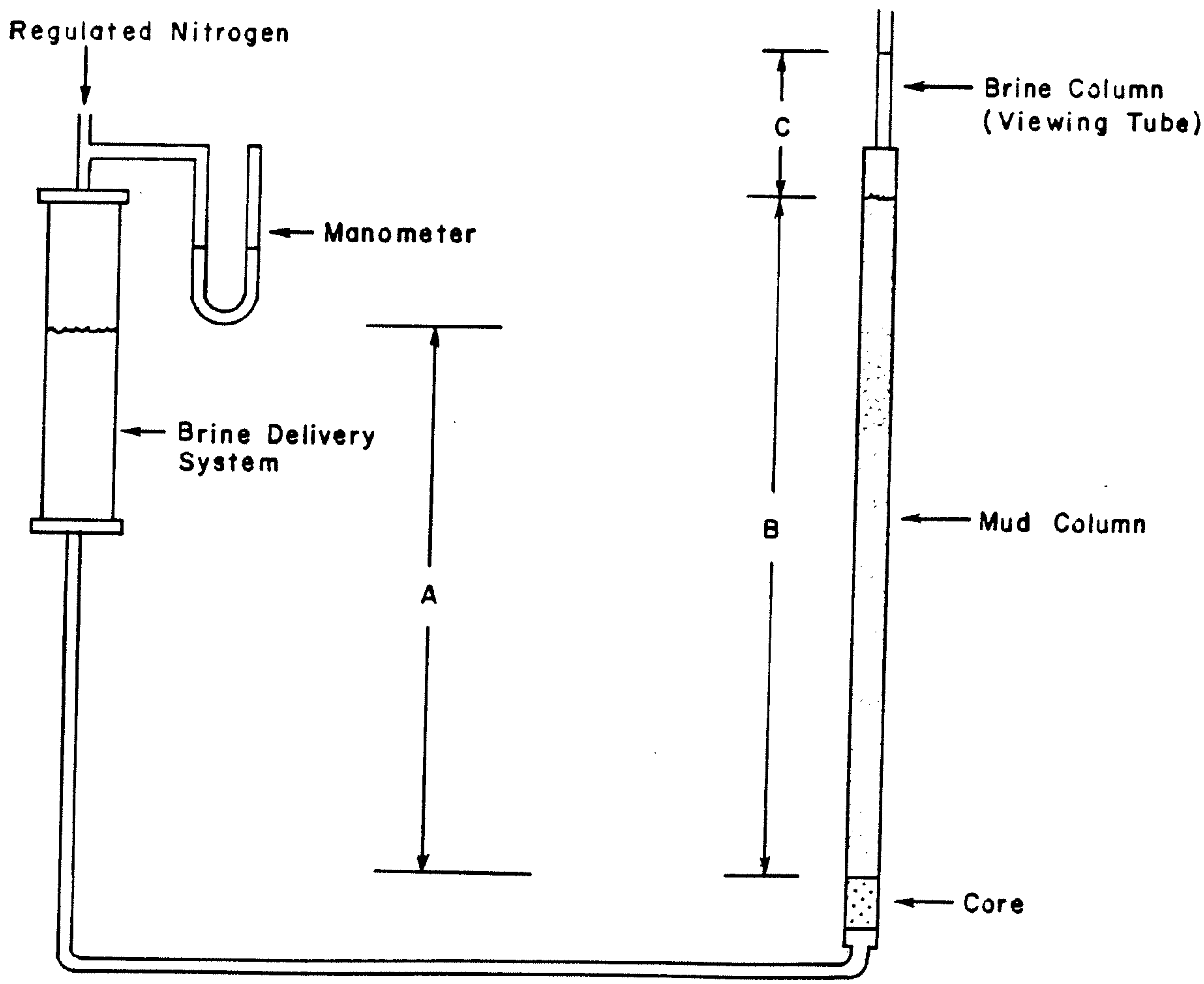

FIGURE I. General Description of Equipment

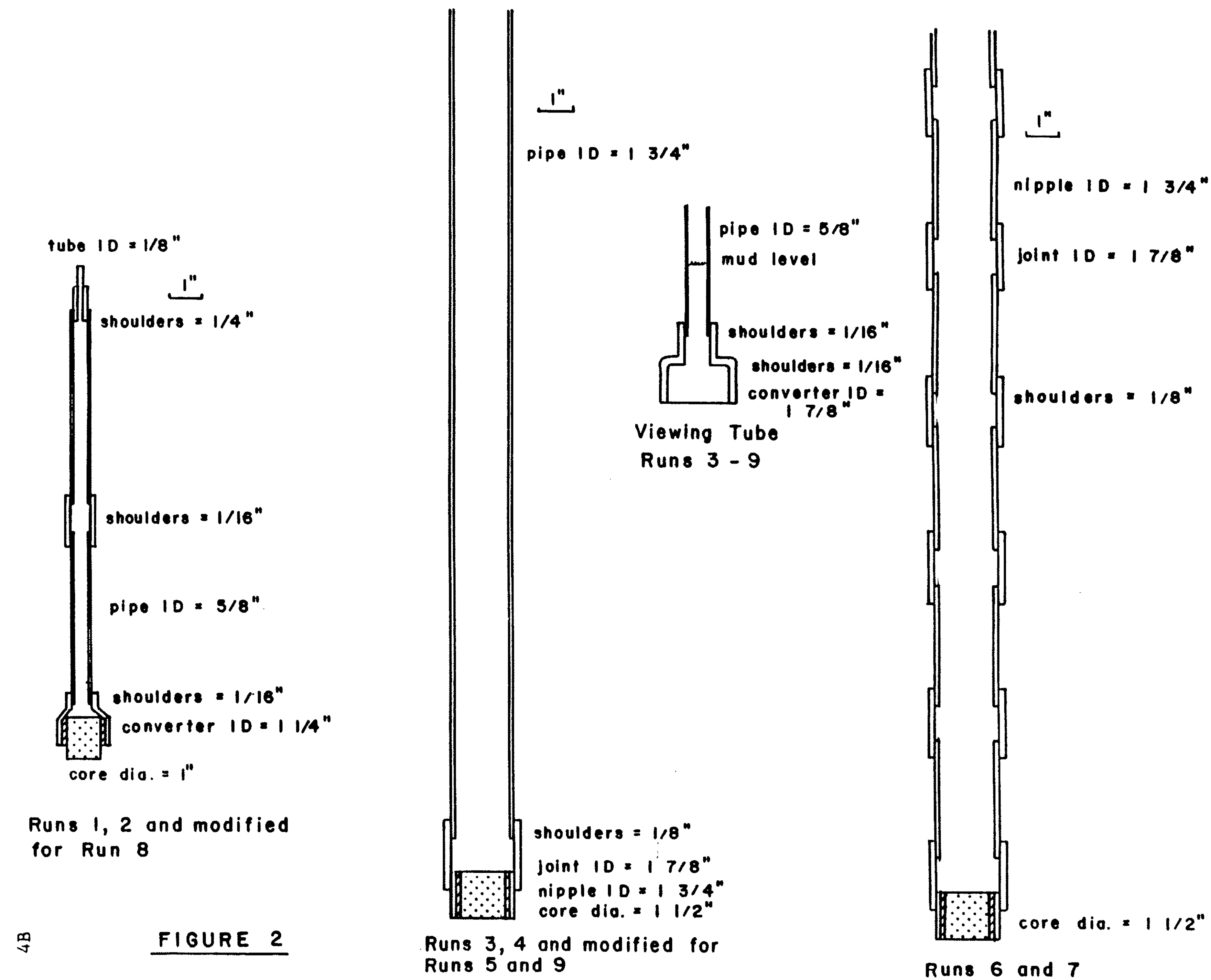
tube ID = 1/8"
1"
shoulders = 1/4"
shoulders = 1/16"
pipe ID = 5/8"
shoulders = 1/16"
converter ID = 1 1/4"
core dia. = 1"
Runs 1, 2 and modified for Run 8
1"
pipe ID = 1 3/4"
shoulders = 1/8"
joint ID = 1 7/8"
nipple ID = 1 3/4"
core dia. = 1 1/2"
Runs 3, 4 and modified for Runs 5 and 9
pipe ID = 5/8"
mud level
shoulders = 1/16"
shoulders = 1/16"
converter ID = 1 7/8"
Viewing Tube
Runs 3 - 9
1"
nipple ID = 1 3/4"
joint ID = 1 7/8"
shoulders = 1/8"
core dia. = 1 1/2"
Runs 6 and 7

FIGURE 2

Calculations and Results

The apparent gel strength, G', of the mud in column is defined using the force balance on the mud column formulated as for a uniform cylindrical column of the same vertical height, B, as the actual column and the same diameter as the inside diameter of the pipe used in the experiment. Note that this computation explicitly excludes allowances for non-uniformity in diameter at nipple joints, etc.

The pressure of brine at the face of the core plug against the mud column is given by (gauge value)

(1) $$P_c = P_m + \rho_b g A$$

where P_m is manometer reading of pressure on brine in the reservoir. The hydrostatic pressure of the mud column and brine on top of the mud is (gauge value)

(2) $$P_h = \rho_m g B + \rho_B g C$$

Then the force balance criterion for on-set of movement of the mud column by shearing of the gel at the cylindrical wall of the column is

(3) $$\pi r_p^2 (P_c - P_h) \geq 2\pi r_p A G'$$

where G' is the apparent gel strength. Thus we calculate G' from the experimental data using

(4) $$G' = \frac{r_p}{2A}(P_c - P_h)$$

The calculated apparent gel strength G' was compared to the Fann gel strength G as a ratio R, where

$$R = G' / G$$

A summary of results is given in Table 1.

Run #	1	2	3	4	5	6	7	8	9
R	5.11	5.05	1.68	0.0	2.77	3.83	3.61	5.76	1.99

TABLE 1. R Values For All Runs

Discussion of Results

The results of Runs 1 and 2 indicate non-uniform geometry profoundly influences the apparent gel strength. Apparently the relative size of diameter constrictions in relation to the cylinder in which the mud stands produced the larger increases in apparent gel strength observed in Runs 1 and 2 as compared to other runs.

In Run 3, the one shoulder in the large pipe produced, approximately, a 68% increase in apparent gel strength over the measured Fann measured value. In Runs 6 and 7, it would be reasonable to assume that the increase in apparent gel strength should be about six times the 68% value observed in Run 3 since 6 shoulders are present. This would produce an R value of 1 + (0.68 * 6) or 5.08 which is larger than the apparent values actually observed in Runs 6 and 7.

Run 5 provides further evidence that geometric irregularities produce increases in apparent gel strength. With the constriction on the top of the pipe (along with the shoulder of Run 3), the apparent gel is increased by nearly three-fold over the Fann measured value.

Run 4 demonstrates that when the mud column is detached from the pipe structure by an oily film, either the brine flows up the pipe around the mud column or the column provides little or no gel strength since it is, in effect, not bonded to the pipe.

Run 8 was to test whether the very large value of G observed in Runs 1 and 2 was due in part to the fact that mud extended into the small diameter viewing tube at the top of the 5/8" ID pipe. Since the observed value of R in Run 8 was even larger, this is not the case.

The objective in Run 9 was to determine whether a tube free of <u>any</u> non-uniformities in diameter of the mud column would yield a G value comparable to that measured in the Fann viscometer. Since the apparent G value in this case was almost double the Fann determined value, this is not the case. Thus, there are <u>other factors involved besides non-uniform diameter of hole</u> which cause the high apparent G values.

We can <u>speculate</u> on the implications of the data obtained in the above experiments:

(1) There is clearly an increase in the contribution of mud gel strength to the threshold pressure for brine entry arising from constrictions or non-uniformities in pipe (simulated borehole) diameter. A factor of about 2 - 5 was observed.

(2) There is another contribution to threshold brine entry pressure not associated with hole geometry. We speculate that this may be due to an "interfacial tension" effect as brine tries to enter gelled mud from the small pores in the core plug.

This interfacial tension effect would contribute a ΔP to the threshold entry pressure as

$$\Delta P = \frac{2\gamma}{r}$$

where r is the radius of the hemispherical bubble of brine entering the mud while γ is an effective interfacial tension. The value of r should be the average of the largest pores open on the core plug face. Thus for the same brine and mud we could see a difference in ΔP for the two core plugs used in our experiments. Also it is possible that upon standing with mud pressure on the core plug, some particulates could enter the larger pores of the core plug so r might be reduced in later experiments using the same core plug. This might account for the results in Runs 8 and 9.

Future Research

Clearly, we have not answered all questions concerning the criteria for brine entry into a mud-filled abandoned well but we have shown that the critical pressure for brine entry is given by an equation of the form (P_{crit} in psi)

$$P_{crit} = \Delta P + 0.052\ \rho_{mud} d + 3.33 \times 10^{-3}\ \frac{G'd}{D}$$

where

ρ_{mud} = mud weight (lb/gal)

G' = apparent gel strength of mud (lb/100 ft^2)

d = total depth to disposal aquifer (ft)

D = mean diameter of abandoned well (inches)

ΔP = possible brine-mud interfacial tension contribution (psi)

In order to fully quantify this equation, more experimentation is required. We propose doing experiments using larger diameter simulated boreholes with a variety of well-defined non-uniformities in diameter, with fluid entry through rock circumferentially as in a real well. We also will design an experiment to directly measure the contribution to P_{crit} defined above as ΔP.

In closing this preliminary report, we note the significance of the results thus far obtained. For a borehole of 5000 ft. depth filled with mud of minimal weight (P_{mud} = 8.16 lb/gal) and minimal gel strength (G' = 50 lb/100 ft^2) we compute for a 9 inch diameter hole,

$$P_{crit} = \Delta P + 2236 + 8.34$$

but if, as indicated by our data, the last term due to gel is increased four-fold by hole irregularities, this is

$$P_{crit} = \Delta P + 2236 + 33.37$$

Now, since normal static aquifer pressure at 5000 ft. is about .437 x 5000 = 2185, we see that mud weight alone gives a tolerable pressure increase in the aquifer of 2236 - 2185 = 51 psi and the gel adds more than half this amount to the critical entry pressure. If this were a typical salt mud, G' would be five times greater and the gel contribution, with hole irregularities, would be about 167 psi or more than three times the mud weight contribution.

Data and Results

Run 1

	in.	cm.
Core Radius	0.5	1.27
Pipe Radius	0.3125	0.7438
Length A	24.409	62.0
Length B	11.5	29.2
Length C	4.53	11.5

	psi	in. Hg
Pm	3.0	
Ps	+0.8937	+ 1.8
Ph	0.5966	1.2
Pc	3.89	7.9

	psi	lbs/100 sq. ft (12 hours)
G		125.0
G'	0.04475	644.0

G'/G = R = 5.11

Run 2

	in.	cm.
Core Radius	0.5	1.27
Pipe Radius	0.3125	0.7438
Length A	14.6	37.0
Length B	12.0	30.5
Length C	3.94	10.0

	psi	in. Hg
Pm	7.859	16.0
Ps	-0.533	-1.1
Ph	0.5966	1.2
Pc	7.326	14.9

	psi	lbs/100 sq. ft (12 hours)
G		250.0
G'	0.08763	1262.0

G'/G = R = 5.05

Run 3

	in.	cm.
Core Radius	0.75	1.91
Pipe Radius	0.8125	2.06
Length A	11.4	29.0
Length B	26.0	66.0
Length C	6.5	16.5

	psi	in. Hg
Pm	3.438	7.0
Ps	-0.418	-0.851
Ph	1.218	2.48
Pc	3.02	6.15

	psi	lbs/100 sq. ft (12 hours)
G		250.0
G'	0.02816	405.0

G'/G = R = 1.68

Run 5

	in.	cm.	
Core Radius	0.75	1.91	
Pipe Radius	0.8125	2.06	small pipe
Length A	12.2	31.0	radius =
Length B	33.9	86.0	0.3125 inch
Length C	3.54	9.0	(see sketch)

	psi	in. Hg
Pm	4.91	10.0
Ps	-0.4476	-0.91
Ph	1.4059	2.86
Pc	4.4643	9.1

	psi	lbs/100 sq. ft (12 hours)
G		210.0
G'	0.04042	582.0

G'/G = R = 2.77

Run 6

	in.	cm.
Core Radius	0.75	1.91
Pipe Radius	0.8125	2.06
Length A	13.8	35.0
Length B	26.0	66.0
Length C	6.3	16.0

	psi	in. Hg
Pm	3.93	8.0
Ps	-0.5044	-1.28
Ph	1.21	2.46
Pc	3.425	6.97

	psi	lbs/100 sq. ft (12 hours)
G		130.0
G'	0.03460	498.0

G'/G = R = 3.83

Run 7

	in.	cm.
Core Radius	0.75	1.91
Pipe Radius	0.8125	2.06
Length A	13.8	35.0
Length B	26.0	66.0
Length C	6.3	16.0

	psi	in. Hg
Pm	4.13	8.4
Ps	-0.5044	-1.28
Ph	1.21	2.46
Pc	3.6214	7.373

	psi	lbs/100 sq. ft (12 hours)
G		150.0
G'	0.03768	542.0

G'/G = R = 3.61

Run 8 Small Pipe - no top constriction

	in.	cm.
Core Radius	0.5	1.27
Pipe Radius	0.3125	0.7938
Length A	21.65	55.0
Length B	9.84	25.0
Length C	3.05	7.75

	psi	in. Hg
Pm	6.1886	12.6
Ps	-0.7925	-1.6135
Ph	0.4827	0.9828
Pc	5.396	10.98

	psi	lbs/100 sq. ft (12 hours)
G		195.0
G'	0.078	1123.0

G'/G = R = 5.76

Run 9

	in.	cm.
Core Radius	0.75	1.91
Pipe Radius	0.75	1.91
Length A	20.866	53.0
Length B	22.441	57.0
Length C	5.906	15.0

	psi	in. Hg
Pm	3.438	7
Ps	-0.7637	-1.555
Ph	1.062	2.162
Pc	2.674	5.444

	psi	lbs/100 sq. ft (12 hours)
G		195.0
G'	0.02694	388.0

G'/G = R = 1.99

FLUID PROPERTIES

	Density (g/cc)	lb/gal	psi/ft	psi/in	psi/cm
Salt	1.0147	8.45	0.4394	0.0366	0.01441
Mud (Run 1)	1.0396	8.65	0.4498	0.0375	0.01476
Mud (Runs 2-7)	1.0444	8.70	0.4520	0.0377	0.01484

Mud Composition:
Run 1: 20 ppb bentonite, 3 ppb salt
Runs 2-9: 30 ppb bentonite

NOMENCLATURE

A,B,C	Vertical dimensions of experimental set-up
r_c	Core Radius
r_p	Pipe Radius
h_p	Pipe Length
Pm	Manometer pressure
Ps	Hydrostatic pressure of brine reservoir
Ph	Hydrostatic head of mud/brine over core
Pc	Pressure at core face

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APPENDIX C

CASE STUDIES

FOR ALL CASES

DEPTH = 5000 FT.

INITIAL PRESSURE = P_O = 2200 PSI

CASE I

EFFECTS OF SEALING FAULT BOUNDARIES AND WELL LOCATIONS

Group 1, Only boundaries are varied

Group 2, Same as Group 1 but with different injection well location

Group 3, Same as Group 1 and 2 but with yet another injection well location

Group 4, Same as Group 2 but with different K and h

Group 5, Same as Group 1 but with K and h of Group 4

Group 6, Complete pressure histories for all abandoned wells for run Case I, Group 1, No. 2

CASE I GROUP 1

PROPERTIES OF THE DISPOSAL ZONE

COMPRESSIBILITY =	0.500E-05	1/PSI
PERMEABILITY =	300.000	MD
VISCOSITY =	1.000	CP
THICKNESS =	50.0	FT
POROSITY =	0.200	

PROPERTIES OF ABANDONED HOLES

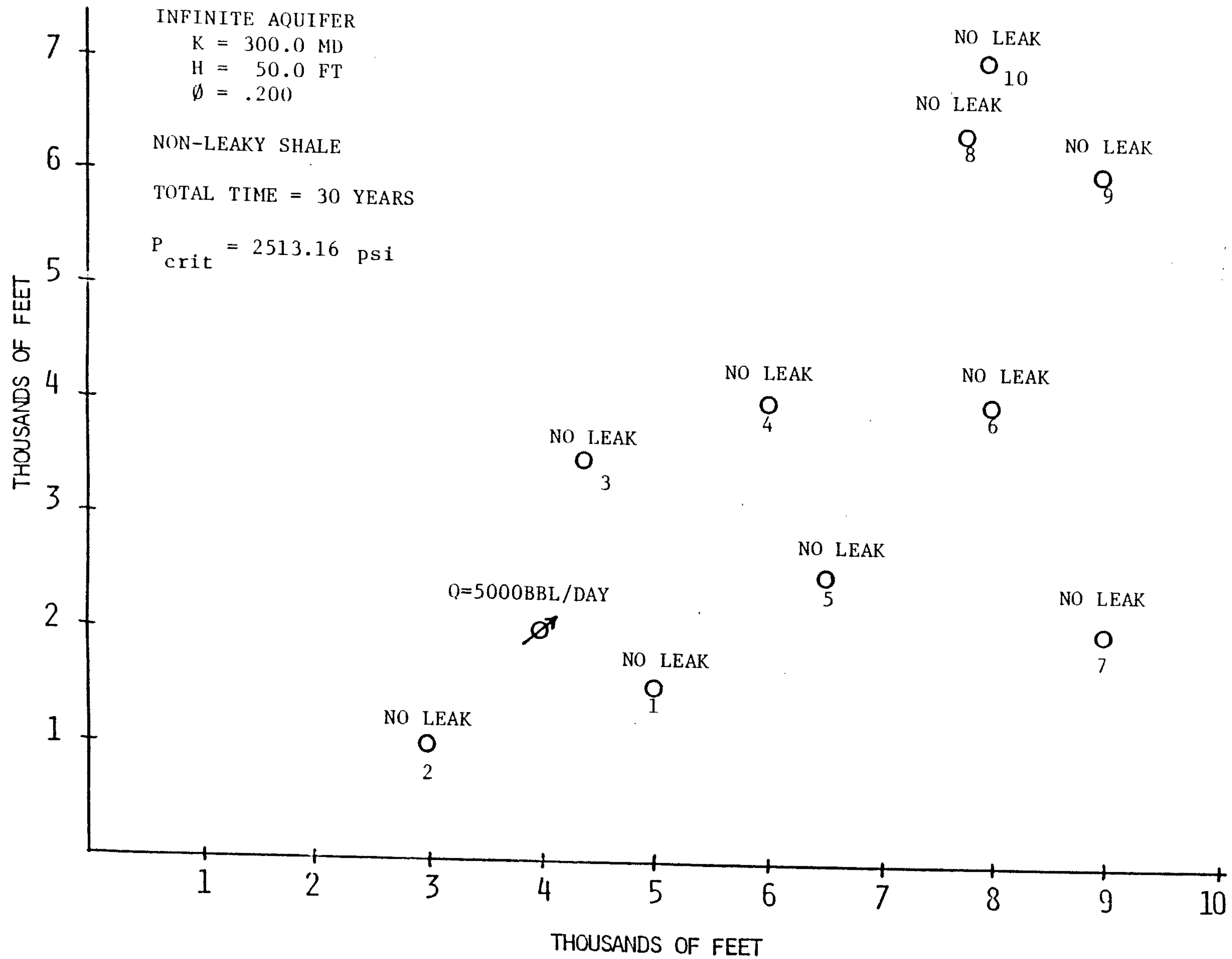
ABAN WELL	WELL DIAM IN	DEPTH TO DISP ZONE FT	DEPTH TO H2O ZONE FT	MUD DENSITY LB/GAL	GEL STRENGTH LB/100FT2	CRITIC PRESSU PSI
1	9.6	5000.00	600.0	9.000	100.00	2513.16
2	9.6	5000.00	600.0	9.000	100.00	2513.16
3	9.6	5000.00	600.0	9.000	100.00	2513.16
4	9.6	5000.00	600.0	9.000	100.00	2513.16
5	9.6	5000.00	600.0	9.000	100.00	2513.16
6	9.6	5000.00	600.0	9.000	100.00	2513.16
7	9.6	5000.00	600.0	9.000	100.00	2513.16
8	9.6	5000.00	600.0	9.000	100.00	2513.16
9	9.6	5000.00	600.0	9.000	100.00	2513.16
10	9.6	5000.00	600.0	9.000	100.00	2513.16

COORDINATES OF THE ABANDONED WELLS

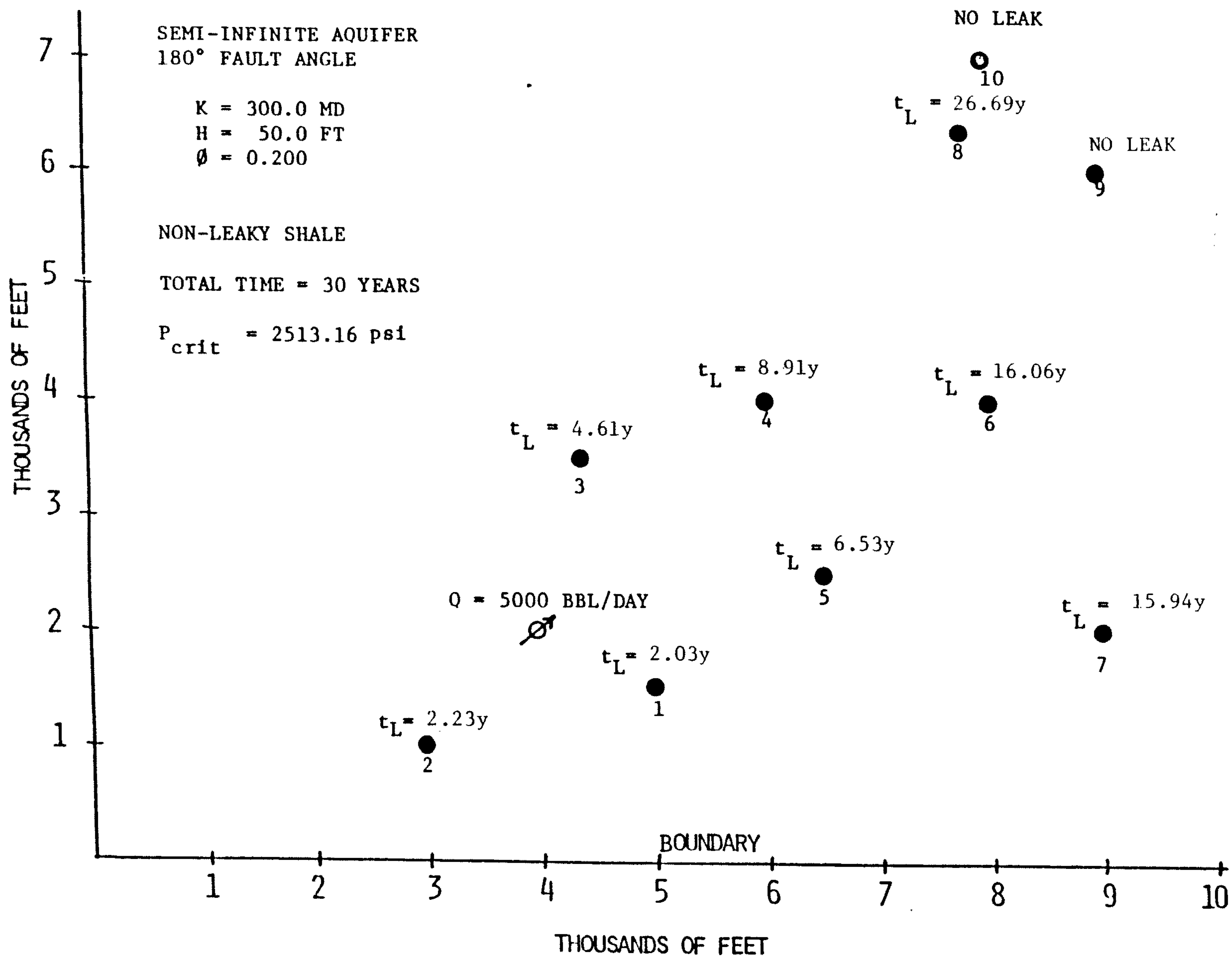
WELL #	X FT.	Y FT.
1	5000.000	1500.000
2	3000.000	1000.000
3	4400.000	3600.000
4	6000.000	4000.000
5	6500.000	2500.000
6	8000.000	4000.000
7	9000.000	2000.000
8	7800.000	6400.000
9	9000.000	6000.000
10	8000.000	7000.000

COORDINATES OF THE INJECTION WELL

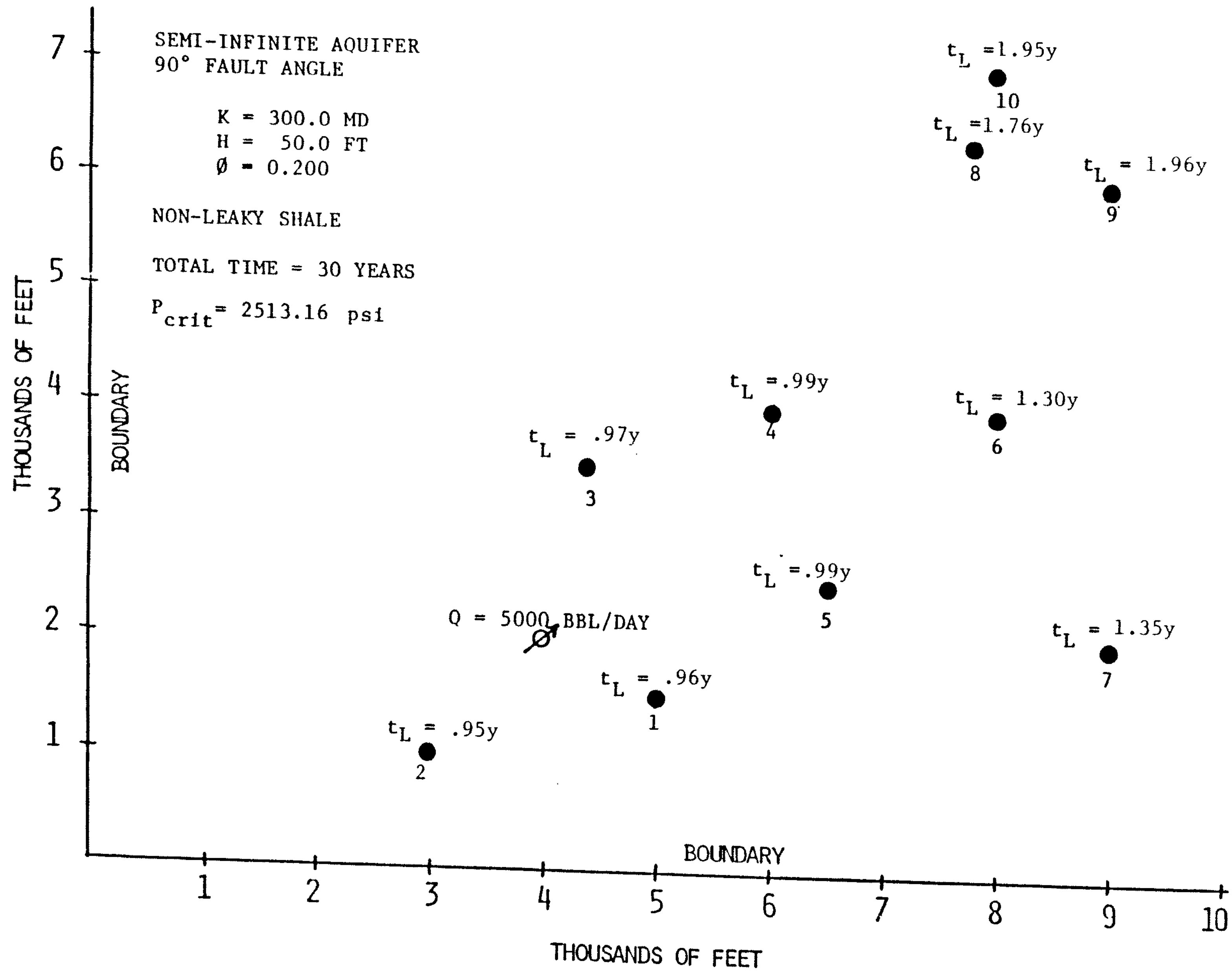
X= 4000.000 Y= 2000.000 FT.
INJECTION RATE =5000. BBL/DAY



