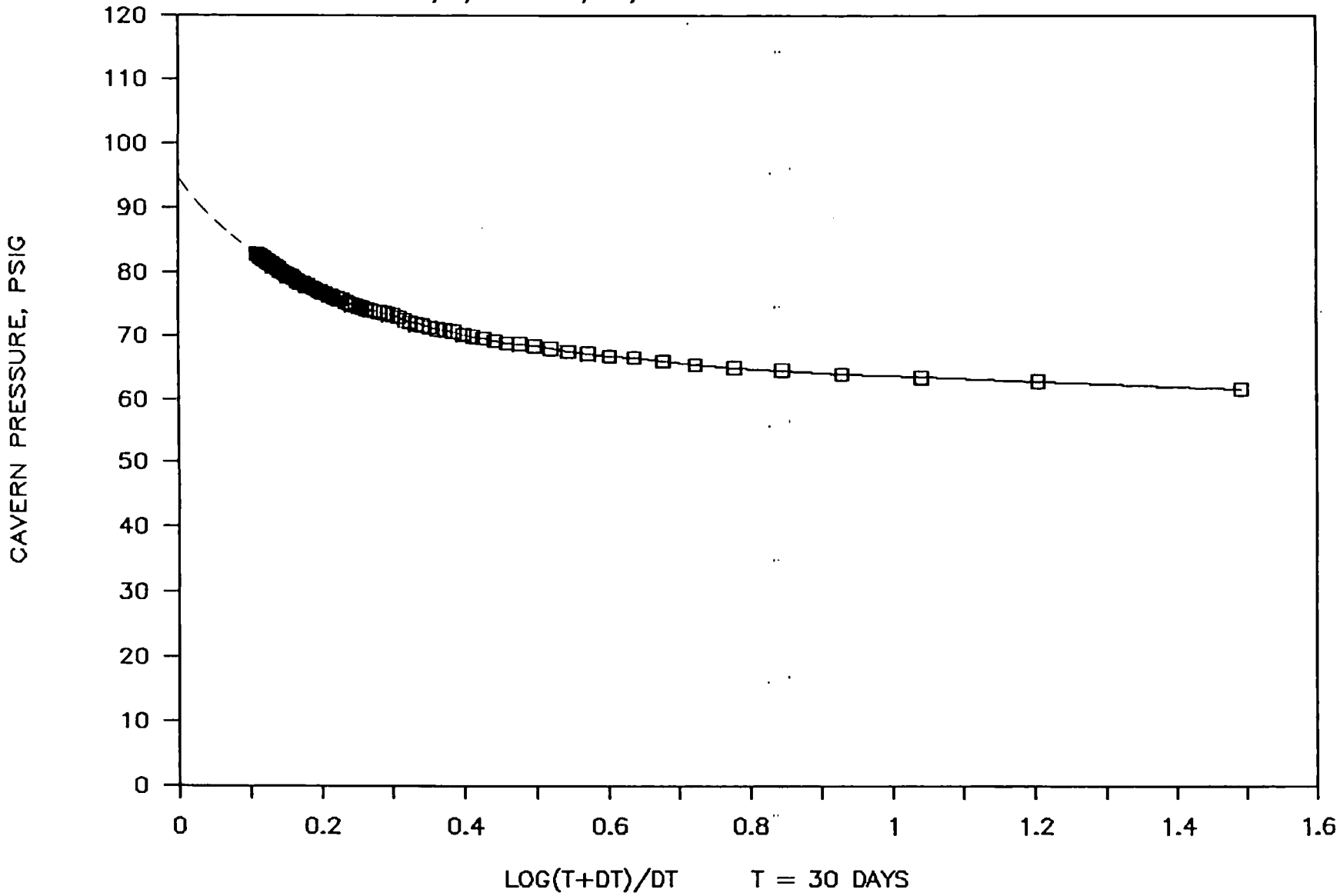
LEYDEN PRESSURE BUILDUP

5/2/91 TO 8/13/91 MODIFIED HORNER PLOT

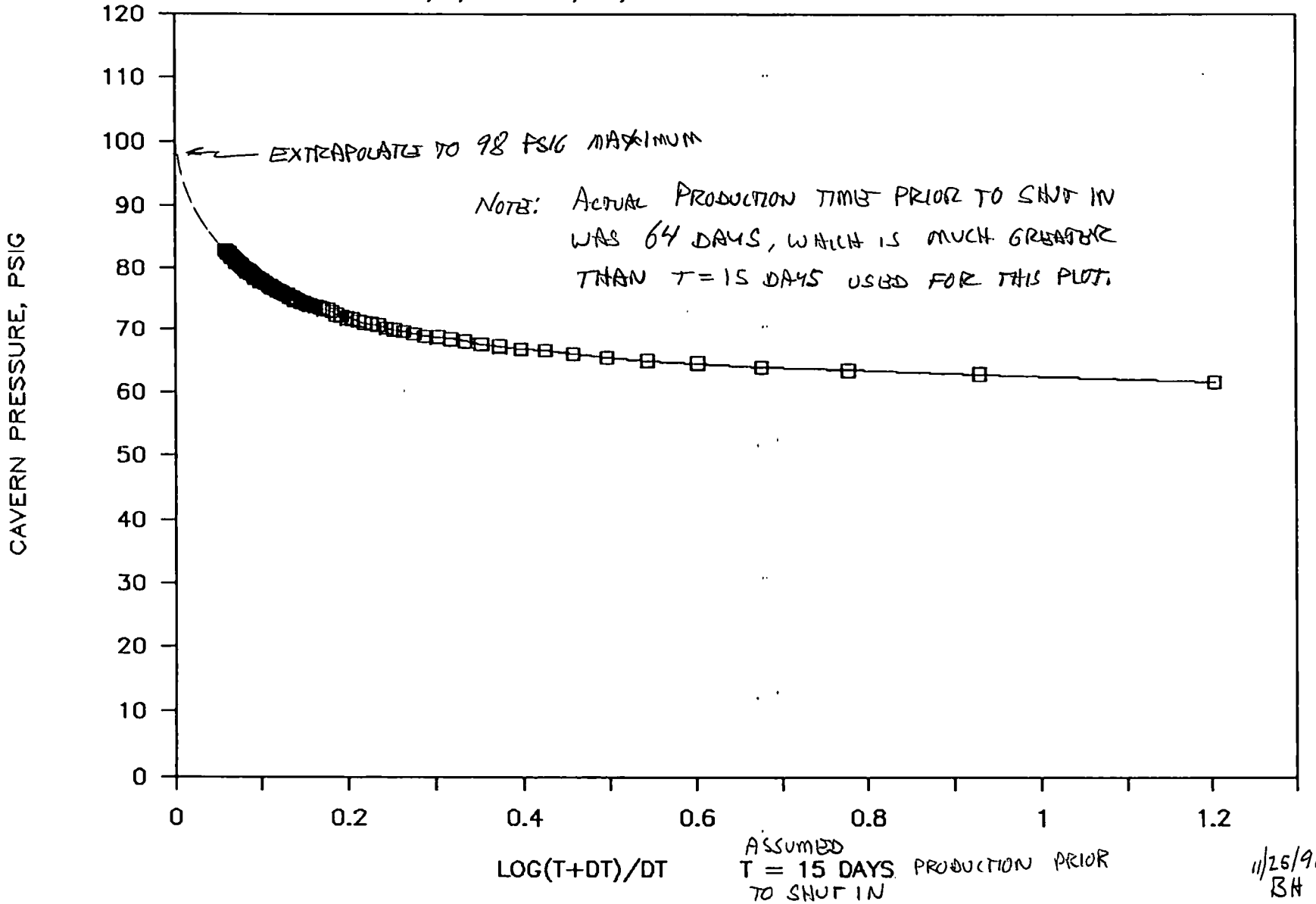


A1.8

PSC 039817

LEYDEN PRESSURE BUILDUP

5/2/91 TO 8/13/91 MODIFIED HORNER PLOT



11/26/91
BH

A1.9

PSC 039818

60 LINES/PAGE

LEYDEN PRESSURE BUILDUP AFTER SHUT IN ON WITHDRAWAL LD91L&U1.
5/2/91 THROUGH 8/13/91 MODIFIED HORNER PLOT
T = 60

DATE	PRESSURE PSIG	DT DAYS	(T+DT)/DT	LOG (T+DT)/T
02-May-91	61.7	1	61	1.785329
03-May-91	62.9	2	31	1.491361
04-May-91	63.5	3	21	1.322219
05-May-91	64	4	16	1.204119
06-May-91	64.6	5	13	1.113943
07-May-91	65	6	11	1.041392
08-May-91	65.5	7	9.571428	0.980976
09-May-91	66.1	8	8.5	0.929418
10-May-91	66.6	9	7.666666	0.884606
11-May-91	66.9	10	7	0.845098
12-May-91	67.3	11	6.454545	0.809865
13-May-91	67.6	12	6	0.778151
14-May-91	68.1	13	5.615384	0.749379
15-May-91	68.5	14	5.285714	0.723103
16-May-91	68.8	15	5	0.698970
17-May-91	69	16	4.75	0.676693
18-May-91	69.3	17	4.529411	0.656041
19-May-91	69.7	18	4.333333	0.636822
20-May-91	70	19	4.157894	0.618873
21-May-91	70.3	20	4	0.602059
22-May-91	70.7	21	3.857142	0.586265
23-May-91	70.9	22	3.727272	0.571391
24-May-91	71.1	23	3.608695	0.557350
25-May-91	71.4	24	3.5	0.544068
26-May-91	71.7	25	3.4	0.531478
27-May-91	71.9	26	3.307692	0.519525
28-May-91	72.2	27	3.222222	0.508155
29-May-91	72.5	28	3.142857	0.497324
30-May-91	73	29	3.068965	0.486992
31-May-91	73.2	30	3	0.477121
01-Jun-91	73.4	31	2.935483	0.467679
02-Jun-91	73.6	32	2.875	0.458637
03-Jun-91	73.8	33	2.818181	0.449969
04-Jun-91	73.9	34	2.764705	0.441648
05-Jun-91	74	35	2.714285	0.433655
06-Jun-91	74.2	36	2.666666	0.425968
07-Jun-91	74.4	37	2.621621	0.418570
08-Jun-91	74.6	38	2.578947	0.411442
09-Jun-91	74.8	39	2.538461	0.404570
10-Jun-91	75	40	2.5	0.397940
11-Jun-91	75.2	41	2.463414	0.391537
12-Jun-91	75.4	42	2.428571	0.385350
13-Jun-91	75.7	43	2.395348	0.379368

14-Jun-91	75.8	44	2.363636	0.373580
15-Jun-91	76	45	2.333333	0.367976
16-Jun-91	76.1	46	2.304347	0.362548
17-Jun-91	76.3	47	2.276595	0.357285
18-Jun-91	76.4	48	2.25	0.352182
19-Jun-91	76.6	49	2.224489	0.347230
20-Jun-91	76.8	50	2.2	0.342422
21-Jun-91	76.9	51	2.176470	0.337752
22-Jun-91	77.1	52	2.153846	0.333214
23-Jun-91	77.2	53	2.132075	0.328802
24-Jun-91	77.4	54	2.111111	0.324511
25-Jun-91	77.6	55	2.090909	0.320335
26-Jun-91	77.7	56	2.071428	0.316269
27-Jun-91	77.8	57	2.052631	0.312311
28-Jun-91	78	58	2.034482	0.308454
29-Jun-91	78.1	59	2.016949	0.304694
30-Jun-91	78.3	60	2	0.301029
01-Jul-91	78.4	61	1.983606	0.297455
02-Jul-91	78.5	62	1.967741	0.293968
03-Jul-91	78.5	63	1.952380	0.290564
04-Jul-91	78.7	64	1.9375	0.287241
05-Jul-91	78.9	65	1.923076	0.283996
06-Jul-91	79.1	66	1.909090	0.280826
07-Jul-91	79.2	67	1.895522	0.277728
08-Jul-91	79.4	68	1.882352	0.274701
09-Jul-91	79.5	69	1.869565	0.271740
10-Jul-91	79.6	70	1.857142	0.268845
11-Jul-91	79.6	71	1.845070	0.266012
12-Jul-91	79.8	72	1.833333	0.263241
13-Jul-91	79.9	73	1.821917	0.260528
14-Jul-91	80	74	1.810810	0.257873
15-Jul-91	80.1	75	1.8	0.255272
16-Jul-91	80.2	76	1.789473	0.252725
17-Jul-91	80.3	77	1.779220	0.250229
18-Jul-91	80.5	78	1.769230	0.247784
19-Jul-91	80.6	79	1.759493	0.245387
20-Jul-91	80.7	80	1.75	0.243038
21-Jul-91	80.8	81	1.740740	0.240734
22-Jul-91	80.9	82	1.731707	0.238474
23-Jul-91	81	83	1.722891	0.236257
24-Jul-91	81.1	84	1.714285	0.234083
25-Jul-91	81.2	85	1.705882	0.231949
26-Jul-91	81.3	86	1.697674	0.229854
27-Jul-91	81.4	87	1.689655	0.227798
28-Jul-91	81.5	88	1.681818	0.225779
29-Jul-91	81.6	89	1.674157	0.223796
30-Jul-91	81.7	90	1.666666	0.221848
31-Jul-91	81.8	91	1.659340	0.219935
01-Aug-91	81.9	92	1.652173	0.218055
02-Aug-91	82	93	1.645161	0.216208

03-Aug-91	82.1	94	1.638297	0.214392
04-Aug-91	82.2	95	1.631578	0.212608
05-Aug-91	82.3	96	1.625	0.210853
06-Aug-91	82.4	97	1.618556	0.209127
07-Aug-91	82.5	98	1.612244	0.207431
08-Aug-91	82.6	99	1.606060	0.205761
09-Aug-91	82.6	100	1.6	0.204119
10-Aug-91	82.7	101	1.594059	0.202504
11-Aug-91	82.8	102	1.588235	0.200914
12-Aug-91	82.8	103	1.582524	0.199350
13-Aug-91	82.9	104	1.576923	0.197810

PSC 039821

RESULTS OF MUSKAT PLOTS — METHOD 2

ANALYSIS OF 5/2/91 TO 8/13/91 BUILDUP

PREDICTED STABILIZED CAV. PRESSURE = 90 PSIG

ESTIMATED LEU = 0.24 BCF

MUSKAT PLOT REFERENCES; ① PETROLEUM ENG. HANDBOOK, SPE, 1989 Pg 30-9
② PRESSURE BUILDUP & FLOW TESTS IN WELLS, SPE, MATTHEWS - RUSSEL, 1967, Pg 30, MONOGRAPH VOL 1,
⟹ ③ ADVANCES IN WELL TEST ANALYSIS, SPE MONOGRAPH VOL 5, 1977, Pg 51 t...

THE INDUSTRY CONVENTION IS TO PUT THE LOG SCALE ON THE "Y" AXIS. I DID NOT DO IT THAT WAY.

APPLICATION — TRIAL & ERROR SOLN

PLOT $P_{ws} - P$ ON LOG SCALE
VS. BUILDUP TIME.

P_{ws} = ESTIMATED STATIC PRESSURE (ASSUMED)
P = ACTUAL BUILDUP PRESSURE AT TIME T
T = ELAPSED TIME SINCE SHUT IN = BUILDUP TIME

CONCAVE UP PLOT IF $P_{ws} > P_{ACTUAL\ STABLE}$
STRAIGHT LINE IF $P_{ws} \approx P_{ACTUAL\ STABLE}$
CONCAVE DOWN PLOT IF $P_{ws} < P_{ACTUAL\ STABLE}$

11/26/91 B. HOLLENBAUGH

A2.1

PSC 039822

CAUTION w/ MUSKAT ANALYSIS;

USE ONLY W/ LONG SHUT-IN TIMES

PER REVIEW OF THE ATTACHED PLOTS, THE STABILIZED PRESSURE APPEARS TO BE ABOUT 90 PSIG.

THE PLOTS BEHAVE AS EXPECTED, BUT WE DON'T KNOW HOW WILL THE MUSKAT METHOD ACTUALLY WORKS AT THE LEMDEN CONDITIONS.

(1) $LEU = V_{BOOK} - V_{THEORY}$

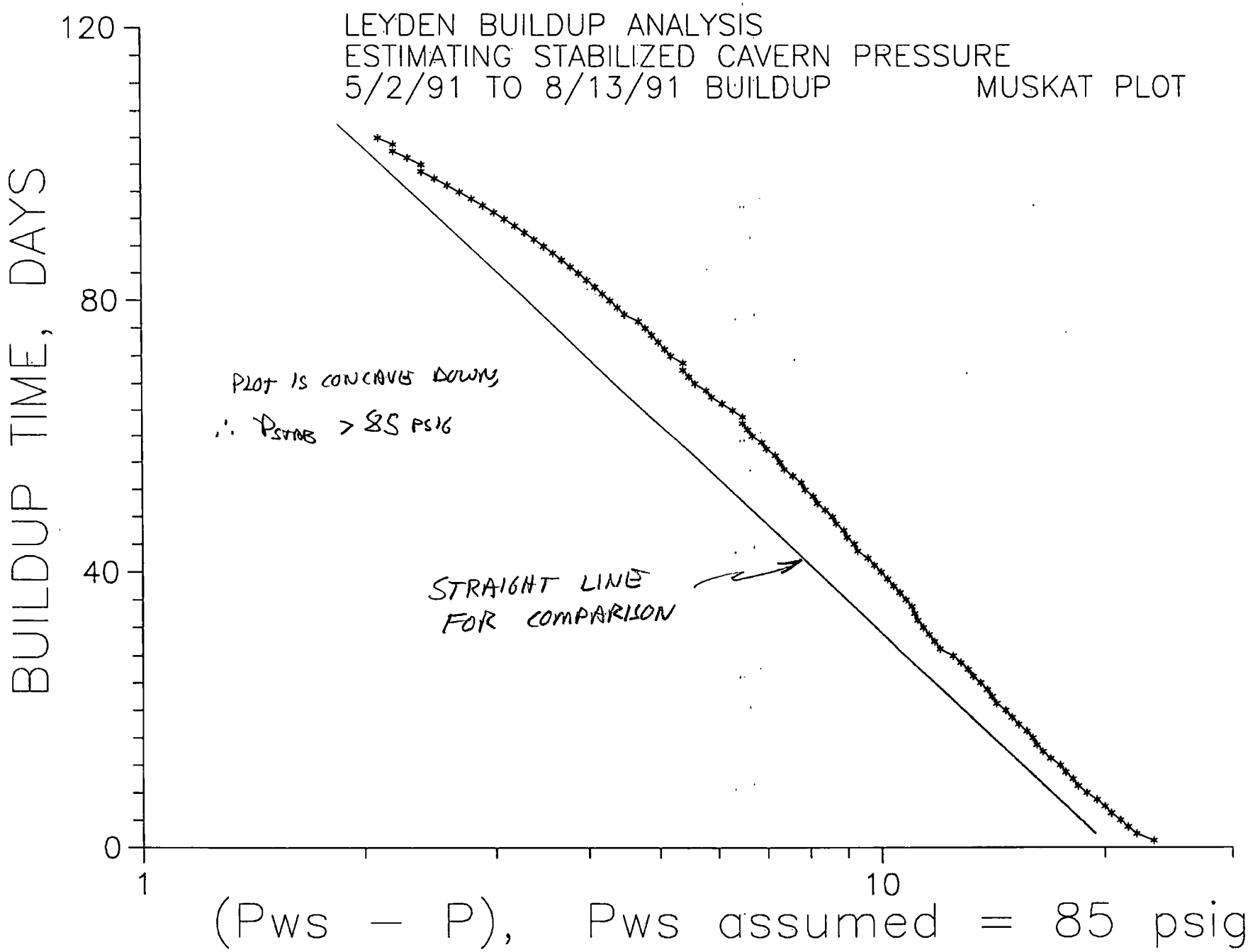
(2) $V_{BOOK} = 1\,281\,196$ MCF (14.65) @ END OF DRAWDOWN

(3) $V_{THEO} = 11.6 \frac{MMCF}{PSIG} \times P_{STAB}$ (PSIG) $\times 1000$, (MCF)