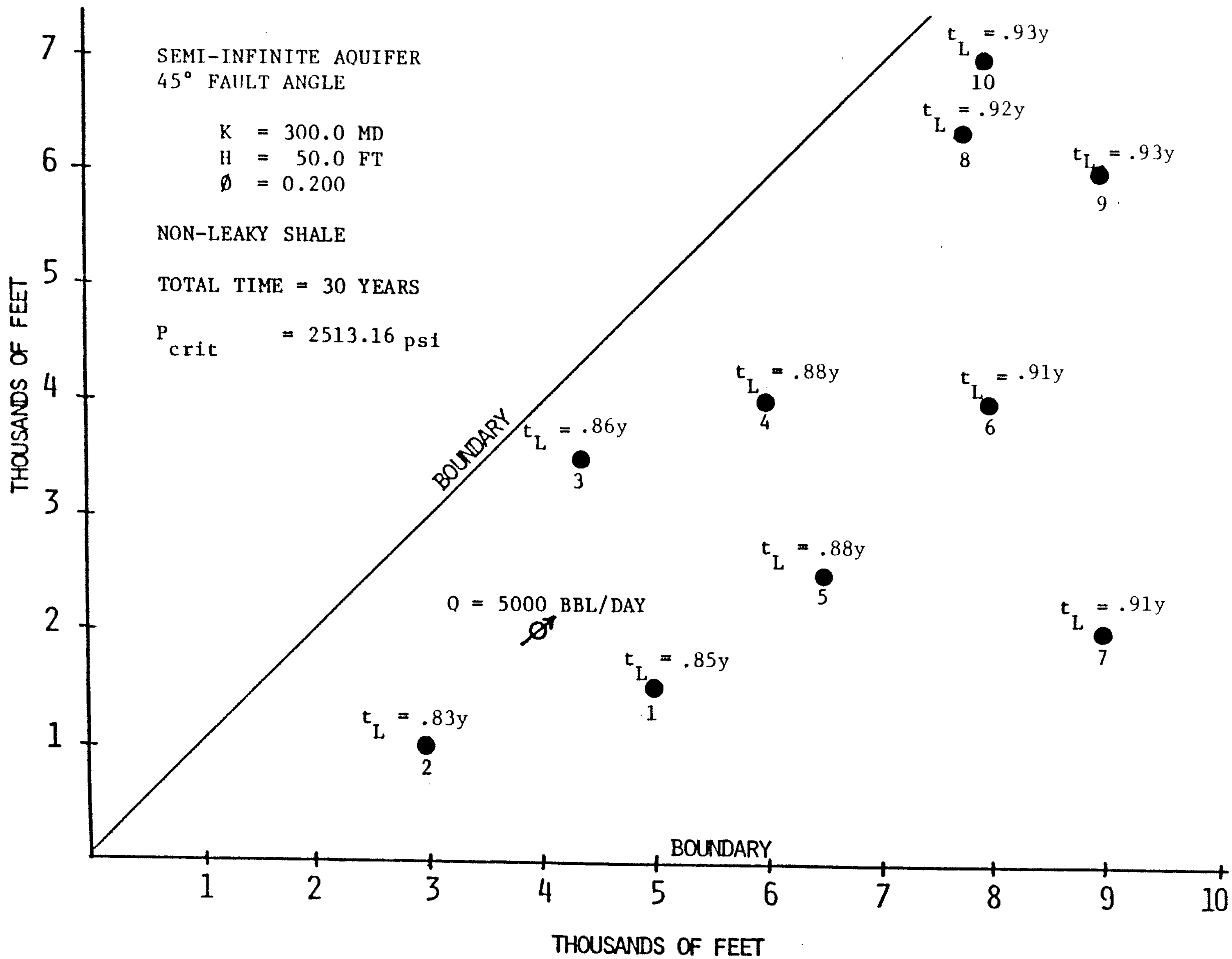
CASE I, GROUP 1, NO. 1



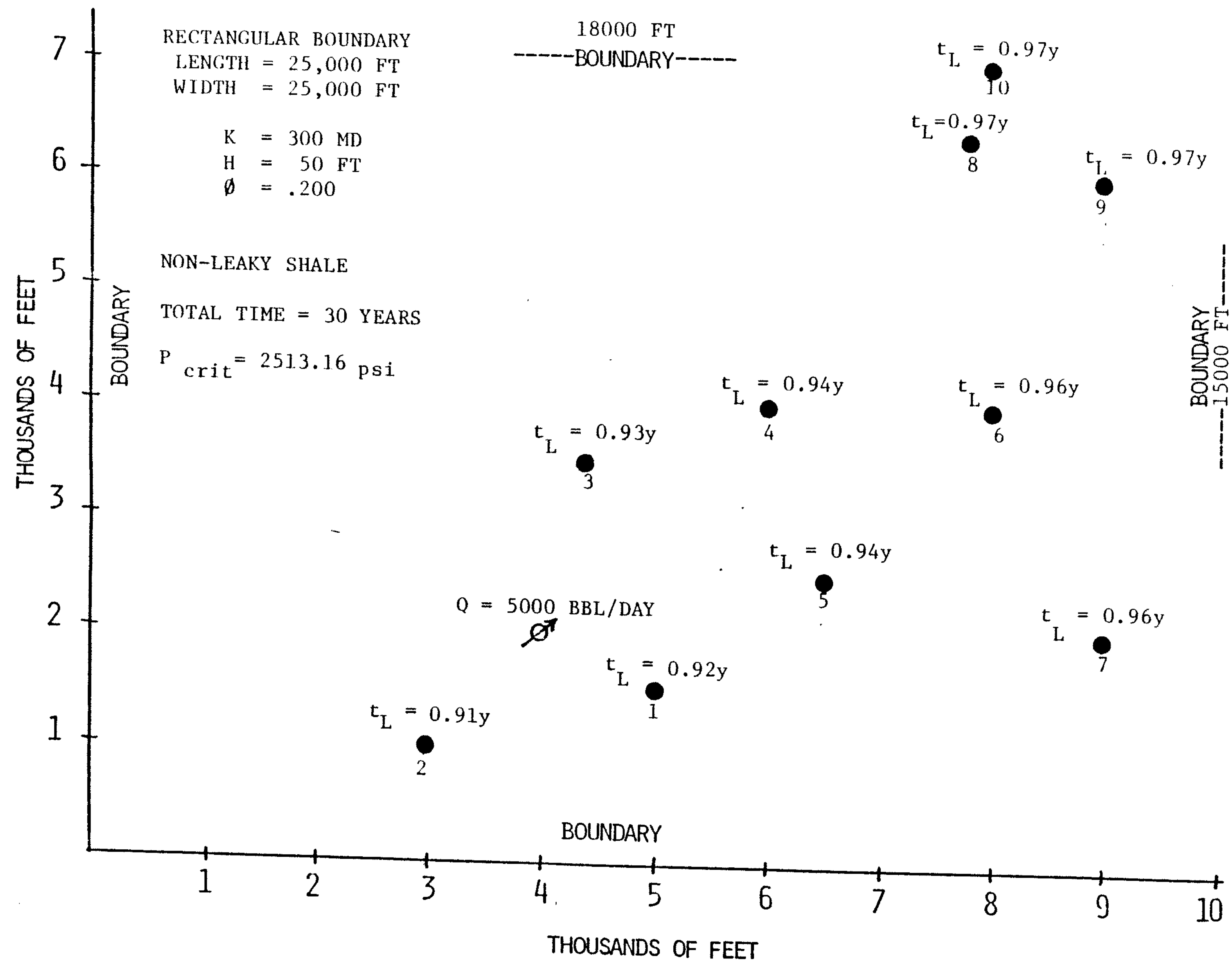
CASE 1, GROUP 1, NO. 2



CASE I. GROUP 1, NO. 3



CASE I , GROUP 1, NO. 4



CASE I, GROUP 1, NO. 5

CASE I, GROUP 2

PROPERTIES OF THE DISPOSAL ZONE

COMPRESSIBILITY =	0.500E-05	1/PSI
PERMEABILITY =	300.000	MD
VISCOSITY =	1.000	CP
THICKNESS =	50.0	FT
POROSITY =	0.200	

PROPERTIES OF ABANDONED HOLES

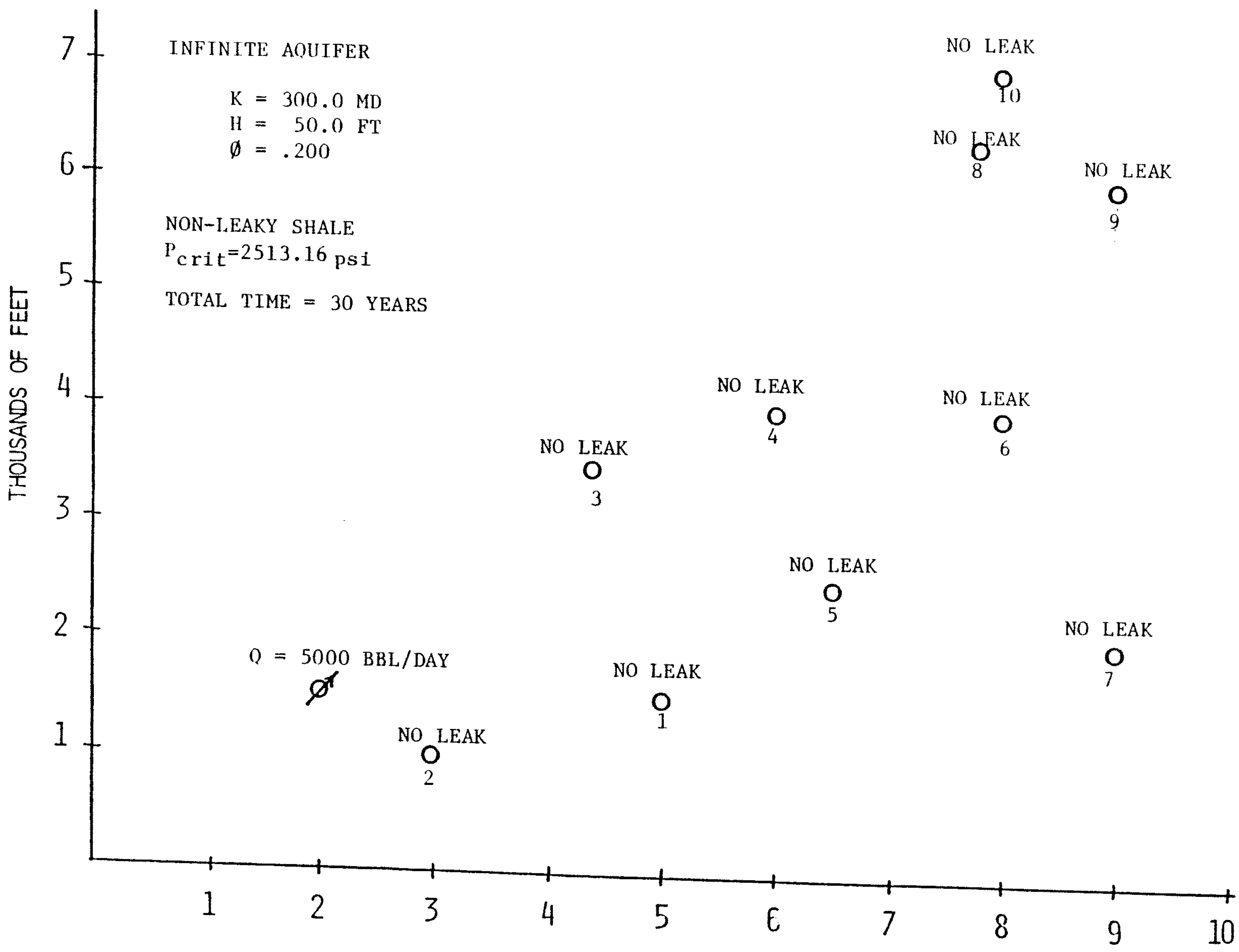
ABAN WELL	WELL DIAM IN	DEPTH TO DISP ZONE FT	DEPTH TO H2O ZONE FT	MUD DENSITY LB/GAL	GEL STRENGTH LB/100FT2	CRITIC PRESSU PSI
1	9.6	5000.00	600.0	9.000	100.00	2513.16
2	9.6	5000.00	600.0	9.000	100.00	2513.16
3	9.6	5000.00	600.0	9.000	100.00	2513.16
4	9.6	5000.00	600.0	9.000	100.00	2513.16
5	9.6	5000.00	600.0	9.000	100.00	2513.16
6	9.6	5000.00	600.0	9.000	100.00	2513.16
7	9.6	5000.00	600.0	9.000	100.00	2513.16
8	9.6	5000.00	600.0	9.000	100.00	2513.16
9	9.6	5000.00	600.0	9.000	100.00	2513.16
10	9.6	5000.00	600.0	9.000	100.00	2513.16

COORDINATES OF THE ABANDONED WELLS

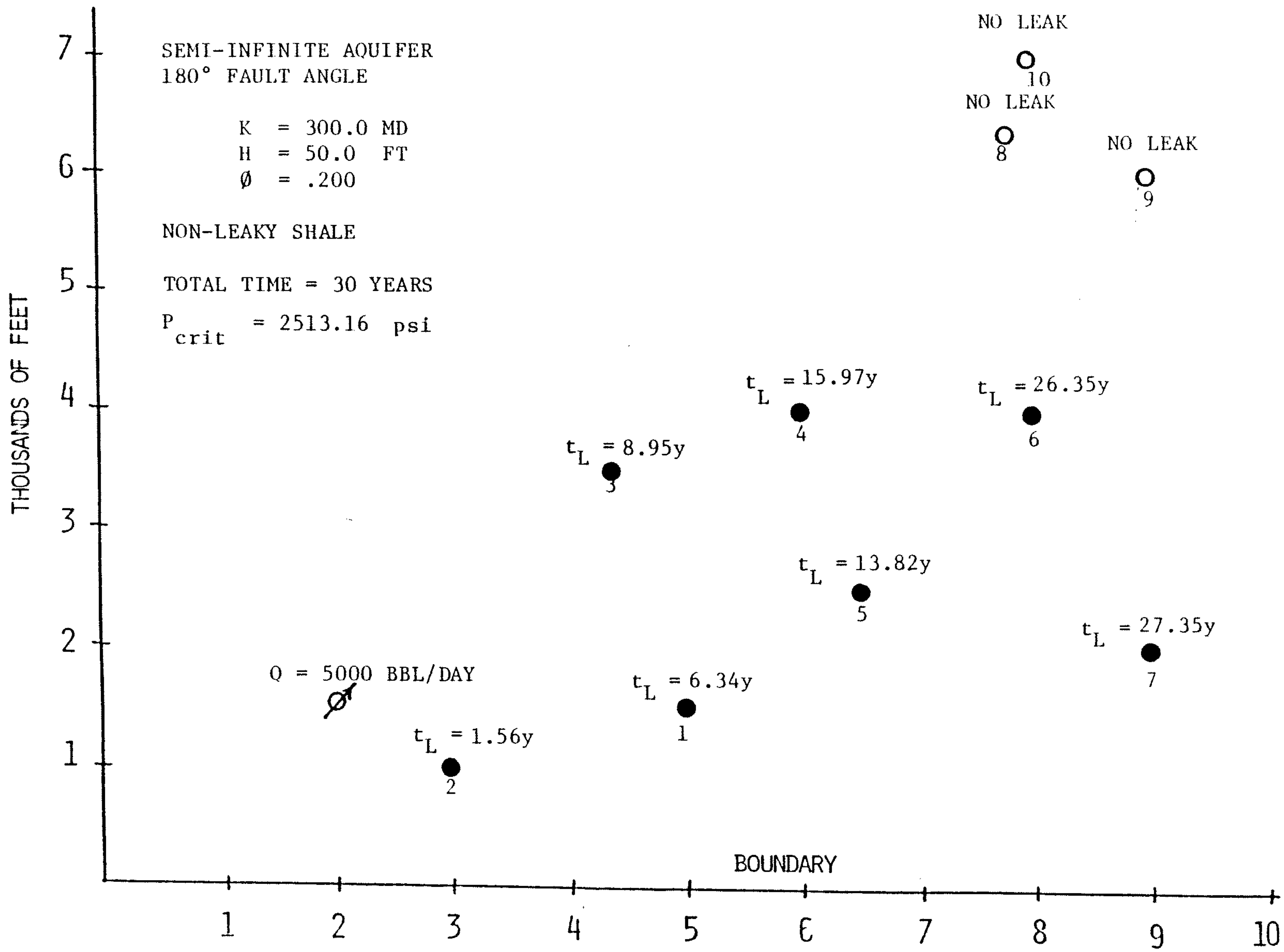
WELL #	X FT.	Y FT.
1	5000.000	1500.000
2	3000.000	1000.000
3	4400.000	3600.000
4	6000.000	4000.000
5	6500.000	2500.000
6	8000.000	4000.000
7	9000.000	2000.000
8	7800.000	6400.000
9	9000.000	6000.000
10	8000.000	7000.000

COORDINATES OF THE INJECTION WELL

X= 2000.000 Y= 1500.000 FT.
INJECTION RATE =5000. BBL/DAY



CASE I, GROUP 2, NO. 1



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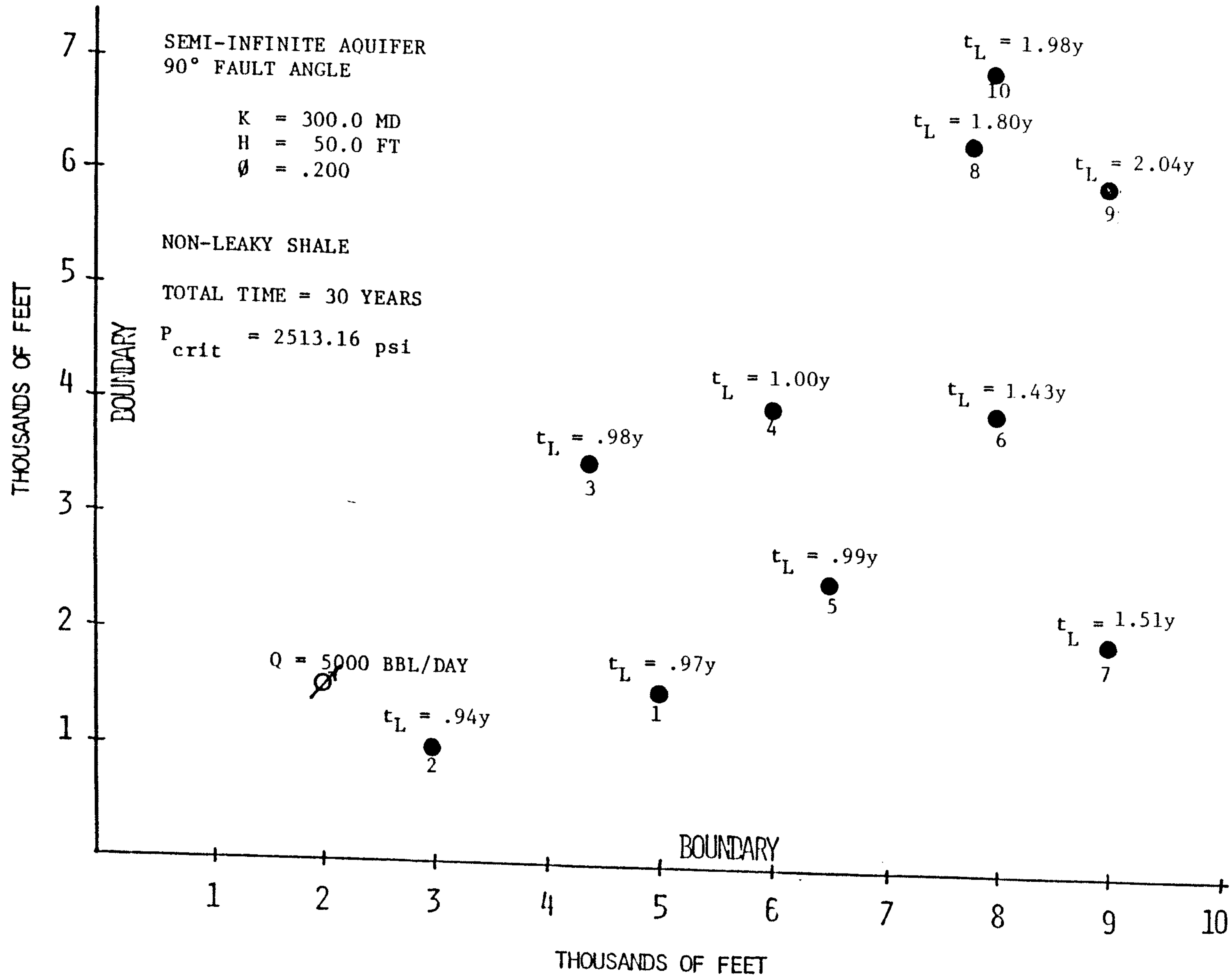

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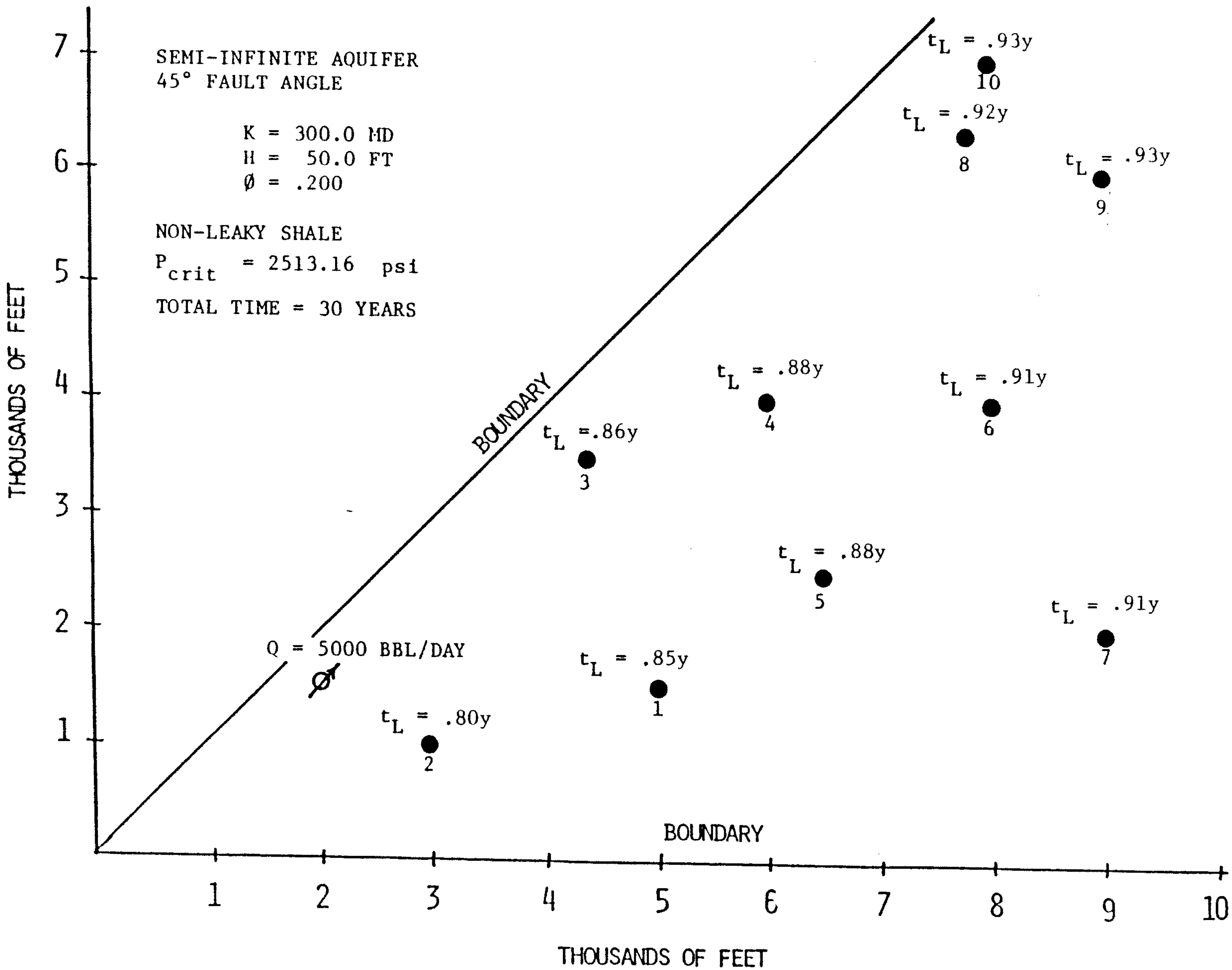

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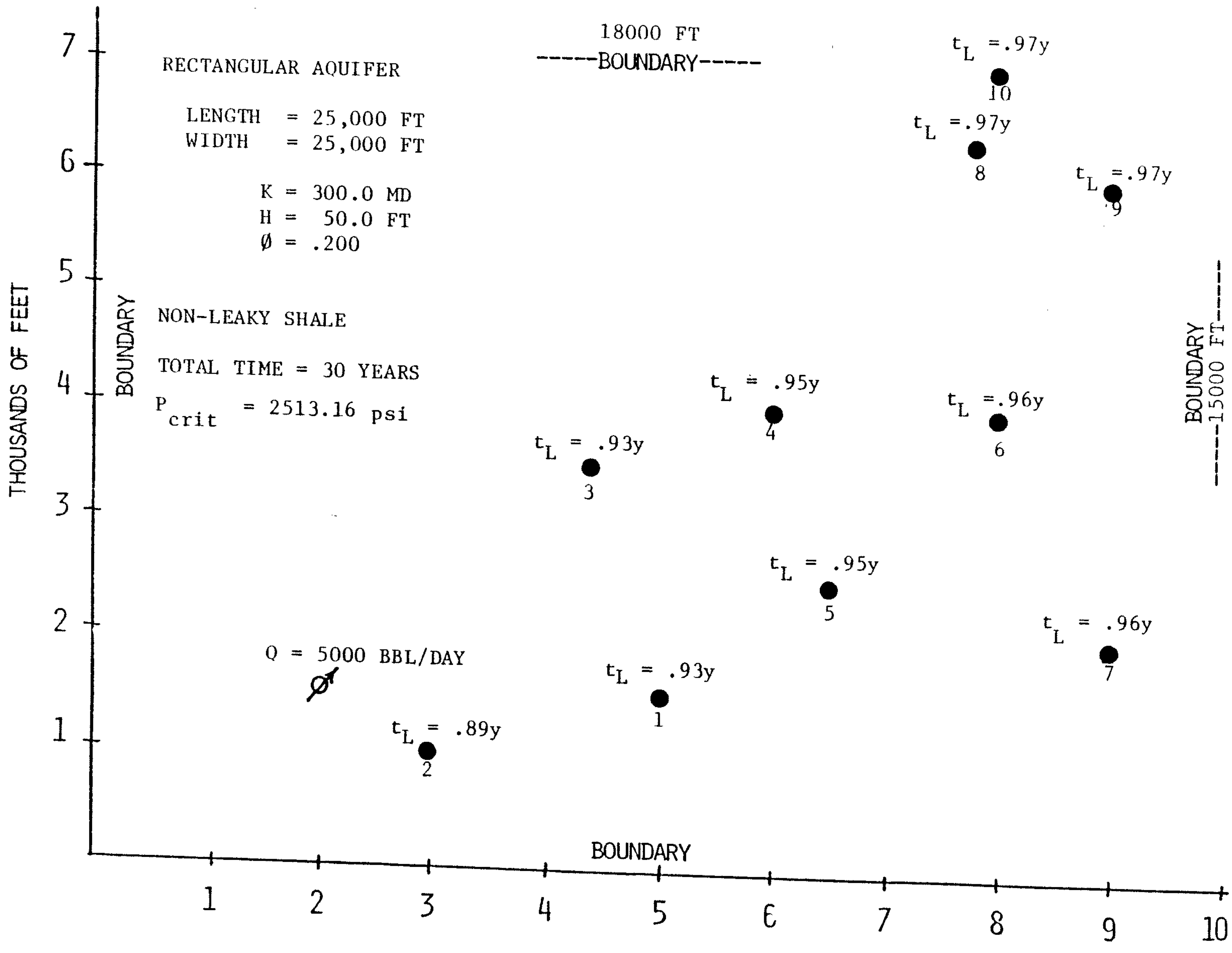