$\therefore LEU = 0.24$ BCF

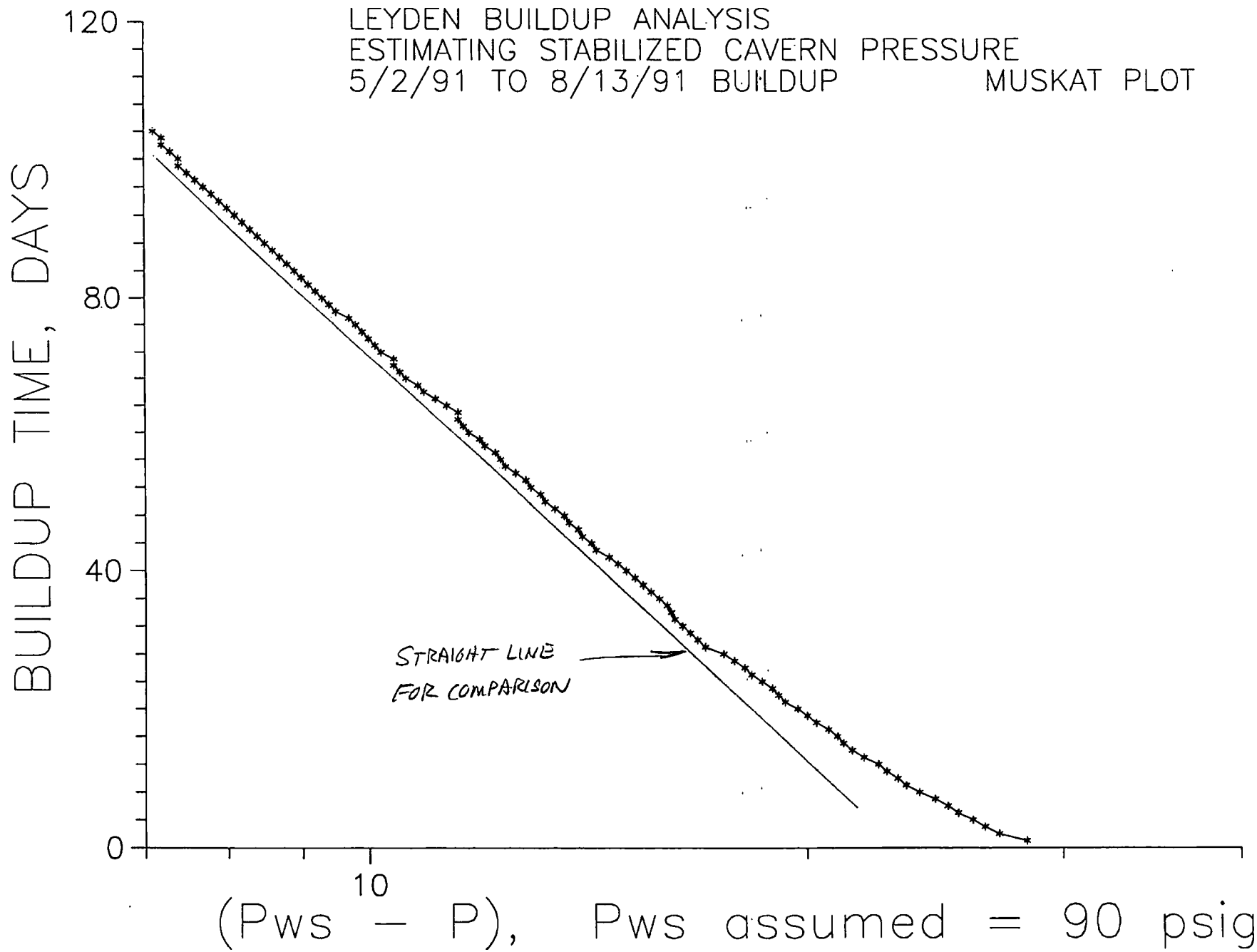
B. HOLLENBAUGH
11/26/91

A2.2



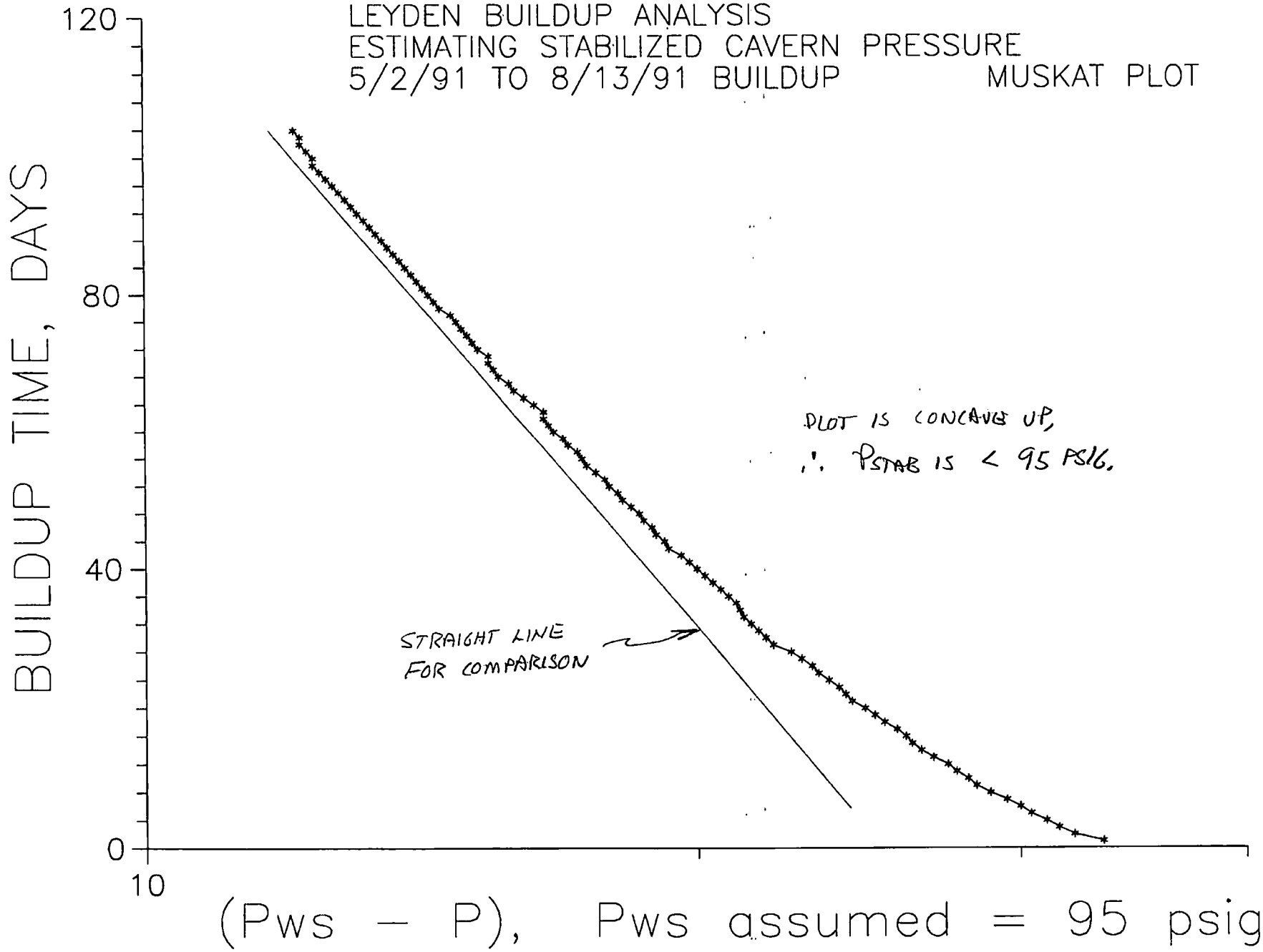
A 2.3

PSC 039824



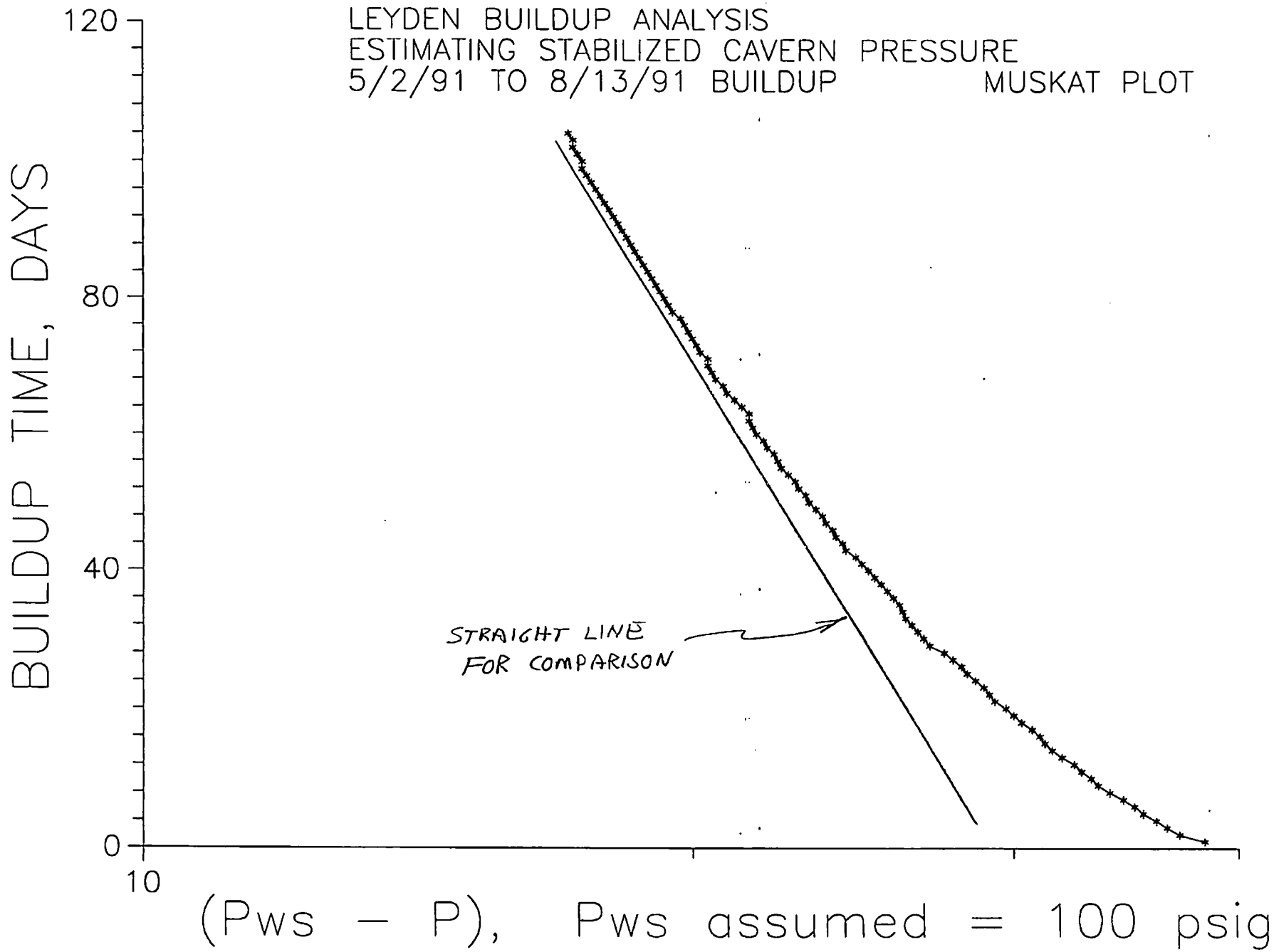
A.2.4

PSC 039825



A2.5

PSC 039826



A2.6

PSC 039827

LEYDEN PRESSURE BUILDUP AFTER SHUT IN ON WITHDRAWAL
5/2/91 THROUGH 8/13/91 MODIFIED HORNER PL

Pws = 90 T = 120

DATE	P = PRESSURE PSIG	DT DAYS	DP = Pws-P	(T+DT)/DT	LOG (T+DT)/T
02-May-91	61.7	1	28.3	121	2.082785
03-May-91	62.9	2	27.1	61	1.785329
04-May-91	63.5	3	26.5	41	1.612783
05-May-91	64	4	26	31	1.491361
06-May-91	64.6	5	25.4	25	1.397940
07-May-91	65	6	25	21	1.322219
08-May-91	65.5	7	24.5	18.14285	1.258705
09-May-91	66.1	8	23.9	16	1.204119
10-May-91	66.6	9	23.4	14.33333	1.156347
11-May-91	66.9	10	23.1	13	1.113943
12-May-91	67.3	11	22.7	11.90909	1.075878
13-May-91	67.6	12	22.4	11	1.041392
14-May-91	68.1	13	21.9	10.23076	1.009908
15-May-91	68.5	14	21.5	9.571428	0.980976
16-May-91	68.8	15	21.2	9	0.954242
17-May-91	69	16	21	8.5	0.929418
18-May-91	69.3	17	20.7	8.058823	0.906271
19-May-91	69.7	18	20.3	7.666666	0.884606
20-May-91	70	19	20	7.315789	0.864261
21-May-91	70.3	20	19.7	7	0.845098
22-May-91	70.7	21	19.3	6.714285	0.826999
23-May-91	70.9	22	19.1	6.454545	0.809865
24-May-91	71.1	23	18.9	6.217391	0.793608
25-May-91	71.4	24	18.6	6	0.778151
26-May-91	71.7	25	18.3	5.8	0.763427
27-May-91	71.9	26	18.1	5.615384	0.749379
28-May-91	72.2	27	17.8	5.444444	0.735953
29-May-91	72.5	28	17.5	5.285714	0.723103
30-May-91	73	29	17	5.137931	0.710788
31-May-91	73.2	30	16.8	5	0.698970
01-Jun-91	73.4	31	16.6	4.870967	0.687615
02-Jun-91	73.6	32	16.4	4.75	0.676693
03-Jun-91	73.8	33	16.2	4.636363	0.666177
04-Jun-91	73.9	34	16.1	4.529411	0.656041
05-Jun-91	74	35	16	4.428571	0.646263
06-Jun-91	74.2	36	15.8	4.333333	0.636822
07-Jun-91	74.4	37	15.6	4.243243	0.627697
08-Jun-91	74.6	38	15.4	4.157894	0.618873
09-Jun-91	74.8	39	15.2	4.076923	0.610332
10-Jun-91	75	40	15	4	0.602059
11-Jun-91	75.2	41	14.8	3.926829	0.594042
12-Jun-91	75.4	42	14.6	3.857142	0.586265
13-Jun-91	75.7	43	14.3	3.790697	0.578719
14-Jun-91	75.8	44	14.2	3.727272	0.571391
15-Jun-91	76	45	14	3.666666	0.564271
16-Jun-91	76.1	46	13.9	3.608695	0.557350
17-Jun-91	76.3	47	13.7	3.553191	0.550618
18-Jun-91	76.4	48	13.6	3.5	0.544068
19-Jun-91	76.6	49	13.4	3.448979	0.537690
20-Jun-91	76.8	50	13.2	3.4	0.531478
21-Jun-91	76.9	51	13.1	3.352941	0.525425
22-Jun-91	77.1	52	12.9	3.307692	0.519525
23-Jun-91	77.2	53	12.8	3.264150	0.513770

MUSKAT PLOT

A2.7

24-Jun-91	[illegible].4	54	12.6	3.222222	0.508155
25-Jun-91	77.6	55	12.4	3.181818	0.502675
26-Jun-91	77.7	56	12.3	3.142857	0.497324
27-Jun-91	77.8	57	12.2	3.105263	0.492098
28-Jun-91	78	58	12	3.068965	0.486992
29-Jun-91	78.1	59	11.9	3.033898	0.482001
30-Jun-91	78.3	60	11.7	3	0.477121
01-Jul-91	78.4	61	11.6	2.967213	0.472348
02-Jul-91	78.5	62	11.5	2.935483	0.467679
03-Jul-91	78.5	63	11.5	2.904761	0.463110
04-Jul-91	78.7	64	11.3	2.875	0.458637
05-Jul-91	78.9	65	11.1	2.846153	0.454258
06-Jul-91	79.1	66	10.9	2.818181	0.449969
07-Jul-91	79.2	67	10.8	2.791044	0.445766
08-Jul-91	79.4	68	10.6	2.764705	0.441648
09-Jul-91	79.5	69	10.5	2.739130	0.437612
10-Jul-91	79.6	70	10.4	2.714285	0.433655
11-Jul-91	79.6	71	10.4	2.690140	0.429775
12-Jul-91	79.8	72	10.2	2.666666	0.425968
13-Jul-91	79.9	73	10.1	2.643835	0.422234
14-Jul-91	80	74	10	2.621621	0.418570
15-Jul-91	80.1	75	9.9	2.6	0.414973
16-Jul-91	80.2	76	9.8	2.578947	0.411442
17-Jul-91	80.3	77	9.7	2.558441	0.407975
18-Jul-91	80.5	78	9.5	2.538461	0.404570
19-Jul-91	80.6	79	9.4	2.518987	0.401225
20-Jul-91	80.7	80	9.3	2.5	0.397940
21-Jul-91	80.8	81	9.2	2.481481	0.394711
22-Jul-91	80.9	82	9.1	2.463414	0.391537
23-Jul-91	81	83	9	2.445783	0.388417
24-Jul-91	81.1	84	8.9	2.428571	0.385350
25-Jul-91	81.2	85	8.8	2.411764	0.382334
26-Jul-91	81.3	86	8.7	2.395348	0.379368
27-Jul-91	81.4	87	8.6	2.379310	0.376451
28-Jul-91	81.5	88	8.5	2.363636	0.373580
29-Jul-91	81.6	89	8.4	2.348314	0.370756
30-Jul-91	81.7	90	8.3	2.333333	0.367976
31-Jul-91	81.8	91	8.2	2.318681	0.365241
01-Aug-91	81.9	92	8.1	2.304347	0.362548
02-Aug-91	82	93	8	2.290322	0.359896
03-Aug-91	82.1	94	7.9	2.276595	0.357285
04-Aug-91	82.2	95	7.8	2.263157	0.354714
05-Aug-91	82.3	96	7.7	2.25	0.352182
06-Aug-91	82.4	97	7.6	2.237113	0.349687
07-Aug-91	82.5	98	7.5	2.224489	0.347230
08-Aug-91	82.6	99	7.4	2.212121	0.344808
09-Aug-91	82.6	100	7.4	2.2	0.342422
10-Aug-91	82.7	101	7.3	2.188118	0.340070
11-Aug-91	82.8	102	7.2	2.176470	0.337752
12-Aug-91	82.8	103	7.2	2.165048	0.335467
13-Aug-91	82.9	104	7.1	2.153846	0.333214

MUSKAT PLOT

METHOD 3

PLOT OF PRESSURE BUILDUP = EXTRAPOLATION OF PRESSURE

ANALYSIS OF 5/2/91 TO 8/13/91 BUILDUP

PER THE ATTACHED GRAPH, THE EXTRAPOLATED CAVERN STABILIZED PRESSURE IS PROBABLY BETWEEN 85 PSIG & 90 PSIG.

⟹ TO ACHIEVE A MINIMAL LEU VALUE, ASSUME P_{STAB} = 90 PSIG. ∴ LEU = 0.24 BCF

(1) $LEU = V_{BOOK} - V_{THEORETICAL}$

(2) V_{BOOK} = 1 281 196 MCF (14.65) @ END OF DRAWDOWN

(3) $V_{THEO} = 11.6 \frac{MMCF}{PSIG} \times P_{STAB}$ (PSIG) × 1000, (MCF)

∴ @ P_{STAB} = 90 PSIG, LEU = 237,196 MCF

LEU = 0.24 BCF

AQUIFER ACTIVITY WILL INFLUENCE THE BUILDUP.

NOTE: LAST YEAR'S LEU CALCS ASSUMED V/P = 11.4 MMCF/PSIG
11.4 PRODUCES A HIGHER LEU THAN DOES 11.6

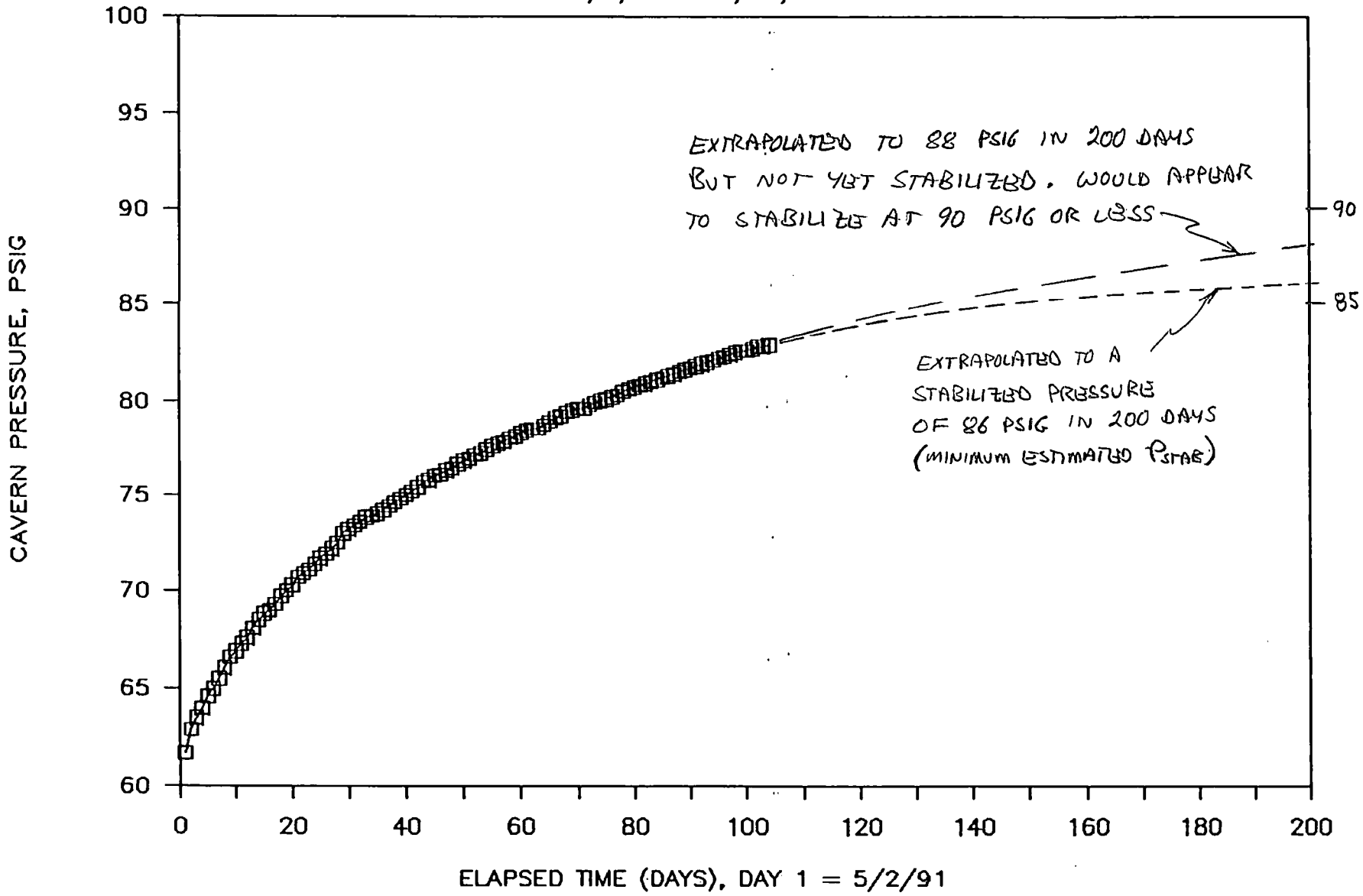
11/26/91 B. HOLLENBAUGH

A-3.1

PSC 039830

LEYDEN PRESSURE BUILDUP

5/2/91 TO 8/13/91



A3.2

PSC 039831

METHOD 4

HORNER

ANALYSIS OF PRESSURE FALLOFF

10/31/91 TO 11/12/91 FALLOFF DATA
SHUT IN AFTER INJECTION.

THE LEU BASED ON THIS ANALYSIS IS 0.17 BCF MINIMUM, AND IS BASED ON AN ASSUMED P_{STAB} = 235 PSIG. THIS IS THE MINIMUM LEU BECAUSE THE ACTUAL P_{STAB} IS PROBABLY LESS THAN 235 PSIG.

THERE WAS INSUFFICIENT PRESSURE FALLOFF DAYS & DATA TO ACCURATELY PREDICT P_{STAB}, BUT WE CAN SAY THAT P_{STAB} IS APPROX EQUAL TO OR LESS THAN 235 PSIG.

$$LEU = V_{BOOK} - V_{THEO}$$

V_{BOOK} = 2 899 385 MCF

V_{THEO} = 11.6 MMCF/PSIG × 235 PSIG × 1000 = 2 726 000 MCF

$\therefore$ LEU = 173 385 MCF = 0.17 BCF MINIMUM

PLOT OF PRESSURE DECLINE VS TIME

REVEALS NOTHING – INSUFFICIENT DATA

HORNER PLOT – APPLIED TO FALL OFF

CAN NOT ACCURATELY EXTRAPOLATE
INSUFFICIENT DATA

PSC 039832

NOTE: HORNER PLOT MAY NOT WORK WELL ON PRESS FALLOFF DATA

B. HOLLENBAUGH
11/27/91

A 4.1

HORNER PLOT (CONT)

WHAT TO USE FOR T ?

PLOTTED W/ T = 274 DAYS ← PROBABLY THE T VALUE TO USE
& T = 56 DAYS ← EASIER TO EXTRAPOLATE

INJECTION PERIOD WAS 68 DAYS T = 68
INJECTION DAYS WAS 56 T = 56

OR

$$T = \frac{\text{CUMMULATIVE INJECTION}}{\text{INJ. RATE AT SHUT IN}} = \frac{V_{comm}}{Q}$$

V_{comm} = 1 641 509 MCF

	Q	T
TYPICAL FOR OCTOBER INJECTION	6000	274 DAYS
	11,700	140 DAYS

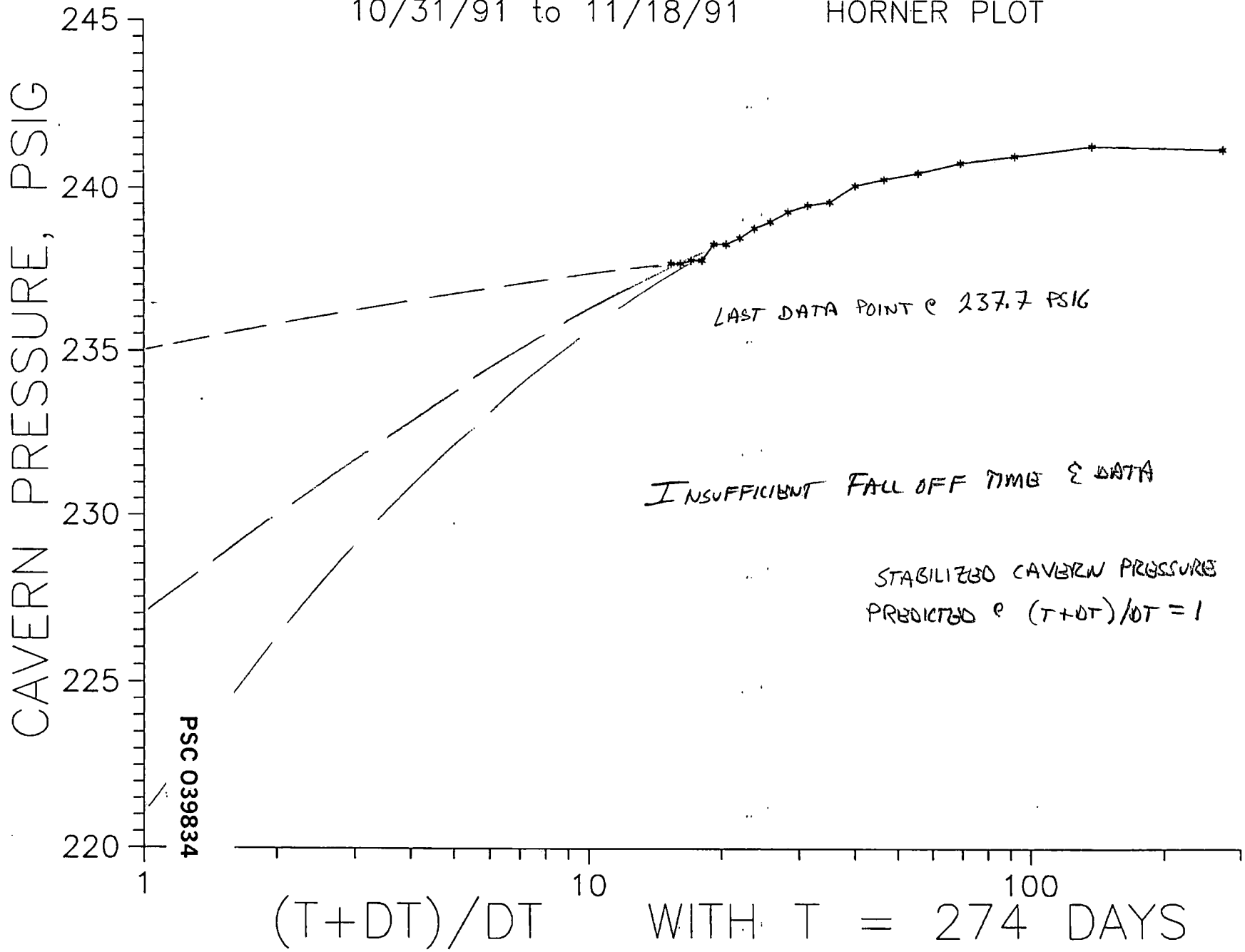
TWO EXTREMES, T = 56
& T = 274

RESULTS ARE PROBABLY NOT THAT DEPENDENT ON T, EVEN IF WE HAVE SUFFICIENT DATA POINTS.

B. HOLLINGSHAUGH
11/27/91

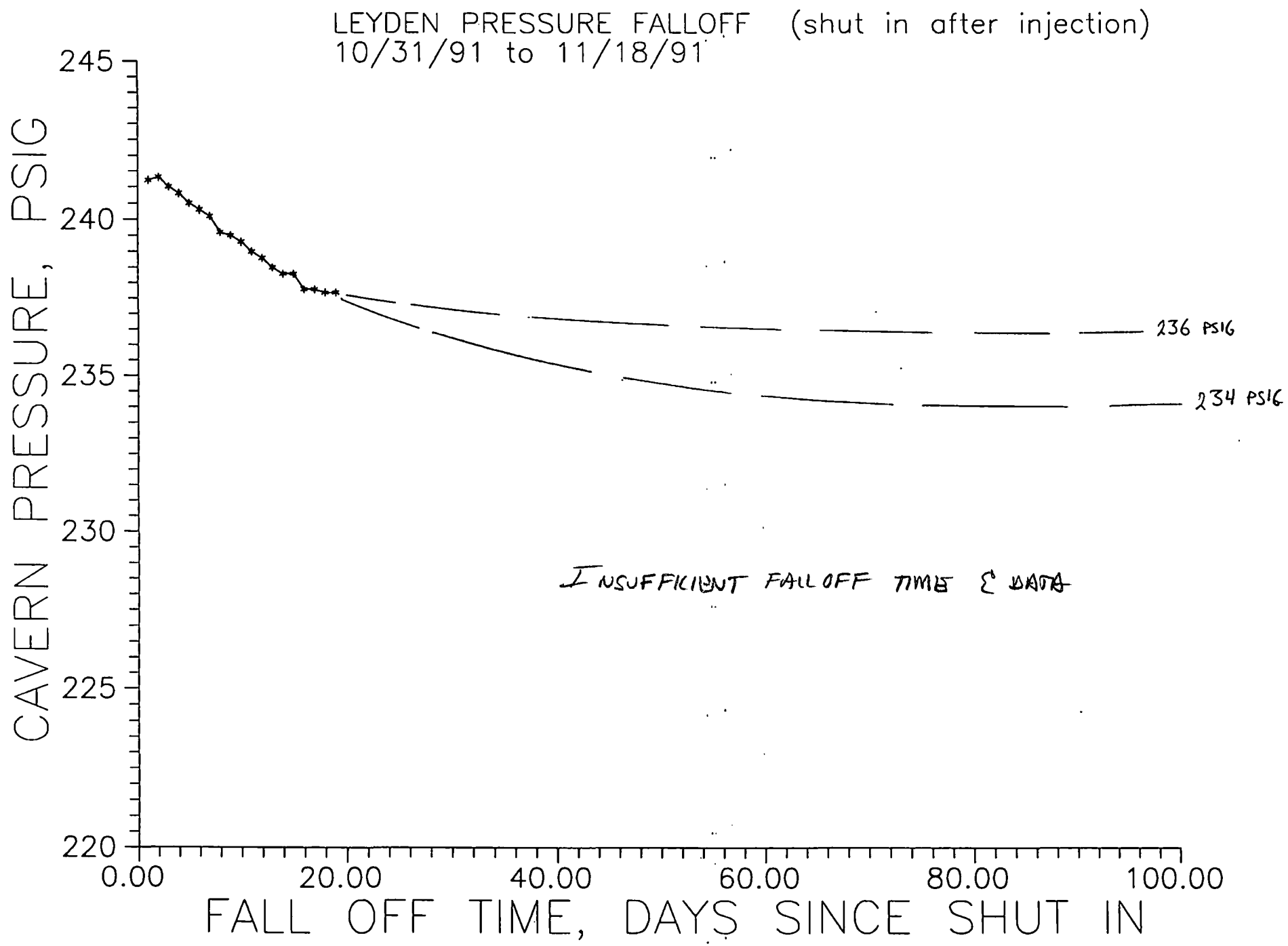
A4.2

LEYDEN PRESSURE FALLOFF (shut in after injection)
10/31/91 to 11/18/91 HORNER PLOT



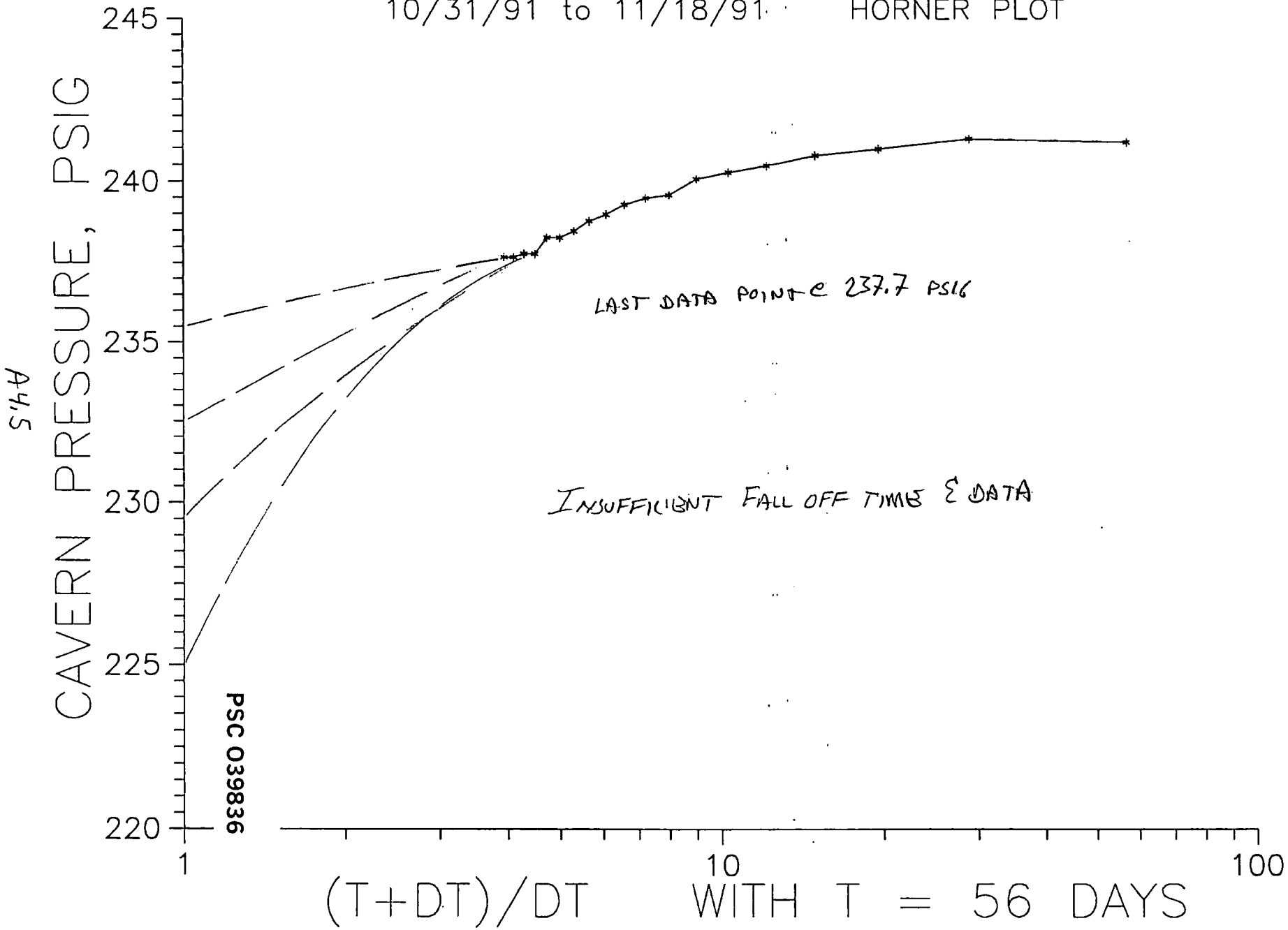
A4.3

PSC 039834


LEYDEN PRESSURE FALLOFF (shut in after injection)
10/31/91 to 11/18/91
CAVERN PRESSURE, PSIG
245
240
235
230
225
220
0.00
20.00
40.00
60.00
80.00
100.00
FALL OFF TIME, DAYS SINCE SHUT IN
236 PSIG
234 PSIG
INSUFFICIENT FALLOFF TIME & DATA

PSC 039835

LEYDEN PRESSURE FALLOFF (shut in after injection)
10/31/91 to 11/18/91 HORNER PLOT



A45

Leyden Pressure Decline, Shut in After Injection Period
Fall Off Data For 10/31/91 to 11/18/91 ld911&u1.wkq

		T =	274	56
			Horner Plot Data	
Date	Day	Pressure psig	(T+DT)/DT	(T+DT)/DT
31-Oct-91	1	241.2	275	57
01-Nov-91	2	241.3	138	29
02-Nov-91	3	241	92.3333333	19.66666
03-Nov-91	4	240.8	69.5	15
04-Nov-91	5	240.5	55.8	12.2
05-Nov-91	6	240.3	46.6666666	10.33333
06-Nov-91	7	240.1	40.1428571	9
07-Nov-91	8	239.6	35.25	8
08-Nov-91	9	239.5	31.4444444	7.222222
09-Nov-91	10	239.3	28.4	6.6
10-Nov-91	11	239	25.9090909	6.090909
11-Nov-91	12	238.8	23.8333333	5.666666
12-Nov-91	13	238.5	22.0769230	5.307692
13-Nov-91	14	238.3	20.5714285	5
14-Nov-91	15	238.3	19.2666666	4.733333
15-Nov-91	16	237.8	18.125	4.5
16-Nov-91	17	237.8	17.1176470	4.294117
17-Nov-91	18	237.7	16.2222222	4.111111
18-Nov-91	19	237.7	15.4210526	3.947368
			↑ T=274	↑ T=56

– some injection, not much

A4.6

METHOD 5

COMPARE VOLUME IN STORAGE, 1991 TO 1990

ANALYSIS OF BUILDUP AFTER DRAWDOWN

THE LEU OVER THE LAST YEAR IS APPROXIMATED AT 0.14 BCF, AS DETERMINED BY COMPARING THE V_{BOOK} IN 1991 TO THE V_{BOOK} IN 1990 FOR THE SAME STABILIZED PRESSURE CONDITION.

1990 DRAWDOWN, MODIFIED HORNER PLOT SUGGESTS A STABILIZED CAVERN PRESSURE OF 90 PSIG (SEE PG. A19 OF 1/3/91 LEU REPORT)*. THE CORRESPONDING BOOK VOLUME AT THE TIME WAS

1 620 628 MCF
− 540 000 LEU WRITTEN OFF SINCE THEN

$V_{BOOK\ 1990}$ = 1 080 628 @ 90 PSIG

*NOTE: THE 1991 HORNER PLOTS SUGGEST A "CONCAVE UP" TREND VS A LINEAR TREND FOR THE MODIFIED HORNER PLOT. THIS SUGGESTS A 90 PSIG P_{STAB} FOR THE 1990 PLOT (PER PG. A19 OF 1991 REPORT).

1991 DRAWDOWN, MODIFIED HORNER & CONVENTIONAL HORNER PLOTS SUGGEST P_{STAB} = 95 PSIG

w/ $V_{BOOK\ 1991}$ = 1 281 196 MCF

THIS NEEDS ADJUSTED TO A $V_{BOOK\ 1991}$ @ 90 PSIG

5 PSIG × 11.6 MMCF/PSIG × 1000 = 58 000 MCF

IF WE WITHDREW 58,000 MCF, WE WOULD EXPECT A P_{STAB} = 90 PSIG

1 281 196
− 58 000

$V_{BOOK\ 1991\ adj}$ 1 223 196 @ 90 PSIG

B. HOLLENBAUGH
11/26/91

A5.1

PSC 039838

$LEU \approx V_{BOOK\ 1991\,adj} - V_{BOOK\ 1990}$ (BOTH @ 90 PSIG)

$$= \begin{array}{r} 1\,223\,196 \text{ MCF} \\ -\ 1\,080\,628 \text{ MCF} \\ \hline 142\,568 \text{ MCF} \end{array} \Rightarrow \underline{0.14 \text{ BCF LEU}}$$

OVER THE LAST YEAR. THIS DOES NOT ACCOUNT FOR ANY "MAKE UP" LEU, IE IT ASSUMES THE 1990 V_{BOOK} WAS THE CORRECT ACTUAL BOOK VOLUME (1 080 628 MCF).

NOTE! PER HISTORIC TREND, WE EXPECTED ABOUT 0.1 BCF LEU FOR THE CURRENT YEAR. DUE TO LOW DRAWDOWN PRESSURES, THE LEU COULD HAVE INCREASED TO ABOUT 0.14 BCF FOR THE CURRENT YEAR.

B. HOLLOWENKOH
11/26/91

PSC 039839

END OF APPENDIX

1990 LEU.

PSC 039840

REVISED

SUMMARY OF GAS DELIVERED

Gas Delivered To: Leyden Storage Project at Leyden

For Period From December 1, 1990 To December 31, 1990

Volume in MCF for	14.65#	12.37#
Injection	407,132	482,166
Withdrawal	- 588,943	- 697,485
L & U Adjustment	- 540,000	- 639,522
Net Withdrawal	721,811	854,841
Storage as of Midnight		
Cushion Gas	794,000	940,334
Working Gas	1,945,030	2,303,510
Total in storage	2,739,030	3,243,844

Interoffice Memo

WestGas®
Western Gas Supply Company

January 14, 1991

To: R. A. Beals, Engineering Manager, WestGas

From: Bill Uding, Supervisor, Reservoir and Storage Engineering

Subj.: Leyden Lost and Unaccounted for Gas

Brad Hollenbaugh has recently completed an intensive study of the gas inventory levels in Leyden. Based on this study, we are recommending that 540,000 Mcf be reported as Lost and Unaccounted For.

The study suggests that losses have been occurring at the rate of about 100,000 Mcf per year since the beginning of operations at Leyden in 1960. The cavern was drawn down to 50 Psig this summer and we had a much longer low pressure shut-in than in previous years. This generated much better data enabling a reliable calculation of the inventory level. A total of only 30,400 Mcf has been reported as L & U since 1982.

If you concur with this recommendation, please forward for approvals and I will ask WestGas Accounting to make the proper reports to Public Service Co.

Bill Uding

Bill Uding

Concurrence:

R. A. Beals, Eng. Manager

Approval:

C. H. Becker, Manager, Eng. Div.

John Peters, Manager, Operation Div.

L. T. Leeburg, V. P. WestGas

FORM (A) 798-22-4892

PSC 039842

LEU HISTORY

BASED ON REPORTED LEU IN GAS MEASUREMENT REPORTS. * INDICATES MICRO FICHE RECORDS.

YEAR	LEU MCF 14.65		CUSHION GAS	COMMENTS
1960				
1961 *				
1962 *				
1963 *			834,000	
1964 *				
1965 *	150,000	DEC		
1966 *				
1967 *				
1968 *				← NO LEU, PER PV TESTING, VOL OF GAS HAS REMAINED RELAT. CONST.
1969 *				
1970 *				
1971 *	345,000	JAN 72		← PER 11/18/71 MEMO, FOR 1966 THRU 1971
1972				
1973	122,880	JAN 74		COMPARED 12/1 WORKING VOL. FROM ONE YEAR TO THE NEXT
1974	106,043	NOV		
1975	98,577	DEC		
1976	19,667	DEC		
1977	132,568	DEC		
1978	(130,404	DEC		
1979 *	130,404	DEC	537,000	
1980 *	155,530	JAN		
1981 *	66,616	JAN		
1982 *	131,089	MAR	794,000	
1983				
1984	−50,000			
1985				
1986	58,400			
1987				
1988	22,000			30,400
1989				
1990				

PSC 039843

B. HOLLENBAUGH
12/28/90

JANUARY 1. 1990
GAS STORED IN UNDERGROUND STORAGE
AT
LEYDEN STORAGE

THESE ARE THE INVENTORY LEVELS FOR LEYDEN STORAGE AS OF JANUARY 1. 1990.

MCF	COST/MCF	TOTAL COST	
40,000	0.076589000	$3,063.56	
1,358,205	0.204999002	$278,430.67	1970
540,651	1.436779993	$803,829.09	1979
3,772	1.983618770	$7,482.21	1980
370,626	3.731990011	$1,383,172.53	
2,572	3.445416019	$8,861.61	1984
33,201	3.415297732	$113,391.30	1985
258,674	2.839499988	734,504.82	1989
2,607,701		3,332,735.79	

134863 left
123,811 used

PSC 039844

1/7/91 STATUS - LEYDEN L&U

THE PSCo RATE DEPARTMENT ALONG W/ ED MEADERS (WESTGAS FINANCE & ADMIN) ARE CURRENTLY EVALUATING THE SITUATION. THEY HAVE A COPY OF THE 1/3/91 L&U REPORT & WILL DECIDE HOW/WHEN TO WRITE OFF THIS GAS. THEY ARE WORKING W/ BILL UDING ON THIS.

Brad Hallett 1/7/91

PSC 039845

EXTRA COPY

LEYDEN L&U REPORT
NOVEMBER 27, 1991

SUMMARY

Calculations indicate 0.17 BCF (14.65) less gas in storage than is being carried on the books. An L&U adjustment of 170,000 MCF should be applied to the book volume, by subtracting this amount from same.

Six methods were used to predict the L&U, and method 4 (below) provides significant justification for the 0.17 BCF recommendation. The recommended L&U adjustment is made up of the current year L&U plus some "catch up" L&U. The current year L&U is estimated between 0.1 and 0.14 BCF. The total catch up L&U is estimated at about 0.16 BCF per review of the 1990 L&U report (0.7 - 0.54). About 19% to 44% of this total catch up L&U is accounted for in the recommended 0.17 BCF write-off.

Assumed current year L&U	Catch Up L&U	% of Total Catch Up	Recommended L&U
0.1 BCF (method 6)	0.07	44%	0.17 BCF
0.14 (method 5)	0.03	19%	0.17 BCF

CONCLUSIONS

Six methods were used to estimated L&U. The first four methods calculate the total L&U, which includes any "catch up" L&U. The last two methods only account for the current year L&U, and do not include any catch up volume.

METHOD 1 0.18 BCF Total L&U

Horner plot applied to pressure buildup data (shut in after withdrawal) to determine stabilized cavern pressure (95 psig). Assumes 11.6 MMCF/psig stabilized.

METHOD 2 0.24 BCF Total L&U

Muskat plot applied to pressure buildup data (shut in after withdrawal) to determine stabilized cavern pressure (90 psig). Assumes 11.6 MMCF/psig stabilized.

PSC 039800

METHOD 3 0.24 BCF Total L&U

Stabilized cavern pressure of 90 psig predicted by evaluating pressure buildup data (shut in after withdrawal). Extrapolated pressure from a curve of Pressure vs. buildup time. Assumes 11.6 MMCF/psig stabilized.

METHOD 4 0.17 BCF Total L&U

Analysis of pressure fall off data (shut in after injection) to predict stabilized cavern pressure. This is conservative in that it is the minimum L&U and the actual L&U is probably higher than this. Assumes 11.6 MMCF/psig stabilized.

METHOD 5 0.14 BCF Current Year L&U

Comparison of book volume in 1991 to book volume in 1990 for a similar stabilized pressure condition. Horner plot used for predicting stabilized cavern pressures. Assumes 11.6 MMCF/psig stabilized, but result is not very dependent on this assumption. The current year L&U could be higher than the historic L&U trend of 0.1 BCF/year due to the extreme low pressure drawdown this summer.

METHOD 6 0.1 BCF Current Year L&U

This is based on the historic trend. Documentation can be found in the 1/3/91 L&U Report.

RECOMMENDATIONS

The Horner plot does not appear to be a great tool for predicting the stabilized cavern pressure. The extrapolation is not obvious, and the results do not agree with the Muskat method. The Horner plot may be adequate when comparing a pressure condition from one year to a similar pressure condition of another year (method 5).

The Muskat plot behaves as expected and may be superior to the Horner plot. Further application of the Muskat plot will help evaluate the effectiveness of this tool in predicting the stabilized cavern pressure.

The application of other plots, theories, and type curves should be investigated in future L&U analysis.

Brad Hollenbaugh
Reservoir & Storage Eng.
WestGas 11/27/91

PSC 039801

PRESSURE DECLINE DUE TO L&U

WHEN EXTRAPOLATING STABILIZED CAVERN PRESSURE, $P_{DECLINE\ L\&U}$ MUST BE CONSIDERED.

i.e., AT HIGHER CAVERN PRESSURES THE PRESS WILL NOT STABILIZE – IT WILL FALL OFF DUE TO L&U.

EXAMPLE:

PSC 039802

ASSUME 0.1 BCF/YEAR L&U AVERAGE

100 000 MCF/YEAR = 274 MCF/DAY

= 0.274 MMCF/DAY

$$0.274 \frac{MMCF}{DAY} \Big/ 11.6 \frac{MMCF}{PSIG} = 0.0236 \ PSIG/DAY$$

OR WE CAN EXPECT THE CAVERN PRESSURE TO DROP OFF AT A RATE OF 0.0236 PSIG/DAY DUE TO GAS LEAKAGE OUT OF THE STORAGE ZONE. IN REALITY THIS COULD APPROACH 0.04 PSIG/DAY AT HIGHER CAV PRESSURES (NEAR 250 PSIG) & MAY BE AT 0.01 PSIG/DAY AT LOWER CAVERN PRESSURES.

THIS MAY NOT BE OF MUCH CONSEQUENCE WHEN PREDICTING $P_{CAV\ STAB}$.

∴ WHEN PREDICTING STABILIZED CAVERN PRESSURE, DON'T EXTRAPOLATE TO $\Delta P = 0$ (from one day to the next). Instead, extrapolate to $\Delta P = 0.01$ to 0.04 PSIG/DAY for decline (after refill) analysis.

B HOLLENBAUGH
12/4/91

LB-Day Balance and L&U Considerations
Leyden Gas Storage 1/3/92

This discussion is not presented as an absolute operating philosophy, but is merely intended as documentation to current theory and direction.

Recommendation

We should lower the operating annual median pressure (lb-day balance) in an attempt to reduce L&U. We should generally not go below 80 psig dynamic cavern pressure. This lower limit will help to minimize L&U, minimize water influx, and minimize roof collapse.

Lb. X Day Balance

An August 1988 Geological Report suggests that the native aquifer pressure is probably about 130 psig. Earlier work suggests an existing aquifer pressure of about 186 psig to 192 psig. The actual operating annual median pressure for recent years and the cumulative median pressure since 1982 are given below.

Target lb-day balance pressure:

Assumed 1982	186 psig
Assumed 1984	192 psig
1988 Report	130 psig

Actual median operating pressure:

Cum. since 1982	178 psig
1989 actual	164 psig
1990 actual	159 psig
1991 estimated	160 psig

The current or existing aquifer pressure is what should be applied in the lb-day concept. The existing aquifer pressure is not necessarily the same as the original "native" aquifer pressure. Depletion of water from the aquifer over time could lower the aquifer pressure. Gas saturation/charging of the aquifer over time could increase the aquifer pressure.

To date there is no correlation between lb-day balance and L&U. Although lb-day balance figures have been compiled since 1982, accurate L&U estimates have not been done on an annual basis. **Accurate annual L&U estimates should be done for all future years.** This will allow us to attempt to correlate lb-day balance with L&U.

PSC 039803

L&U Gas

Two factors which contribute to L&U are; (1) operating at a pressure in excess of the current aquifer pressure, and (2) drawdown to very low cavern pressures (less than about 60 psig).

Theoretically, the lower the annual median cavern pressure, the lower the L&U. If we lower the median cavern pressure we would expect an increase in water influx. This would result in a reduced storage volume.

Drawdown to a very low cavern pressure will serve to lower the median pressure, but won't necessarily lower the L&U. When the pressure is lowered significantly below the aquifer pressure, water influx can "pinch out" gas which is stored in the formation. The majority of this gas is probably not recoverable. As was evident during the 1990 field drawdown, severe water influx can be expected at pressures near and below 50 psig.

Practical Aspects

1. It is often impossible to accurately estimate annual L&U.

2. lb-day balance is being done from September 1 of one year to September 1 of the next year. Therefore L&U calculations should also be done from September to September if possible.

3. If we lower the practicing lb-day balance, we should try to detect any change in storage volume. Storage volume will probably be even more difficult to quantify as a function of lb-day balance than the L&U.

4. Gas supply economics and environmental liability must be considered along with L&U when developing injection & withdrawal guidelines. L&U is currently estimated at about 0.1 BCF/year, which is $300,000/year @ $3.00 per MCF. Spot market gas is often available early in the summer. An early injection program will allow us to purchase this low cost gas, but can increase L&U by conflicting with lb-day balance. Environmental liability occurs if the lost gas contaminates a formation or aquifer to the point that traditional uses are in jeopardy.

5. Some drilling & workover operations require that the cavern pressure be lowered to less than 80 psig.

PSC 039804

6. In order to lower our practicing lb-day balance, we must do one or more of the following;

- start withdrawal earlier in the year
- maintain the "low" cavern pressure as long as possible
- start injection as late in the year as possible
- maintain a lower "winter" pressure

Formation Overburden Stress

The 1/13/86 Dames & Moore report/memo suggests that the mine pressure be kept above 125 psig in order to minimize roof collapse. This is difficult to do given the constraints of drilling programs, workovers, and the lb-day balance concept. The cavern pressure has been lowered to less than 70 psig on several occasions, and to date there is no evidence of roof collapse associated with this practice. However, the closer the cavern pressure is to this theoretical minimum pressure of 125 psig, the less likely the occurrence of roof collapse.

Brad Hollenbaugh
Senior Res. Eng.
WestGas
1/3/92

PSC 039805

1988

November 1, 1988

To: Curt Dallinger, Engineering Manager

From: Bill Uding, Reservoir and Storage Engineering Supervisor

Subj: Storage Field L&U

We have completed our annual review of L&U gas from storage fields, and are reporting the following volumes:

Leyden

2,410,323 Per Book
2,388,323 Per Memo
22,000

Calculations indicate 22,000 Mcf less gas-in-storage then is being carried on the books. As of September 30, 1988 the working volume should be 2,388,323 Mcf @-14.65 Psia.

Asbury

2,974,641 Per Book
2,866,088 Per Memo
108,553

Calculation indicate 100,100 → 100,647 Mcf less gas-in-storage then is being carried on the books. As of September 24, 1988 the working volume should be 2,850,522 Mcf @ 14.73 Psia.

Fruita

270,094 Per Book
269,961 Per Memo
133

There has been no activity and no change in the shut-in pressure for the Fruita Field. The booked working gas volume as of September 30, 1988 should be 268,495 Mcf @ 14.73 Psia.

Roundup

4,603,542 Per Book
4,585,128 Per Memo
18,414

Calculations do not indicate that a significant volume of gas has been lost since the last L&U calculation. The booked volume for gas-in-storage as of September 30, 1988 should be 7,585,128 Mcf @ 14.65 Psia. of which 3,000,000 Mcf is cushion gas.

It is recommended that the above volumes be reported to the Office Department of WestGas for use in their year-end closing report and various other statistical reports.

EXAMPLE - FORMAT FOR REPORTING L&U

Bill Uding

PSC 039806

1991. LEU

PSC 039807

Leyden L&U Report
December 8, 1992

Summary

Calculations indicate 0.12 BCF (14.65) less gas in storage than is being carried on the books. An L&U adjustment of 120,000 MCF (14.65) should be applied to the book volume by subtracting this amount from the book volume.

Five methods were used to evaluate the L&U as outlined below. The first three give reasonable results. Because of the adjustment last year for L&U from previous years there is no need to make such an adjustment this year.

Current year L&U MCF (14.65)	Method	
120,000	1	(Muskat Plot)
127,000	2	(Vol in - Vol out)
100,000	3	(History)
12,000	4	(P/Z) Plot
501,000	5	(Horner Plot)

Method 1

A Muskat plot was applied to pressure buildup data to determine a stabilized cavern pressure of 120 psig. This method assumes 11.6 MMCF/psig stabilized. This method appears to be one of the more reliable method for calculating total L&U.

Method 2

Comparison of book volume in 1992 to book volume in 1991. This method assumes 11.6 MMCF/psig stabilized to equate the two year end volumes to the same pressure.

Method 3

This is based on the historic trend. Documentation can be found in the 1/3/91 L&U Report.

Method 4

A plot of P/Z vs Cumulative production was done this year to see if meaningful results could be obtained. The plot resulted in a volume of gas in the cavern which was almost identical to the current book volume. The graph did show water influx into the cavern.