CASE I, GROUP 2, NO. 5

CASE I, GROUP 3

PROPERTIES OF THE DISPOSAL ZONE

COMPRESSIBILITY	= 0.500E-05	1/PSI
PERMEABILITY	= 300.000	MD
VISCOSITY	= 1.000	CP
THICKNESS	= 50.0	FT
POROSITY	=0.200	

PROPERTIES OF ABANDONED HOLES

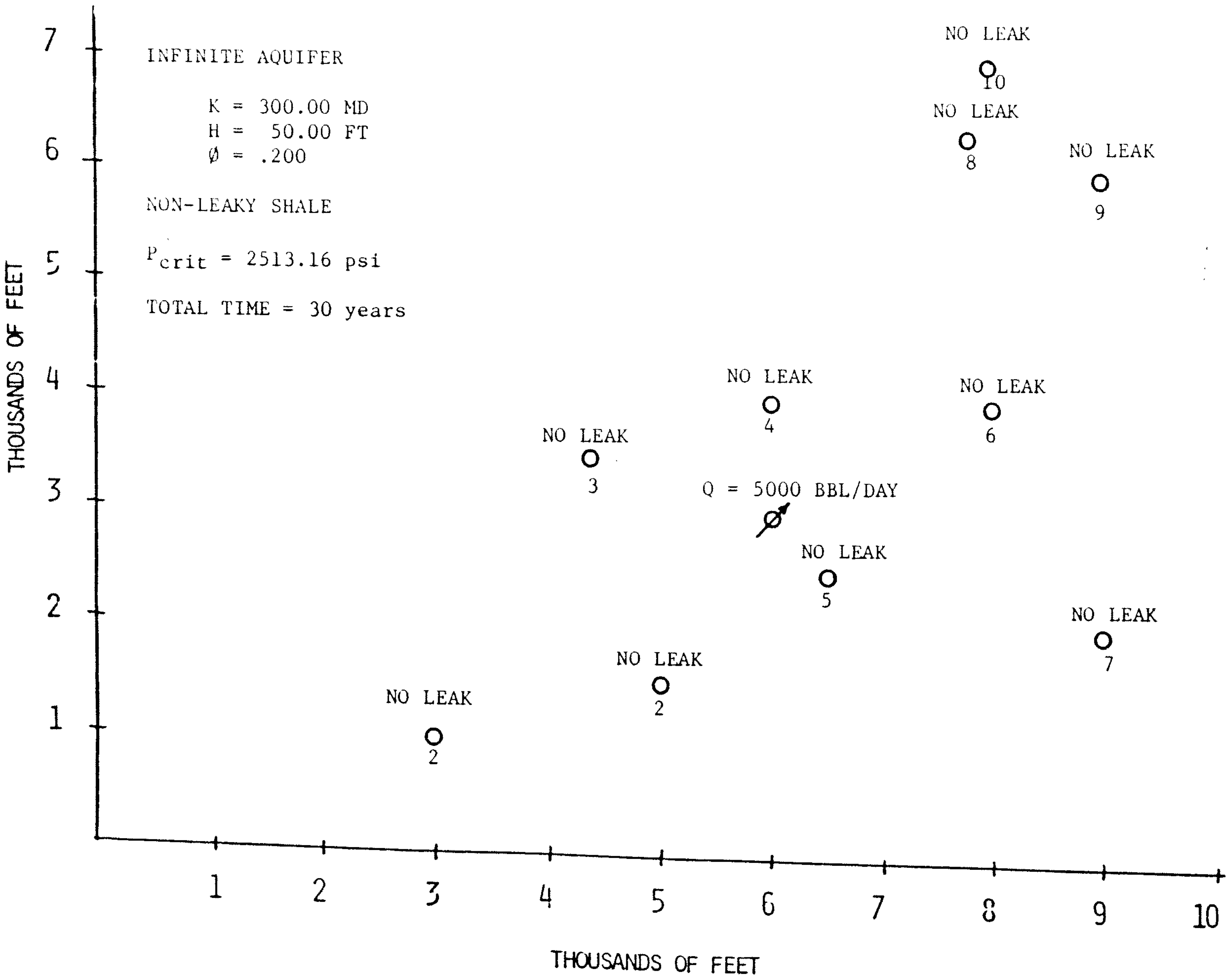
ABAN WELL	WELL DIAM IN	DEPTH TO DISP ZONE FT	DEPTH TO H2O ZONE FT	MUD DENSITY LB/GAL	GEL STRENGTH LB/100FT2	CRITIC PRESSU PSI
1	9.6	5000.00	600.0	9.000	100.00	2513.16
2	9.6	5000.00	600.0	9.000	100.00	2513.16
3	9.6	5000.00	600.0	9.000	100.00	2513.16
4	9.6	5000.00	600.0	9.000	100.00	2513.16
5	9.6	5000.00	600.0	9.000	100.00	2513.16
6	9.6	5000.00	600.0	9.000	100.00	2513.16
7	9.6	5000.00	600.0	9.000	100.00	2513.16
8	9.6	5000.00	600.0	9.000	100.00	2513.16
9	9.6	5000.00	600.0	9.000	100.00	2513.16
10	9.6	5000.00	600.0	9.000	100.00	2513.16

COORDINATES OF THE ABANDONED WELLS

WELL #	X FT.	Y FT.
1	5000.000	1500.000
2	3000.000	1000.000
3	4400.000	3600.000
4	6000.000	4000.000
5	6500.000	2500.000
6	8000.000	4000.000
7	9000.000	2000.000
8	7800.000	6400.000
9	9000.000	6000.000
10	8000.000	7000.000

COORDINATES OF THE INJECTION WELL

X= 6000.000 Y= 3000.000 FT.
INJECTION RATE =5000. BBL/DAY



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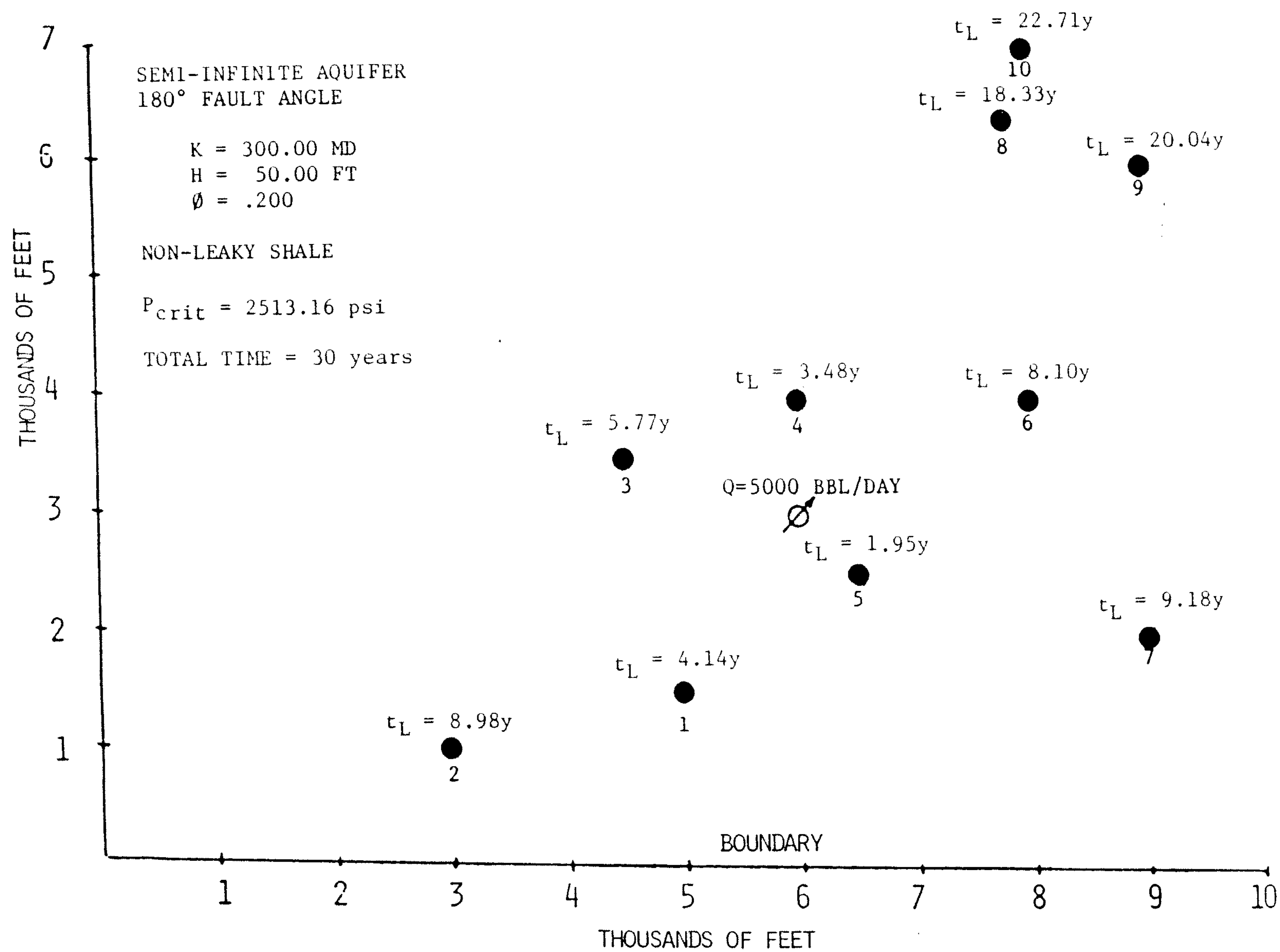

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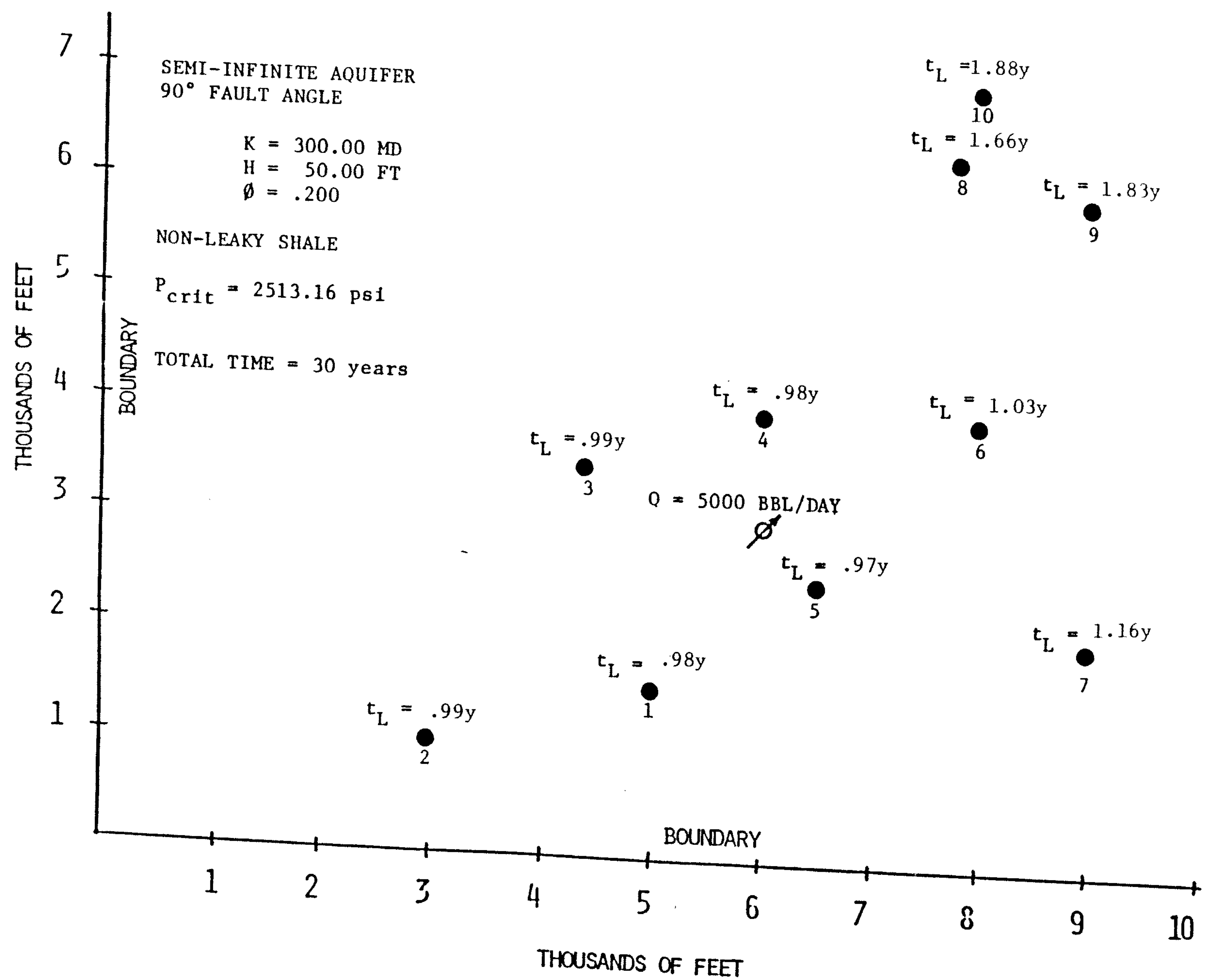

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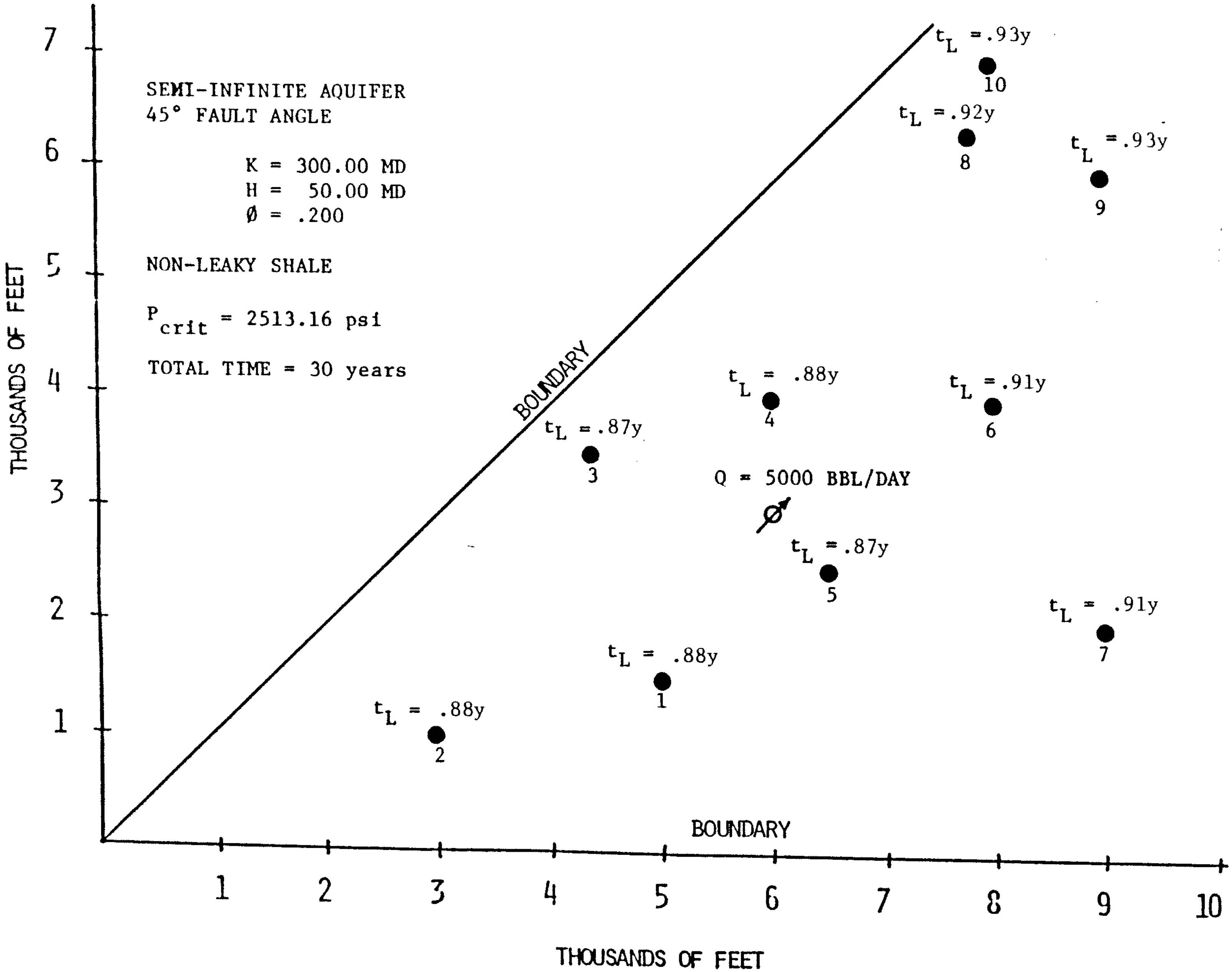

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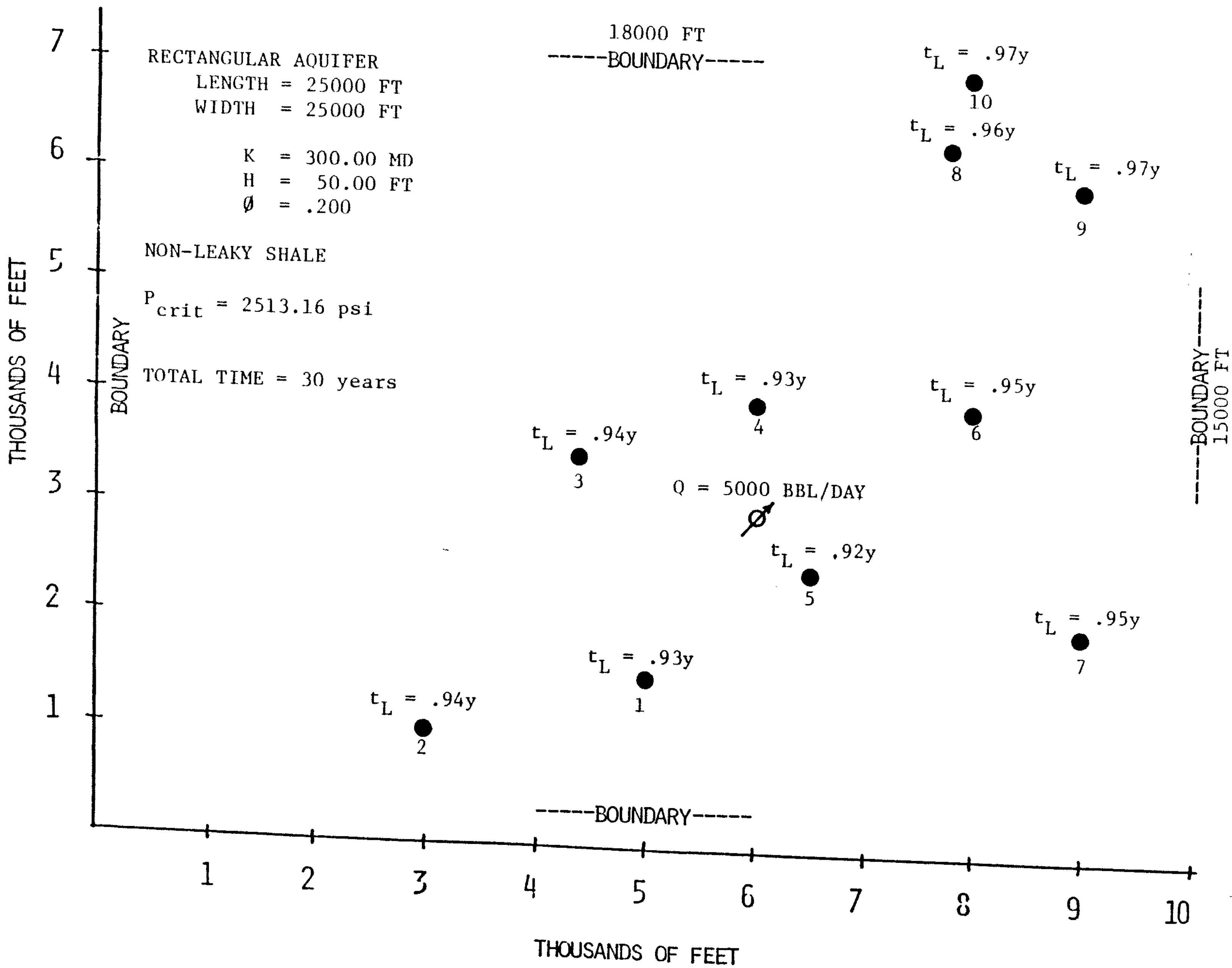


CASE I, GROUP 3, NO. 5

CASE I, GROUP 4

PROPERTIES OF THE DISPOSAL ZONE

****

COMPRESSIBILITY = 0.500E-05 1/PSI
PERMEABILITY = 100.000 MD
VISCOSITY = 1.000 CP
THICKNESS = 300.0 FT
POROSITY =0.200

****

PROPERTIES OF ABANDONED HOLES

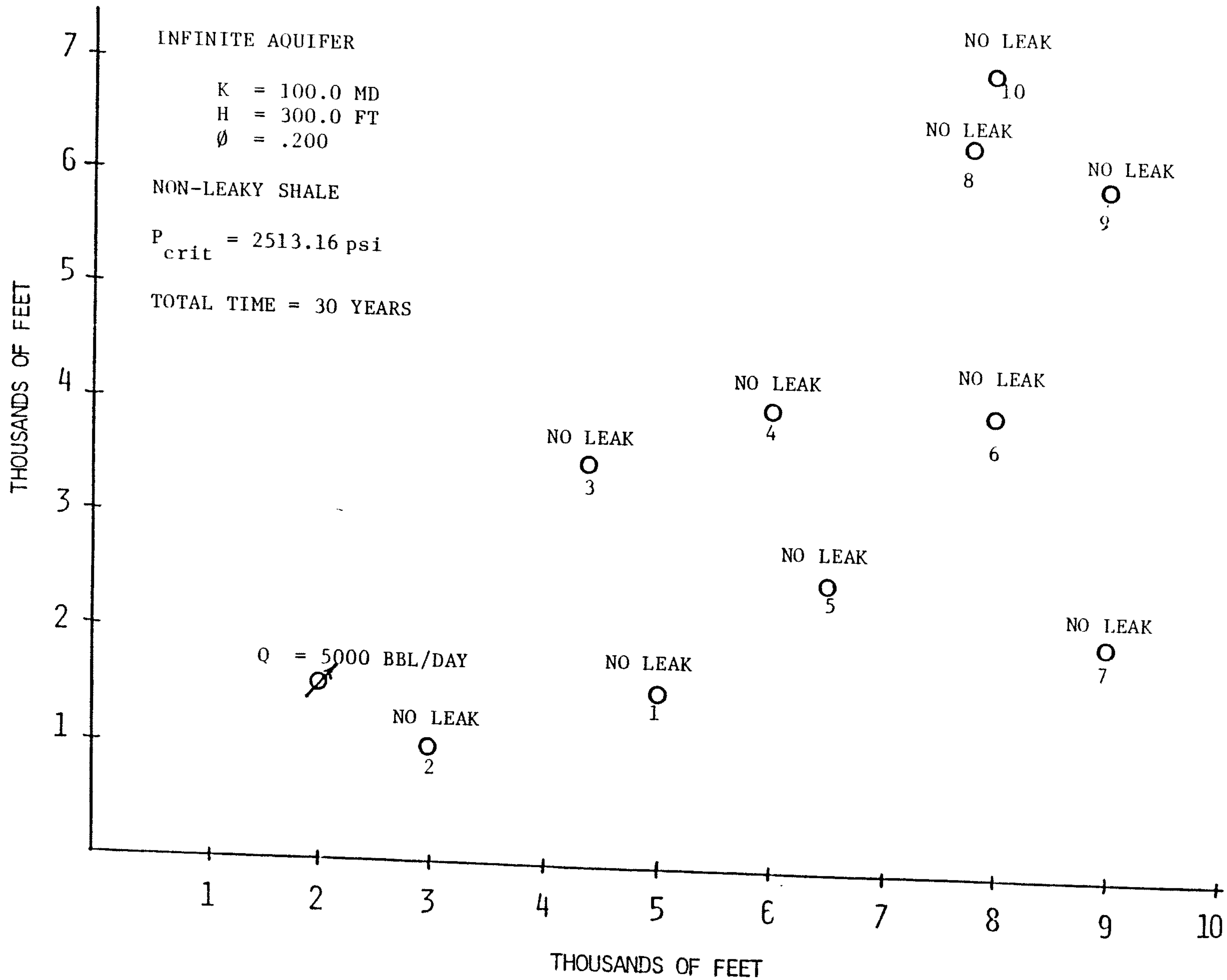
ABAN WELL	WELL DIAM IN	DEPTH TO DISP ZONE FT	DEPTH TO H2O ZONE FT	MUD DENSITY LB/GAL	GEL STRENGTH LB/100FT2	CRITIC PRESSU PSI
1	9.6	5000.00	600.0	9.000	100.00	2513.16
2	9.6	5000.00	600.0	9.000	100.00	2513.16
3	9.6	5000.00	600.0	9.000	100.00	2513.16
4	9.6	5000.00	600.0	9.000	100.00	2513.16
5	9.6	5000.00	600.0	9.000	100.00	2513.16
6	9.6	5000.00	600.0	9.000	100.00	2513.16
7	9.6	5000.00	600.0	9.000	100.00	2513.16
8	9.6	5000.00	600.0	9.000	100.00	2513.16
9	9.6	5000.00	600.0	9.000	100.00	2513.16
10	9.6	5000.00	600.0	9.000	100.00	2513.16

COORDINATES OF THE ABANDONED WELLS

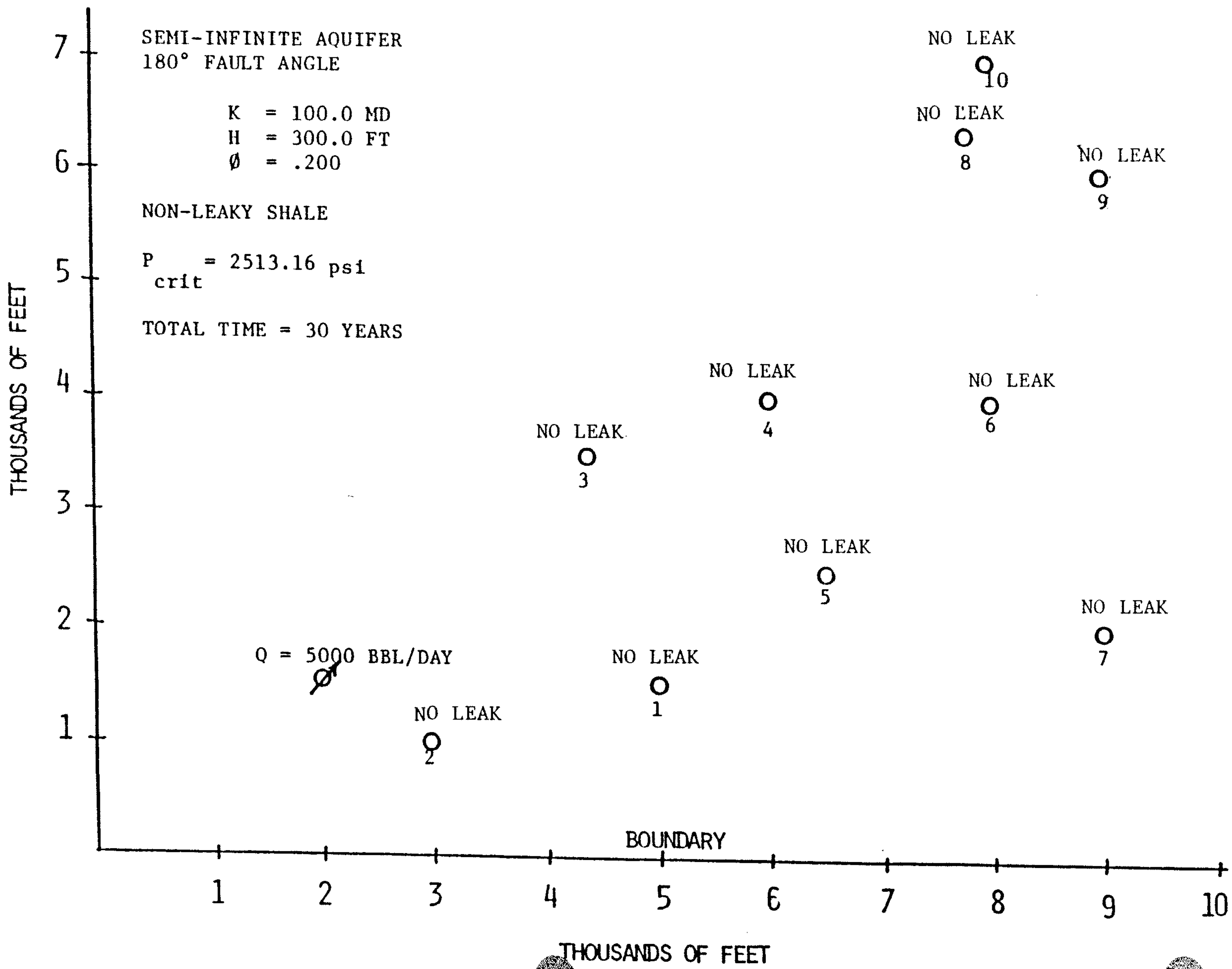
WELL #	X FT.	Y FT.
1	5000.000	1500.000
2	3000.000	1000.000
3	4400.000	3600.000
4	6000.000	4000.000
5	6500.000	2500.000
6	8000.000	4000.000
7	9000.000	2000.000
8	7800.000	6400.000
9	9000.000	6000.000
10	8000.000	7000.000