Method 5

A Horner plot was used again this year to see if the results were any better than in previous years. They were

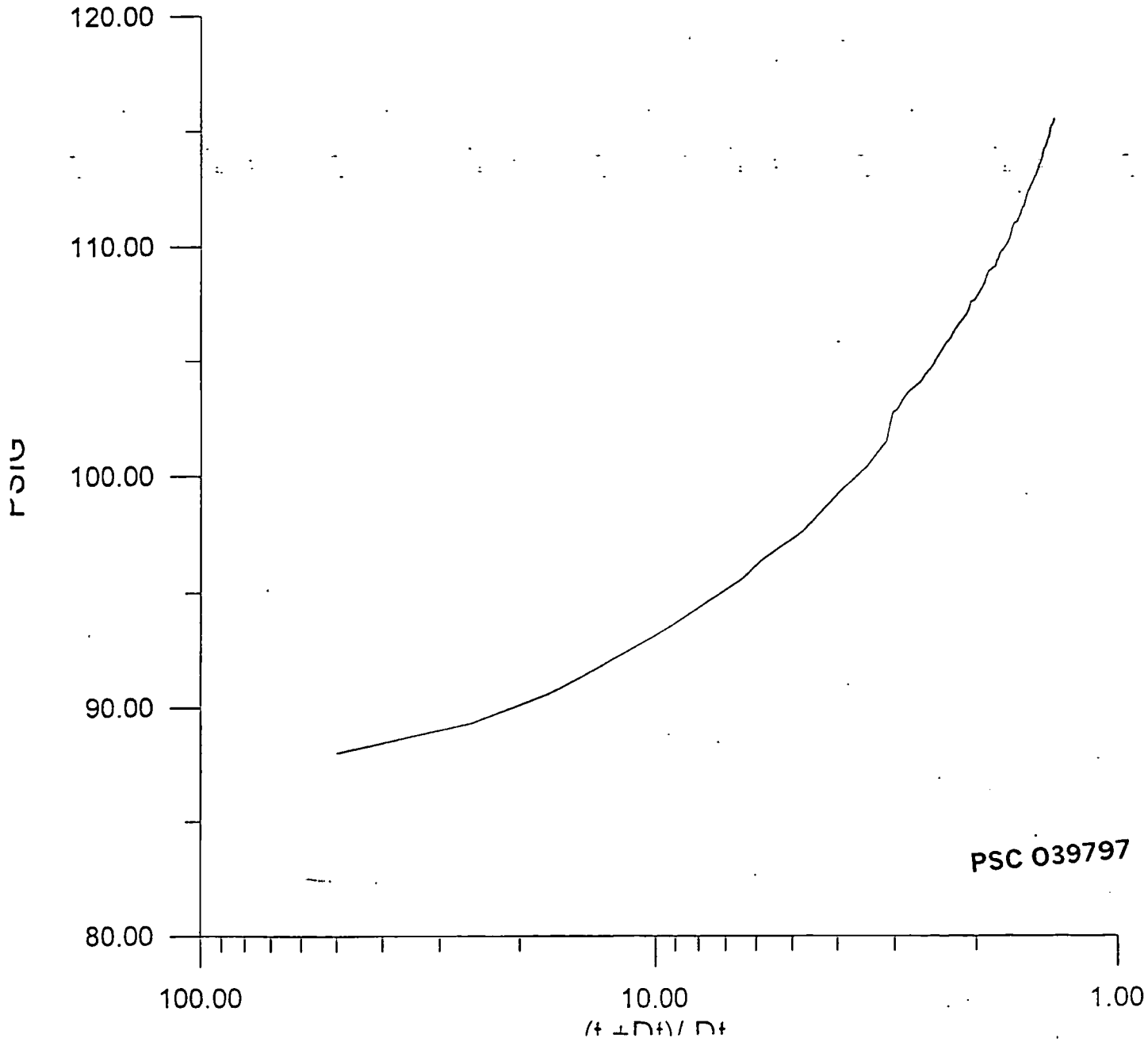
not. The stabilized pressure from the plot was 87 psig. The straight line period was relatively short and therefore difficult to identify. This method assume 11.6 MMCF/psig stabilized.

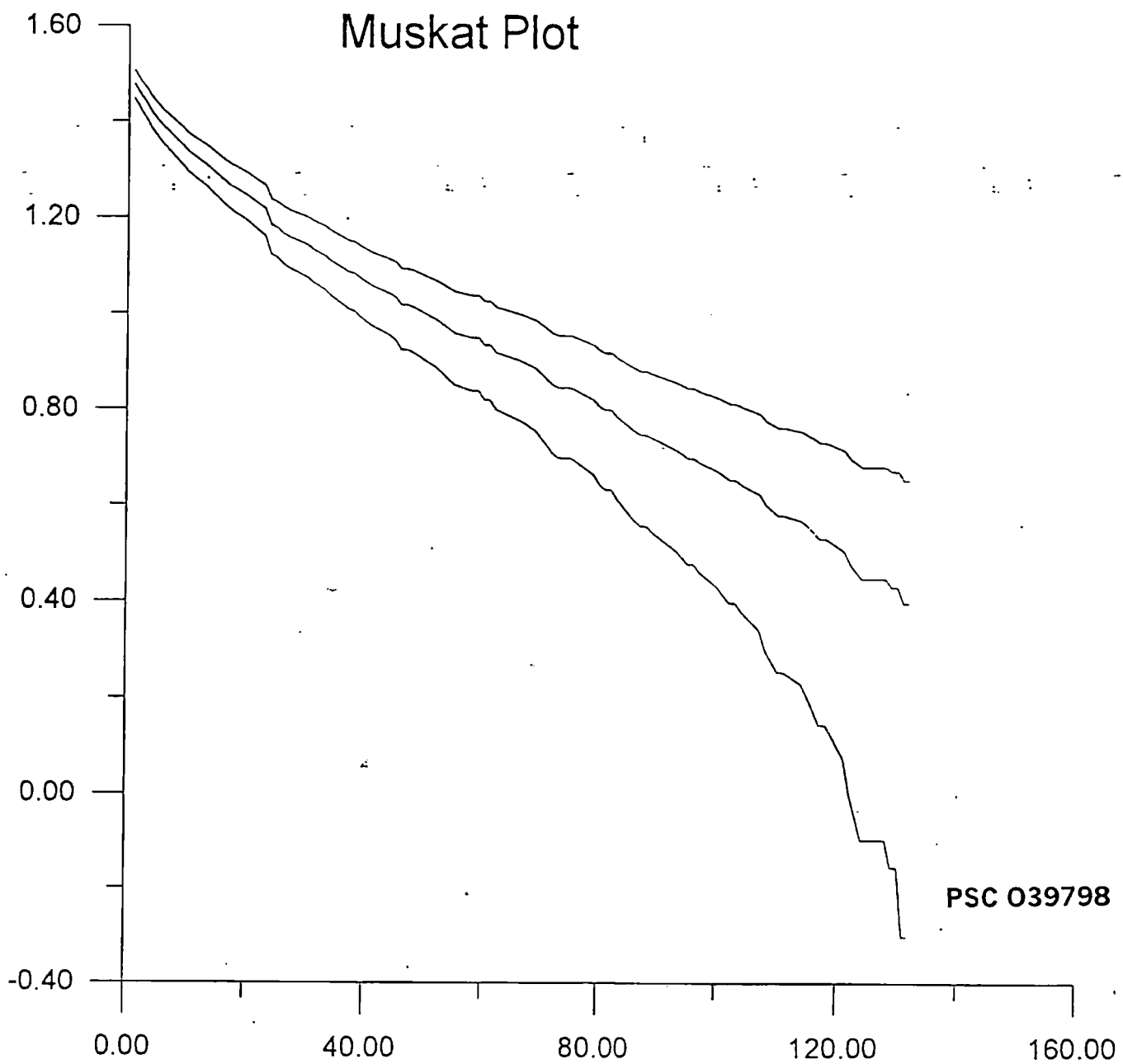
Conclusions

It appears that the Muskat plot and a comparison of the book volumes from one year to the next are two of the more reliable methods for calculating L&U. A Different method, P/Z, was investigated this year which proved to be of little value.

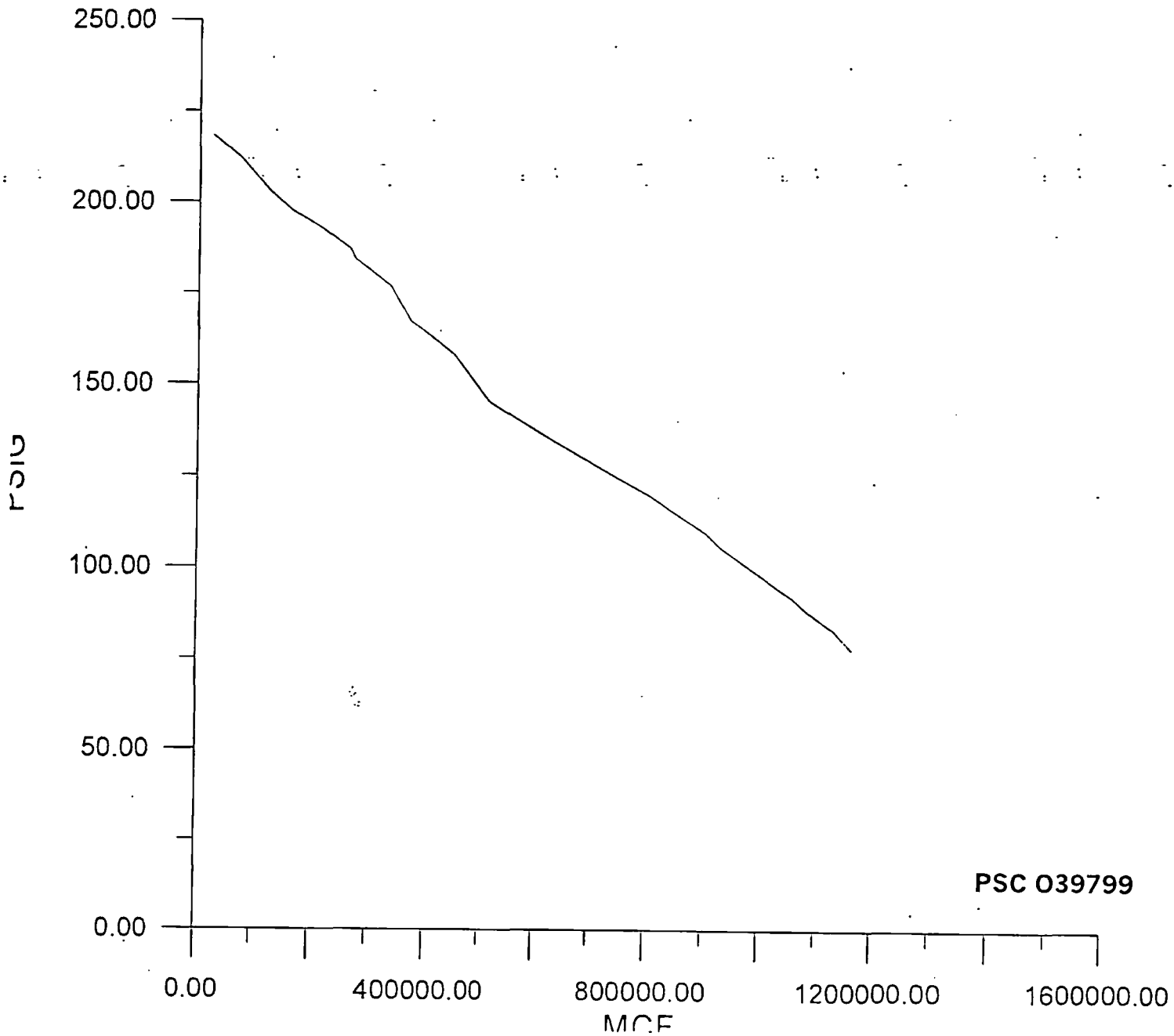
Liz Niemtschik
Reservoir Engineer
WestGas 12/8/92

Horner Plot




Muskat Plot
1.60
1.20
0.80
0.40
0.00
-0.40
0.00
40.00
80.00
120.00
160.00
PSC 039798

P/Z vs Production



LEYDEN L&U REPORT
November 30, 1993

Summary

Calculations indicate 0.09 BCF (@14.65 psi) less gas in storage than is being carried on the books. An L&U adjustment of 90,000 MCF (@14.65 psi) should be applied to the book volume by subtracting same from the book volume.

Four methods were used to evaluate the L&U as outlined below. The first three methods gave similar results.

Current year L&U MCF (@14.65 psi)	*Method*	
75,400	*1*	*(Muskat Plot)*
101,700	*2*	*(Vol in - Vol out)*
100,000	*3*	*(History)*
400,200	*4*	*(Horner Plot)*

Method 1

A muskat plot was applied to the pressure buildup data obtained from May 13, 1993 (end of drawdown) through August 31, 1993 before re-fill at Leyden. Upon analysis, a stabilized cavern pressure of 108 psig was chosen from the plot as the best straight line. Applying the stabilized Pressure - Volume relationship of 11.6 MMCF/psig for the current Field operations at Leyden, the theoretical volume was obtained. The L&U was the difference between the theoretical volume in the cavern and the book volume.

This method appears to be one of the more reliable methods for calculating total L&U. It is of interest to note that a stabilized cavern pressure of 106 psig yields an L&U figure of 98,600 mcf.

Method 2

This method compared the book volume in 1993 to the 1992 book volume. The method also assumes the stabilized PV relationship of 11.6 MMCF/psig to equate the two year end volumes to the same pressure.

Method 3

This is based on the historic trend. Documentation can be found in the 1/3/91 Leyden L&U Report.

Method 4

This method is based on the Horner Plot Analysis of the build up data . The stabilized pressure from the plot was 80 psig. The straight line period was relatively short and difficult to identify. The stabilized PV relationship of 11.6 MMCF/psig was also applied to the 80 psig stabilized pressure to come up with the L&U. The estimated L&U figure of 0.4 bcf based on the Horner analysis is somewhat questionable and therefor unreliable.

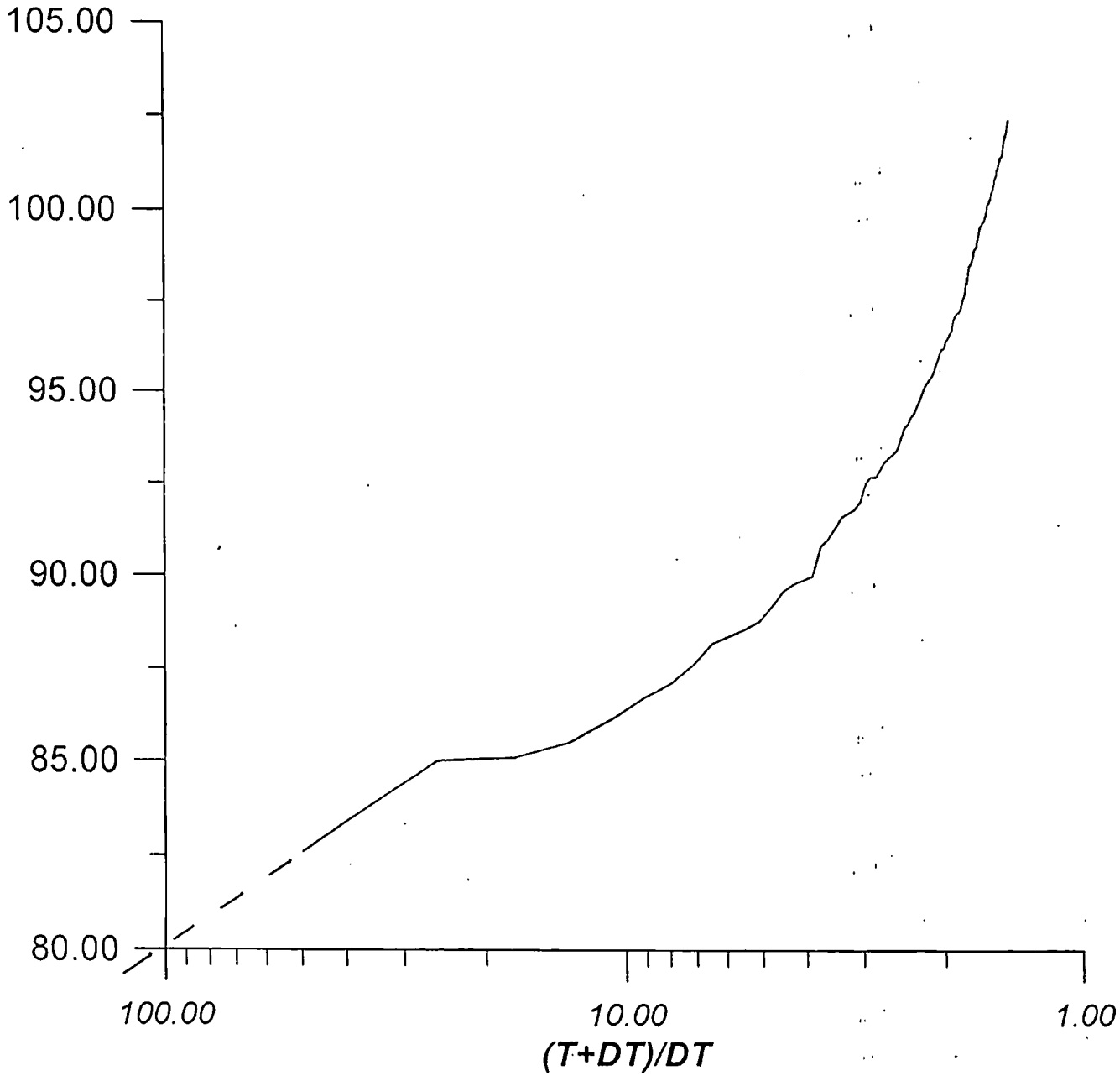
Conclusions

Based on the results from the different approaches, it appears that the Muskat Plot Analysis and a comparison of the book volumes from one year to the next are two of the most reliable methods for calculating L& U. It was also significant to note how close the L&U from these two methods were to the historical trend.

Nat Olowu
Reservoir Engineer
Public Service Co (NGG)
Nov. 30, 1993

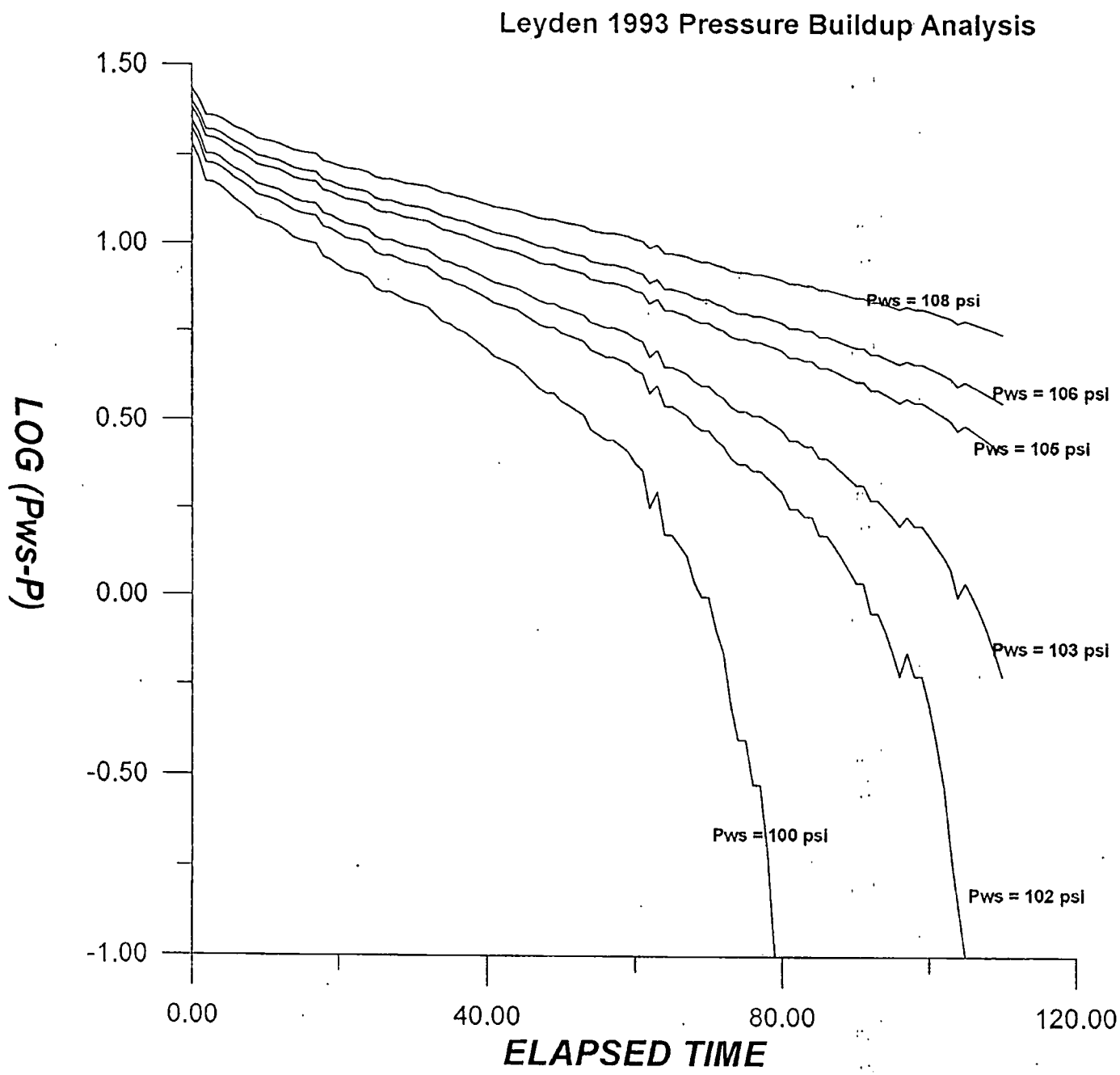
HORNER PLOT

LEYDEN 1993 PRESSURE BUILD-UP DATA



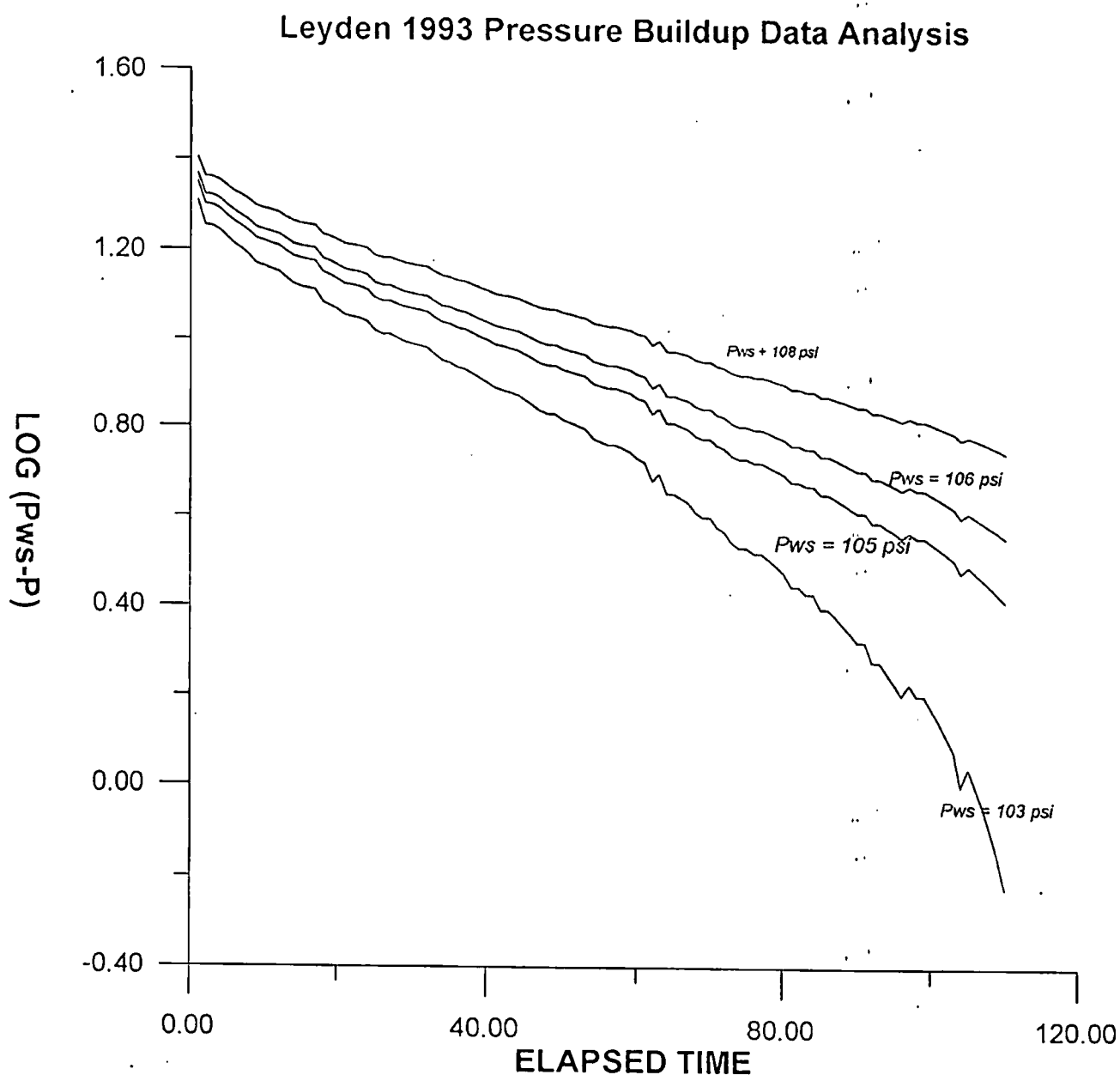
PSC 039789

MUSKAT PLOT



PSC 039790

MUSKAT PLOT



PSC 039791

19, Leyden L & U

Method 4: Horner Plot

The pressure buildup data from end of w/d on May 13, 1993 up until the beginning of injectn on Sept 1, 1993 was analyzed.

The horner plot indicated a stabilized cavern pressure of 80psig.

$$L \& U = V_{book} - V_{theoretical}$$

$$V_{book} = 1,328,204 \text{ Mcf } (14.65 \text{ psi}) \text{ @ end of drawdown}$$

$$V_{theo} = 11.6 \frac{\text{mmcf}}{\text{psig}} \times P_{stab} (\text{psig}) \times 1000, \text{ mcf}$$

$$= 928,000 \text{ mcf}$$

$$\therefore L \& U = 400,204 \text{ mcf}$$

$$= 0.40 \text{ bcf}$$

Method 1

Muskat Analysis:

By using several guesses for P_{ws}, the one c best straight line indicated a stabilize pressure of 108psig.

$$\therefore L \& U = V_{book} - V_{theoretical}$$

$$= 1,328,204 - \left(11.6 \frac{\text{mmcf}}{\text{psig}} \times 108 \text{psig} \times 1000, (\text{mcf})\right)$$

$$= 1328\,204 - 1,252,800$$

$$= 75,404 \text{ mcf}$$

$$= 0.0754 \text{ bcf}$$

Method 2: Comparison of Book Volume. [Year-end @ W/D]

V_{1992} = 1,511,118 mcf @ 14.65

P_{stab} = 87 psig in 1992 (Horner)

V_{1993} = 1,328,204

P_{stab} = 80 psig (Horner)

$\therefore$ $P_{1993} - P_{1992} = -7$ psig

$7 \times 11.6 \frac{mmcf}{psig} \times 1000$ mcf = 81,200 mcf

$\therefore$ 1328204 + 81200 (to bring 1993 volume to same pressure base as in 1992)

= 1,409,404 mcf

but in 1992 V was 1,511,118 mcf

$\therefore$ L & U = 1,511,118 − 1409404

= 101,714 mcf

PSC 039793

Method 3:

Historic trend of (See 1/3/91 L & U Rpt)

Method 5:

The P/Z vs Cum Prod

This was not analyzed b/c it is not reliable or very applicable to Leyden.

LEYDEN L&U REPORT
November 23, 1994

Summary

Calculations indicate 0.85 BCF (@ 14.65 psi) less gas in storage than is being carried on the books. Therefore, an L&U adjustment of 85,000 MCF (@ 14.65 psi) should be applied to the book volume by subtracting same from the book volume.

Four methods were used to evaluate the L&U gas as outlined below. The two methods which gave similar results were averaged to come up with an L&U figure.

Current year L&U, MCF (@14.65 psi)		*Method*
(10,712)	*1*	*(Muskat Plot)*
68,716	*2*	*(Vol in - Vol out)*
100,000	*3*	*(History)*
331,488	*4*	*(Horner Plot)*

Method 1

Analysis of the Muskat plot of the pressure build-up data obtained from May 6, 1994 (end of drawdown) through August 11, 1994 prior to the Leyden storage cavern refill. The analysis indicated a stabilized cavern pressure of 118 psig. Obtained the theoretical volume of gas in the cavern by applying the stabilized P/V relationship of 11.6 MMCF/psig which still represents the current operating condition at Leyden. The L&U was obtained by establishing the difference between the book volume and the theoretical volume. Based on the data analyzed, it shows that theoretical volume was 10,712 mcf more than book volume. The operating nature of the cavern with relation to the intermittent short withdrawals and injections could mask the results obtained.

Method 2

This method compared the book volume in 1994 to the book volume in 1993. The method also assumes the stabilized P/V relationship of 11.6 MMCF/psig to equate the two year end volumes to the same pressure.

Method 3

This is based on the historic trends. Documentation can be found in the 1/3/91 Leyden L&U report.

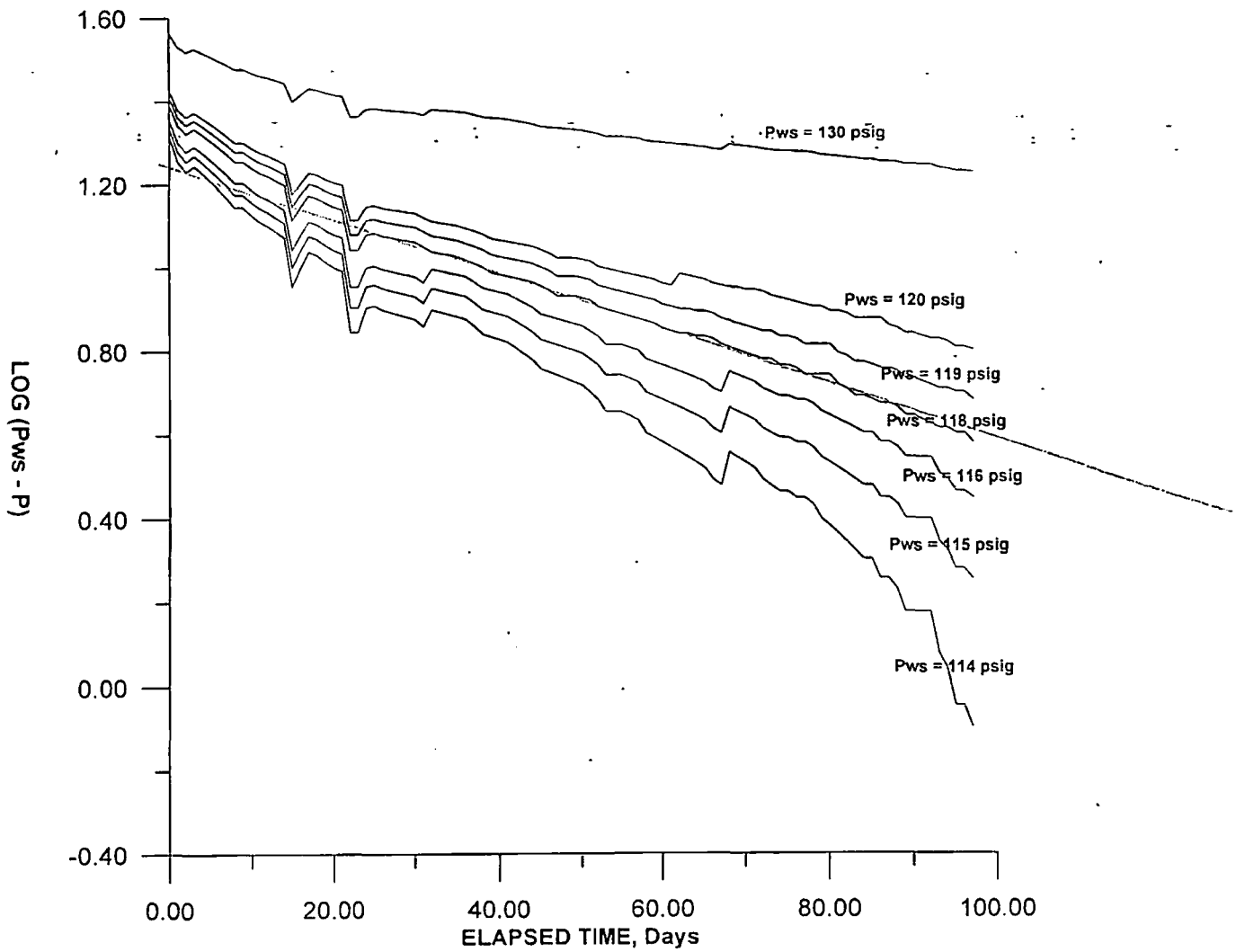
Method 4

This method uses the Horner Plot Analysis of the pressure build data. The stabilized pressure from the plot was 88.5 psig. The last straight line period was relatively short and difficult to identify. The stabilized P/V relationship of 11.6 MMCF/psig was also applied to the 88.5 psig stabilized pressure to obtain the L&U. The estimated L&U figure of 0.33 bcf based on the Horner analysis is somewhat questionable and therefore unreliable.

Nat Olowu
Reservoir Engineer
PSCo (Natural Gas Group)
Nov 23, 1994

MUSKAT PLOT

Leyden 1994 Pressure Buildup Analysis

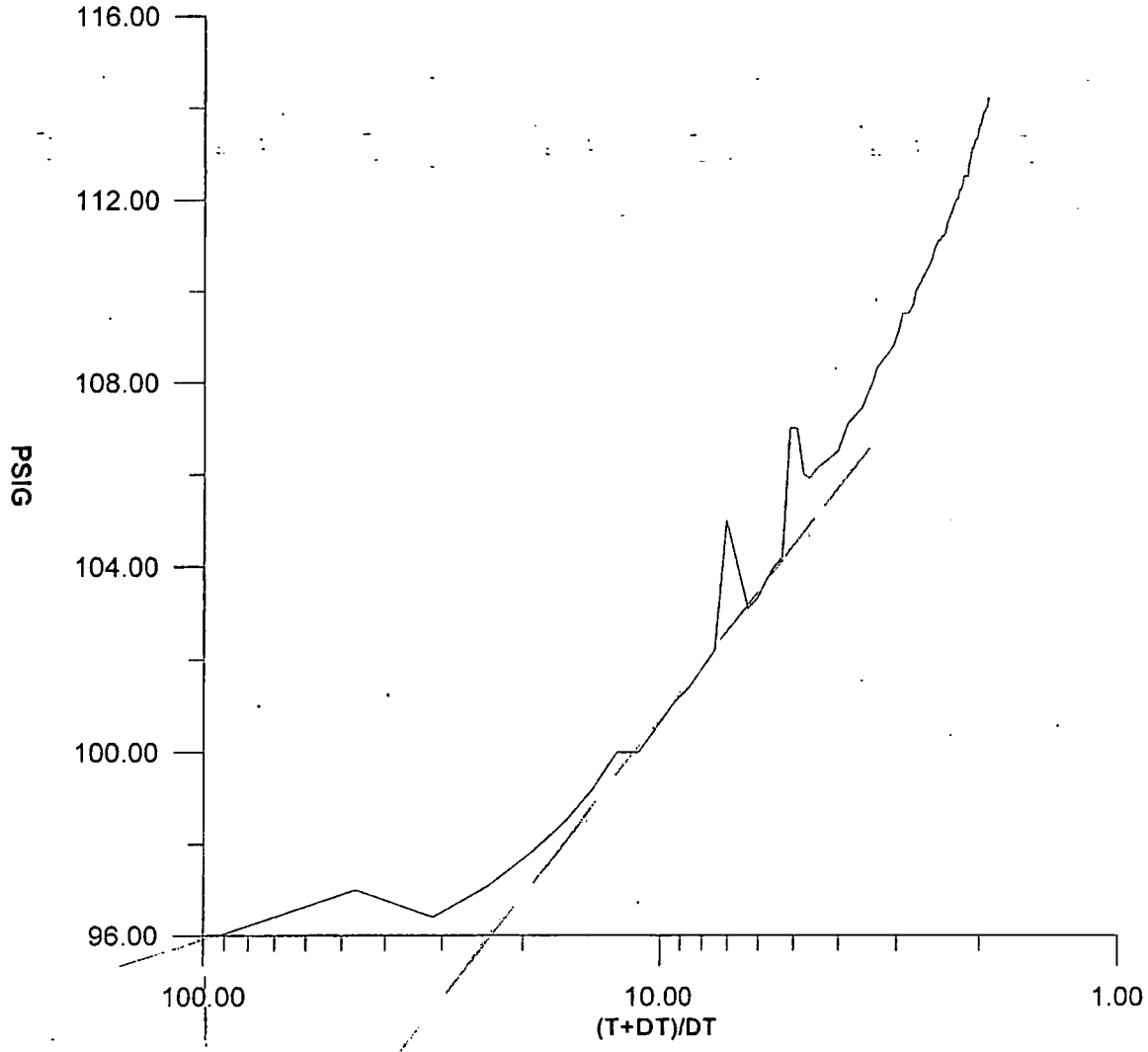


PSC 039782

Date	Dt	Pressure psig	pws 120 log(pws-p)	pws 130 log(pws-p)	pws 115 log(pws-p)	pws 116 log(pws-p)	pws 114 log(pws-p)	pws 118 log(pws-p)	pws 119 log(pws-p)
6-May-94	0	93.3	1.426511261	1.564666064	1.336459734	1.356025857	1.315970345	1.392695953	1.409933123
7-May-94	1	96	1.380211242	1.531478917	1.278753601	1.301029996	1.255272505	1.342422681	1.361727836
8-May-94	2	97	1.361727836	1.51851394	1.255272505	1.278753601	1.230448921	1.322219295	1.342422681
9-May-94	3	96.4	1.372912003	1.526339277	1.269512944	1.292256071	1.245512668	1.334453751	1.354108439
10-May-94	4	97.1	1.359835482	1.517195898	1.252853031	1.276461804	1.227886705	1.320146286	1.340444115
11-May-94	5	97.8	1.346352974	1.507855872	1.235528447	1.260071388	1.209515015	1.305351369	1.326335861
12-May-94	6	98.5	1.33243846	1.498310554	1.217483944	1.243038049	1.190331698	1.290034611	1.311753861
13-May-94	7	99.2	1.318063335	1.488550717	1.198657087	1.225309282	1.170261715	1.274157849	1.29666519
14-May-94	8	100	1.301029996	1.477121255	1.176091259	1.204119983	1.146128036	1.255272505	1.278753601
15-May-94	9	100	1.301029996	1.477121255	1.176091259	1.204119983	1.146128036	1.255272505	1.278753601
16-May-94	10	100.6	1.28780173	1.46834733	1.158362492	1.187520721	1.127104798	1.240549248	1.264817823
17-May-94	11	101.1	1.276461804	1.460897843	1.1430148	1.173186268	1.11058971	1.227886705	1.252853031
18-May-94	12	101.4	1.269512944	1.456366033	1.133538908	1.164352856	1.100370545	1.220108088	1.245512668
19-May-94	13	101.8	1.260071388	1.450249108	1.120573931	1.152288344	1.086359831	1.209515015	1.235528447
20-May-94	14	102.2	1.250420002	1.444064796	1.10720997	1.139879086	1.071882007	1.198657087	1.225309282
21-May-94	15	105	1.176091259	1.397940009	1	1.041392685	0.954242509	1.113943352	1.146128036
22-May-94	16	104	1.204119983	1.414973348	1.041392685	1.079181246	1	1.146128036	1.176091259
23-May-94	17	103.1	1.227886705	1.42975228	1.075546961	1.11058971	1.037426498	1.173186268	1.201397124
24-May-94	18	103.3	1.222716471	1.426511261	1.068185862	1.103803721	1.029383778	1.167317335	1.195899652
25-May-94	19	103.7	1.212187604	1.419955748	1.053078443	1.089905111	1.012837225	1.155336037	1.184691431
26-May-94	20	104	1.204119983	1.414973348	1.041392685	1.079181246	1	1.146128036	1.176091259
27-May-94	21	104.2	1.198657087	1.411619706	1.033423755	1.071882007	0.991226076	1.139879086	1.170261715
28-May-94	22	107	1.113943352	1.361727836	0.903089987	0.954242509	0.84509804	1.041392685	1.079181246
29-May-94	23	107	1.113943352	1.361727836	0.903089987	0.954242509	0.84509804	1.041392685	1.079181246
30-May-94	24	106	1.146128036	1.380211242	0.954242509	1	0.903089987	1.079181246	1.113943352
31-May-94	25	105.9	1.149219113	1.382017043	0.959041392	1.004321374	0.908485019	1.08278537	1.117271296
1-Jun-94	26	106.1	1.1430148	1.378397901	0.949390007	0.995635195	0.897627091	1.075546961	1.11058971
2-Jun-94	27	106.2	1.139879086	1.376576957	0.944482672	0.991226076	0.892094603	1.071882007	1.10720997
3-Jun-94	28	106.3	1.136720567	1.374748346	0.939519253	0.986771734	0.886490725	1.068185862	1.103803721
4-Jun-94	29	106.4	1.133538908	1.372912003	0.934498451	0.982271233	0.880813592	1.064457989	1.100370545
5-Jun-94	30	106.5	1.130333768	1.371067862	0.929418926	0.977723605	0.875061263	1.06069784	1.096910013
6-Jun-94	31	106.8	1.120573931	1.365487985	0.913813852	0.963787827	0.857332496	1.049218023	1.086359831
7-Jun-94	32	107.1	1.11058971	1.378397901	0.949390007	0.995635195	0.897627091	1.037426498	1.075546961
8-Jun-94	33	107.2	1.10720997	1.376576957	0.944482672	0.991226076	0.892094603	1.033423755	1.071882007
9-Jun-94	34	107.3	1.103803721	1.374748346	0.939519253	0.986771734	0.886490725	1.029383778	1.068185862
10-Jun-94	35	107.4	1.100370545	1.372912003	0.934498451	0.982271233	0.880813592	1.025305865	1.064457989
11-Jun-94	36	107.6	1.093421685	1.371067862	0.929418926	0.977723605	0.875061263	1.017033339	1.056904851
12-Jun-94	37	107.8	1.086359831	1.365487985	0.913813852	0.963787827	0.857332496	1.008600172	1.049218023
13-Jun-94	38	108	1.079181246	1.359835482	0.897627091	0.949390007	0.838849091	1	1.041392685
14-Jun-94	39	108.3	1.068185862	1.357934847	0.892094603	0.944482672	0.832508913	0.986771734	1.029383778
15-Jun-94	40	108.4	1.064457989	1.356025857	0.886490725	0.939519253	0.826074803	0.982271233	1.025305865
16-Jun-94	41	108.5	1.06069784	1.354108439	0.880813592	0.934498451	0.819543936	0.977723605	1.021189299
17-Jun-94	42	108.6	1.056904851	1.350248018	0.86923172	0.924279286	0.806179974	0.973127854	1.017033339
18-Jun-94	43	108.7	1.053078443	1.346352974	0.857332496	0.913813852	0.792391689	0.968482949	1.012837225
19-Jun-94	44	108.8	1.049218023	1.342422681	0.84509804	0.903089987	0.77815125	0.963787827	1.008600172
20-Jun-94	45	109	1.041392685	1.336459734	0.826074803	0.886490725	0.755874856	0.954242509	1
21-Jun-94	46	109.2	1.033423755	1.334453751	0.819543936	0.880813592	0.748188027	0.944482672	0.991226076
22-Jun-94	47	109.5	1.021189299	1.33243846	0.812913357	0.875061263	0.740362689	0.929418926	0.977723605
23-Jun-94	48	109.5	1.021189299	1.330413773	0.806179974	0.86923172	0.73239376	0.929418926	0.977723605
24-Jun-94	49	109.5	1.021189299	1.328379603	0.799340549	0.86332286	0.72427587	0.929418926	0.977723605
25-Jun-94	50	109.6	1.017033339	1.326335861	0.792391689	0.857332496	0.716003344	0.924279286	0.973127854
26-Jun-94	51	109.7	1.012837225	1.322219295	0.77815125	0.84509804	0.698970004	0.919078092	0.968482949
27-Jun-94	52	110	1	1.318063335	0.763427994	0.832508913	0.681241237	0.903089987	0.954242509
28-Jun-94	53	110.1	0.995635195	1.311753861	0.740362689	0.812913357	0.653212514	0.897627091	0.949390007
29-Jun-94	54	110.2	0.991226076	1.311753861	0.740362689	0.812913357	0.653212514	0.892094603	0.944482672
30-Jun-94	55	110.3	0.986771734	1.311753861	0.740362689	0.812913357	0.653212514	0.886490725	0.939519253
1-Jul-94	56	110.4	0.982271233	1.309630167	0.73239376	0.806179974	0.643452676	0.880813592	0.934498451
2-Jul-94	57	110.5	0.977723605	1.307496038	0.72427587	0.799340549	0.633468456	0.875061263	0.929418926
3-Jul-94	58	110.6	0.973127854	1.301029996	0.698970004	0.77815125	0.602059991	0.86923172	0.924279286
4-Jul-94	59	110.7	0.968482949	1.298853076	0.69019608	0.770852012	0.591064607	0.86332286	0.919078092
5-Jul-94	60	110.9	0.959041392	1.29666519	0.681241237	0.763427994	0.579783597	0.851258349	0.908485019
6-Jul-94	61	111	0.954242509	1.294466226	0.672097858	0.755874856	0.568201724	0.84509804	0.903089987
7-Jul-94	62	111.1	0.982271233	1.292256071	0.662757832	0.748188027	0.556302501	0.838849091	0.897627091
8-Jul-94	63	111.1	0.977723605	1.290034611	0.653212514	0.740362689	0.544068044	0.838849091	0.897627091
9-Jul-94	64	111.2	0.973127854	1.28780173	0.643452676	0.73239376	0.531478917	0.832508913	0.892094603
10-Jul-94	65	111.2	0.968482949	1.285557309	0.633458456	0.72427587	0.51851394	0.832508913	0.892094603
11-Jul-94	66	111.3	0.959041392	1.281033367	0.612783857	0.707570176	0.491361694	0.826074803	0.886490725
12-Jul-94	67	111.5	0.954242509	1.278753601	0.602059991	0.698970004	0.477121255	0.812913357	0.875061263
13-Jul-94	68	111.6	0.949390007	1.292256071	0.662757832	0.748188027	0.556302501	0.806179974	0.86923172
14-Jul-94	69	111.7	0.949390007	1.290034611	0.653212514	0.740362689	0.544068044	0.799340549	0.86332286
15-Jul-94	70	111.8	0.944482672	1.28780173	0.643452676	0.73239376	0.531478917	0.792391689	0.857332496
16-Jul-94	71	111.9	0.944482672	1.285557309	0.633468456	0.72427587	0.51851394	0.785329835	0.851258349
17-Jul-94	72	112	0.939519253	1.281033367	0.612783857	0.707570176	0.491361694	0.77815125	0.84509804
18-Jul-94	73	112	0.929418926	1.278753601	0.602059991	0.698970004	0.477121255	0.77815125	0.84509804
19-Jul-94	74	112.2	0.924279286	1.276461804	0.591064607	0.69019608	0.462397998	0.763427994	0.832508913
20-Jul-94	75	112.2	0.919078092	1.276461804	0.591064607	0.69019608	0.462397998	0.763427994	0.832508913
21-Jul-94	76	112.3	0.913813852	1.274157849	0.579783597	0.681241237	0.447158031	0.755874856	0.826074803
22-Jul-94	77	112.5	0.908485019	1.274157849	0.579783597	0.681241237	0.447158031	0.740362689	0.812913357
23-Jul-94	78	112.5	0.903089987	1.271841607	0.568201724	0.672097858	0.431363764	0.740362689	0.812913357
24-Jul-94	79	112.5	0.903089987	1.267171728	0.544068044	0.653212514	0.397940009	0.740362689	0.812913357
25-Jul-94	80	112.5	0.892094603	1.264817823	0.531478917	0.643452676	0.380211242	0.740362689	0.812913357
26-Jul-94	81	112.8	0.892094603	1.26245109	0.51851394	0.633468456	0.361727836	0.716003344	0.792391689
27-Jul-94	82	112.9	0.886490725	1.260071388	0.505149978	0.62324929	0.342422681	0.707570176	0.785329835
28-Jul-94	83	113.1	0.875061263	1.257678575	0.491361694	0.612783857	0.322219295	0.69019608	0.770852012
29-Jul-94	84	113.1	0.875061263	1.255272505	0.477121255	0.602059991	0.301029996	0.69019608	0.770852012
30-Jul-94	85	113.2	0.875061263	1.255272505	0.477121255	0.602059991	0.301029996	0.681241237	0.763427994
31-Jul-94	86	113.3	0.875061263	1.250420002	0.447158031	0.579783597	0.255272505	0.672097858	0.755874856
1-Aug-94	87	113.3	0.857332496	1.250420002	0.447158031	0.579783597	0.255272505	0.672097858	0.755874856
2-Aug-94	88	113.4	0.851258349	1.247973266	0.431363764	0.568201724	0.230448921	0.662757832	0.748188027
3-Aug-94	89	113.6	0.838849091	1.243038049	0.397940009	0.544068044	0.176091259	0.643452676	0.73239376
4-Aug-94	90	113.6	0.838849091	1.243038049	0.397940009	0.544068044	0.176091259	0.643452676	0.73239376
5-Aug-94	91	113.7	0.832508913	1.243038049	0.397940009	0.544068044	0.176091259	0.633468456	0.72427587
6-Aug-94	92	113.8	0.826074803	1.243038049	0.397940009	0.544068044	0.176091259	0.62324929	0.716003344
7-Aug-94	93	113.9	0.826074803	1.235528447	0.342422681	0.505149978	0.079181246	0.612783857	0.707570176
8-Aug-94	94	113.9	0.819543936	1.23299611	0.322219295	0.491361694	0.041392685	0.612783857	0.707570176
9-Aug-94	95	114	0.806179974	1.227886705	0.278753601	0.462397998	-0.04575749	0.602059991	0.698970004
10-Aug-94	96	114	0.806179974	1.227886705	0.278753601	0.462397998	-0.04575749	0.602059991	0.698970004
11-Aug-94	97	114.2	0.799340549	1.225309282	0.255272505	0.447158031	-0.09691001	0.579783597	0.681241237

HORNER PLOT

Leyden 1994 Pressure Build-up Data



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PSC 039784

Method 4: Horner Plot

The pressure build-up data from end of w/d (May 6, 1994) through August 11, prior to refill was analyzed.

The Horner plot indicated a stabilized cavern pressure of 88.5 psig.

$$L \& U = V_{book} - V_{theoretical}$$

$$V_{book} = 1{,}358{,}088 \text{ Mcf } (@ 14.65 \text{ psig})$$

$$V_{theoretical} = 11.6 \text{ mmcf/psig} \times P_{stab} \times 1000 \text{ ; mcf}$$

$$= 1{,}026{,}600 \text{ mcf}$$

$$\therefore L \& U = 331{,}488 \text{ mcf}$$

$$= \underline{0.33 \text{ bcf}}$$

Method 1: Muskat Analysis

By using several guesses for P_{ws}, the one with the best straight line indicates a stabilize pressure of 118 psig.

$$\therefore L \& U = V_{book} - V_{theory}$$

$$= 1358088 - (11.6 \times 118 \times 1000)$$

$$= -10{,}712 \text{ mcf}$$

$$= -0.0107 \text{ bcf}$$

i.e a gain

Method 2: Book Volume Comparison

V_{1993} 1,328,204
P_{stab} 80 psig (Horner)

V_{1994} 1,358,088
P_{stab} 88.5 psig

$\therefore P_{1994} - P_{1993} = 8.5$

$\therefore 8.5 \times 11.6 \times 1000 = 98,600$ mcf

$\therefore$ 1358088 − 98600 (to bring 1994 vol to same pressure base as in 1993)

$= 1,259,488$ mcf

but in 1993, V was 1,328,204

$\therefore L \propto U = 1,328,204 - 1,259,488$

$= 68,716$ mcf
$= 0.07$ bcf

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Method 3:

Historic trend of 100,000 mcf (See 1/3/91 report).

≈ 0.10 bcf

LEYDEN L&U REPORT
December 28, 1995

Summary

Calculations indicate 0.065 BCF (@ 14.65 psi) less gas in storage than is being carried on the books. Therefore, an L&U adjustment of 65,000 MCF (@ 14.65 psi) should be applied to the book volume by subtracting same from the book volume.

Four methods were used to evaluate the L&U gas as outlined below. The two methods which gave reasonable estimates were averaged to come up with an L&U figure.

Current year L&U, MCF (@14.65 psi)		*Method*
29,848	*1*	*(Muskat Plot)*
(54,480)	*2*	*(Vol in - Vol out)*
100,000	*3*	*(History)*
385,968	*4*	*(Horner Plot)*

Method 1

Analysis of the Muskat plot of the pressure build-up data obtained from May 31, 1995 (end of the year-long interchangeable withdrawal/injection operation) through July, 7 1995 prior to sustained injection to refill the Leyden storage cavern. The analysis indicated a stabilized cavern pressure of 122 psig. Obtained the theoretical volume of gas in the cavern by applying the stabilized P/V relationship of 11.6 MMCF/psig which still represents the current operating condition at Leyden. The L&U was obtained by establishing the difference between the book volume and the theoretical volume. Based on the data analyzed, it shows that theoretical volume was 29,848 mcf less than book

volume. The operating nature of the cavern with relation to the intermittent short withdrawals and injections could mask the results obtained.