COORDINATES OF THE INJECTION WELL

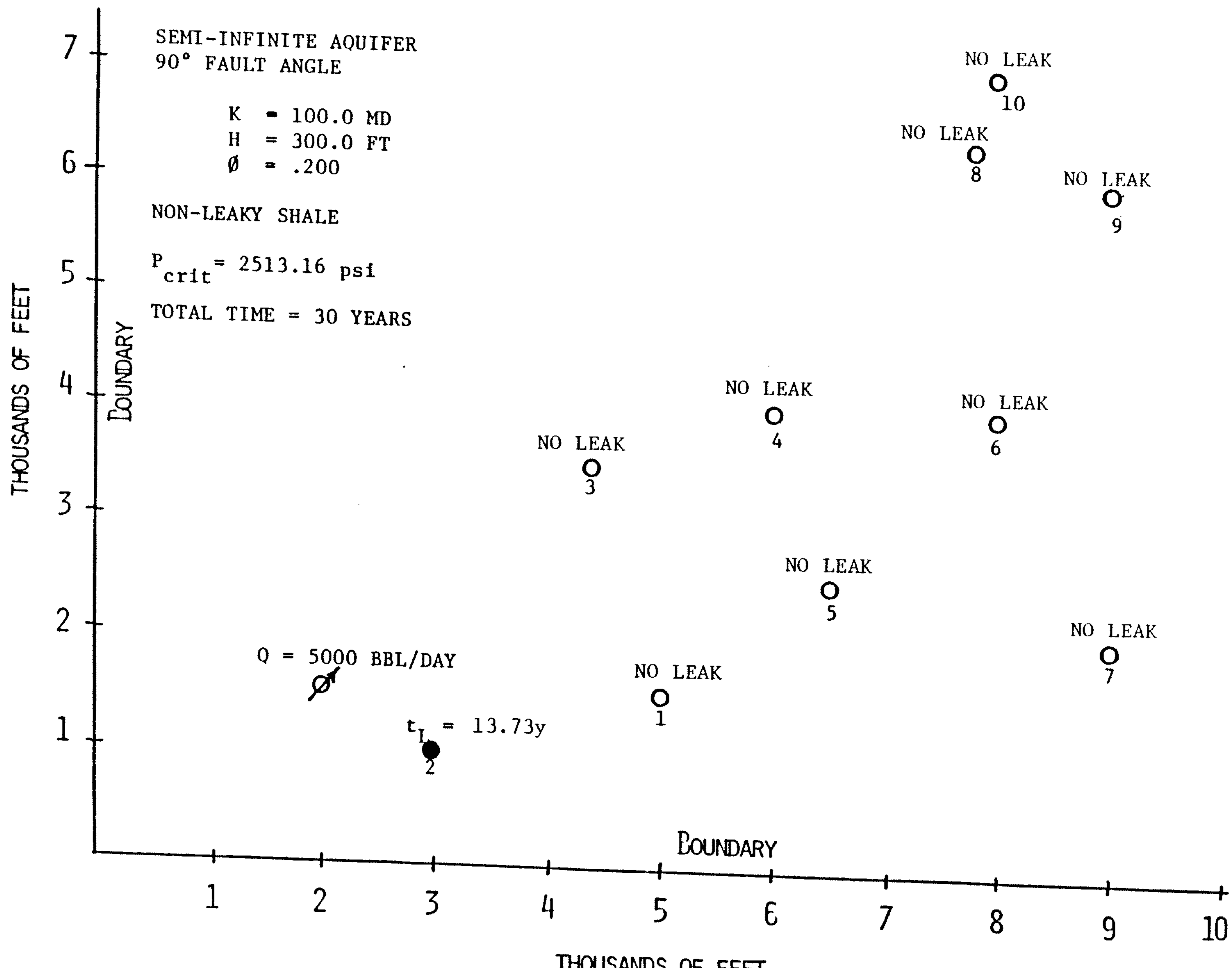
X= 2000.000 Y= 1500.000 FT.
INJECTION RATE =5000. BBL/DAY



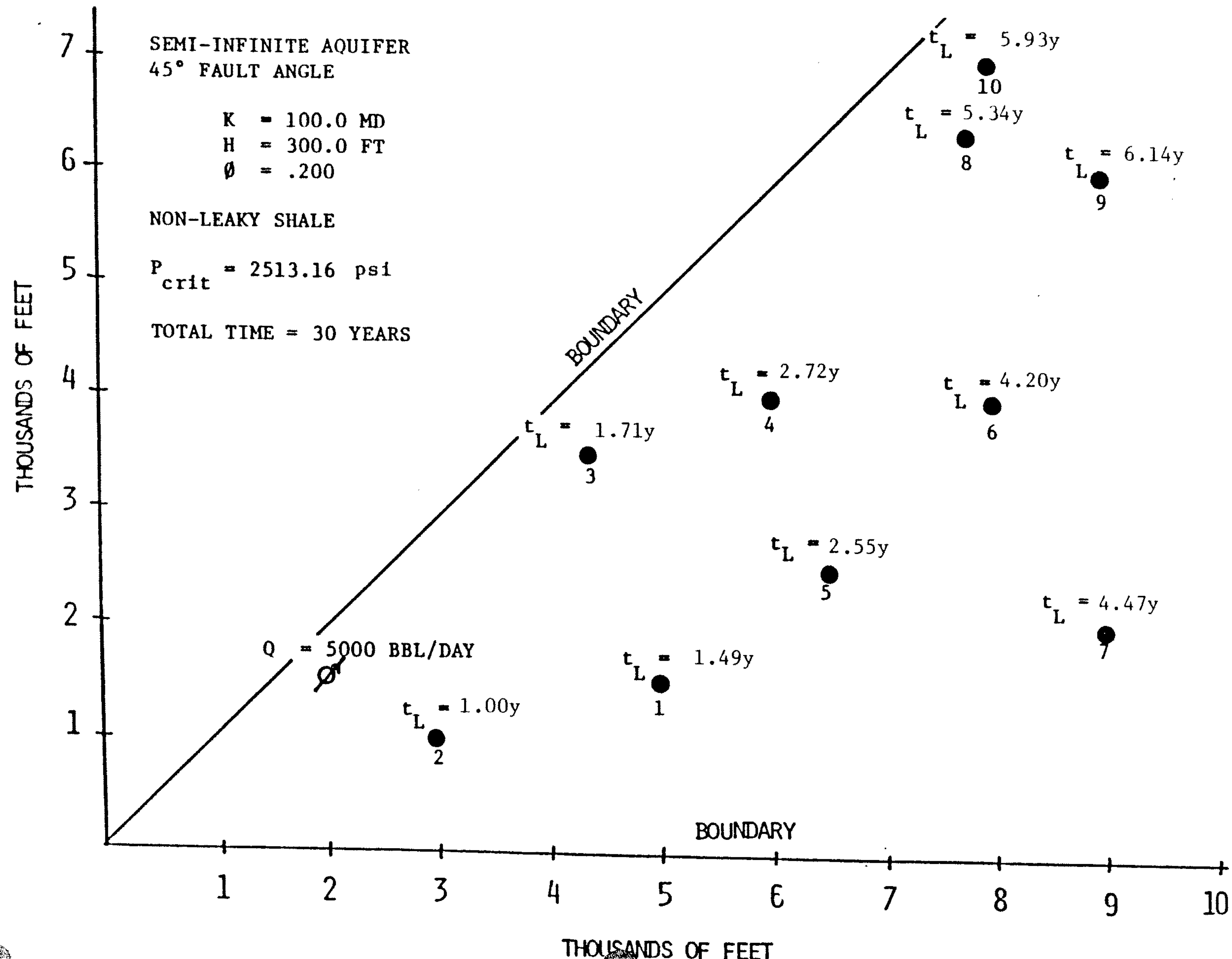
CASE I, GROUP 4, NO. 1



CASE I, GROUP 4, NO. 2



CASE I, GROUP 4, NO. 3



CASE I, GROUP 4, NO. 4

CASE I, GROUP 5

PROPERTIES OF THE DISPOSAL ZONE

COMPRESSIBILITY = 0.500E-05 1/PSI
PERMEABILITY = 100.000 MD
VISCOSITY = 1.000 CP
THICKNESS = 300.0 FT
POROSITY =0.200

PROPERTIES OF ABANDONED HOLES

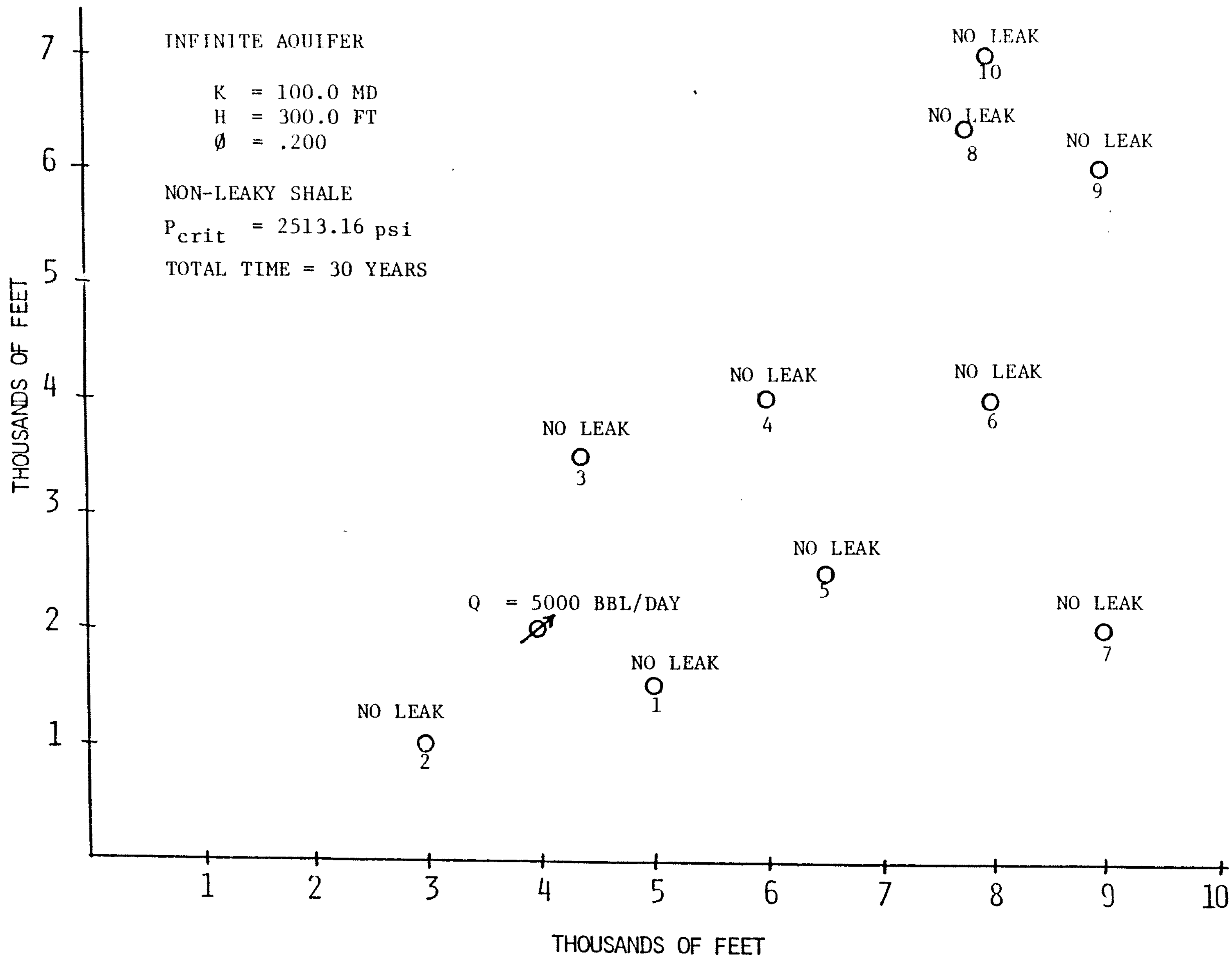
ABAN WELL	WELL DIAM IN	DEPTH TO DISP ZONE FT	DEPTH TO H2O ZONE FT	MUD DENSITY LB/GAL	GEL STRENGTH LB/100FT2	CRITIC PRESSU PSI
1	9.6	5000.00	600.0	9.000	100.00	2513.16
2	9.6	5000.00	600.0	9.000	100.00	2513.16
3	9.6	5000.00	600.0	9.000	100.00	2513.16
4	9.6	5000.00	600.0	9.000	100.00	2513.16
5	9.6	5000.00	600.0	9.000	100.00	2513.16
6	9.6	5000.00	600.0	9.000	100.00	2513.16
7	9.6	5000.00	600.0	9.000	100.00	2513.16
8	9.6	5000.00	600.0	9.000	100.00	2513.16
9	9.6	5000.00	600.0	9.000	100.00	2513.16
10	9.6	5000.00	600.0	9.000	100.00	2513.16

COORDINATES OF THE ABANDONED WELLS

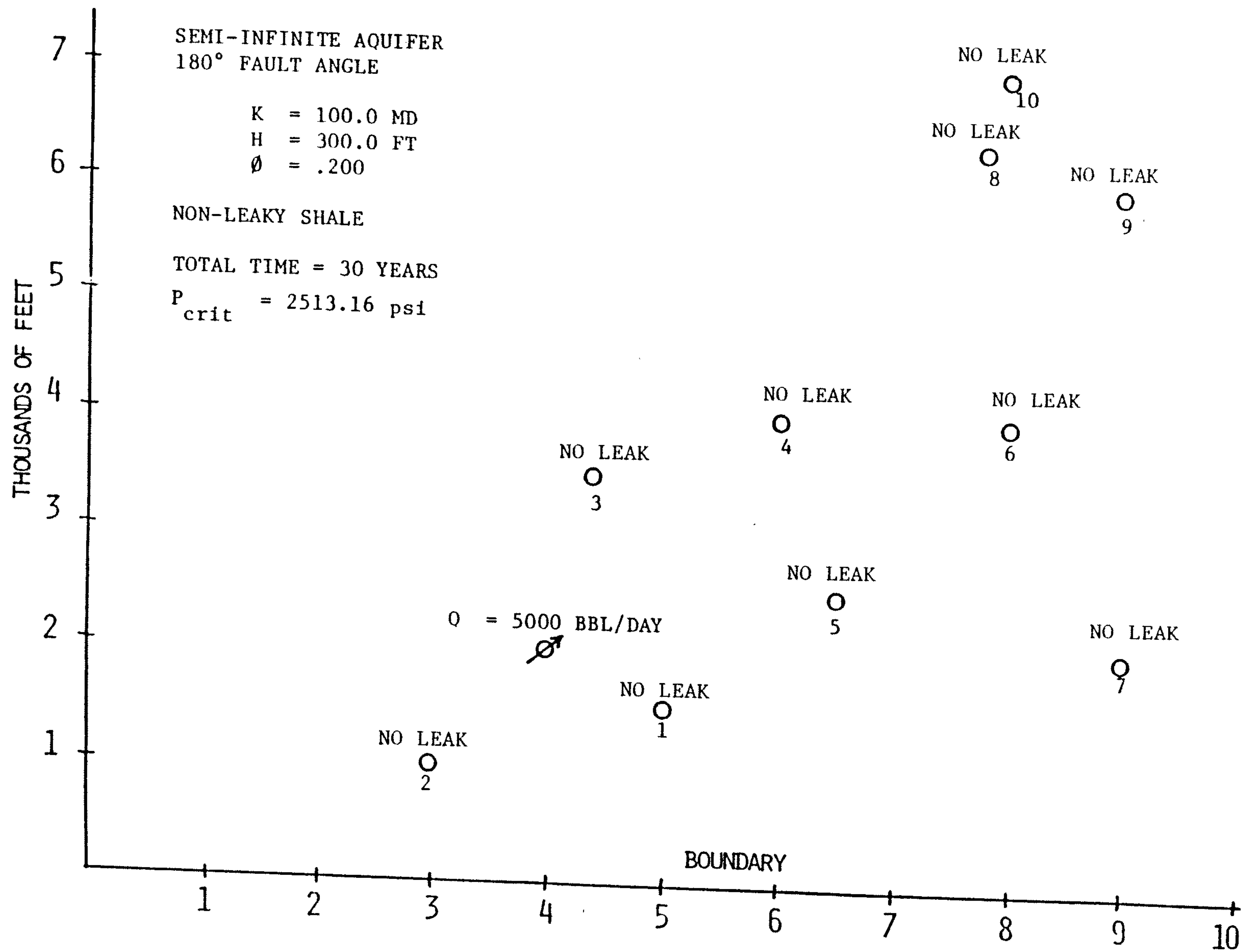
WELL #	X FT.	Y FT.
1	5000.000	1500.000
2	3000.000	1000.000
3	4400.000	3600.000
4	6000.000	4000.000
5	6500.000	2500.000
6	8000.000	4000.000
7	9000.000	2000.000
8	7800.000	6400.000
9	9000.000	6000.000
10	8000.000	7000.000

COORDINATES OF THE INJECTION WELL

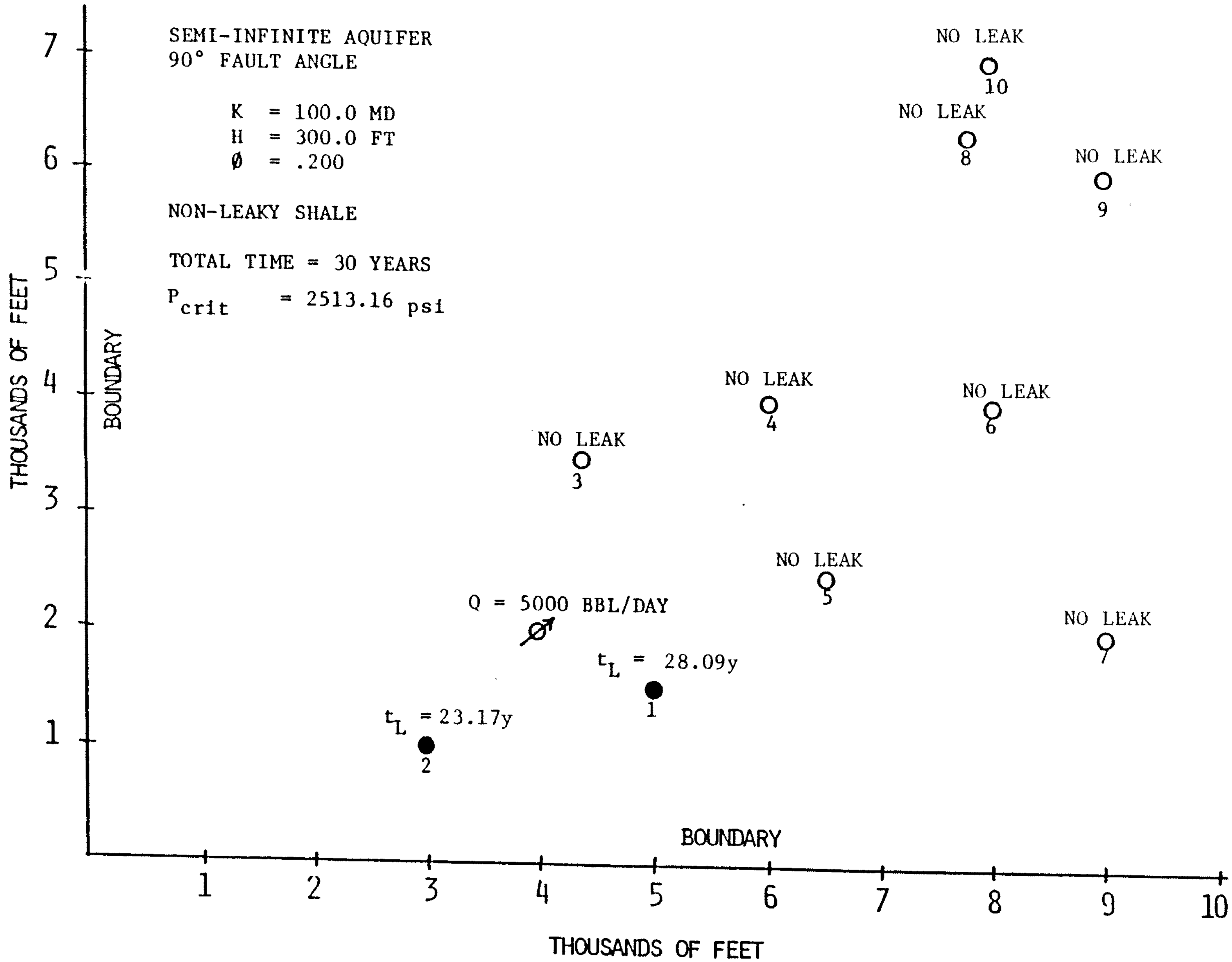
X= 4000.000 Y= 2000.000 FT.
INJECTION RATE =5000. BBL/DAY



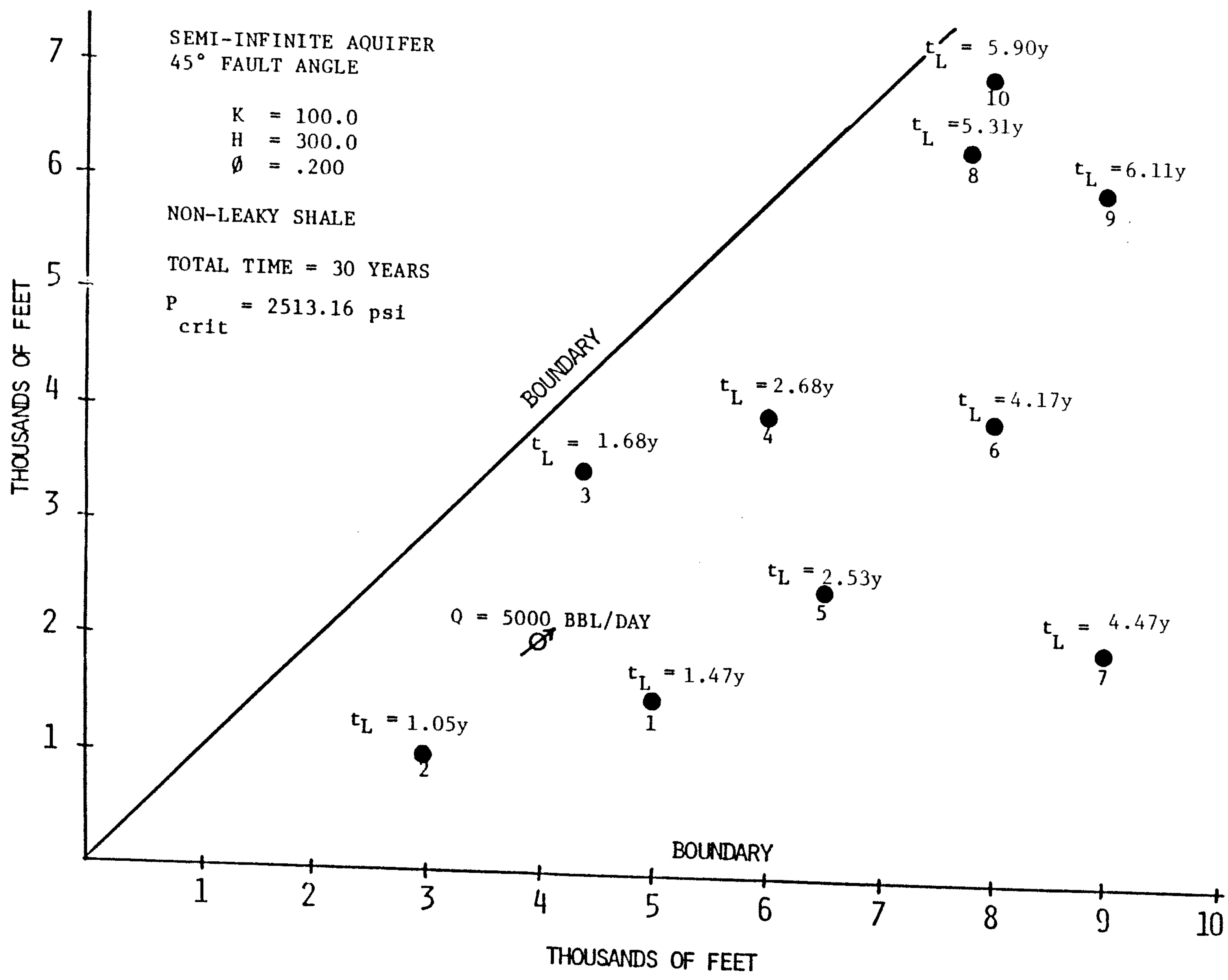
CASE I, GROUP 5, NO. 1



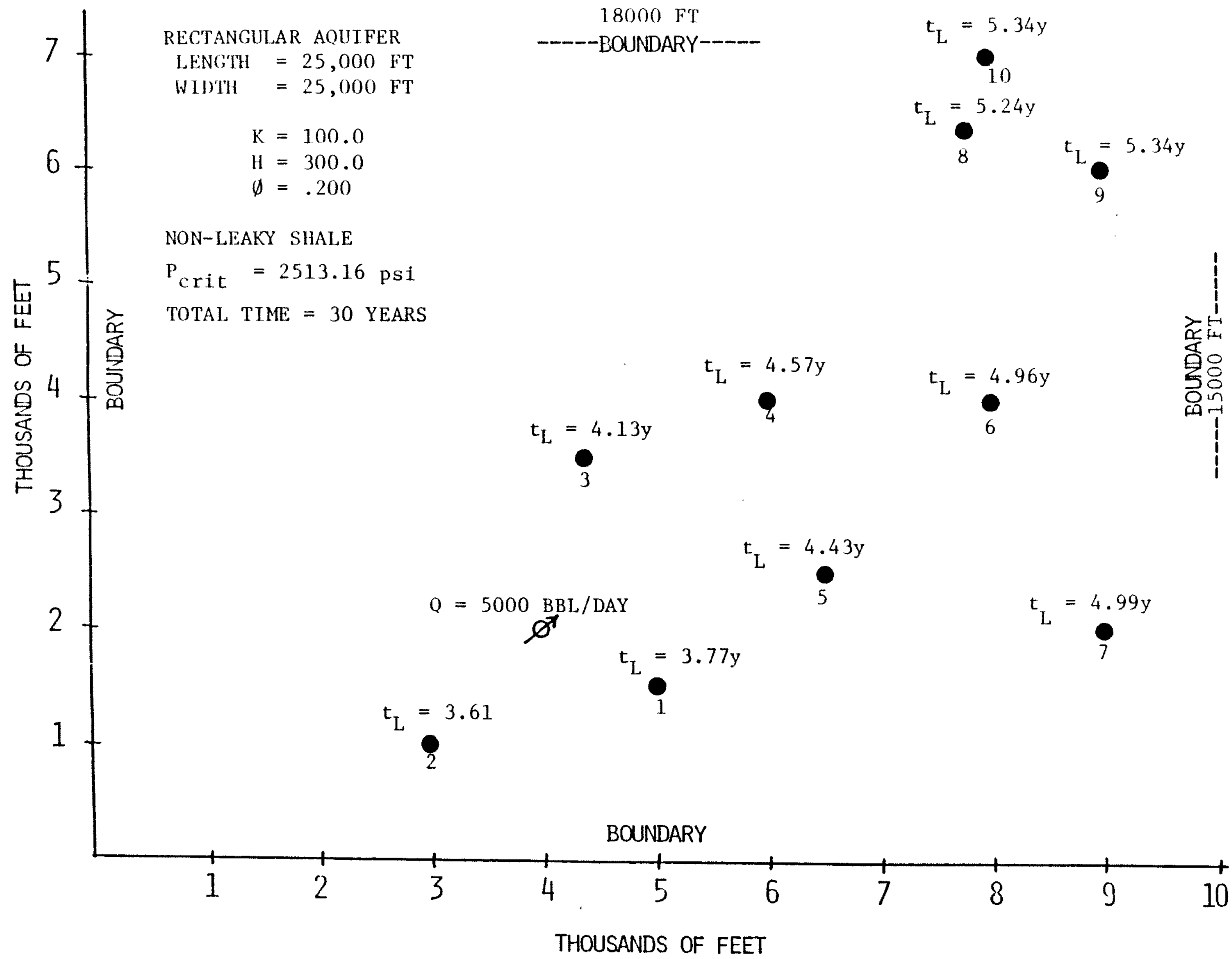
CASE I, GROUP 5, NO. 2



CASE I, GROUP 5, NO. 3



CASE I, GROUP 5, NO. 4



CASE I, GROUP 5, NO. 5

CASE I GROUP 6

PRESSURE HISTORIES
AT ABANDONED WELLS
CASE I, GROUP 1, NO. 2

TIME	WELL NUMBER (PRESSURES IN PSI)									
YEARS	1	2	3	4	5	6	7	8	9	10
1.0	2480.0	2475.5	2441.5	2410.6	2425.0	2383.1	2383.4	2359.5	2354.0	2352.1
2.0	2512.6	2508.1	2474.0	2443.0	2457.5	2415.4	2415.7	2391.7	2386.1	2384.1
3.0	2531.6	2527.2	2493.0	2462.0	2476.6	2434.4	2434.7	2410.6	2405.0	2403.0
4.0	2545.2	2540.7	2506.5	2475.5	2490.1	2447.9	2448.2	2424.0	2418.4	2416.4
5.0	2555.7	2551.2	2517.0	2486.0	2500.6	2458.3	2458.7	2434.5	2428.9	2426.9
6.0	2564.2	2559.8	2525.6	2494.6	2509.1	2466.9	2467.2	2443.0	2437.4	2435.4
7.0	2571.5	2567.0	2532.8	2501.8	2516.4	2474.1	2474.5	2450.3	2444.7	2442.6
8.0	2577.8	2573.3	2539.1	2508.1	2522.7	2480.4	2480.7	2456.5	2450.9	2448.9
9.0	2583.3	2578.9	2544.6	2513.7	2528.2	2485.9	2486.3	2462.1	2456.5	2454.4
10.0	2588.3	2583.8	2549.6	2518.6	2533.2	2490.9	2491.2	2467.0	2461.4	2459.4
11.0	2592.8	2588.3	2554.1	2523.1	2537.7	2495.4	2495.7	2471.5	2465.9	2463.9
12.0	2596.8	2592.4	2558.2	2527.2	2541.7	2499.5	2499.8	2475.6	2470.0	2467.9
13.0	2600.6	2596.2	2561.9	2530.9	2545.5	2503.2	2503.6	2479.3	2473.7	2471.7
14.0	2604.1	2599.7	2565.4	2534.4	2549.0	2506.7	2507.0	2482.8	2477.2	2475.2
15.0	2607.3	2602.9	2568.7	2537.7	2552.2	2510.0	2510.3	2486.1	2480.4	2478.4
16.0	2610.4	2605.9	2571.7	2540.7	2555.3	2513.0	2513.3	2489.1	2483.5	2481.5
17.0	2613.2	2608.8	2574.6	2543.6	2558.1	2515.8	2516.2	2492.0	2486.3	2484.3
18.0	2615.9	2611.5	2577.2	2546.3	2560.8	2518.5	2518.9	2494.6	2489.0	2487.0
19.0	2618.5	2614.0	2579.8	2548.8	2563.4	2521.1	2521.4	2497.2	2491.6	2489.5
20.0	2620.9	2616.4	2582.2	2551.2	2565.8	2523.5	2523.8	2499.6	2494.0	2491.9
21.0	2623.2	2618.7	2584.5	2553.5	2568.1	2525.8	2526.1	2501.9	2496.3	2494.2
22.0	2625.4	2620.9	2586.7	2555.7	2570.3	2528.0	2528.3	2504.1	2498.5	2496.4
23.0	2627.5	2623.0	2588.8	2557.8	2572.4	2530.1	2530.4	2506.2	2500.5	2498.5
24.0	2629.5	2625.0	2590.8	2559.8	2574.4	2532.1	2532.4	2508.2	2502.5	2500.5
25.0	2631.4	2626.9	2592.7	2561.7	2576.3	2534.0	2534.3	2510.1	2504.5	2502.4
26.0	2633.2	2628.8	2594.5	2563.6	2578.1	2535.8	2536.2	2511.9	2506.3	2504.3
27.0	2635.0	2630.6	2596.3	2565.3	2579.9	2537.6	2537.9	2513.7	2508.1	2506.1
28.0	2636.7	2632.3	2598.0	2567.0	2581.6	2539.3	2539.7	2515.4	2509.8	2507.8
29.0	2638.4	2633.9	2599.7	2568.7	2583.3	2541.0	2541.3	2517.1	2511.4	2509.4
30.0	2640.0	2635.5	2601.3	2570.3	2584.9	2542.6	2542.9	2518.7	2513.0	2511.0