Method 2

This method compared the book volume in 1995 to the book volume in 1994. The method also assumes the stabilized P/V relationship of 11.6 MMCF/psig to equate the two year end volumes to the same pressure.

Method 3

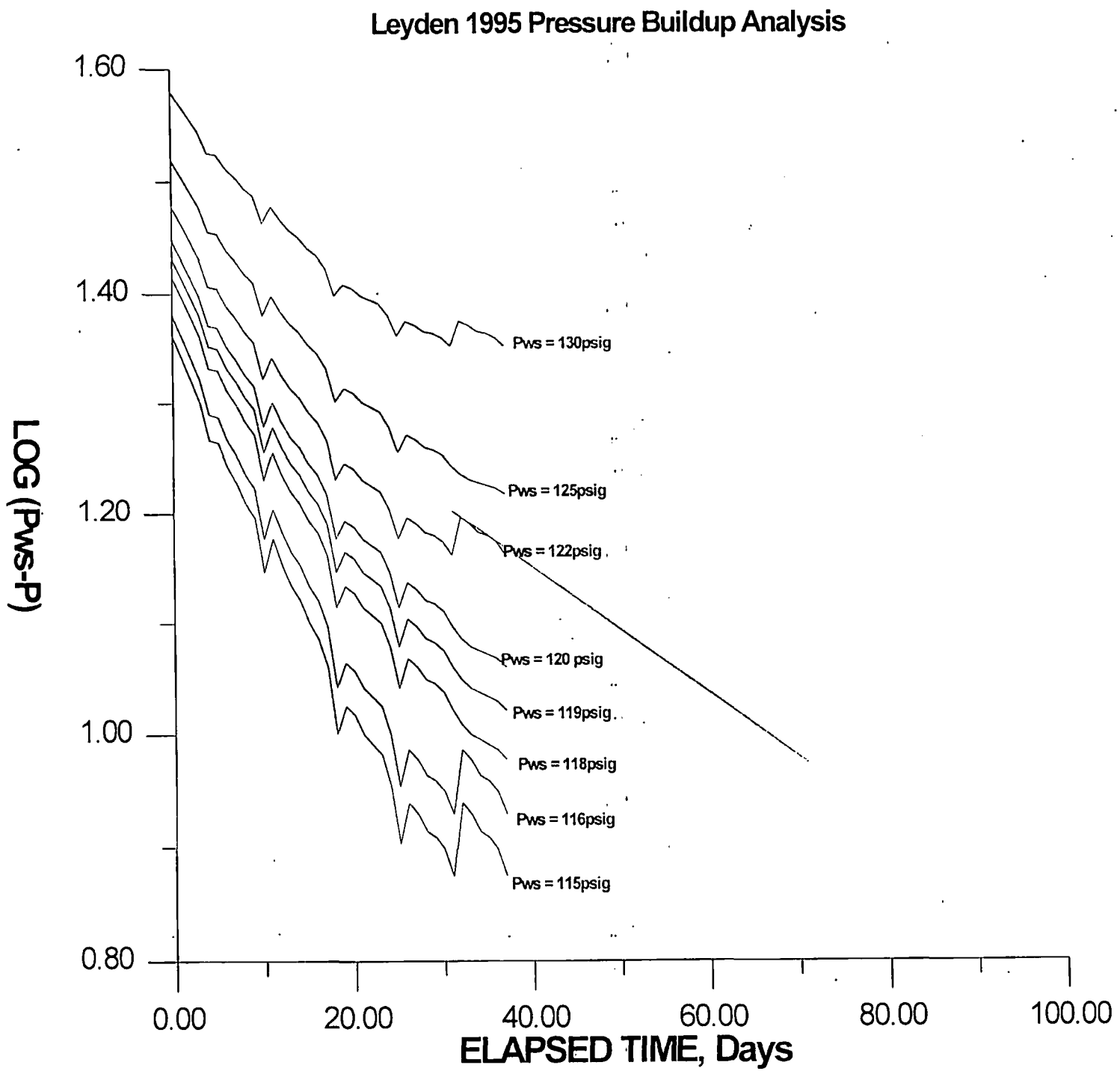
This is based on the historic trends. Documentation can be found in the 1/3/91 Leyden L&U report.

Method 4

This method uses the Horner Plot Analysis of the pressure build up data. The stabilized pressure from the plot was 91.3 psig. The last straight line period was relatively short and difficult to identify. The stabilized P/V relationship of 11.6 MMCF/psig was also applied to the stabilized pressure to obtain the L&U. The estimated L&U figure of 385,968 mcf (0.34 bcf) based on the Horner analysis is somewhat questionable and therefore unreliable.

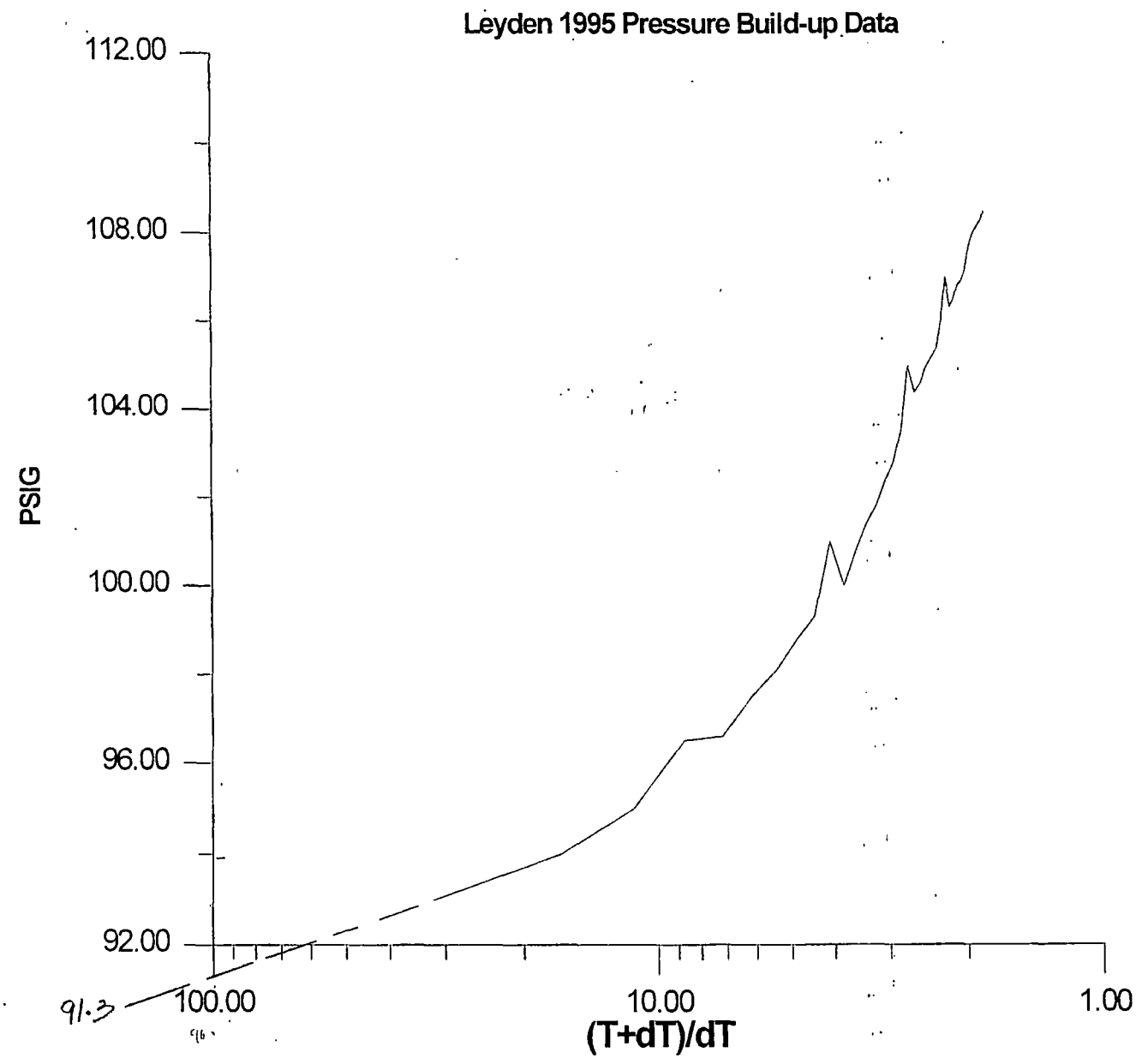
Nat Olowu
Reservoir Engineer
PSCo (Natural Gas Group)
December 28, 1995

MUSKAT PLOT



PSC 039769

HORNER PLOT



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HORNER PLOT DATA

MUSKAT PLOT DATA

Date	Pressure, psig	t= 31	Dt	(t+Dt)/Dt	pwa 120	log(pws-p)	pwa 130	log(pws-p)	pwa 115	log(pws-p)	pwa 116	log(pws-p)	pwa 114	log(pws-p)	pwa 122	log(pws-p)	pwa 118	log(pws-p)	pwa 110	log(pws-p)	pwa 125	log(pws-p)	pwa 122	log(pws-p)
31-May-95	92		0			1.447158031		1.579783597		1.361727838		1.380211242		1.342422681		1.477121255		1.414973348		1.431363764		1.51851394		1.477121255
1-Jun-95	93		1	32		1.431363764		1.568201724		1.342422681		1.361727838		1.322219295		1.462397998		1.397940009		1.414973348		1.505149978		1.462397998
2-Jun-95	94		2	16.5		1.414973348		1.556302501		1.322219295		1.342422681		1.301029996		1.447158031		1.380211242		1.397940009		1.491361694		1.447158031
3-Jun-95	95		3	11.33333333		1.397940009		1.544068044		1.301029996		1.322219295		1.278753601		1.431363764		1.361727838		1.380211242		1.477121255		1.431363764
4-Jun-95	96.5		4	8.75		1.371067862		1.525044807		1.267171728		1.290034611		1.243038049		1.40654018		1.33243846		1.352182518		1.45434468		1.40654018
5-Jun-95	96.8		5	7.2		1.369215857		1.523746467		1.204817823		1.28780173		1.240549248		1.404833717		1.330413773		1.350248018		1.45331834		1.404833717
6-Jun-95	97.5		6	0.166666667		1.352182518		1.511883361		1.243038049		1.267171728		1.217483944		1.389166084		1.311753861		1.33243846		1.439332694		1.389166084
7-Jun-95	98.1		7	5.428571429		1.340444115		1.503790683		1.227886705		1.252853031		1.201397124		1.378397901		1.298853076		1.320146280		1.42975228		1.378397901
8-Jun-95	98.8		8	4.875		1.328335861		1.494154594		1.209515015		1.235528447		1.181843588		1.365487985		1.283301229		1.305351369		1.418301291		1.365487985
9-Jun-95	99.3		9	4.444444444		1.315970345		1.487138375		1.195899652		1.222716471		1.167317335		1.356025857		1.271841607		1.294466226		1.409933123		1.356025857
10-Jun-95	101		10	4.1		1.278753601		1.462397998		1.140128036		1.176091259		1.113943352		1.322219295		1.230448921		1.255272505		1.380211242		1.322219295
11-Jun-95	100		11	3.818181818		1.301029996		1.477121255		1.176091259		1.204119983		1.146128036		1.342422681		1.255272505		1.278753601		1.397940009		1.342422681
12-Jun-95	100.8		12	3.583333333		1.283301229		1.465382851		1.162288344		1.181843588		1.120573931		1.326335861		1.235528447		1.260071388		1.383815366		1.326335861
13-Jun-95	101.4		13	3.384615385		1.269512944		1.456366033		1.133538908		1.164352856		1.100370545		1.31388722		1.220108088		1.245512668		1.372912003		1.31388722
14-Jun-95	101.8		14	3.214285714		1.260071388		1.450249108		1.120573931		1.152288344		1.080359831		1.305351369		1.209515015		1.235528447		1.365487985		1.305351369
15-Jun-95	102.4		15	3.066666667		1.245512668		1.440909082		1.100370545		1.133538908		1.064457989		1.292256071		1.193124598		1.220108088		1.354108439		1.292256071
16-Jun-95	102.8		16	2.9375		1.235528447		1.434568904		1.086359831		1.120573931		1.049218023		1.283301229		1.181843588		1.209515015		1.346352974		1.283301229
17-Jun-95	103.5		17	2.823529412		1.217483944		1.423245874		1.06069784		1.096910013		1.021189299		1.267171728		1.161368002		1.190331698		1.33243846		1.267171728
18-Jun-95	105		18	2.722222222		1.176091259		1.397940009		1		1.041392685		0.954242509		1.230448921		1.113943352		1.146128036		1.301029996		1.230448921
19-Jun-95	104.4		19	2.631578947		1.193124598		1.408239965		1.025305865		1.064457989		0.982271233		1.245512668		1.133538908		1.164352856		1.31388722		1.245512668
20-Jun-95	104.8		20	2.55		1.187520721		1.404833717		1.017033339		1.056904851		0.973127854		1.240549248		1.127104798		1.158362492		1.309630187		1.240549248
21-Jun-95	105		21	2.476190476		1.176091259		1.397940009		1		1.041392685		0.954242509		1.230448921		1.113943352		1.146128036		1.301029996		1.230448921
22-Jun-95	105.2		22	2.409090909		1.170261715		1.394451681		0.991226076		1.033423755		0.944482672		1.225309282		1.10720997		1.139879086		1.29666519		1.225309282
23-Jun-95	105.4		23	2.347826087		1.164352856		1.390935107		0.982271233		1.025305865		0.934498451		1.220108088		1.100370545		1.133538908		1.292256071		1.220108088
24-Jun-95	106		24	2.291666667		1.146128036		1.380211242		0.954242509		1		0.903089987		1.204119983		1.079181246		1.113943352		1.278753601		1.204119983
25-Jun-95	107		25	2.24		1.113943352		1.361727838		0.903089987		0.954242509		0.84509804		1.176091259		1.041392685		1.079181246		1.255272505		1.176091259
26-Jun-95	106.3		26	2.192307692		1.138720567		1.374748346		0.939519253		0.988771734		0.885490725		1.195899652		1.068185862		1.103803721		1.271841607		1.195899652
27-Jun-95	106.5		27	2.148148148		1.130333768		1.371067862		0.929419926		0.977723605		0.875061263		1.190331698		1.06069784		1.096910013		1.267171728		1.190331698
28-Jun-95	106.8		28	2.107142857		1.120573931		1.365487985		0.913813852		0.963787827		0.857332496		1.181843588		1.049218023		1.086359831		1.260071388		1.181843588
29-Jun-95	106.9		29	2.068965517		1.117271296		1.36361198		0.908485019		0.959041392		0.851258349		1.178976947		1.045322979		1.08278537		1.257678575		1.178976947
30-Jun-95	107.1		30	2.033333333		1.11058971		1.359835482		0.897627091		0.949390007		0.838849091		1.173186268		1.037426498		1.075546961		1.252853031		1.173186268
1-Jul-95	107.5		31	2		1.096910013		1.352182518		0.875061263		0.929419926		0.812913357		1.161368002		1.021189299		1.06069784		1.243038049		1.161368002
2-Jul-95	107.8		32	1.96875		1.088359831		1.374748346		0.939519253		0.988771734		0.885490725		1.195899652		1.008600172		1.049218023		1.235528447		1.152288344
3-Jul-95	108		33	1.939393939		1.079181246		1.371067862		0.929419926		0.977723605		0.875061263		1.190331698		1		1.041392685		1.230448921		1.146128036
4-Jul-95	108.1		34	1.911764706		1.075546961		1.365487985		0.913813852		0.963787827		0.857332496		1.181843588		0.995635195		1.037426498		1.227886705		1.1430148
5-Jul-95	108.2		35	1.885714286		1.071882007		1.36361198		0.908485019		0.959041392		0.851258349		1.178976947		0.991226076		1.033423755		1.225309282		1.139879086
6-Jul-95	108.3		36	1.861111111		1.068185862		1.359835482		0.897627091		0.949390007		0.838849091		1.173186268		0.988771734		1.029383778		1.222716471		1.138720567
7-Jul-95	108.5		37	1.837837838		1.06069784		1.352182518		0.875061263		0.929419926		0.812913357		1.161368002		0.977723605		1.021189299		1.217483944		1.130333768

PSC 039771

HORNER PLOT DATA

MUSKAT PLOT DATA

Date	Pressure, psig	t= 31	Dt	(t+Dt)/Dt	pws 120	log(pws-p)	pws 130	log(pws-p)	pws 115	log(pws-p)	pws 116	log(pws-p)	pws 114	log(pws-p)	pws 122	log(pws-p)
31-May-95	92		0			1.44715803		1.5797836		1.36172784		1.380211242		1.342422681		1.477121255
1-Jun-95	93		1	32		1.43136376		1.56820172		1.34242268		1.361727836		1.322219295		1.462397998
2-Jun-95	94		2	16.5		1.41497335		1.5563025		1.32221929		1.342422681		1.301029996		1.447158031
3-Jun-95	95		3	11.33333333		1.39794001		1.54406804		1.30103		1.322219295		1.278753601		1.431363764
4-Jun-95	96.5		4	8.75		1.37106786		1.52504481		1.26717173		1.290034611		1.243038049		1.40654018
5-Jun-95	96.6		5	7.2		1.36921586		1.52374647		1.26481782		1.28780173		1.240549248		1.404833717
6-Jun-95	97.5		6	6.166666667		1.35218252		1.51188336		1.24303805		1.267171728		1.217483944		1.389166084
7-Jun-95	98.1		7	5.428571429		1.34044411		1.50379068		1.2278867		1.252853031		1.201397124		1.378397901
8-Jun-95	98.8		8	4.875		1.32633586		1.49415459		1.20951501		1.235528447		1.181843588		1.365487985
9-Jun-95	99.3		9	4.444444444		1.31597035		1.48713838		1.19589965		1.222716471		1.167317335		1.356025857
10-Jun-95	101		10	4.1		1.2787536		1.462398		1.14612804		1.176091259		1.113943352		1.322219295
11-Jun-95	100		11	3.818181818		1.30103		1.47712125		1.17609126		1.204119983		1.146128036		1.342422681
12-Jun-95	100.8		12	3.583333333		1.28330123		1.46538285		1.15228834		1.181843588		1.120573931		1.326335861
13-Jun-95	101.4		13	3.384615385		1.26951294		1.45636603		1.13353891		1.164352856		1.100370545		1.31386722
14-Jun-95	101.8		14	3.214285714		1.26007139		1.45024911		1.12057393		1.152288344		1.086359831		1.305351369
15-Jun-95	102.4		15	3.066666667		1.24551267		1.44090908		1.10037055		1.133538908		1.064457989		1.292256071
16-Jun-95	102.8		16	2.9375		1.23552845		1.4345689		1.08635983		1.120573931		1.049218023		1.283301229
17-Jun-95	103.5		17	2.823529412		1.21748394		1.42324587		1.06069784		1.096910013		1.021189299		1.267171728
18-Jun-95	105		18	2.722222222		1.17609126		1.39794001		1		1.041392685		0.954242509		1.230448921
19-Jun-95	104.4		19	2.631578947		1.1931246		1.40823997		1.02530587		1.064457989		0.982271233		1.245512668
20-Jun-95	104.6		20	2.55		1.18752072		1.40483372		1.01703334		1.056904851		0.973127854		1.240549248
21-Jun-95	105		21	2.476190476		1.17609126		1.39794001		1		1.041392685		0.954242509		1.230448921
22-Jun-95	105.2		22	2.409090909		1.17026172		1.39445168		0.99122608		1.033423755		0.944482672		1.225309282
23-Jun-95	105.4		23	2.347826087		1.16435286		1.39093511		0.98227123		1.025305865		0.934498451		1.220108088
24-Jun-95	106		24	2.291666667		1.14612804		1.38021124		0.95424251		1		0.903089987		1.204119983
25-Jun-95	107		25	2.24		1.11394335		1.36172784		0.90308999		0.954242509		0.84509804		1.176091259
26-Jun-95	106.3		26	2.192307692		1.13672057		1.37474835		0.93951925		0.986771734		0.886490725		1.195899652
27-Jun-95	106.5		27	2.148148148		1.13033377		1.37106786		0.92941893		0.977723605		0.875061263		1.190331698
28-Jun-95	106.8		28	2.107142857		1.12057393		1.36548798		0.91381385		0.963787827		0.857332496		1.181843588
29-Jun-95	106.9		29	2.068965517		1.1172713		1.36361198		0.90848502		0.959041392		0.851258349		1.178976947
30-Jun-95	107.1		30	2.033333333		1.11058971		1.35983548		0.89762709		0.949390007		0.838849091		1.173186268
1-Jul-95	107.5		31	2		1.09691001		1.35218252		0.87506126		0.929418926		0.812913357		1.161368002
2-Jul-95	107.8		32	1.96875		1.08635983		1.37474835		0.93951925		0.986771734		0.886490725		1.195899652
3-Jul-95	108		33	1.939393939		1.07918125		1.37106786		0.92941893		0.977723605		0.875061263		1.190331698
4-Jul-95	108.1		34	1.911764706		1.07554696		1.36548798		0.91381385		0.963787827		0.857332496		1.181843588
5-Jul-95	108.2		35	1.885714286		1.07188201		1.36361198		0.90848502		0.959041392		0.851258349		1.178976947
6-Jul-95	108.3		36	1.861111111		1.06818586		1.35983548		0.89762709		0.949390007		0.838849091		1.173186268
7-Jul-95	108.5		37	1.837837838		1.06069784		1.35218252		0.87506126		0.929418926		0.812913357		1.161368002

PSC 039772

Method 1: Muskat Analysis

By using several guesses for P_{ws}, the one with the best straight line indicated a stabilize pressure of 122 psig.

$$\therefore L\&U = V_{book} - V_{theoretical}$$

$$= 1{,}445{,}048 - (11.6 \times 122 \times 1000)$$

$$= 1{,}445{,}048 - 1{,}415{,}200$$

$$= 29{,}848 \text{ mcf}$$

$$= 0.0298 \text{ bcf}$$

$$= \boxed{0.03 \text{ bcf}}$$

Method 2: Book Volume Comparison

$V_{1994} = 1{,}358{,}088$

$P_{stabilized} = 88.5$ psig (from Horner plot)

$V_{1995} = 1{,}445{,}048$

$P_{stabilized} = 91.3$ psig

$\therefore P_{1995} - P_{1994} = 91.3 - 88.5$

$= 2.8$ psig

$\therefore 2.8 \times 11.6 \times 1000 = 32{,}480$ mcf

$\therefore 1{,}445{,}048 - 32{,}480$ (to bring 1995 volume to the same 1994 pressure base)

$= 1{,}412{,}568$ mcf

But V_{1994} was $1{,}358{,}088$

$\therefore L\&U = 1{,}358{,}088 - 1{,}412{,}568$

$= 54{,}480$ mcf

$= 0.055$ bcf gain

PSC 039773

22-141 50 SHEETS
22-142 100 SHEETS
22-144 200 SHEETS
AMPAD

Method 3: Historic Trend Analysis

Historic trend of 100,000 mcf (See 1/3/91 L&U report).

$\approx$ **0.10 bcf**

Method 4: Horner Plot

The pressure build up for the short period from end of w/d and inj (May 31 1995) thro' July 7, 1995 prior to sustained injection or refill, was analyzed. (interchangeable)

The horner plot indicated a stabilized Cavern pressure of 91.3 psig.

$$L\&U = V_{book} - V_{theoretical}$$

V_{book} = 1,445,048 mcf @ 14.65 psig. (from Leyden Summary of Gas Delivered report)

$$V_{theoretical} = 11.6 \frac{mmcf}{psig} \times P_{stab} \times 1000 \text{ ; mcf}$$

$$= 11.6 \times 91.3 \times 1000$$

$$= 1{,}059{,}080 \text{ mcf}$$

$$\therefore L\&U = 385{,}968 \text{ mcf}$$

$$= \boxed{0.386 \text{ bcf}}$$

OGCC FORM 4
Rev 8/89

STATE OF COLORADO
OIL AND GAS CONSERVATION COMMISSION
DEPARTMENT OF NATURAL RESOURCES

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SUNDRY NOTICES AND REPORTS ON WELLS

(Do not use this form for proposals to drill or to deepen or plug back to a different reservoir. Use "APPLICATION FOR PERMIT—" for such proposals.)

5 FEDERAL INDIAN OR STATE LEASE NO

1 ☐ OIL WELL ☐ GAS WELL ☐ COALBED METHANE ☐ INJECTION WELL ☒ OTHER Gas Storage

6 PERMIT NO 93-1153

2 NAME OF OPERATOR: Public Service Company of Colorado

7 API NO 050596018

3 ADDRESS OF OPERATOR: 1225 17th St., Suite 1100

8 WELL NAME

CITY: Denver, STATE: CO ZIP CODE: 80202

9 WELL NUMBER: Leyden #31

4 LOCATION OF WELL (Report location clearly and in accordance with any State requirements. See also space 17 below.)
At surface: 971' FSL, 1182 FEL, S22
At proposed prod. zone: Same

10 FIELD OR WILDCAT: Leyden Gas Storage

12 COUNTY: Jefferson

11 QTR. QTR. SEC., T.R. AND MERIDIAN: SESE, S22, T2S, R70W 6th P.M.

Check Appropriate Box To Indicate Nature of Notice, Report or Notification

13A. NOTICE OF INTENTION TO:
- ☐ PLUG AND ABANDON
- ☐ MULTIPLE COMPLETION
- ☐ COMMINGLE ZONES
- ☐ FRACTURE TREAT
- ☐ REPAIR WELL
- ☐ OTHER _____

13B. SUBSEQUENT REPORT OF:
- ☐ FINAL PLUG AND ABANDONMENT (SUBMIT 3RD PARTY CEMENT VERIFICATION AND JOB LOG)
- ☐ ABANDONED LOCATION (WELL NEVER DRILLED - SITE MUST BE RESTORED WITHIN 6 MONTHS)
- ☐ REPAIRED WELL
- ☐ OTHER

Use Form 5 - Well Completion or Recompletion Report and Log for subsequent report of Multiple/Commingled Completions and Recompletions

13C. NOTIFICATION OF:
- ☐ SHUT-IN, TEMPORARILY ABANDONED (DATE _____) (REQUIRED EVERY 6 MONTHS)
- ☐ PRODUCTION RESUMED (DATE _____)
- ☐ LOCATION CHANGE (SUBMIT NEW PLAT)
- ☐ WELL NAME CHANGE
- XX OTHER Additional data to correct Completion Report

14. DESCRIBE PROPOSED OR COMPLETED OPERATIONS ON THIS FORM (Clearly state all pertinent details, and give pertinent dates, including estimated date of starting any proposed work. If well is directionally drilled, give subsurface locations and measured and true vertical depths for all markers and zones pertinent.