CASE II

EFFECTS OF ABANDONED WELL PARAMETERS

Group 1, Only boundaries are varied, P_{crit} = 2668.9 psi

Group 2, Same as Group 1 but with P_{crit} = 2409.16 Psi, "box" boundaries omitted (all leaked early)

Group 3, Same as Group 1 but with P_{crit} = 2322.58 Psi and a different injection well location

Group 4, Two examples same as Case I, Group 1, No. 1 but with a leaky shale aquiclude and P_{crit} values of 2365.87 and 2409.16 Psi respectively

CASE II, GROUP 1

PROPERTIES OF THE DISPOSAL ZONE

COMPRESSIBILITY	= 0.500E-05	1/PSI
PERMEABILITY	= 300.000	MD
VISCOSITY	= 1.000	CP
THICKNESS	= 50.0	FT
POROSITY	=0.200	

PROPERTIES OF ABANDONED HOLES

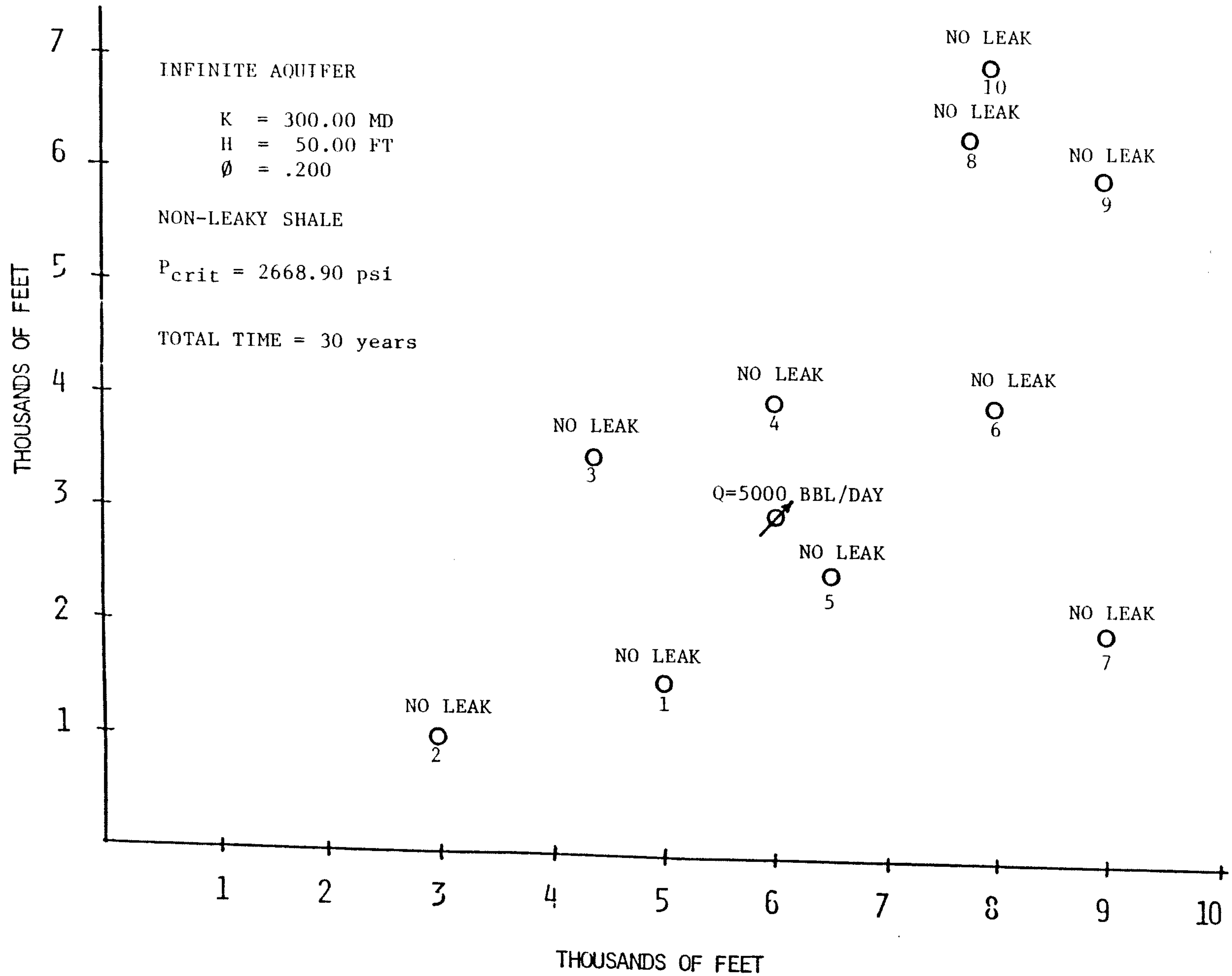
ABAN WELL	WELL DIAM IN	DEPTH TO DISP ZONE FT	DEPTH TO H2O ZONE FT	MUD DENSITY LB/GAL	GEL STRENGTH LB/100FT2	CRITIC PRESSU PSI
1	9.6	5000.00	600.0	8.600	250.00	2668.90
2	9.6	5000.00	600.0	8.600	250.00	2668.90
3	9.6	5000.00	600.0	8.600	250.00	2668.90
4	9.6	5000.00	600.0	8.600	250.00	2668.90
5	9.6	5000.00	600.0	8.600	250.00	2668.90
6	9.6	5000.00	600.0	8.600	250.00	2668.90
7	9.6	5000.00	600.0	8.600	250.00	2668.90
8	9.6	5000.00	600.0	8.600	250.00	2668.90
9	9.6	5000.00	600.0	8.600	250.00	2668.90
10	9.6	5000.00	600.0	8.600	250.00	2668.90

COORDINATES OF THE ABANDONED WELLS

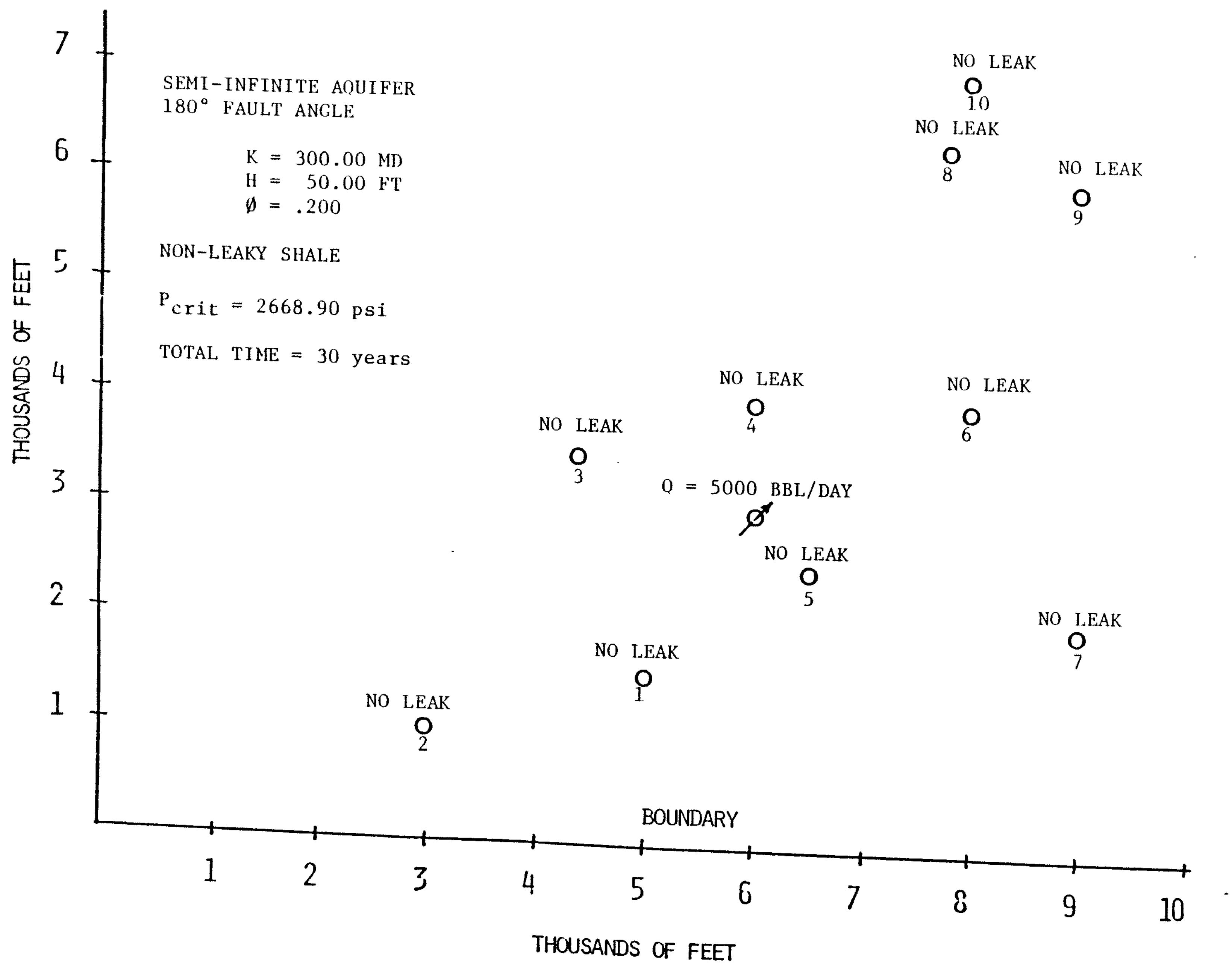
WELL #	X FT.	Y FT.
1	5000.000	1500.000
2	3000.000	1000.000
3	4400.000	3600.000
4	6000.000	4000.000
5	6500.000	2500.000
6	8000.000	4000.000
7	9000.000	2000.000
8	7800.000	6400.000
9	9000.000	6000.000
10	8000.000	7000.000

COORDINATES OF THE INJECTION WELL

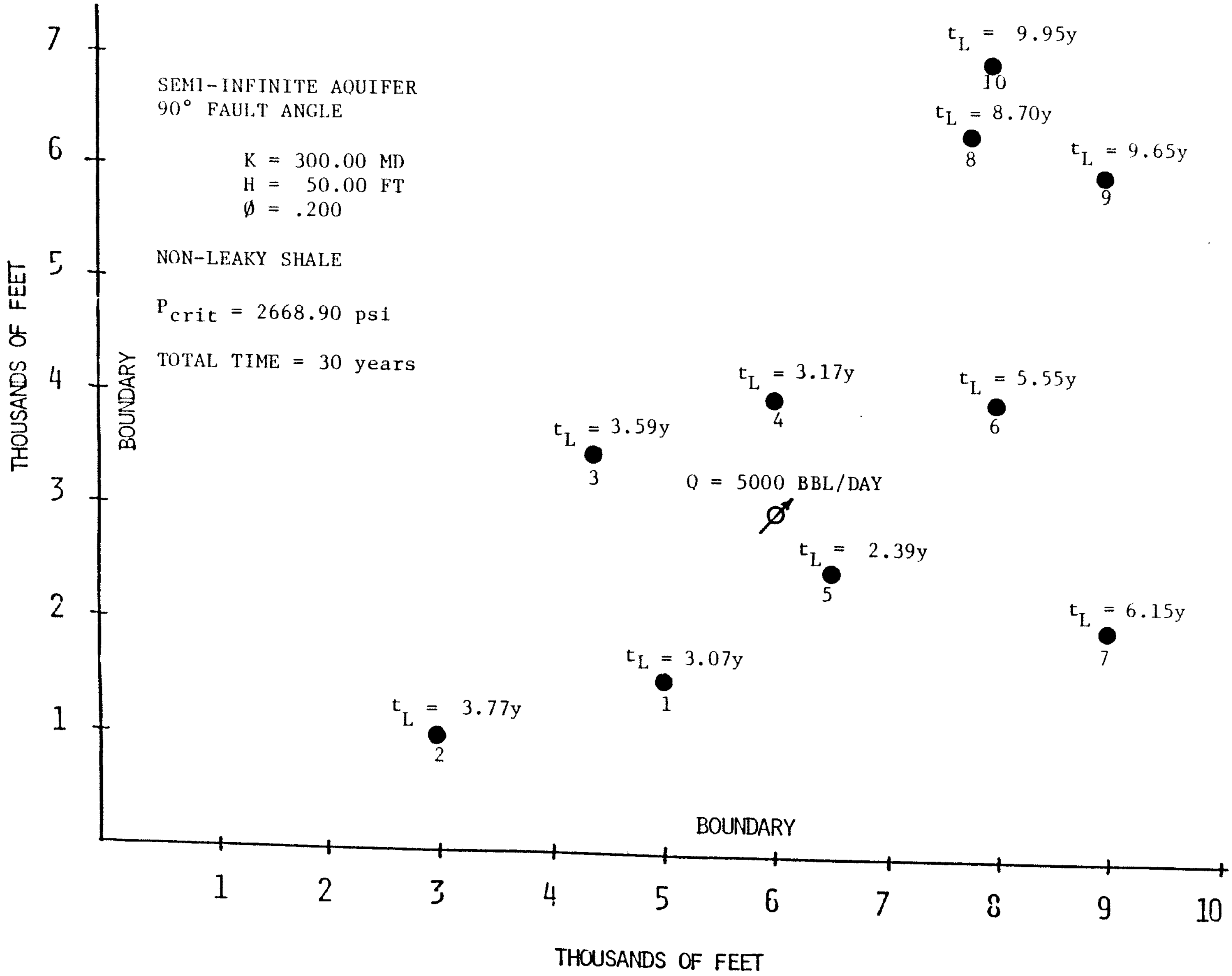
X= 6000.000 Y= 3000.000 FT.
INJECTION RATE =5000. BBL/DAY



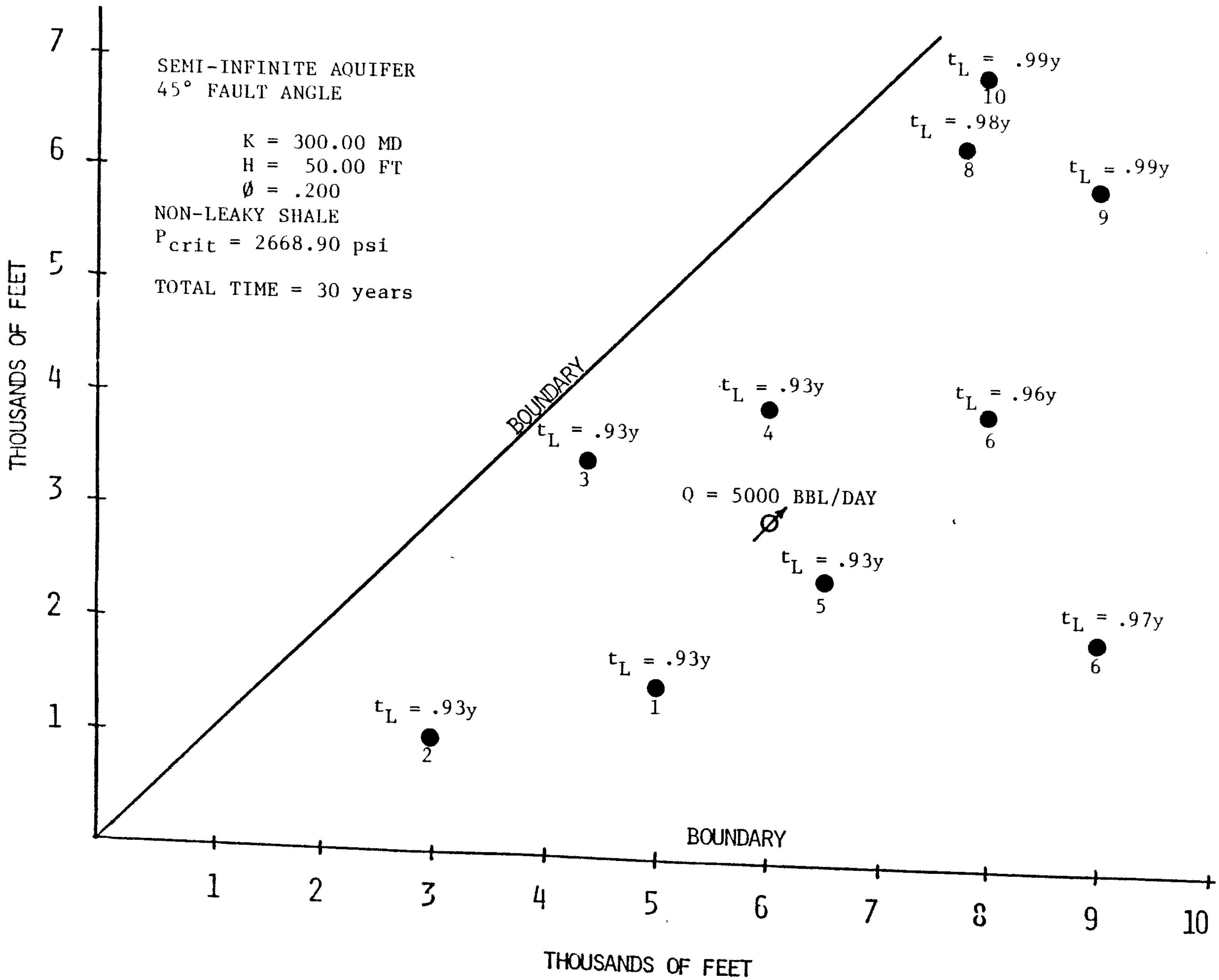
CASE II, GROUP 1, NO. 1



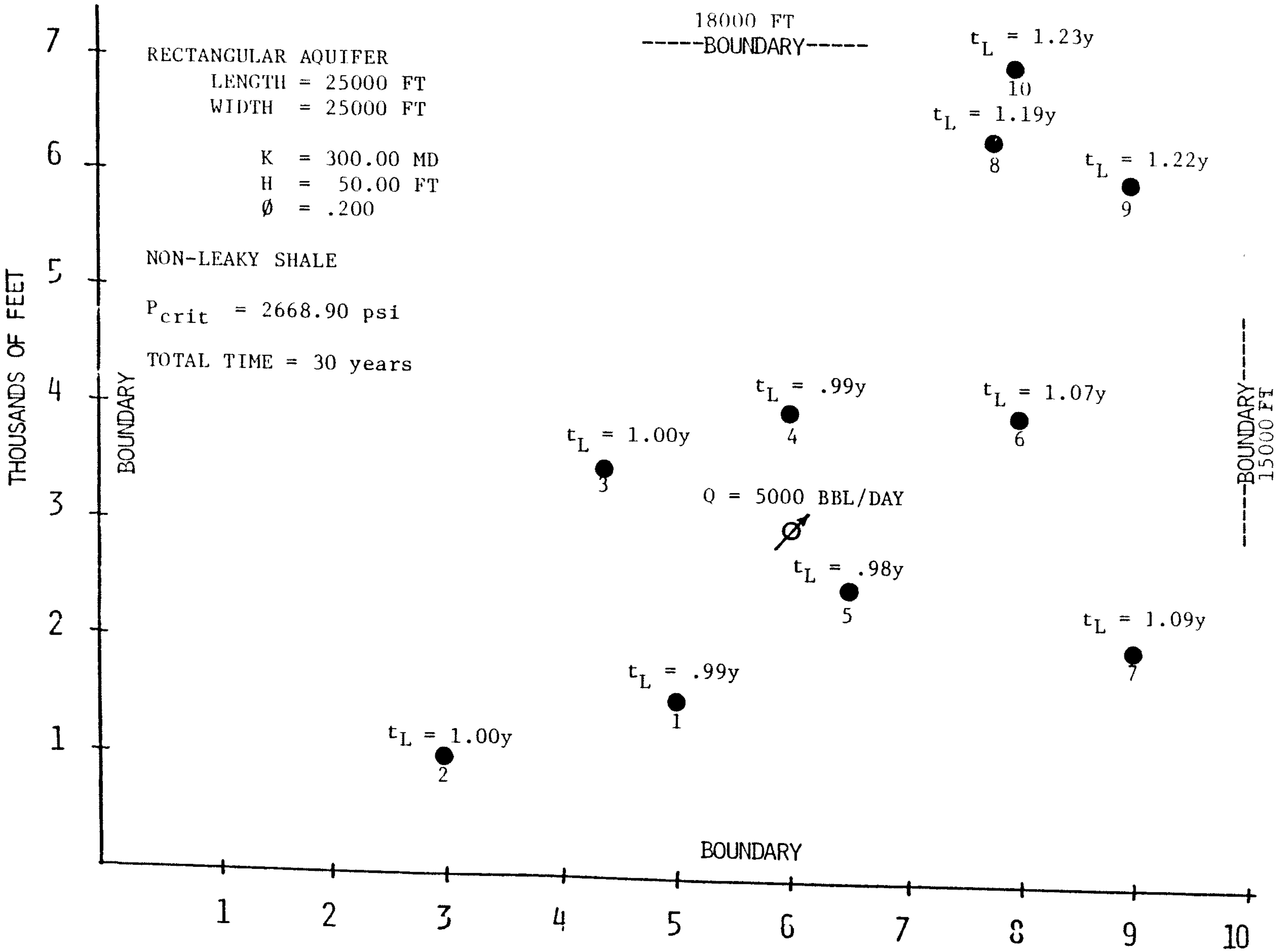
CASE II, GROUP 1, NO. 2



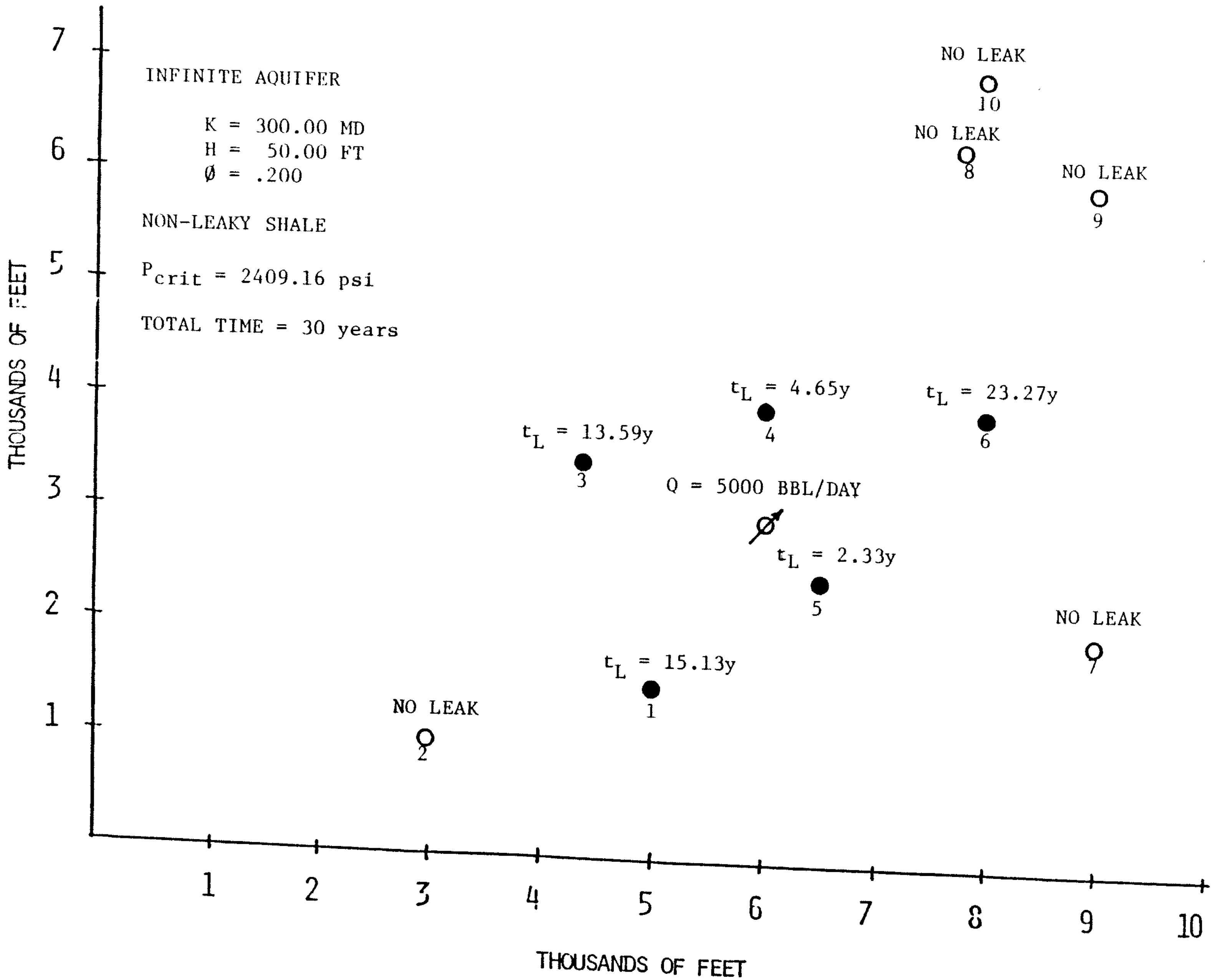
CASE II, GROUP 1, NO. 3



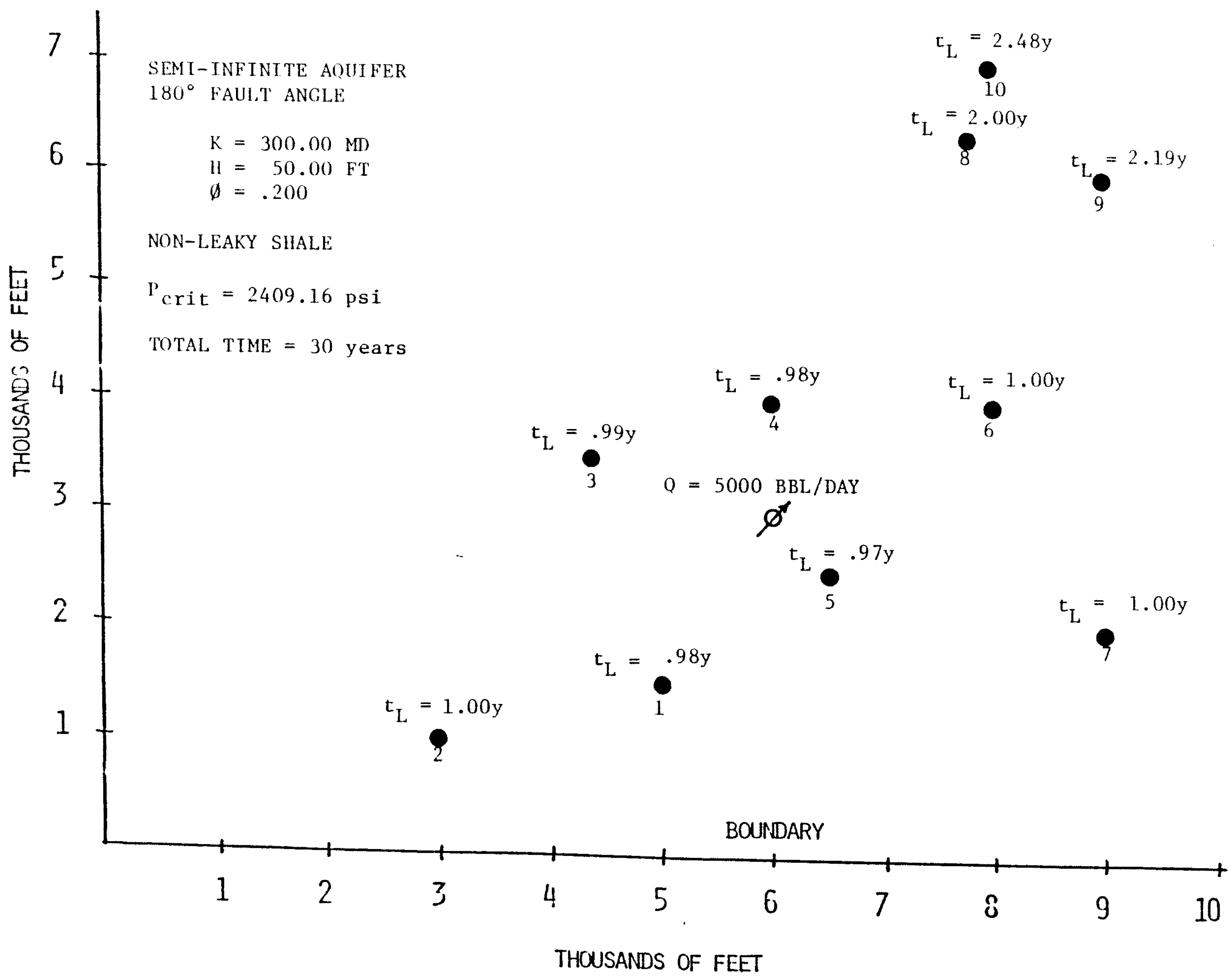
CASE II, GROUP 1, NO. 4



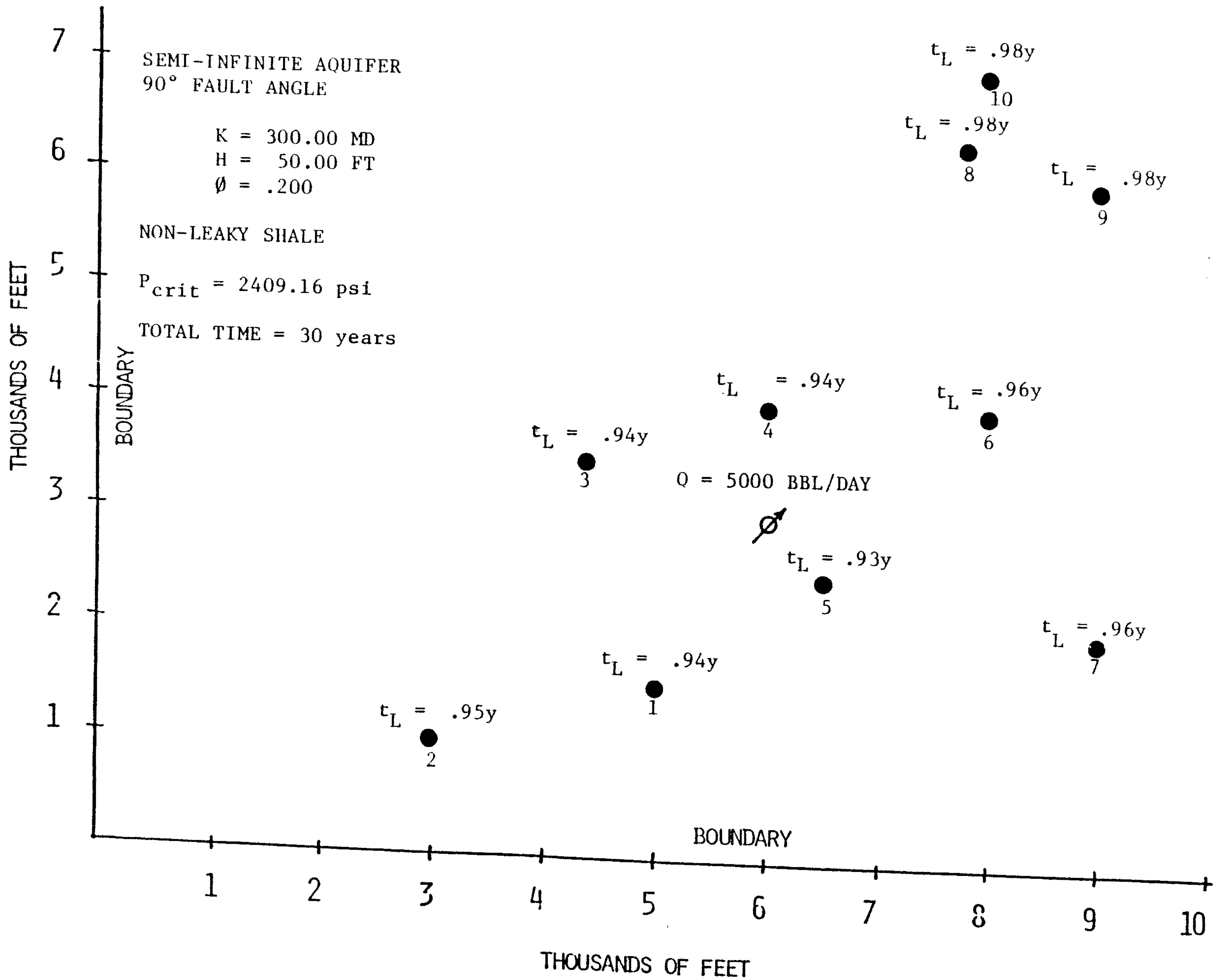
CASE II, GROUP 1, NO. 5



CASE II, GROUP 2, NO. 1



CASE II, GROUP 2, NO. 2



CASE II, GROUP 2, NO. 3

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CASE II

PROPERTIES OF THE DISPOSAL ZONE

COMPRESSIBILITY	= 0.500E-05	1/PSI
PERMEABILITY	= 300.000	MD
VISCOSITY	= 1.000	CP
THICKNESS	= 50.0	FT
POROSITY	=0.200	

PROPERTIES OF THE FRESH WATER ZONE

COMPRESSIBILITY	= 0.100E-04	1/PSI
PERMEABILITY	= 30.000	MD
VISCOSITY	= 1.000	CP
THICKNESS	= 50.0	FT
POROSITY	=0.200	

PROPERTIES OF THE SHALE LAYER

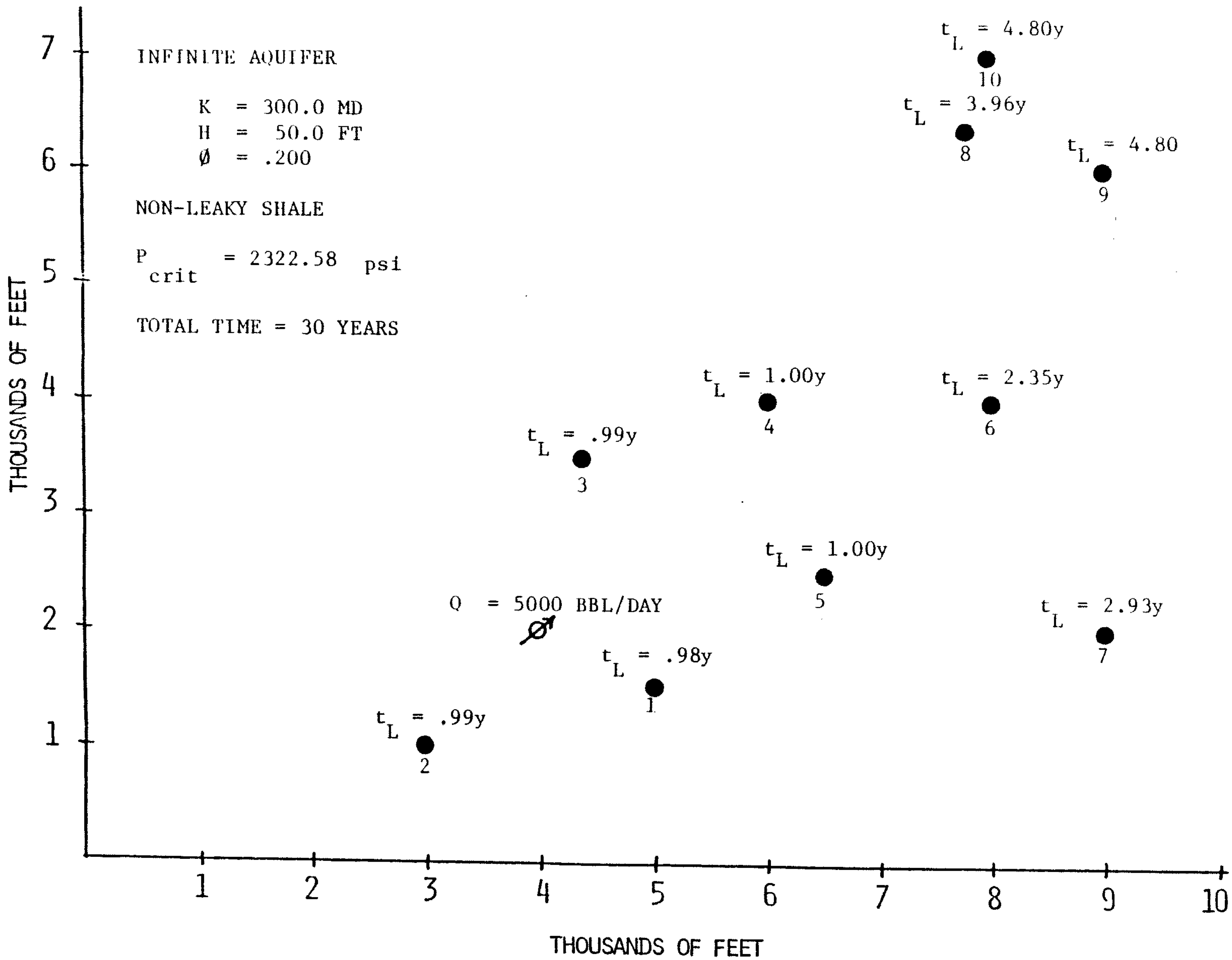
SHALE PERMEABILITY =0.10000E-02 MD
SHALE THICKNESS = 1.00000 FT

PROPERTIES OF ABANDONED HOLES

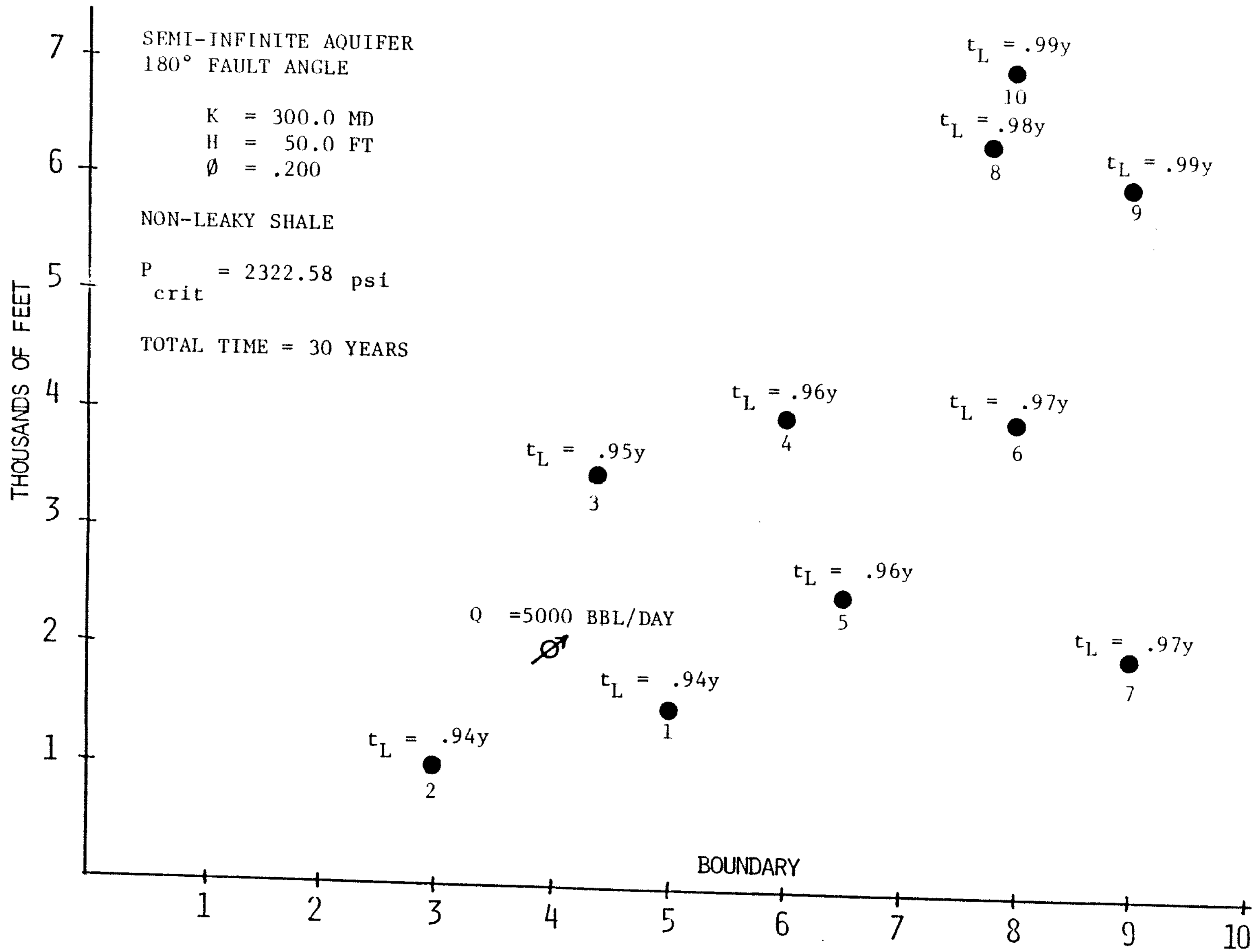
ABAN WELL	WELL DIAM IN	DEPTH TO DISP ZONE FT	DEPTH TO H2O ZONE FT	MUD DENSITY LB/GAL	GEL STRENGTH LB/100FT2	CRITIC PRESSU PSI
1	9.6	5000.00	600.0	8.600	75.00	2365.87
2	9.6	5000.00	600.0	8.600	75.00	2365.87
3	9.6	5000.00	600.0	8.600	75.00	2365.87
4	9.6	5000.00	600.0	8.600	75.00	2365.87
5	9.6	5000.00	600.0	8.600	75.00	2365.87
6	9.6	5000.00	600.0	8.600	75.00	2365.87
7	9.6	5000.00	600.0	8.600	75.00	2365.87
8	9.6	5000.00	600.0	8.600	75.00	2365.87
9	9.6	5000.00	600.0	8.600	75.00	2365.87
10	9.6	5000.00	600.0	8.600	75.00	2365.87

COORDINATES OF THE ABANDONED WELLS

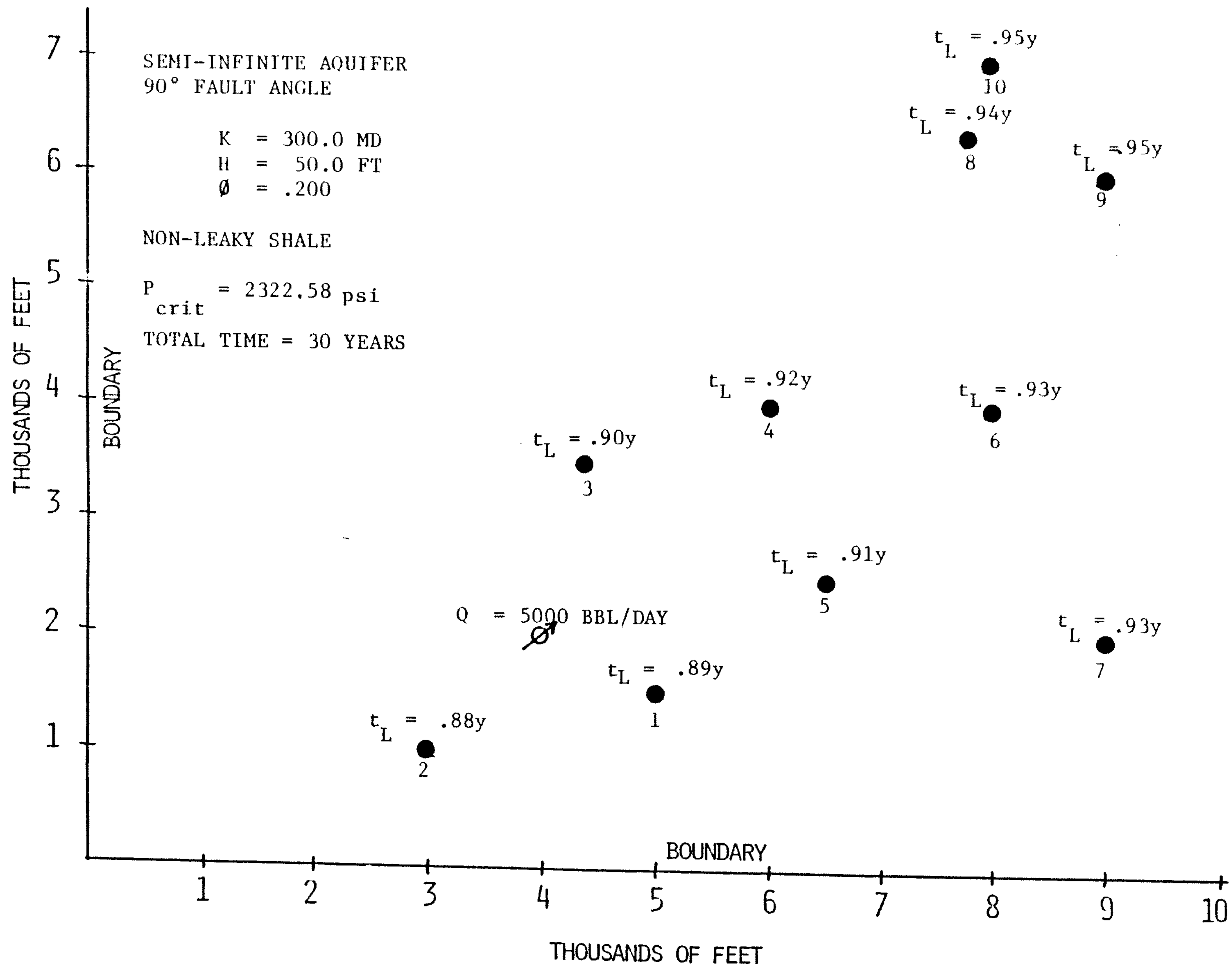
WELL #	X FT.	Y FT.
1	5000.000	1500.000
2	3000.000	1000.000
3	4400.000	3600.000
4	6000.000	4000.000
5	6500.000	2500.000
6	8000.000	4000.000
7	9000.000	2000.000
8	7800.000	6400.000
9	9000.000	6000.000
10	8000.000	7000.000



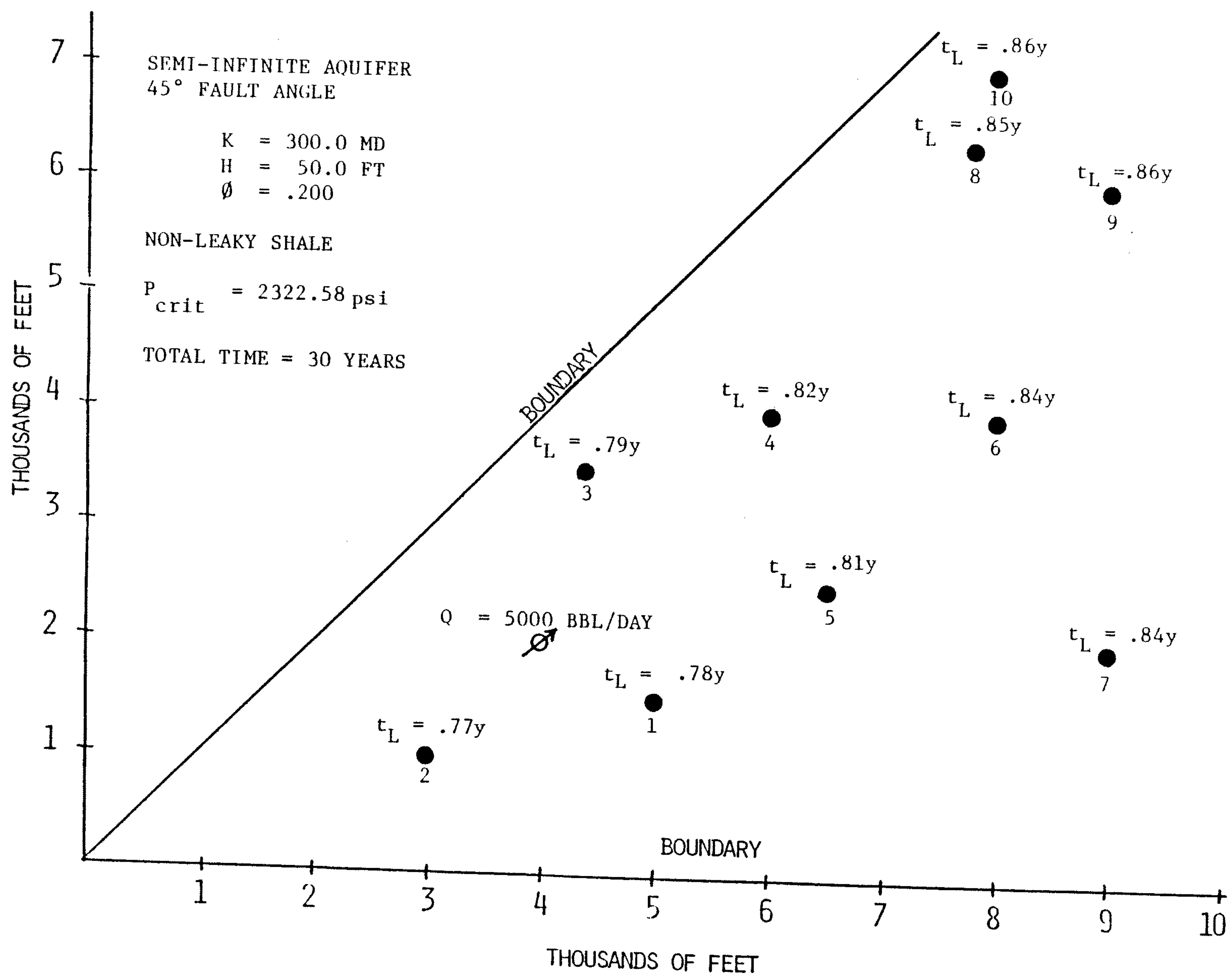
CASE II, GROUP 3, NO. 1



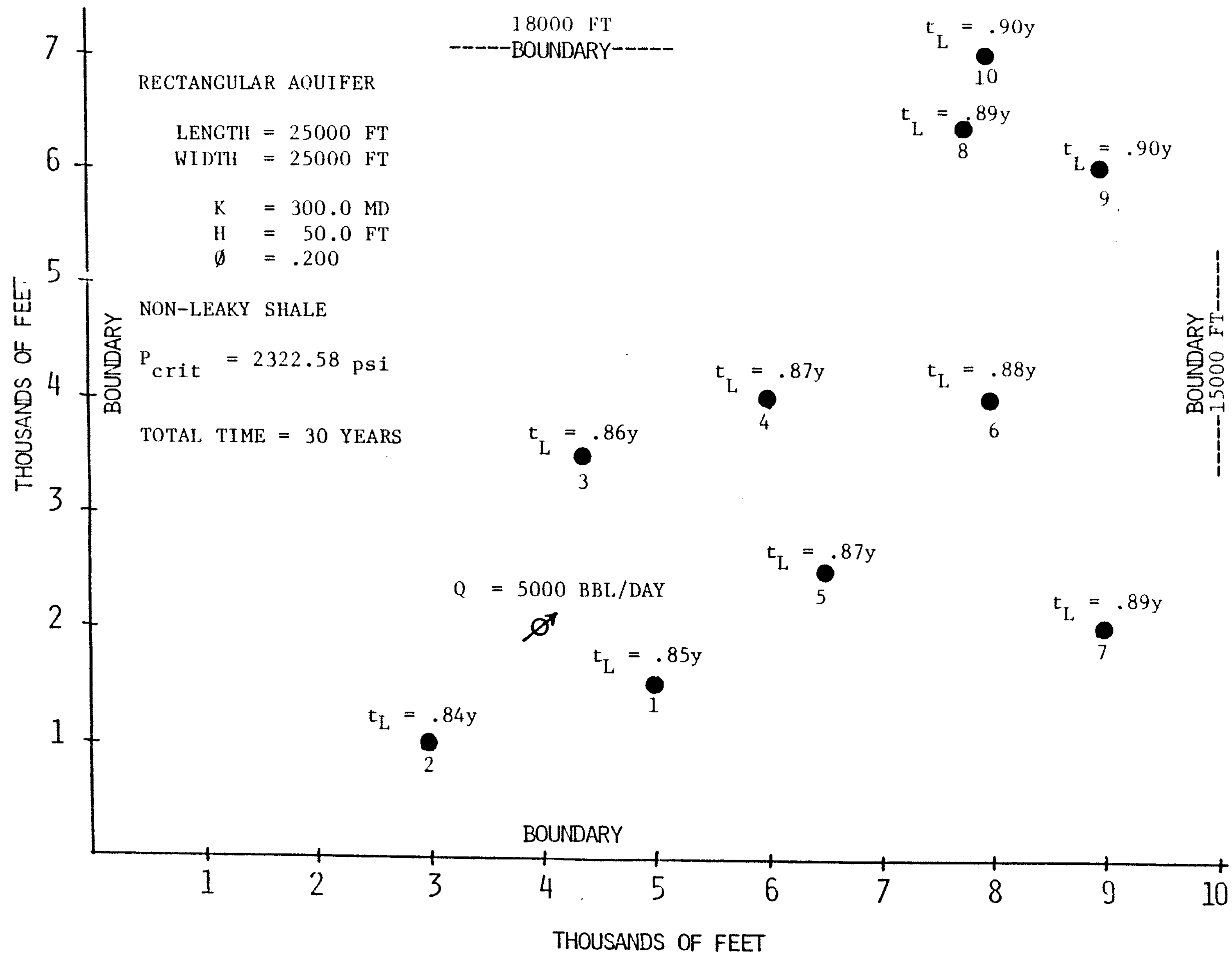
CASE II, GROUP 3, NO. 2



CASE II, GROUP 3, NO. 3



CASE II, GROUP 3, NO. 4



CASE II, GROUP 3, NO. 5

CASE II, GROUP 4

PROPERTIES OF THE DISPOSAL ZONE

COMPRESSIBILITY	= 0.500E-05 1/PSI
PERMEABILITY	= 300.000 MD
VISCOSITY	= 1.000 CP
THICKNESS	= 50.0 FT
POROSITY	=0.200

PROPERTIES OF THE SHALE LAYER

SHALE PERMEABILITY =0.10000E-02 MD
SHALE THICKNESS = 1.00000 FT

PROPERTIES OF ABANDONED HOLES

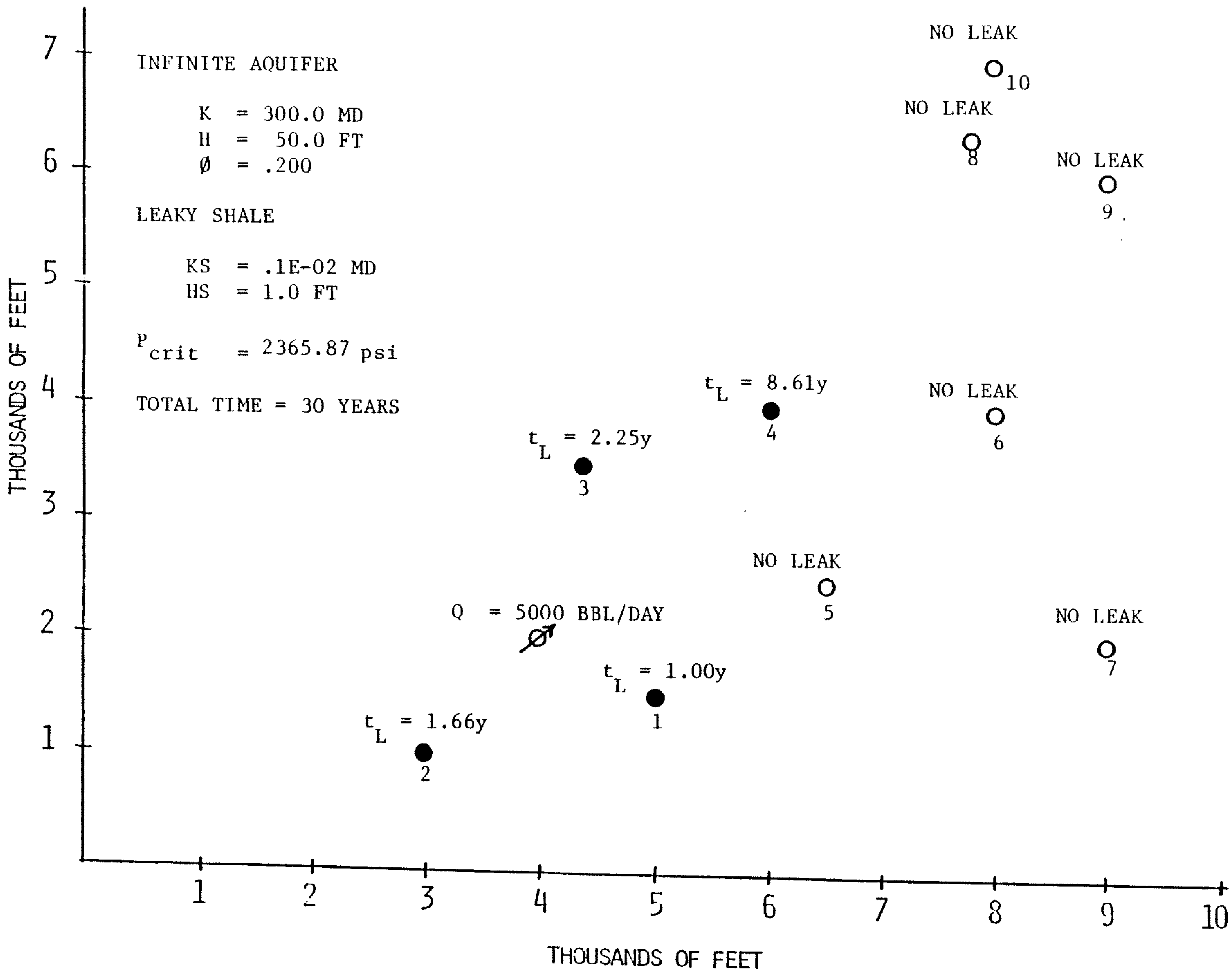
ABAN WELL	WELL DIAM IN	DEPTH TO DISP ZONE FT	DEPTH TO H2O ZONE FT	MUD DENSITY LB/GAL	GEL STRENGTH LB/100FT2	CRITIC PRESSU PSI
1	9.6	5000.00	600.0	8.600	75.00	2365.87
2	9.6	5000.00	600.0	8.600	75.00	2365.87
3	9.6	5000.00	600.0	8.600	75.00	2365.87
4	9.6	5000.00	600.0	8.600	75.00	2365.87
5	9.6	5000.00	600.0	8.600	75.00	2365.87
6	9.6	5000.00	600.0	8.600	75.00	2365.87
7	9.6	5000.00	600.0	8.600	75.00	2365.87
8	9.6	5000.00	600.0	8.600	75.00	2365.87
9	9.6	5000.00	600.0	8.600	75.00	2365.87
10	9.6	5000.00	600.0	8.600	75.00	2365.87

COORDINATES OF THE ABANDONED WELLS

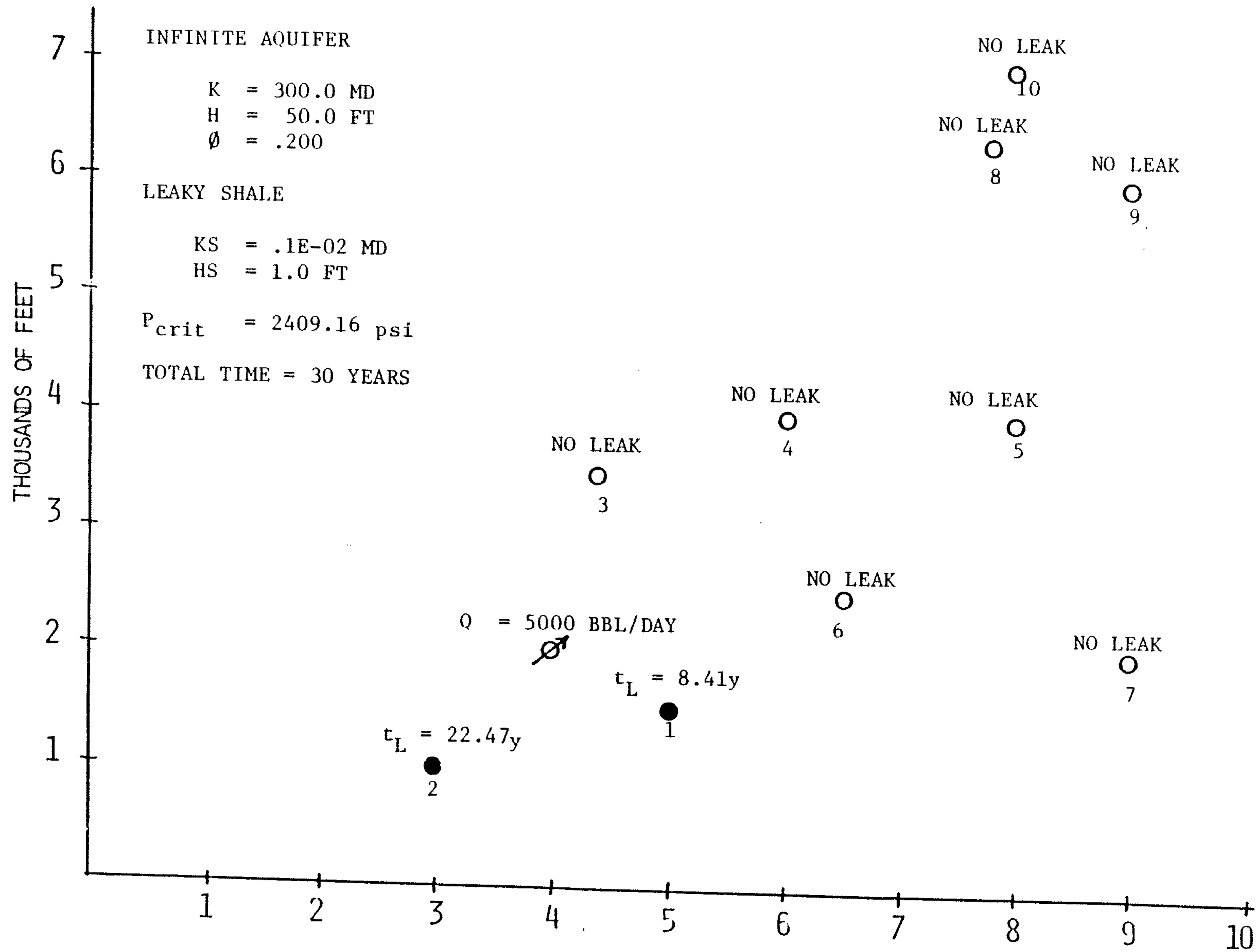
WELL #	X FT.	Y FT.
1	5000.000	1500.000
2	3000.000	1000.000
3	4400.000	3600.000
4	6000.000	4000.000
5	6500.000	2500.000
6	8000.000	4000.000
7	9000.000	2000.000
8	7800.000	6400.000
9	9000.000	6000.000
10	8000.000	7000.000