15. DATE OF WORK _____

Since the Completion Report was filed in November 1993, additional gas composition analysis data has been acquired and compared with our Leyden Storage gas. From this new information we conclude that the gas found in #31 is not migrated storage gas and that the Completion Report is in error on that subject. Copies of those gas analysis are included.

Also at the request of the OGCC we have provided a historical summary of our reported Lost & Unaccounted for Gas from Leyden Storage.

16. I hereby certify that the foregoing is true and correct

SIGNED Bill Uding TELEPHONE NO. 294-8307

NAME (PRINT) Bill Uding TITLE Lead Reservoir Engineer DATE 11/7/95

(This space for Federal or State office use)

APPROVED _____ TITLE _____ D

CONDITIONS OF APPROVAL, IF ANY:

PSC 039775

Location:	Inlet	Inlet	Inlet	Inlet?	Inlet	Inlet?	**
Date:	30-Oct-95	########	########	########	15-Jan-91	21-Oct-91	Average
COMPONENT	Mol %*	Mol %*	Mol %*	Mol %	Mol %	Mol %	Mol %
Carbon Dioxide	1.879	1.819	2.369	2.558	2.33	2.30	*2.390*
Oxygen	0.000	0.000	0.000	2.061	1.50	1.83	*1.797*
Nitrogen	5.914	6.585	8.580	7.809	6.56	7.27	*7.213*
Methane	86.310	84.940	80.477	75.818	80.64	78.09	*78.755*
Ethane	5.192	5.495	7.439	9.843	7.60	8.94	*8.456*
Propane	0.528	0.845	0.952	1.508	1.06	1.26	*1.194*
i-Butane	0.055	0.100	0.065	0.129	0.11	0.11	*0.103*
n-Butane	0.060	0.119	0.085	0.186	0.13	0.13	*0.133*
i-Pentane	0.020	0.035	0.013	0.033	0.03	0.03	*0.027*
n-Pentane	0.014	0.024	0.010	0.024	0.02	0.02	*0.019*
Hexanes Plus	0.028	0.038	0.010	0.031	0.02	0.02	*0.020*
TOTAL:	100.000	100.000	100.000	100.000	100.00	100.00	*xx*

Outlet	Outlet	Outlet	Outlet?	**
########	########	11-Mar-91	24-Apr-91	Average
Mol %	Mol %	Mol %	Mol %	Mol %
3.024	2.939	2.85	3.56	*3.093*
0.000	0.128	0.25	0.16	*0.179*
6.251	7.246	7.09	7.22	*7.184*
82.261	80.296	79.75	78.69	*80.249*
7.272	7.681	8.32	8.63	*7.975*
0.959	1.357	1.37	1.38	*1.268*
0.092	0.127	0.14	0.13	*0.123*
0.088	0.157	0.15	0.14	*0.134*
0.028	0.032	0.04	0.10	*0.049*
0.011	0.018	0.02	0.00	*0.012*
0.014	0.019	0.02	0.00	*0.013*
100.000	100.000	100.00	100.00	*xx*

* Nitrogen and oxygen combined. **Averages exclude 1995 samples.

**O2 and N2 averages exclude 1995 samples.

COMPONENT	% of Total Hydrocarbon Content						
Methane	93.60%	92.73%	90.37%	86.58%	89.99%	88.14%	*88.77%*
Ethane	5.63%	6.00%	8.35%	11.24%	8.48%	10.09%	*9.54%*
Propane	0.57%	0.92%	1.07%	1.72%	1.18%	1.42%	*1.35%*
i-Butane	0.06%	0.11%	0.07%	0.15%	0.12%	0.12%	*0.12%*
n-Butane	0.07%	0.13%	0.10%	0.21%	0.15%	0.15%	*0.15%*
i-Pentane	0.02%	0.04%	0.01%	0.04%	0.03%	0.04%	*0.03%*
n-Pentane	0.02%	0.03%	0.01%	0.03%	0.02%	0.03%	*0.02%*
Hexanes Plus	0.03%	0.04%	0.01%	0.04%	0.02%	0.02%	*0.02%*
TOTAL:	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	######

% of Total Hydrocarbon Content				
90.67%	89.53%	88.80%	88.34%	*89.34%*
8.02%	8.56%	9.26%	9.68%	*8.88%*
1.06%	1.51%	1.53%	1.55%	*1.41%*
0.10%	0.14%	0.16%	0.15%	*0.14%*
0.10%	0.18%	0.17%	0.16%	*0.15%*
0.03%	0.04%	0.04%	0.11%	*0.05%*
0.01%	0.02%	0.02%	0.00%	*0.01%*
0.02%	0.02%	0.02%	0.00%	*0.01%*
100.00%	100.00%	100.00%	100.00%	######

Rosemarie A. Halchuk
1-Nov-95

PSC 039776

Location:	Valve 27	Well #21	Well #16	Well #16	Well #25	Well #8	Well #16	**
Date:	########	#########	#########	15-Jan-91	11-Mar-91	15-Oct-91	15-Oct-91	Average
COMPONENT	Mol %*	Mol %	Mol %	Mol %	Mol %	Mol %	Mol %	Mol %
Carbon Dioxide	0.040	2.388	2.059	2.84	4.83	3.31	2.06	*2.915*
Oxygen	0.000	0.092	0.190	0.04	0.33	0.54	0.10	*0.215*
Nitrogen	86.257	7.476	7.789	6.53	8.00	7.60	7.68	*7.512*
Methane	12.647	80.833	79.500	81.66	77.45	76.71	81.02	*79.528*
Ethane	0.789	7.751	8.890	7.53	7.86	9.81	7.70	*8.256*
Propane	0.184	1.201	1.305	1.09	1.23	1.62	1.19	*1.271*
i-Butane	0.016	0.120	0.126	0.11	0.13	0.15	0.11	*0.124*
n-Butane	0.021	0.084	0.089	0.13	0.11	0.18	0.10	*0.115*
i-Pentane	0.020	0.035	0.035	0.03	0.04	0.05	0.03	*0.036*
n-Pentane	0.013	0.006	0.000	0.02	0.01	0.03	0.01	*0.012*
Hexanes Plus	0.013	0.015	0.017	0.02	0.01	0.01	0.01	*0.014*
TOTAL:	100.000	100.000	100.000	100.00	100.00	100.00	100.00	*100.000*

Well #31	Well #31	Well #31	
30-Oct-95	18-Oct-93	20-Oct-93	Average
Mol %*	Mol %	Mol %	Mol %
0.081	1.228	1.224	*0.844*
0.000	0.076	0.084	*0.053*
13.524	14.411	14.414	*14.116*
79.001	76.974	76.957	*77.644*
5.089	4.942	4.948	*4.993*
1.811	1.841	1.842	*1.831*
0.169	0.178	0.178	*0.175*
0.250	0.257	0.258	*0.255*
0.040	0.040	0.040	*0.040*
0.026	0.027	0.027	*0.027*
0.009	0.027	0.028	*0.021*
100.000	100.000	100.000	*100.000*

* Nitrogen and oxygen combined.

** Average excludes Valve 27.

COMPONENT	% of Total Hydrocarbon Content							
Methane	92.29%	89.77%	88.37%	90.14%	89.19%	86.63%	89.86%	*88.99%*
Ethane	5.76%	8.61%	9.88%	8.31%	9.05%	11.08%	8.54%	*9.24%*
Propane	1.34%	1.33%	1.45%	1.20%	1.42%	1.82%	1.31%	*1.42%*
i-Butane	0.12%	0.13%	0.14%	0.12%	0.15%	0.17%	0.12%	*0.14%*
n-Butane	0.15%	0.09%	0.10%	0.14%	0.13%	0.20%	0.12%	*0.13%*
i-Pentane	0.15%	0.04%	0.04%	0.03%	0.05%	0.05%	0.04%	*0.04%*
n-Pentane	0.09%	0.01%	0.00%	0.02%	0.01%	0.04%	0.01%	*0.01%*
Hexanes Plus	0.09%	0.02%	0.02%	0.02%	0.01%	0.01%	0.01%	*0.02%*
TOTAL:	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	######

% of Total Hydrocarbon Content			
91.44%	91.33%	91.31%	*91.36%*
5.89%	5.86%	5.87%	*5.87%*
2.10%	2.18%	2.19%	*2.16%*
0.20%	0.21%	0.21%	*0.21%*
0.29%	0.30%	0.31%	*0.30%*
0.05%	0.05%	0.05%	*0.05%*
0.03%	0.03%	0.03%	*0.03%*
0.01%	0.03%	0.03%	*0.03%*
100.00%	100.00%	100.00%	######

Rosemarie A. Halchuk
1-Nov-95

PSC 039777

SUMMARY - AVERAGE VALUES

Location:	Inlet	Outlet	Wells	Well #31
COMPONENT	Mol %*	Mol %*	Mol %*	Mol %
Carbon Dioxide	2.390	3.093	2.915	0.844
Oxygen	1.797	0.179	0.215	0.053
Nitrogen	7.213	7.184	7.512	14.116
Methane	78.755	80.249	79.528	77.644
Ethane	8.456	7.975	8.256	4.993
Propane	1.194	1.268	1.271	1.831
i-Butane	0.103	0.123	0.124	0.175
n-Butane	0.133	0.134	0.115	0.255
i-Pentane	0.027	0.049	0.036	0.040
n-Pentane	0.019	0.012	0.012	0.027
Hexanes Plus	0.020	0.013	0.014	0.021
TOTAL:	xx	xx	100.000	100.000

* Nitrogen and oxygen combined.

COMPONENT	% of Total Hydrocarbon Content			
Methane	88.77%	89.34%	88.99%	91.36%
Ethane	9.54%	8.88%	9.24%	5.87%
Propane	1.35%	1.41%	1.42%	2.16%
i-Butane	0.12%	0.14%	0.14%	0.21%
n-Butane	0.15%	0.15%	0.13%	0.30%
i-Pentane	0.03%	0.05%	0.04%	0.05%
n-Pentane	0.02%	0.01%	0.01%	0.03%
Hexanes Plus	0.02%	0.01%	0.02%	0.03%
TOTAL:	100.00%	100.00%	100.00%	100.00%

Rosemarie A. Halchuk
1-Nov-95

PSC 039778

Presented below is a table listing the annual volume activity for Leyden Gas Storage Facility and the estimated Lost and Unaccounted for Gas Volumes. The L & U gas was not calculated annually during the early years of operation. Some of the larger write offs are corrections for losses over the several preceding years and do not represent a lost volume for that single year. The components that contribute to the L&U figures includes metering error, gas lost during workover operations, gathering system pigging and seasonal blow-down, separator fuel and operation, and gas dissolved in produced water.

Leyden Historical Activity			
Year	**injection**	**Withdrawal**	**Reported L& U**
1963	1,221,265	466,096	
1964	2,555,422	2,367,484	
1965	4,240,333	3,965,501	150,000
1966	2,793,165	2,904,758	
1967	2,492,612	2,874,759	
1968	2,513,328	2,345,001	
1969	3,372,195	2,886,755	
1970	2,371,900	1,951,494	
1971	1,225,805	1,088,610	345,000
1972	2,441,378	2,570,220	
1973	1,997,856	1,772,579	122,880
1974	2,526,165	2,446,193	106,043
1975	3,178,862	3,051,850	98,577
1976	2,706,279	2,707,792	19,667
1977	3,063,997	2,865,967	132,568
1978	3,299,630	3,763,276	130,404
1979	3,942,511	3,246,330	130,404
1980	915,289	818,041	155,530
1981	1,870,500	1,685,936	66,616
1982	2,250,854	2,250,777	131,089
1983	2,178,244	2,306,530	
1984	1,271,501	898,303	-50,000
1985	98,561	874,220	
1986	1,357,006	1,209,532	58,400
1987	625,041	461,790	
1988	1,629,912	1,936,261	22,000
1989	2,121,220	1,862,546	
1990	2,290,520	1,224,707	570,000
1991	1,955,867	1,692,580	170,000
1992	1,444,380	1,349,765	120,000
1993	1,838,660	1,948,287	90,000
1994	1,594,069	1,791,113	85,000
Totals	69,384,327	65,585,053	2,654,178
Total L&U / Total Injections = .03825			
(All volumes in 14.65 Psia)			

LEYDEN L&U REPORT
August 13, 1999

Summary

No recent L&U calculations have been made at Leyden since July 1995. The following calculations covers July 1995 through July 1999 (4years).

Calculations indicate 0.402 BCF (@ 14.65 psi) less gas in storage than is being carried on the books. Therefore, an L&U adjustment of 402,200 MCF (@ 14.65 psi) should be applied to the book volume by subtracting same from the book volume.

Four methods were used to evaluate the L&U gas as outlined below. The four methods were averaged to come up with the L&U figure.

Current period's L&U, MCF (@14.65 psi)	*Method*	
397,848	*1*	*(Muskat Plot)*
212,560	*2*	*(Vol in - Vol out)*
400,000	*3*	*(History)*
598,528	*4*	*(Horner Plot)*

Method 1

Established an acceptable quiet period in between injection and withdrawal at the Leyden storage cavern. Performed an analysis of the Muskat plot of the pressure build-up data obtained from June 28, 1999 through July 21, 1999. The analysis indicated a stabilized cavern pressure of 1.02psig. Obtained the theoretical volume of gas in the cavern by applying the stabilized P/V relationship of 11.6 MMCF/psig which still represents the current operating condition at Leyden. The L&U was obtained by establishing the difference between the book volume and the theoretical volume. Based on the data analyzed, it shows that theoretical volume was 397,848 mcf less than book volume.

Method 2

This method compared the book volume in 1995 to the book volume in 1999. The method also assumes the stabilized P/V relationship of 11.6 MMCF/psig to equate the two year end volumes to the same pressure.

Method 3

This is based on the historic trends. Documentation can be found in the 1/3/91 Leyden L&U report.

Method 4

This method uses the Horner Plot Analysis of the pressure build up data. The stabilized pressure from the plot was 84.7 psig. The stabilized P/V relationship of 11.6 MMCF/psig was also applied to the stabilized pressure to obtain the L&U.

Nat Olowu
Reservoir Engineer
PSCo (Natural Gas Group)
August 13,1999

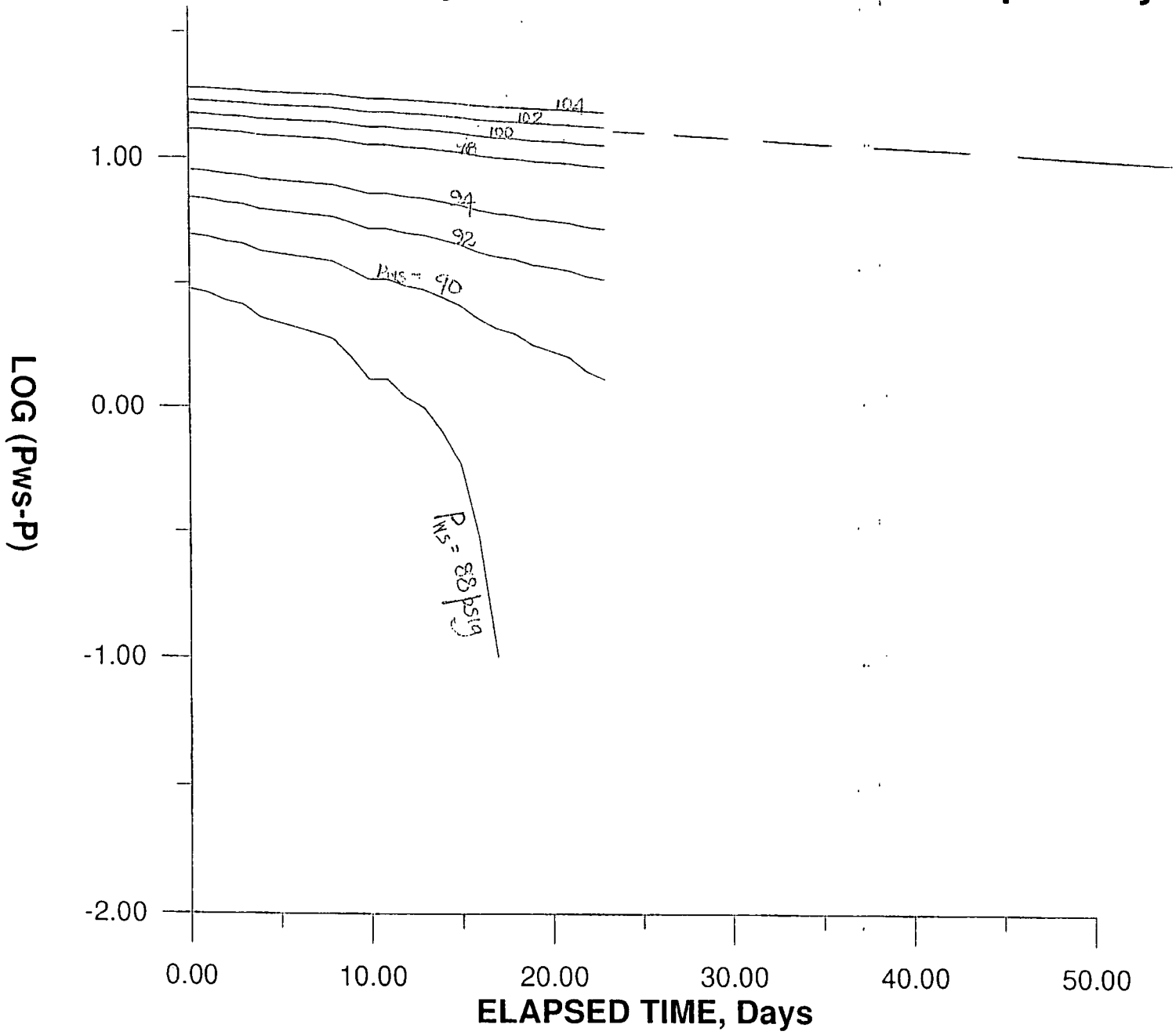
HORNER PLOT DATA

MUSKAT PLOT DATA

Date	Pressure, psig	t= 24	Dt	(t+Dt)/Dt	pws 88 log(pws-p)	pws 90 log(pws-p)	pws 92 log(pws-p)	pws 94 log(pws-p)	pws 96 log(pws-p)	pws 98 log(pws-p)	pws 100 log(pws-p)	pws 102 log(pws-p)	pws 104 log(pws-p)	pws 106 log(pws-p)
28-Jun-99	85		0		0.477121255	0.698970004	0.84509804	0.954242509	1.041392685	1.113943352	1.176091259	1.230448921	1.278753601	1.322219295
29-Jun-99	85.1		1	25	0.462397998	0.69019608	0.838849091	0.949390007	1.037426498	1.11058971	1.173186268	1.227886705	1.276461804	1.320146286
30-Jun-99	85.3		2	13	0.431363764	0.672097858	0.826074803	0.939519253	1.029383778	1.103803721	1.167317335	1.222716471	1.271841607	1.315970345
1-Jul-99	85.4		3	9	0.414973348	0.662757832	0.819543936	0.934498451	1.025305865	1.100370545	1.164352856	1.220108088	1.269512944	1.31386722
2-Jul-99	85.7		4	7	0.361727836	0.633468456	0.799340549	0.919078092	1.012837225	1.089905111	1.155336037	1.212187604	1.26245109	1.307496038
3-Jul-99	85.8		5	5.8	0.342422681	0.62324929	0.792391689	0.913813852	1.008600172	1.086359831	1.152288344	1.209515015	1.260071388	1.305351369
4-Jul-99	85.9		6	5	0.322219295	0.612783857	0.785329835	0.908485019	1.004321374	1.08278537	1.149219113	1.206825876	1.257678575	1.303196057
5-Jul-99	86		7	4.428571429	0.301029996	0.602059991	0.77815125	0.903089987	1	1.079181246	1.146128036	1.204119983	1.255272505	1.301029996
6-Jul-99	86.1		8	4	0.278753601	0.591064607	0.770852012	0.897627091	0.995635195	1.075546961	1.1430148	1.201397124	1.252853031	1.298853076
7-Jul-99	86.4		9	3.666666667	0.204119983	0.556302501	0.748188027	0.880813592	0.982271233	1.064457989	1.133538908	1.193124598	1.245512668	1.292256071
8-Jul-99	86.7		10	3.4	0.113943352	0.51851394	0.72427587	0.86332286	0.968482949	1.053078443	1.123851641	1.184691431	1.238046103	1.285557309
9-Jul-99	86.7		11	3.181818182	0.113943352	0.51851394	0.72427587	0.86332286	0.968482949	1.053078443	1.123851641	1.184691431	1.238046103	1.285557309
10-Jul-99	86.9		12	3	0.041392685	0.491361694	0.707570176	0.851258349	0.959041392	1.045322979	1.117271296	1.178976947	1.23299611	1.281033367
11-Jul-99	87		13	2.846153846	0	0.477121255	0.698970004	0.84509804	0.954242509	1.041392685	1.113943352	1.176091259	1.230448921	1.278753601
12-Jul-99	87.2		14	2.714285714	-0.09691001	0.447158031	0.681241237	0.832508913	0.944482672	1.033423755	1.10720997	1.170261715	1.225309282	1.274157849
13-Jul-99	87.4		15	2.6	-0.22184875	0.414973348	0.662757832	0.819543936	0.934498451	1.025305865	1.100370545	1.164352856	1.220108088	1.269512944
14-Jul-99	87.7		16	2.5	-0.52287875	0.361727836	0.633468456	0.799340549	0.919078092	1.012837225	1.089905111	1.155336037	1.212187604	1.26245109
15-Jul-99	87.9		17	2.411764706	-1	0.322219295	0.612783857	0.785329835	0.908485019	1.004321374	1.08278537	1.149219113	1.206825876	1.257678575
16-Jul-99	88		18	2.333333333	#NUM!	0.301029996	0.602059991	0.77815125	0.903089987	1	1.079181246	1.146128036	1.204119983	1.255272505
17-Jul-99	88.2		19	2.263157895	#NUM!	0.255272505	0.579783597	0.763427994	0.892094603	0.991226076	1.071882007	1.139879086	1.198657087	1.250420002
18-Jul-99	88.3		20	2.2	#NUM!	0.230448921	0.568201724	0.755074856	0.886490725	0.986771734	1.068185862	1.136720567	1.195899652	1.247973266
19-Jul-99	88.4		21	2.142857143	#NUM!	0.204119983	0.556302501	0.748188027	0.880813592	0.982271233	1.064457989	1.133538908	1.193124598	1.245512668
20-Jul-99	88.6		22	2.090909091	#NUM!	0.146128036	0.531478917	0.73239376	0.86923172	0.973127854	1.056904851	1.127104798	1.187520721	1.240549248
21-Jul-99	88.7		23	2.043478261	#NUM!	0.113943352	0.51851394	0.72427587	0.86332286	0.968482949	1.053078443	1.123851641	1.184691431	1.238046103