COORDINATES OF THE INJECTION WELL

X= 4000.000 Y= 2000.000 FT.
INJECTION RATE =5000. BBL/DAY



CASE II, GROUP 4, NO. 1



CASE II, GROUP4, NO. 2

CASE III

EFFECTS OF PARTIALLY-SEALING FAULTS

CASE III

PROPERTIES OF THE DISPOSAL ZONE

COMPRESSIBILITY =	0.500E-05	1/PSI
PERMEABILITY =	300.000	MD
VISCOSITY =	1.000	CP
THICKNESS =	50.0	FT
POROSITY =	0.200	

PROPERTIES OF ABANDONED HOLES

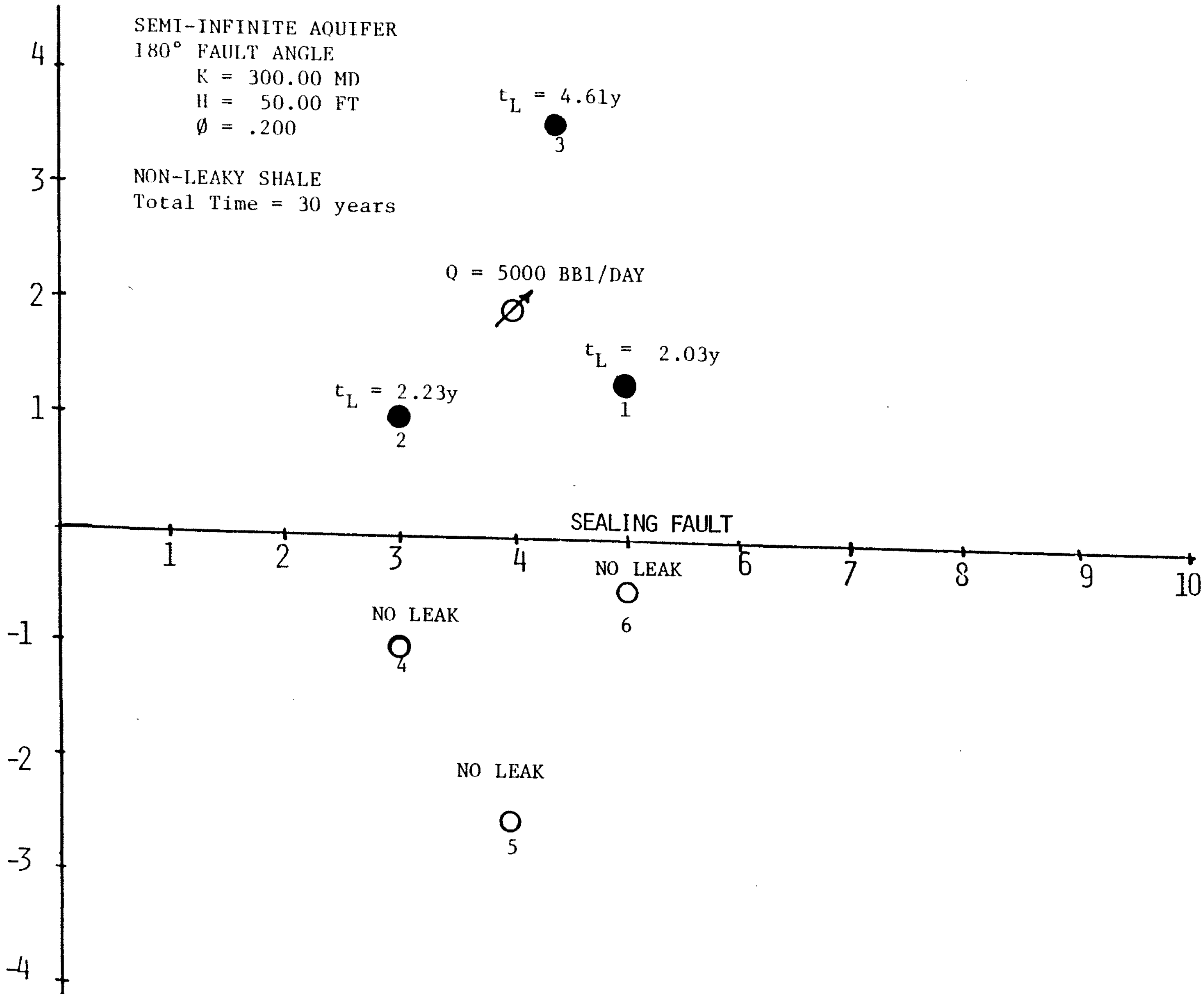
ABAN WELL	WELL DIAM IN	DEPTH TO DISP ZONE FT	DEPTH TO H2O ZONE FT	MUD DENSITY LB/GAL	GEL STRENGTH LB/100FT2	CRITIC PRESSU PSI
1	9.6	5000.00	600.0	9.000	100.00	2513.16
2	9.6	5000.00	600.0	9.000	100.00	2513.16
3	9.6	5000.00	600.0	9.000	100.00	2513.16
4	9.6	5000.00	600.0	9.000	100.00	2513.16
5	9.6	5000.00	600.0	9.000	100.00	2513.16
6	9.6	5000.00	600.0	9.000	100.00	2513.16

COORDINATES OF THE ABANDONED WELLS

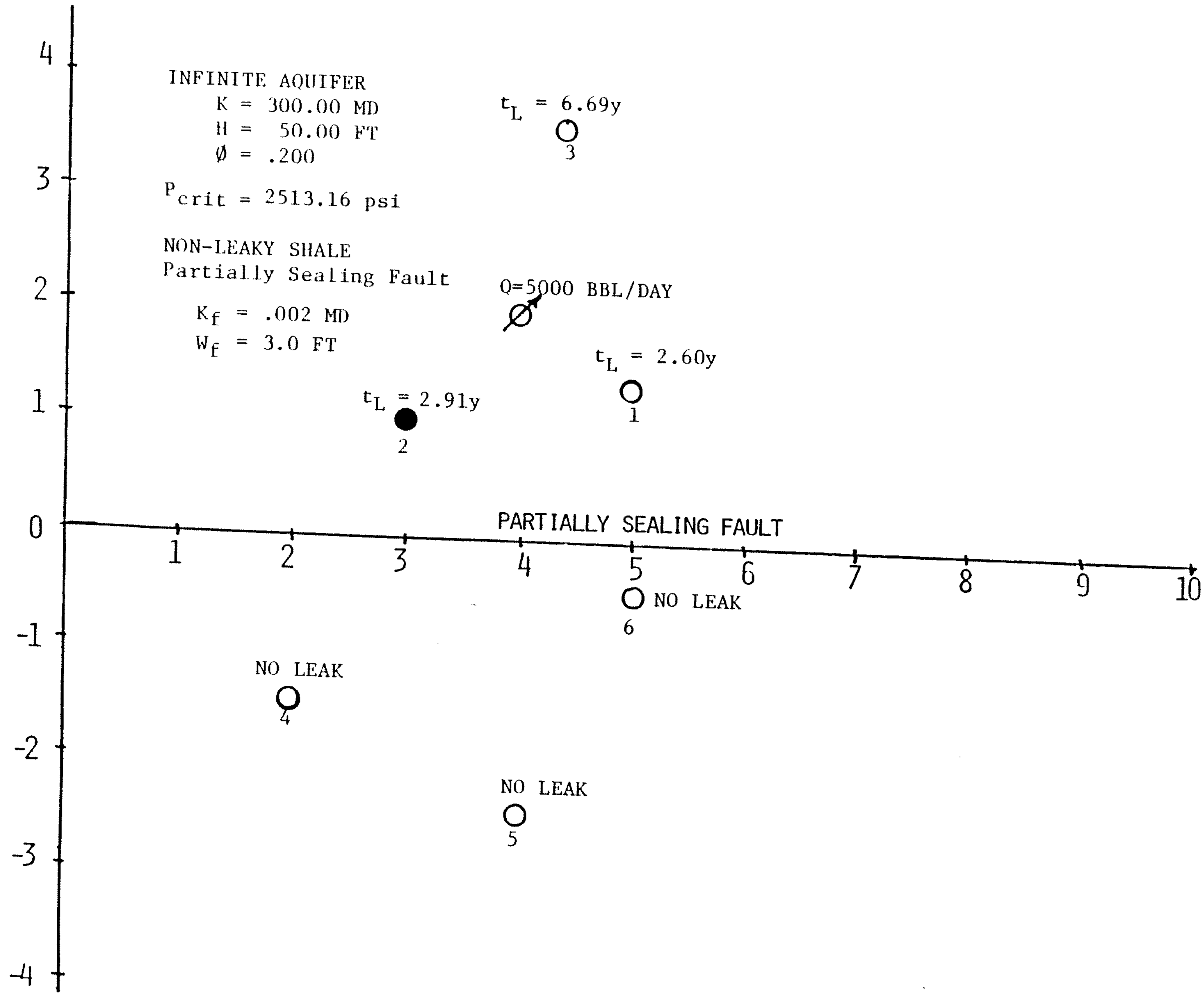
WELL #	X FT.	Y FT.
1	5000.000	1500.000
2	3000.000	1000.000
3	4400.000	3600.000
4	3000.000	-1000.000
5	4000.000	-2500.000
6	5000.000	-500.000

COORDINATES OF THE INJECTION WELL

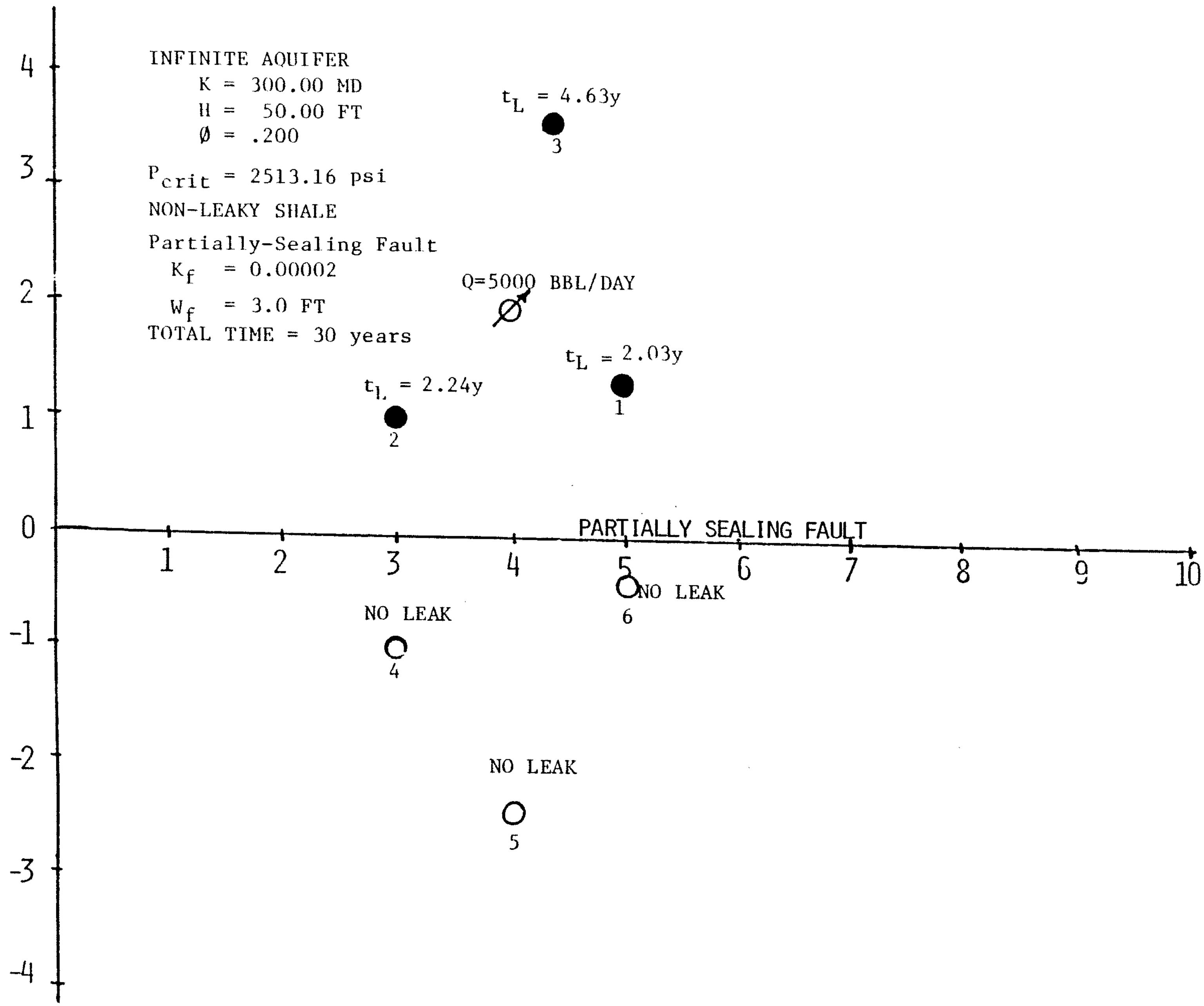
X= 4000.000 Y= 2000.000 FT.
INJECTION RATE =5000. BBL/DAY

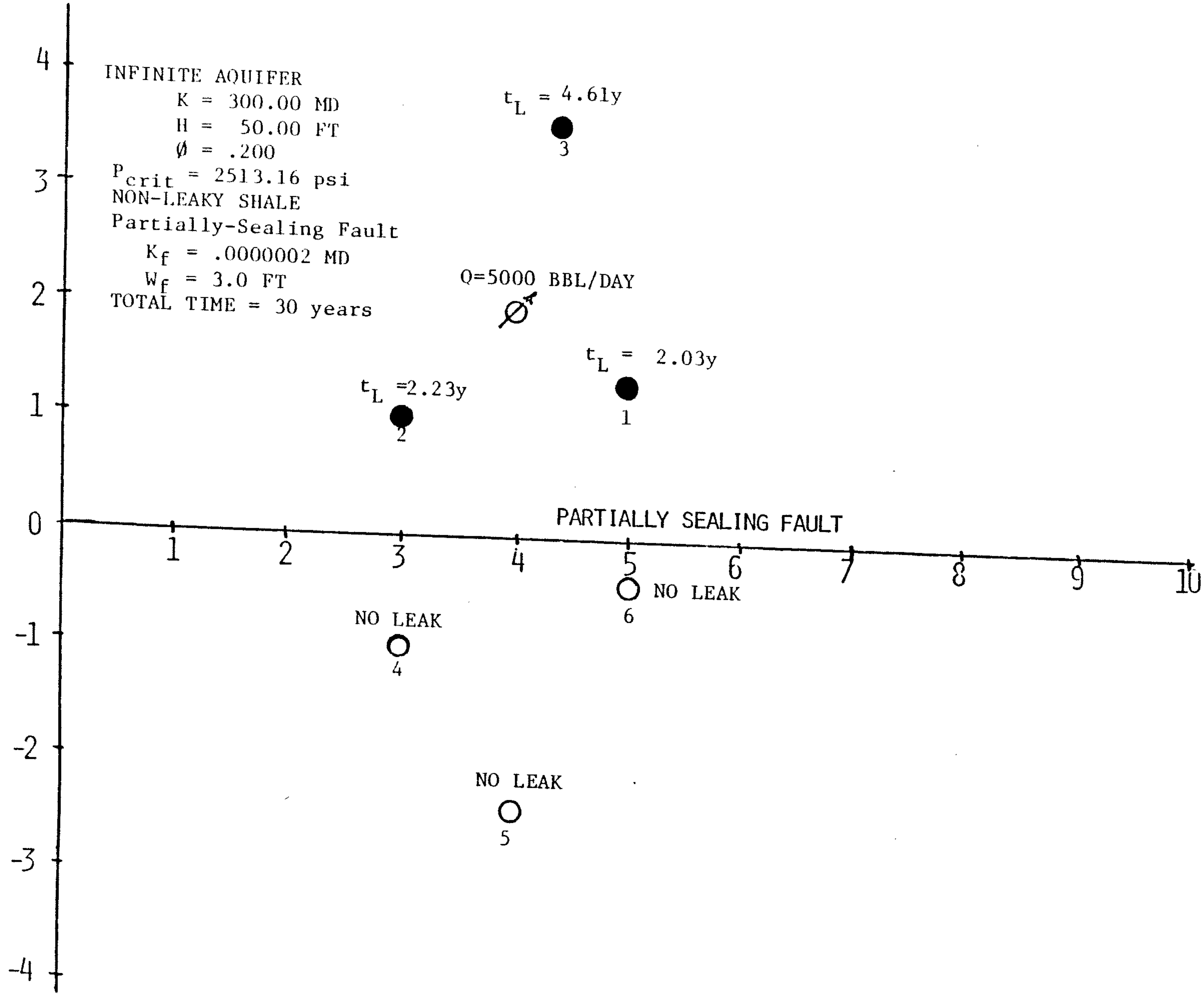


SEMI-INFINITE AQUIFER
180° FAULT ANGLE
K = 300.00 MD
H = 50.00 FT
Ø = .200
NON-LEAKY SHALE
Total Time = 30 years
t_L = 4.61y
Q = 5000 BBl/DAY
t_L = 2.03y
t_L = 2.23y
SEALING FAULT
NO LEAK
NO LEAK
NO LEAK



INFINITE AQUIFER
K = 300.00 MD
H = 50.00 FT
Ø = .200
Pcrit = 2513.16 psi
NON-LEAKY SHALE
Partially Sealing Fault
Kf = .002 MD
Wf = 3.0 FT
tL = 6.69y
3
Q=5000 BBL/DAY
tL = 2.60y
1
tL = 2.91y
2
PARTIALLY SEALING FAULT
NO LEAK
6
NO LEAK
4
NO LEAK
5
4
3
2
1
0
-1
-2
-3
-4
1
2
3
4
5
6
7
8
9
10


INFINITE AQUIFER
K = 300.00 MD
H = 50.00 FT
Ø = .200
P crit = 2513.16 psi
NON-LEAKY SHALE
Partially-Sealing Fault
K f = 0.00002
W f = 3.0 FT
TOTAL TIME = 30 years
t L = 4.63y
Q=5000 BBL/DAY
t L = 2.03y
t L = 2.24y
PARTIALLY SEALING FAULT
NO LEAK
NO LEAK
NO LEAK
1
2
3
4
5
6
7
8
9
10
0
-1
-2
-3
-4


INFINITE AQUIFER
K = 300.00 MD
H = 50.00 FT
Ø = .200
Pcrit = 2513.16 psi
NON-LEAKY SHALE
Partially-Sealing Fault
Kf = .0000002 MD
Wf = 3.0 FT
TOTAL TIME = 30 years
tL = 4.61y
3
Q=5000 BBL/DAY
tL = 2.03y
1
tL =2.23y
2
PARTIALLY SEALING FAULT
NO LEAK
6
NO LEAK
4
NO LEAK
5
4
3
2
1
0
-1
-2
-3
-4
1
2
3
4
5
6
7
8
9
10

CASE IV

EFFECTS OF LEAKY SHALE AQUICLUDES

Group 1, Comparison of leaking and non-leaking shale aquicludes for 45^{o} fault angle case

Group 2, Effect of boundaries on leaky-shale case

Group 3, Same as Group 2 but with different injection well location

Group 4, Same as Group 3 but again a different injection well location

Group 5, Two runs, same as Group 2, No. 1 for a shale thickness of 5.0 and 10.0 ft respectively

Group 6, Same as Group 1 above but with P_{crit} changed from 2513.16 to 2322.58 Psi

Group 7, Same as Group 6 but with P_{crit} set to 2668.9 Psi

NOTE: An artificially large value for shale permeability K_s, and a small value for shale thickness, h_s, were used in these examples in order to demonstrate large effects of shale leakage on pressure response for illustrative purposes.

CASE IV, GROUP 1

PROPERTIES OF THE DISPOSAL ZONE

COMPRESSIBILITY = 0.500E-05 1/PSI
PERMEABILITY = 100.000 MD
VISCOSITY = 1.000 CP
THICKNESS = 300.0 FT
POROSITY =0.200

PROPERTIES OF THE SHALE LAYER

SHALE PERMEABILITY =0.10000E-02 MD
SHALE THICKNESS = 1.00000 FT

PROPERTIES OF ABANDONED HOLES

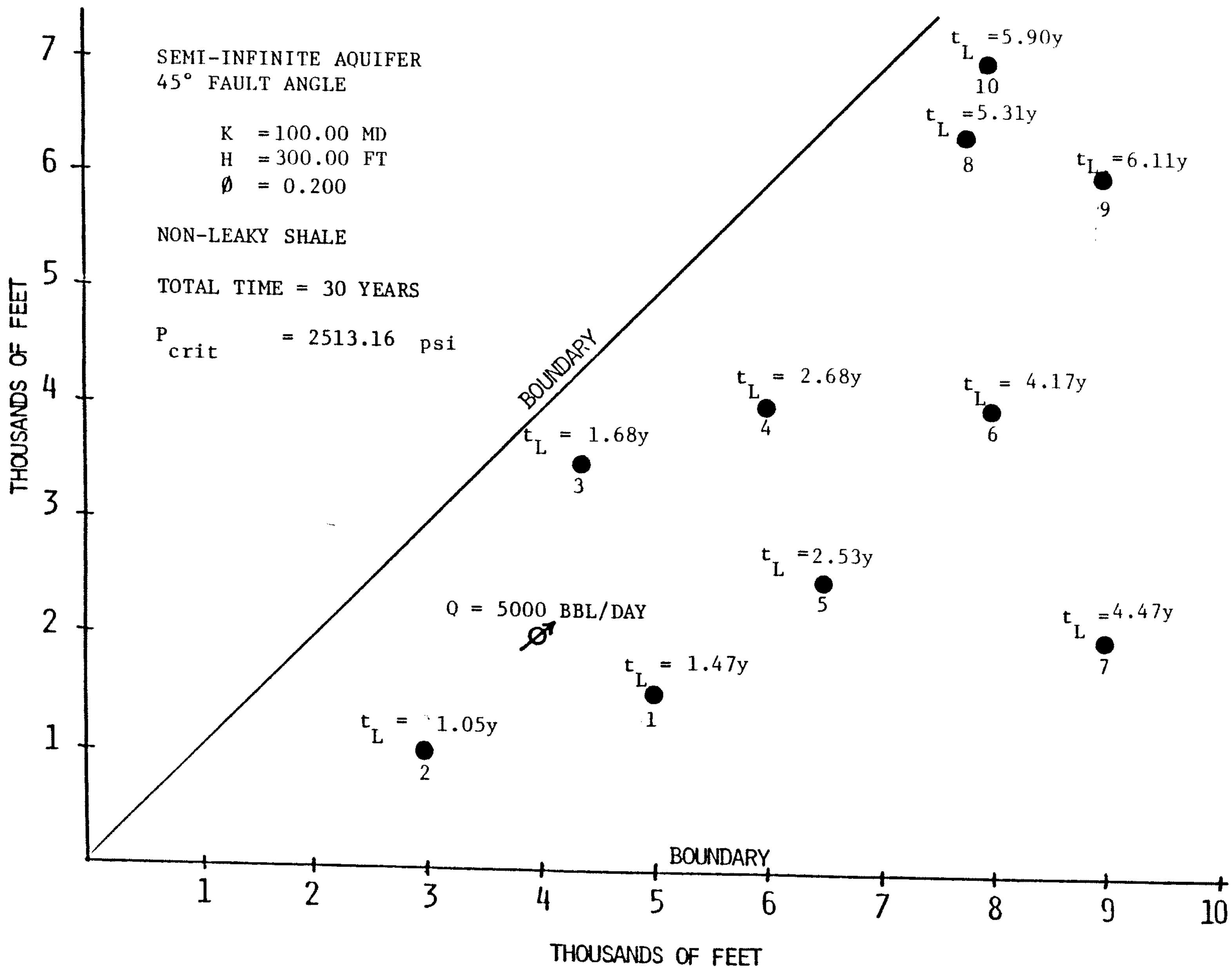
ABAN WELL	WELL DIAM IN	DEPTH TO DISP ZONE FT	DEPTH TO H2O ZONE FT	MUD DENSITY LB/GAL	GEL STRENGTH LB/100FT2	CRITIC PRESSU PSI
1	9.6	5000.00	600.0	9.000	100.00	2513.16
2	9.6	5000.00	600.0	9.000	100.00	2513.16
3	9.6	5000.00	600.0	9.000	100.00	2513.16
4	9.6	5000.00	600.0	9.000	100.00	2513.16
5	9.6	5000.00	600.0	9.000	100.00	2513.16
6	9.6	5000.00	600.0	9.000	100.00	2513.16
7	9.6	5000.00	600.0	9.000	100.00	2513.16
8	9.6	5000.00	600.0	9.000	100.00	2513.16
9	9.6	5000.00	600.0	9.000	100.00	2513.16
10	9.6	5000.00	600.0	9.000	100.00	2513.16

COORDINATES OF THE ABANDONED WELLS

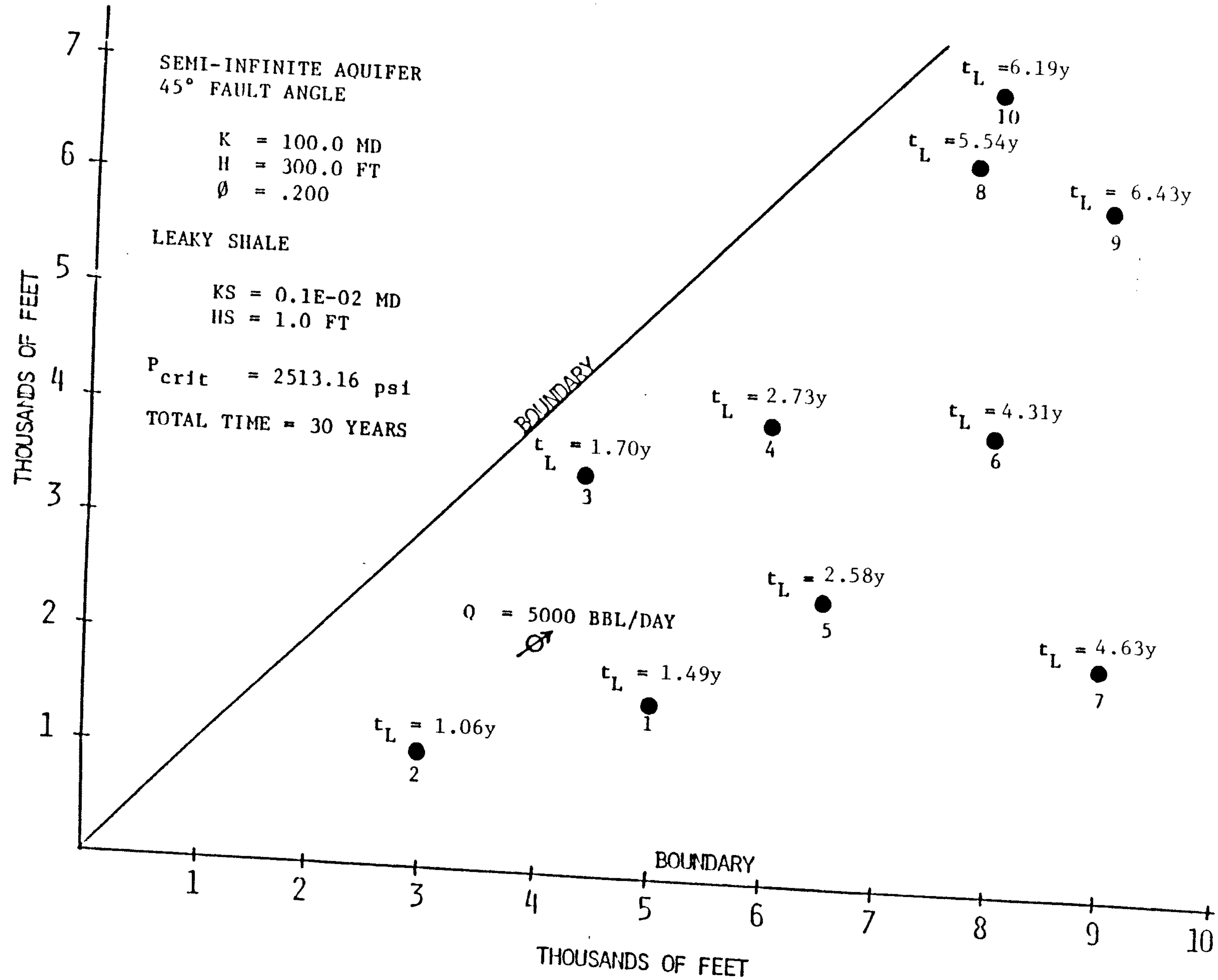
WELL #	X FT.	Y FT.
1	5000.000	1500.000
2	3000.000	1000.000
3	4400.000	3600.000
4	6000.000	4000.000
5	6500.000	2500.000
6	8000.000	4000.000
7	9000.000	2000.000
8	7800.000	6400.000
9	9000.000	6000.000
10	8000.000	7000.000

COORDINATES OF THE INJECTION WELL

X= 4000.000 Y= 2000.000 FT.
INJECTION RATE =5000. BBL/DAY



ASE IV, GROUP 1, NO. 1



CASE IV, GROUP 1, NO. 2

CASE IV GROUP 2

PROPERTIES OF THE DISPOSAL ZONE
****
COMPRESSIBILITY = 0.500E-05 1/PSI
PERMEABILITY = 100.000 MD
VISCOSITY = 1.000 CP
THICKNESS = 300.0 FT
POROSITY =0.200
****