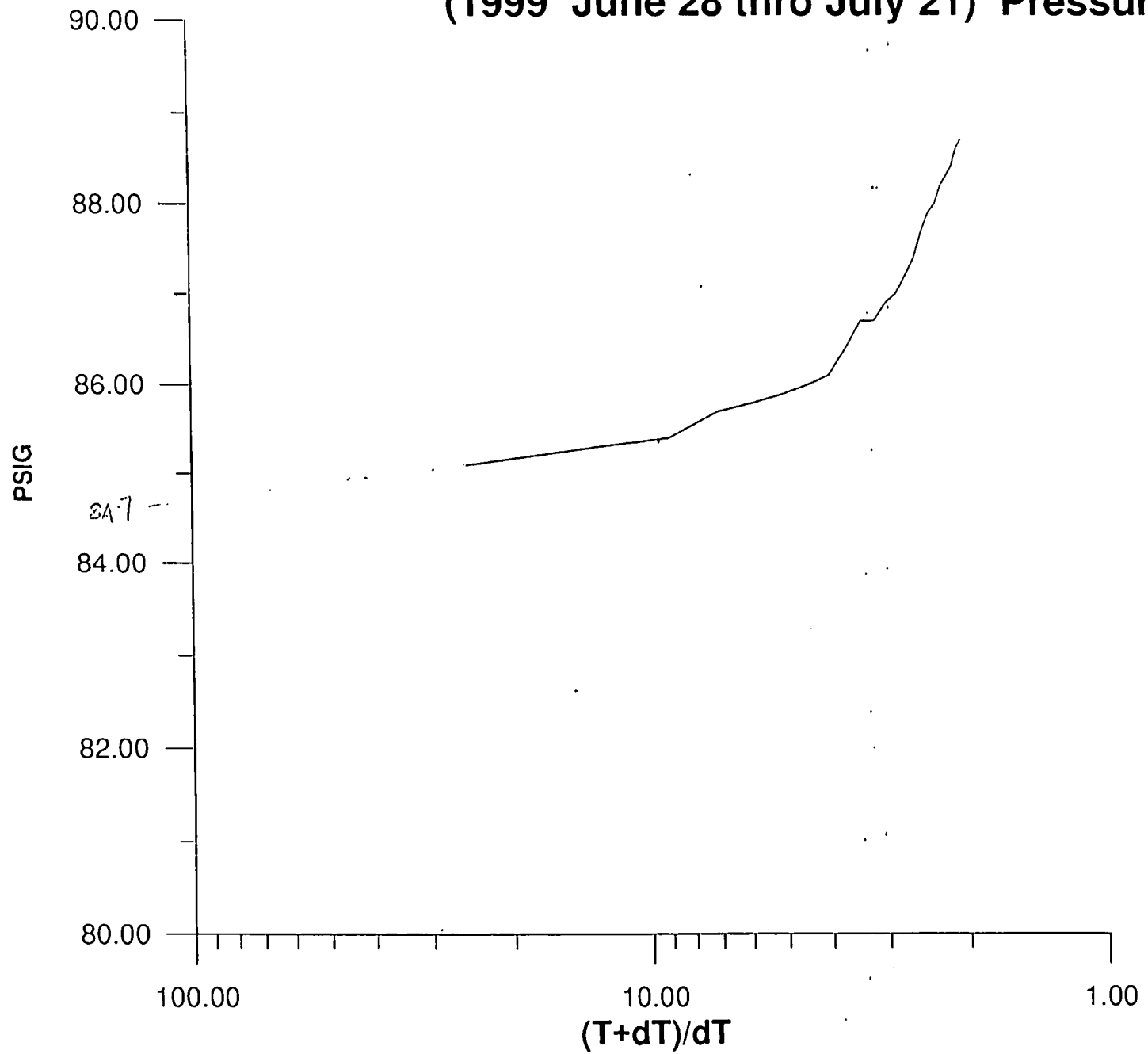
MUSKAT PLOT

Leyden 1999 Pressure Buildup Analysis



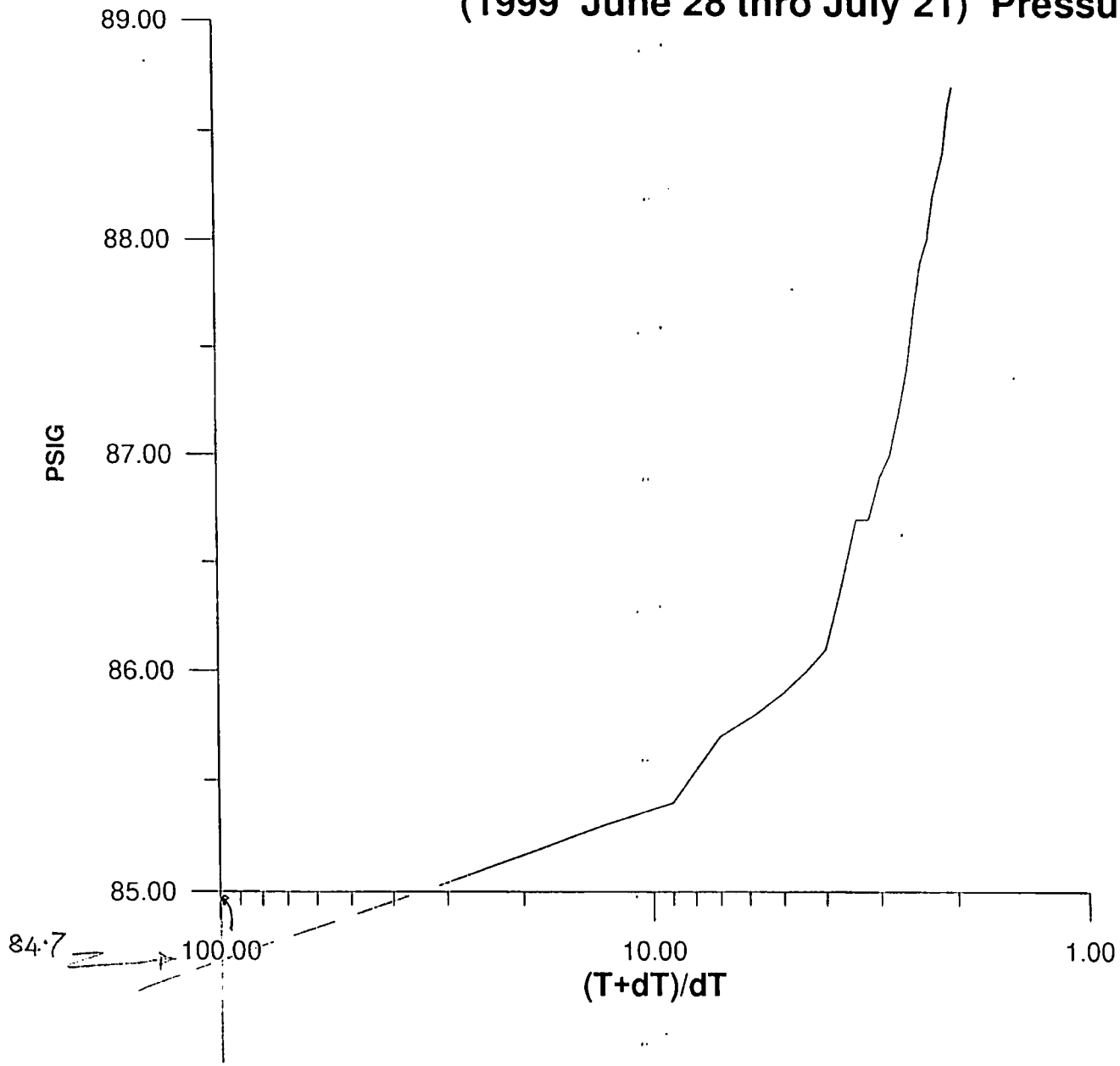
HORNER PLOT--- LEYDEN MINE DATA

(1999 June 28 thro July 21) Pressure Build-up Data



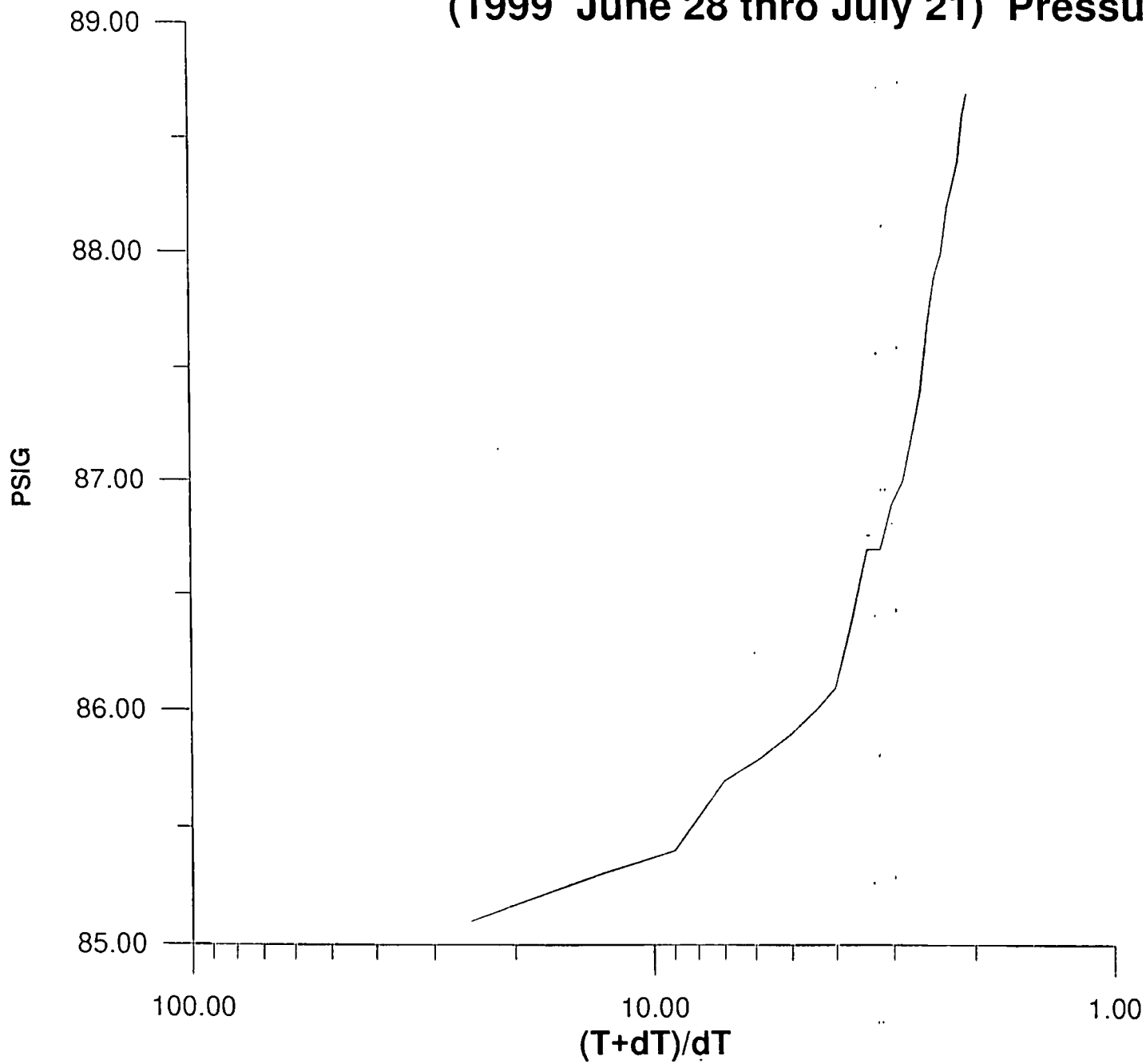
HORNER PLOT--- LEYDEN MINE DATA

(1999 June 28 thro July 21) Pressure Build-up Data



HORNER PLOT--- LEYDEN MINE DATA

(1999 June 28 thro July 21) Pressure Build-up Data



LEYDEN L&U REPORT
December 2, 2002

Summary

No recent L&U calculations have been made at Leyden since June 1999. The following calculations cover July 1999 through April 2002 (~3years).

Calculations indicate **0.281 BCF** (@ 14.65 psi) less gas in storage than is being carried on the books. Therefore, an L&U adjustment of **281,038 MCF** (@ 14.65 psi) should be applied to the book volume by subtracting same from the book volume.

Four methods were used to evaluate the L&U gas as outlined below. The four methods were averaged to come up with the L&U figure.

Current period's L&U, MCF (@14.65 psi)	*Method*	
225,973	*1*	*(Muskat Plot)*
208,995	*2*	*(Vol in - Vol out)*
300,000	*3*	*(History)*
389,185	*4*	*(Horner Plot)*

Method 1

Established an acceptable quiet period in between injection and withdrawal at the Leyden storage cavern. Performed an analysis of the Muskat plot of the pressure build-up data obtained from April 3, 2002 through April 30, 2002. The analysis indicated a stabilized cavern pressure of 132 psig. Obtained the theoretical volume of gas in the cavern by applying the stabilized P/V relationship of 11.6 MMCF/psig which still represents the current operating

condition at Leyden. The L&U was obtained by establishing the difference between the book volume and the theoretical volume. Based on the data analyzed, it shows that theoretical volume was 365,173 MCF less than book volume.

Method 2

This method compared the book volume at end of June 1999 to the book volume at end of April 2002. The method also assumes the stabilized P/V relationship of 11.6 MMCF/psig to equate the two year's end volumes to the same pressure.

Method 3

This is based on the historic trends. Documentation can be found in the 1/3/91 Leyden L&U report.

Method 4

This method uses the Horner Plot Analysis of the pressure build up data. The stabilized pressure from the plot was 117.9 psig. The stabilized P/V relationship of 11.6 MMCF/psig was also applied to the stabilized pressure to obtain the L&U.

Nat Olowu
Senior Specialty Engineer
Xcel Energy
December 2, 2002

Leyden L & U as of end April 2002.

No L & U calculations were made since July 1999

Method 2 :~ Book Volume Comparison.

$Volume_{(end\ of\ June\ 1999)} = 1{,}581{,}048$ MCF @ $P_{Stabilized} = 84.7$ psig

$Volume_{(end\ of\ April\ 2002)} = 1{,}757{,}173$ MCF @ $P_{Stabilized} = 117.9$ psig

$\therefore P_{2002} - P_{1999} = 117.9 - 84.7 = 33.2$ psig

$\therefore 33.2 \times 11.6 \times 1000 = 385{,}120$ MCF

$\therefore 1757173 - 385120 = 1372053$ (to bring 2002 vol to the same 1999 pressure base)

But $V_{1999} = 1581048$

$\therefore L \& U = 1{,}581{,}048 - 1{,}372{,}053$

$= \boxed{208{,}995 \text{ MCF}}$ (Loss) $\approx 70{,}000$ MCF/yr.

Method 1 :— Muskat Analysis

$P_{WS} = 132$ psig

$\therefore L \& U = V_{book} - V_{theoretical}$

$= 1757173 - (11.6 * 120 * 1000)$

$= 1757173 - 1531000$

$\therefore$ in 3 yrs $= 225972$ MCF $\approx 75{,}300$ MCF/yr.

Method 3: — Historic Trend Analysis

Based on historic trend, 100,000 MCF/yr

∴ in 3 yrs,

$\boxed{300{,}000 \text{ MCF}}$

Method 4: Horner Plot

Horner plot analysis indicated a $P_s = 117.93$ psig.

$$L \,\varepsilon\, U = V_{book} - V_{theoretical}$$

$$V_{book} = 1{,}757{,}173 \text{ MCF @ } 14.65 \text{ psig}$$

→ from Leyden's Summary of Gas Delivered Report.

$$V_{theoretical} = 11.6 \frac{\text{mmcf}}{\text{psig}} * P_{stabilized} * 1000$$

$$= 11.6 * 117.93 * 1000 = 1{,}367{,}988 \text{ mcf}$$

$$\therefore L \,\varepsilon\, U = 1757173 - 1367988$$

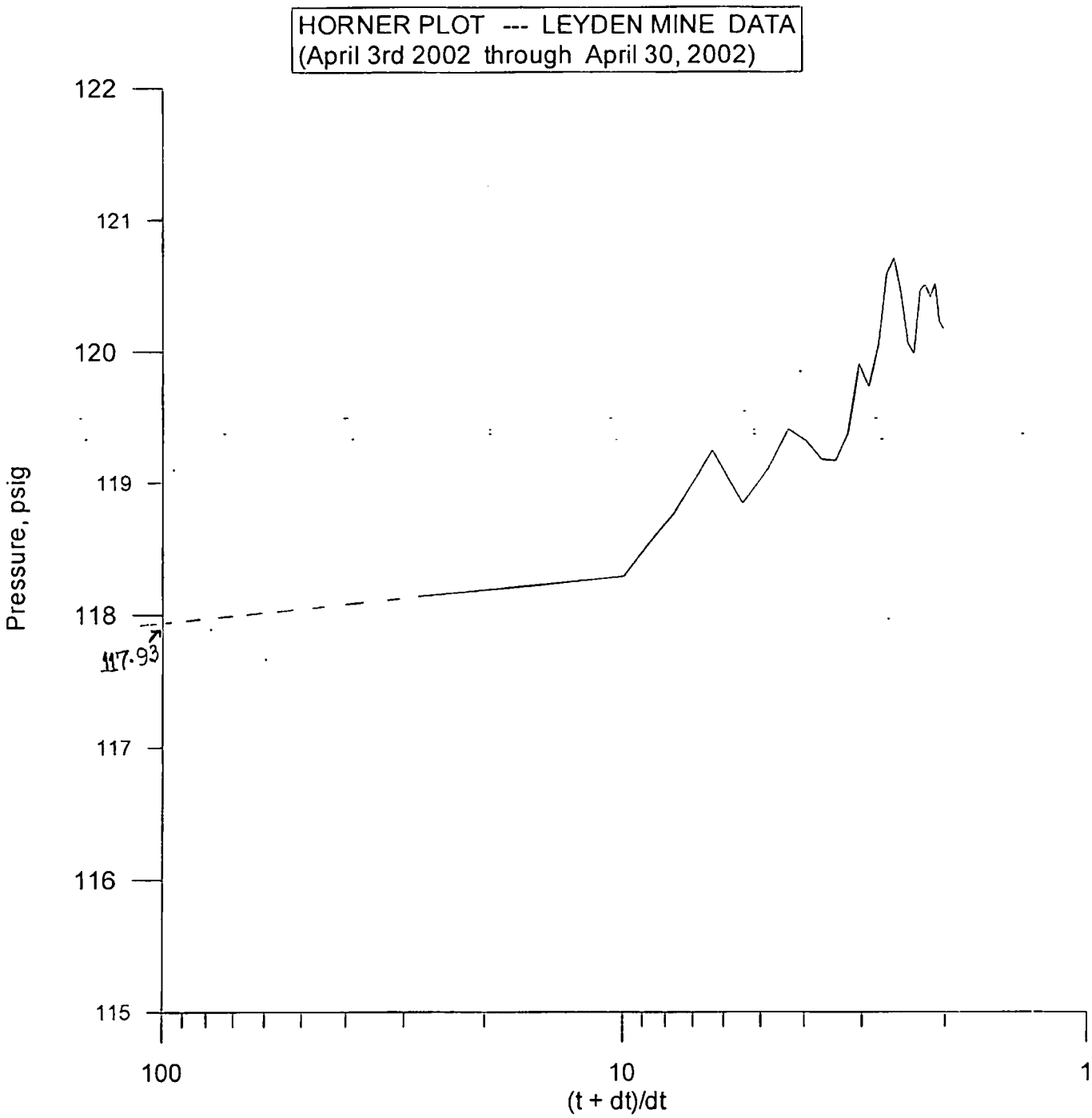
$$= \boxed{389185^{*} \text{ mcf}} \approx 129{,}700 \text{ MCF/yr}$$

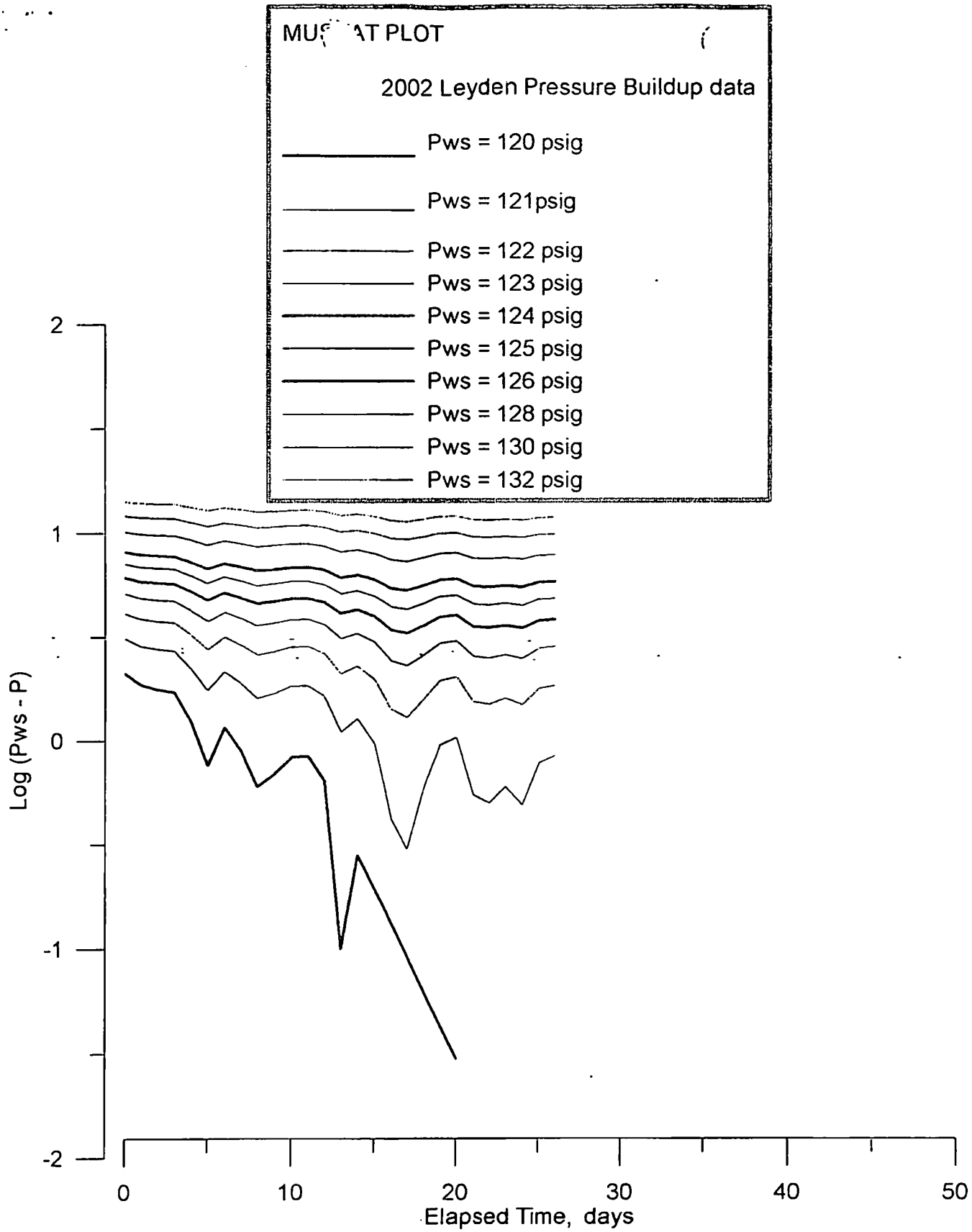
* 3 yr Calculator

1999 - 2000

2000 - 2001

2001 - 2002


HORNER PLOT --- LEYDEN MINE DATA
(April 3rd 2002 through April 30, 2002)
122
121
120
119
118
117.93
117
116
115
Pressure, psig
100
10
1
(t + dt)/dt


MUSKAT PLOT
2002 Leyden Pressure Buildup data
Pws = 120 psig
Pws = 121psig
Pws = 122 psig
Pws = 123 psig
Pws = 124 psig
Pws = 125 psig
Pws = 126 psig
Pws = 128 psig
Pws = 130 psig
Pws = 132 psig
Log (Pws - P)
2
1
0
-1
-2
0
10
20
30
40
50
Elapsed Time, days

HORNER PLOT DATA

MUSKAT PLOT DATA

Date	Pressure, psig	t= 27	Dt	(t+Dt)/Dt	G pws 120 log(pws-p)	I pws 121 log(pws-p)	K pws 122 log(pws-p)	M pws 123 log(pws-p)	O pws 124 log(pws-p)	Q pws 125 log(pws-p)	S pws 126 log(pws-p)	U pws 128 log(pws-p)	W pws 130 log(pws-p)	Y pws 132 log(pws-p)
3-Apr-02	117.89		0		0.324282455	0.492760389	0.613841822	0.7084209	0.78604121	0.851869601	0.909020854	1.004751156	1.083144143	1.149527014
4-Apr-02	118.14		1	28	0.269512944	0.456366033	0.586587305	0.686636269	0.767897616	0.836324126	0.895422546	0.993576915	1.074084689	1.14176323
5-Apr-02	118.23		2	14.5	0.247973266	0.442479769	0.57634135	0.678518379	0.761175813	0.830588669	0.890421019	0.989894564	1.070776463	1.13893394
6-Apr-02	118.29		3	10	0.23299611	0.432969291	0.56937391	0.673020907	0.756636108	0.82672252	0.887054378	0.98721923	1.068556895	1.137037455
7-Apr-02	118.76		4	7.75	0.093421685	0.350248018	0.51054501	0.627365857	0.719331287	0.79518459	0.859738566	0.965671971	1.050766311	1.121887985
8-Apr-02	119.24		5	6.4	-0.11918641	0.245512668	0.440909082	0.575187845	0.677606953	0.760422483	0.829946696	0.942504106	1.031812271	1.105850674
9-Apr-02	118.84		6	5.5	0.064457989	0.334453751	0.499687083	0.619093331	0.712649702	0.789580712	0.854913022	0.961895474	1.047664195	1.119255869
10-Apr-02	119.1		7	4.857142857	-0.04575749	0.278753601	0.462397998	0.591064607	0.69019608	0.770852012	0.838849091	0.949390007	1.037426498	1.11058971
11-Apr-02	119.4		8	4.375	-0.22184875	0.204119983	0.414973348	0.556302501	0.662757832	0.748188027	0.819543936	0.934498451	1.025305865	1.100370545
12-Apr-02	119.31		9	4	-0.16115091	0.237886705	0.42975228	0.567026366	0.671172843	0.755113266	0.825426118	0.939019776	1.028977705	1.103461622
13-Apr-02	119.17		10	3.7	-0.08092191	0.26245109	0.451786436	0.583198774	0.683947131	0.765668555	0.834420704	0.945960704	1.034628457	1.108226656
14-Apr-02	119.16		11	3.454545455	-0.07572071	0.264817823	0.45331834	0.584331224	0.684845362	0.766412847	0.835056102	0.946452265	1.035029282	1.108565024
15-Apr-02	119.36		12	3.25	-0.19382003	0.214843848	0.421603927	0.561101384	0.666517981	0.751279104	0.822168079	0.936513742	1.026941628	1.101747074
16-Apr-02	119.9		13	3.076923077	-1	0.041392685	0.322219795	0.491361694	0.612783857	0.707570176	0.785329835	0.908485019	1.004321374	1.08278537
17-Apr-02	119.72		14	2.928571429	-0.55284197	0.10720997	0.357934847	0.515873844	0.631443769	0.722633923	0.797959644	0.918030337	1.011993115	1.089198367
18-Apr-02	120.03		15	2.8	#NUM!	-0.01322827	0.294466226	0.472756449	0.598790507	0.696356389	0.775974331	0.901458321	0.998695158	1.07809415
19-Apr-02	120.58		16	2.6875	#NUM!	-0.37675071	0.152288344	0.303015366	0.534026106	0.645422269	0.733999287	0.870403905	0.974050903	1.057666104
20-Apr-02	120.7		17	2.588235294	#NUM!	-0.52287875	0.113943352	0.361727836	0.51851394	0.633468456	0.72427587	0.86332286	0.968482949	1.053078443
21-Apr-02	120.42		18	2.5	#NUM!	-0.21657201	0.198657087	0.411619706	0.553883027	0.660865478	0.746634199	0.879669206	0.981365509	1.063708559
22-Apr-02	120.05		19	2.421052632	#NUM!	-0.02227639	0.290034611	0.469822016	0.596597096	0.694605199	0.774516966	0.900367129	0.997823081	1.077367905
23-Apr-02	119.97		20	2.35	-1.52287875	0.012837225	0.307496038	0.481442629	0.605305046	0.701567985	0.780317312	0.904715545	1.001300933	1.080265627
24-Apr-02	120.45		21	2.285714286	#NUM!	-0.23963731	0.190331698	0.40654018	0.550228353	0.658011397	0.744292983	0.877946952	0.980003372	1.062581984
25-Apr-02	120.5		22	2.227272727	#NUM!	-0.30103	0.176091259	0.397940009	0.544068044	0.653212514	0.740362689	0.875061263	0.977723605	1.06069784
26-Apr-02	120.4		23	2.173913043	#NUM!	-0.22184875	0.204119983	0.414973348	0.556302501	0.662757832	0.748188027	0.880813592	0.982271233	1.064457989
27-Apr-02	120.51		24	2.125	#NUM!	-0.30980392	0.173186268	0.396199347	0.542825427	0.652246341	0.739572344	0.874481810	0.977266212	1.060320029
28-Apr-02	120.22		25	2.08	#NUM!	-0.1079054	0.250420002	0.444044796	0.5774918	0.679427897	0.761927038	0.890979597	0.990338855	1.07114529
29-Apr-02	120.16		26	2.038461538	#NUM!	-0.07572071	0.264817823	0.45331834	0.584331224	0.604045362	0.766412847	0.894316063	0.992995098	1.073351702