PROPERTIES OF THE SHALE LAYER
****

SHALE PERMEABILITY =0.10000E-02 MD
SHALE THICKNESS = 1.00000 FT

PROPERTIES OF ABANDONED HOLES

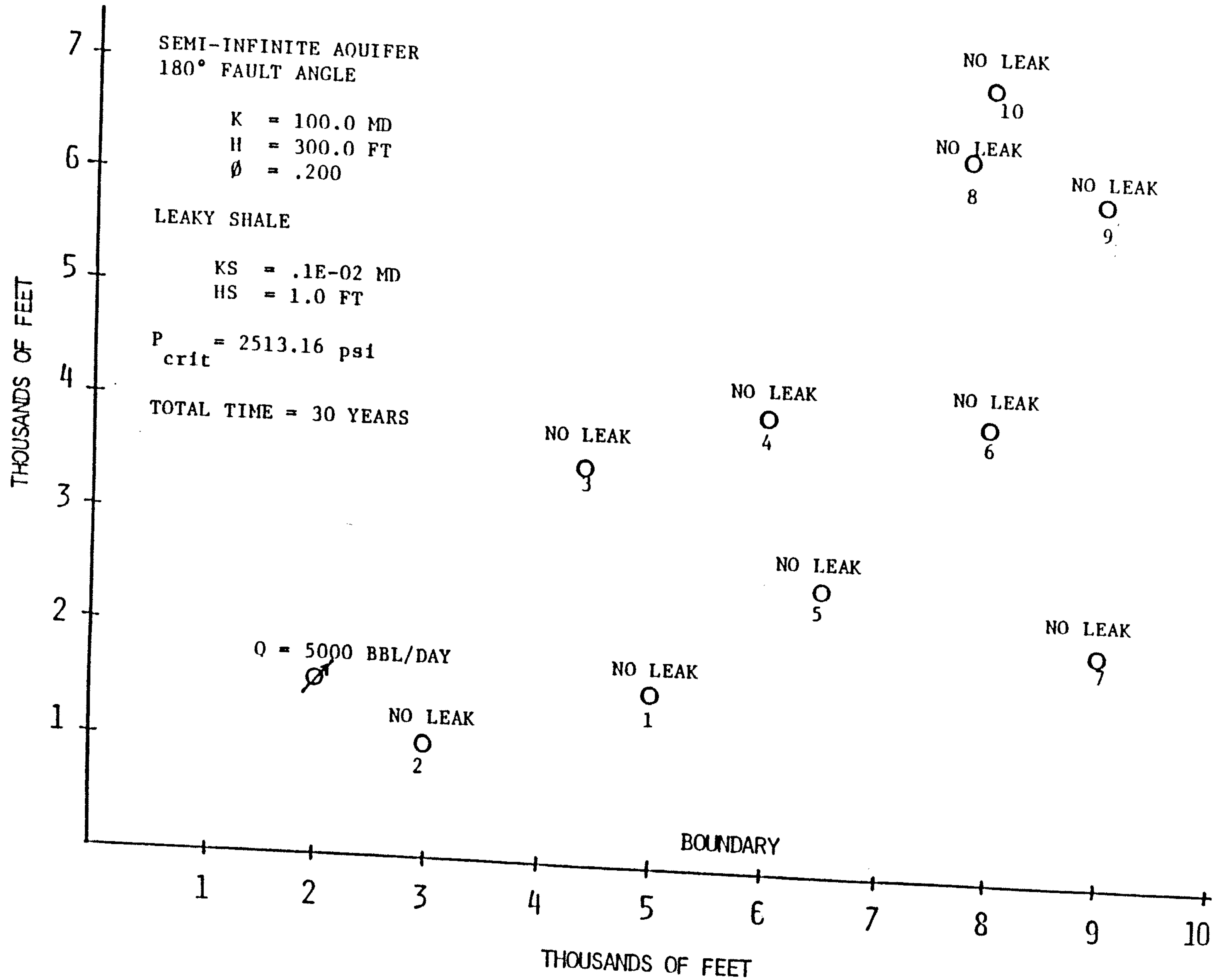
ABAN WELL	WELL DIAM IN	DEPTH TO DISP ZONE FT	DEPTH TO H2O ZONE FT	MUD DENSITY LB/GAL	GEL STRENGTH LB/100FT2	CRITIC PRESSU PSI
1	9.6	5000.00	600.0	9.000	100.00	2513.16
2	9.6	5000.00	600.0	9.000	100.00	2513.16
3	9.6	5000.00	600.0	9.000	100.00	2513.16
4	9.6	5000.00	600.0	9.000	100.00	2513.16
5	9.6	5000.00	600.0	9.000	100.00	2513.16
6	9.6	5000.00	600.0	9.000	100.00	2513.16
7	9.6	5000.00	600.0	9.000	100.00	2513.16
8	9.6	5000.00	600.0	9.000	100.00	2513.16
9	9.6	5000.00	600.0	9.000	100.00	2513.16
10	9.6	5000.00	600.0	9.000	100.00	2513.16

COORDINATES OF THE ABANDONED WELLS

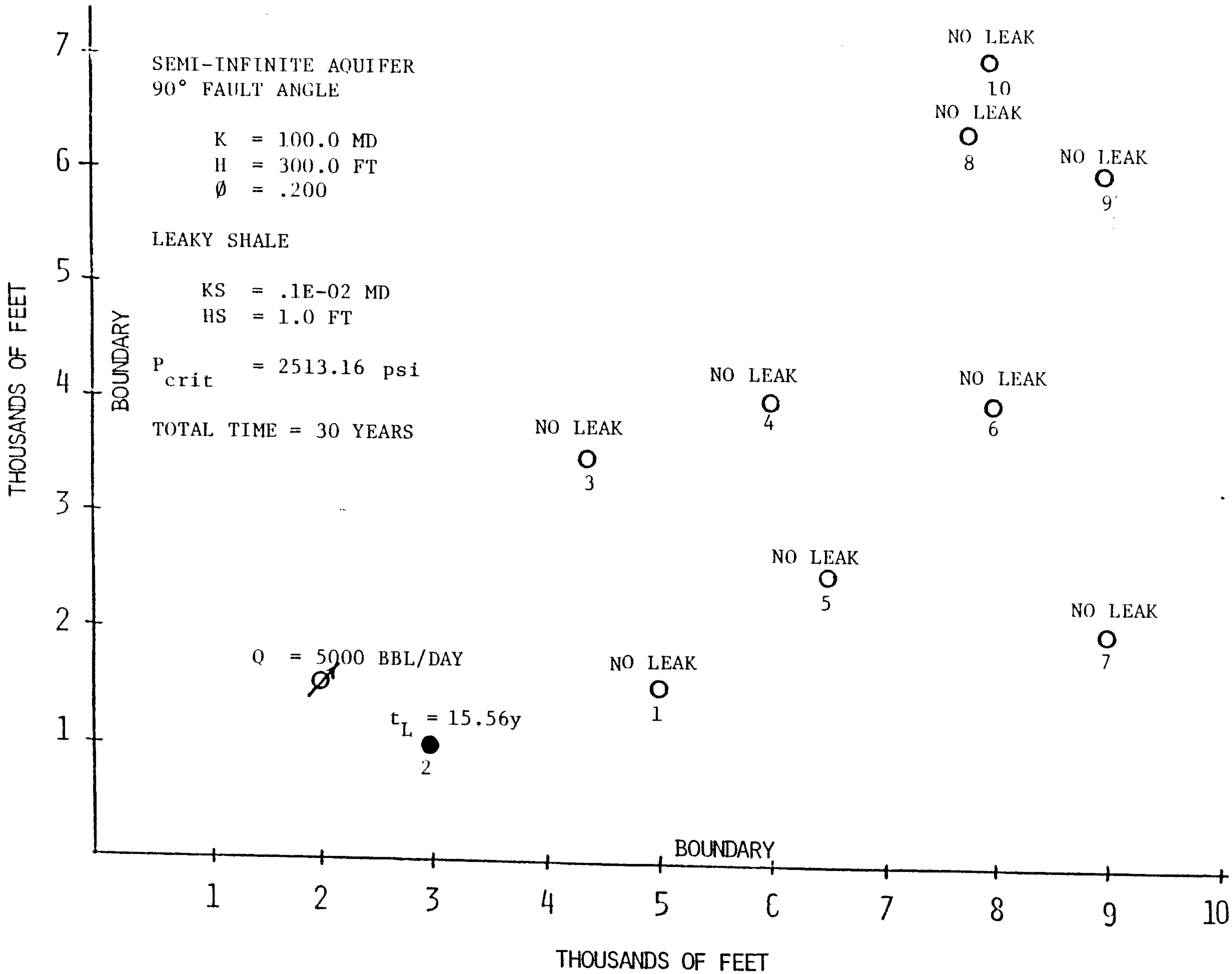
WELL # ******	X FT.	Y FT.
1	5000.000	1500.000
2	3000.000	1000.000
3	4400.000	3600.000
4	6000.000	4000.000
5	6500.000	2500.000
6	8000.000	4000.000
7	9000.000	2000.000
8	7800.000	6400.000
9	9000.000	6000.000
10	8000.000	7000.000

COORDINATES OF THE INJECTION WELL

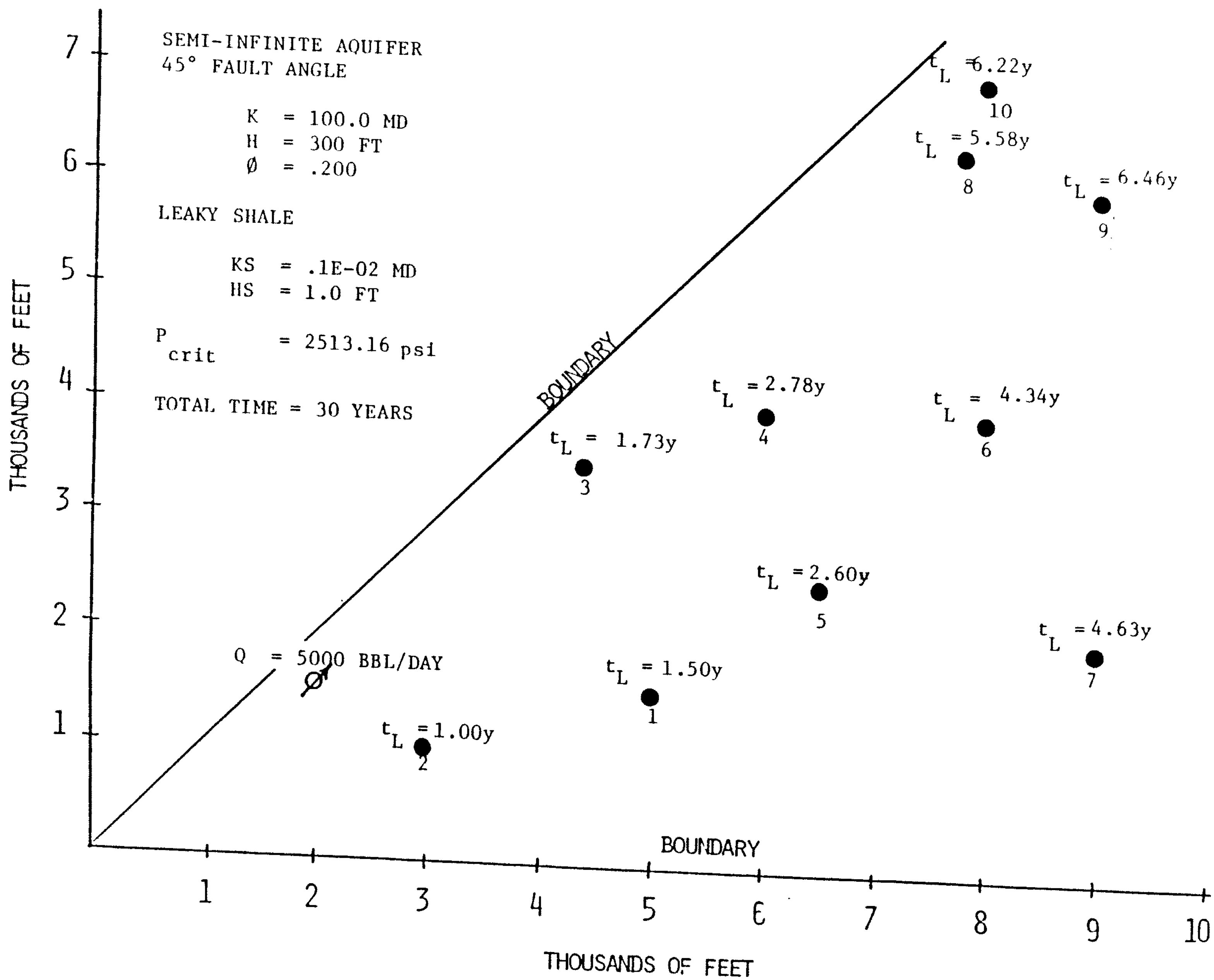
X= 2000.000 Y= 1500.000 FT.
INJECTION RATE =5000. BBL/DAY



CASE IV, GROUP 2, NO. 1



IV, GROUP 2, NO. 2



CASE IV, GROUP 2, NO. 3

CASE IV, GROUP 3

PROPERTIES OF THE DISPOSAL ZONE

COMPRESSIBILITY = 0.500E-05 1/PSI
PERMEABILITY = 300.000 MD
VISCOSITY = 1.000 CP
THICKNESS = 50.0 FT
POROSITY =0.200

PROPERTIES OF THE SHALE LAYER

SHALE PERMEABILITY =0.10000E-02 MD
SHALE THICKNESS = 1.00000 FT

PROPERTIES OF ABANDONED HOLES

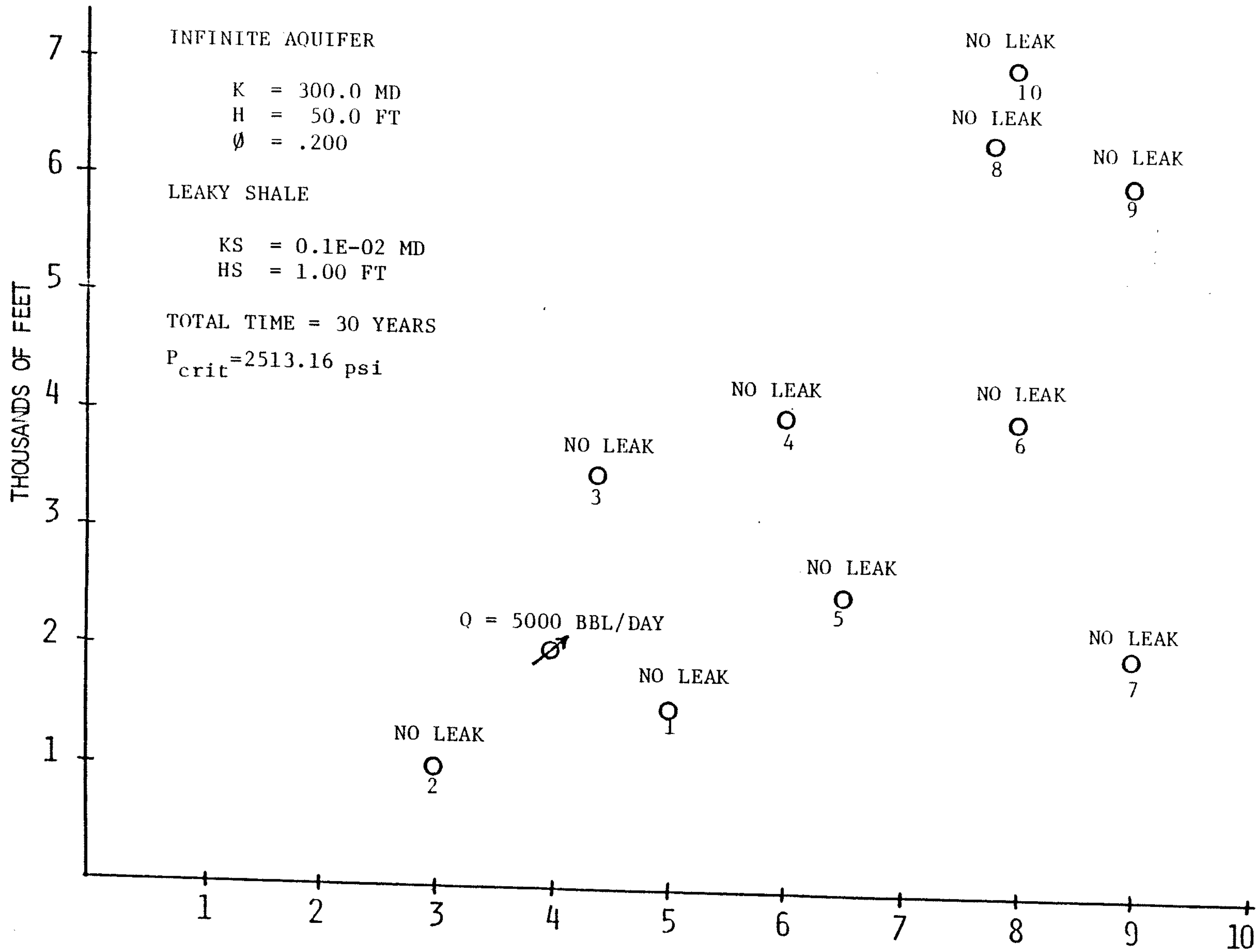
ABAN WELL	WELL DIAM IN	DEPTH TO DISP ZONE FT	DEPTH TO H2O ZONE FT	MUD DENSITY LB/GAL	GEL STRENGTH LB/100FT2	CRITIC PRESSU PSI
1	9.6	5000.00	600.0	9.000	100.00	2513.16
2	9.6	5000.00	600.0	9.000	100.00	2513.16
3	9.6	5000.00	600.0	9.000	100.00	2513.16
4	9.6	5000.00	600.0	9.000	100.00	2513.16
5	9.6	5000.00	600.0	9.000	100.00	2513.16
6	9.6	5000.00	600.0	9.000	100.00	2513.16
7	9.6	5000.00	600.0	9.000	100.00	2513.16
8	9.6	5000.00	600.0	9.000	100.00	2513.16
9	9.6	5000.00	600.0	9.000	100.00	2513.16
10	9.6	5000.00	600.0	9.000	100.00	2513.16

COORDINATES OF THE ABANDONED WELLS

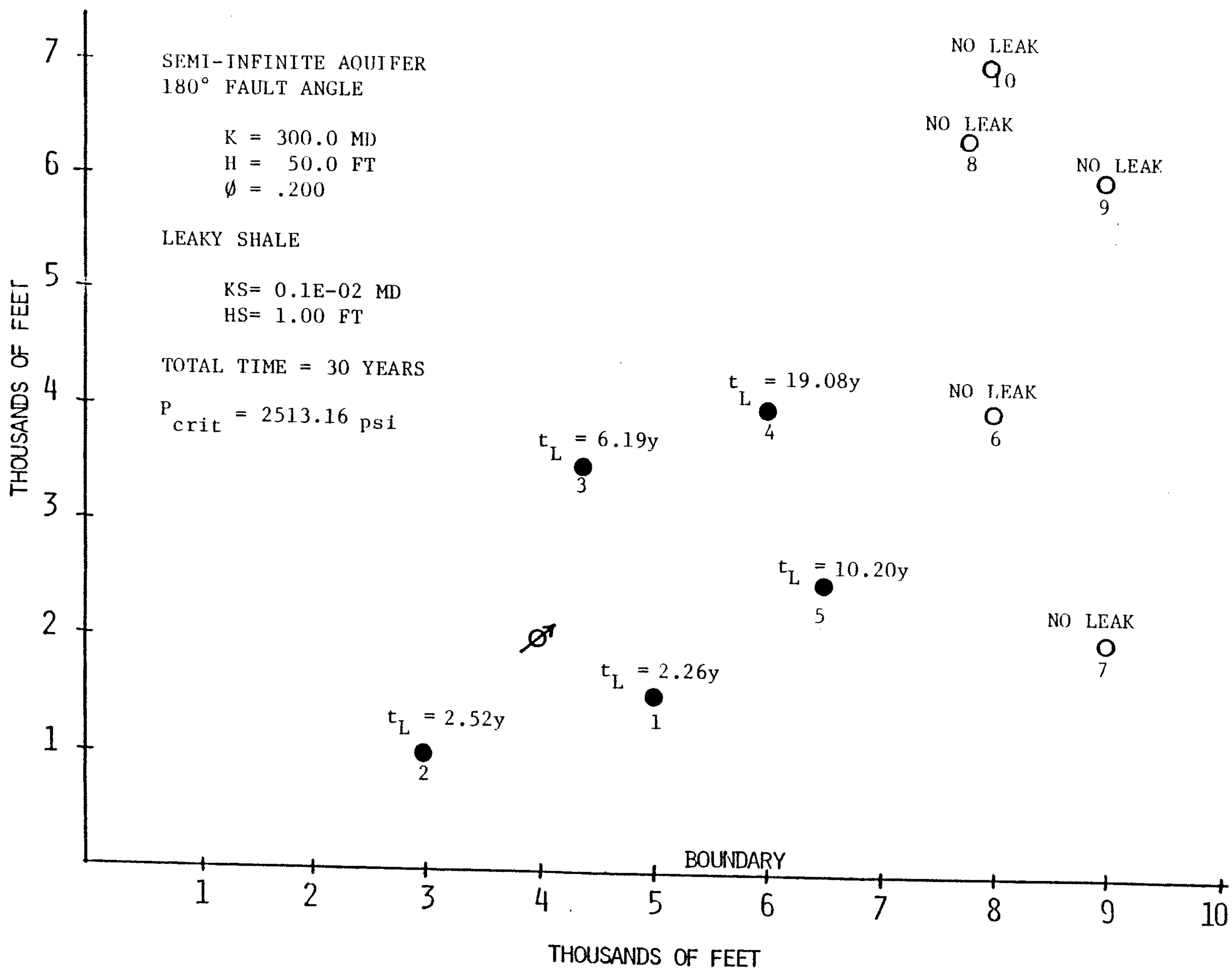
WELL #	X FT.	Y FT.
1	5000.000	1500.000
2	3000.000	1000.000
3	4400.000	3600.000
4	6000.000	4000.000
5	6500.000	2500.000
6	8000.000	4000.000
7	9000.000	2000.000
8	7800.000	6400.000
9	9000.000	6000.000
10	8000.000	7000.000

COORDINATES OF THE INJECTION WELL

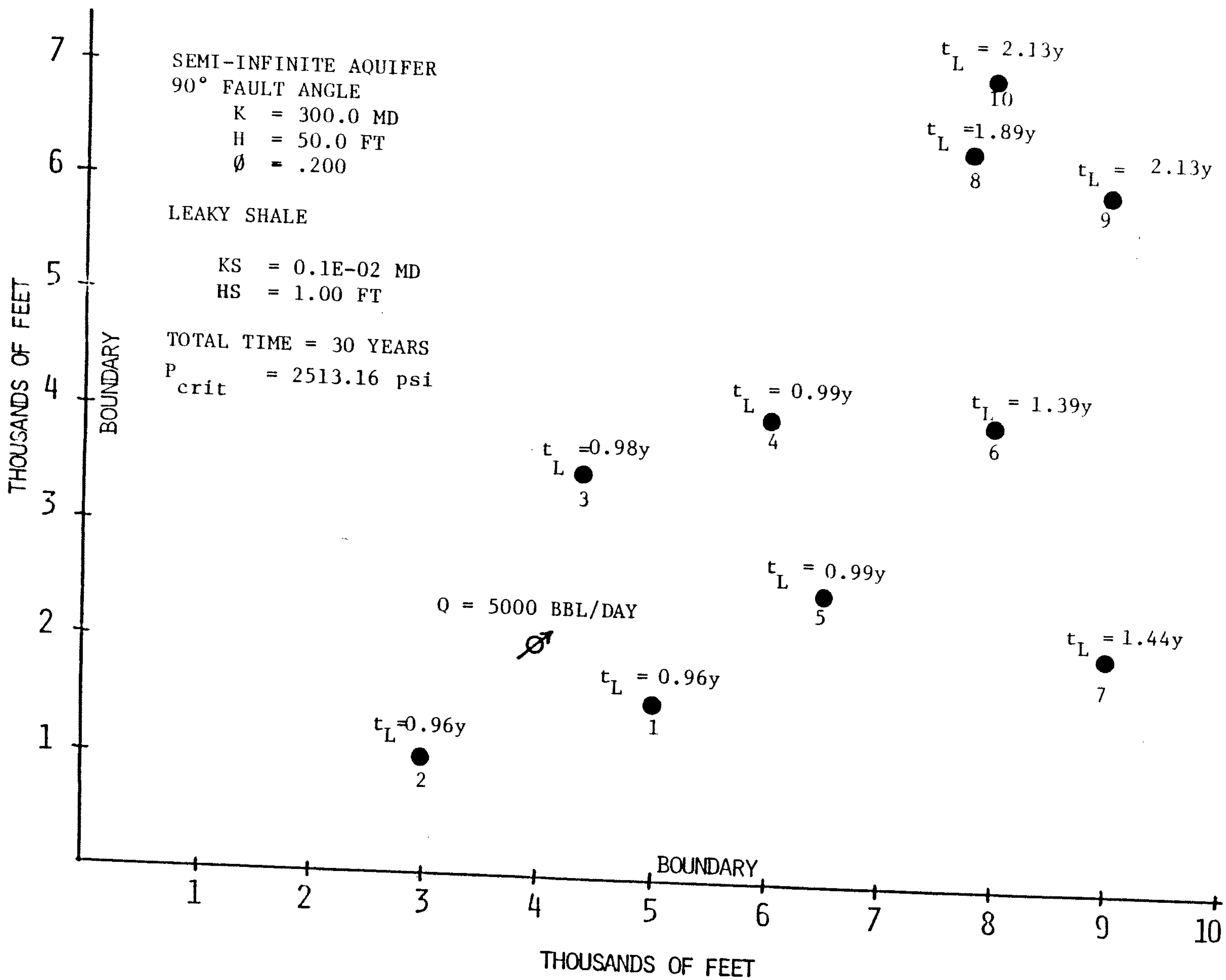
X= 4000.000 Y= 2000.000 FT.
INJECTION RATE =5000. BBL/DAY



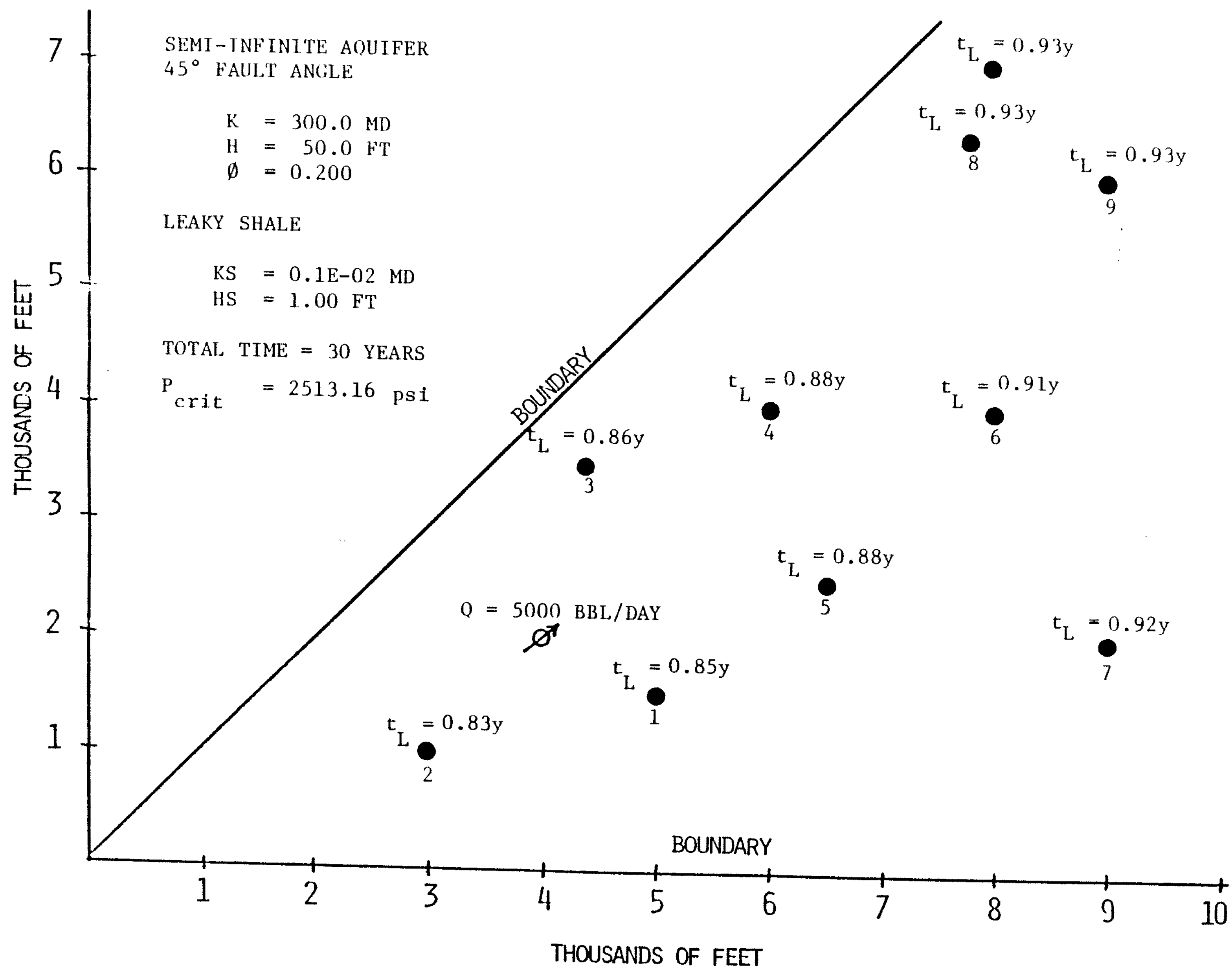
CASE IV, GROUP 3, NO. 1



CASE IV, GROUP 3, NO. 2



CASE IV, GROUP 3, NO. 3



CASE IV, GROUP 3, NO. 4

PROPERTIES OF THE DISPOSAL ZONE

****

COMPRESSIBILITY = 0.500E-05 1/PSI
PERMEABILITY = 300.000 MD
VISCOSITY = 1.000 CP
THICKNESS = 50.00 FT
POROSITY =0.200

****

PROPERTIES OF THE SHALE LAYER

****

SHALE PERMEABILITY =0.10000E-02 MD
SHALE THICKNESS = 1.00000 FT

PROPERTIES OF ABANDONED HOLES

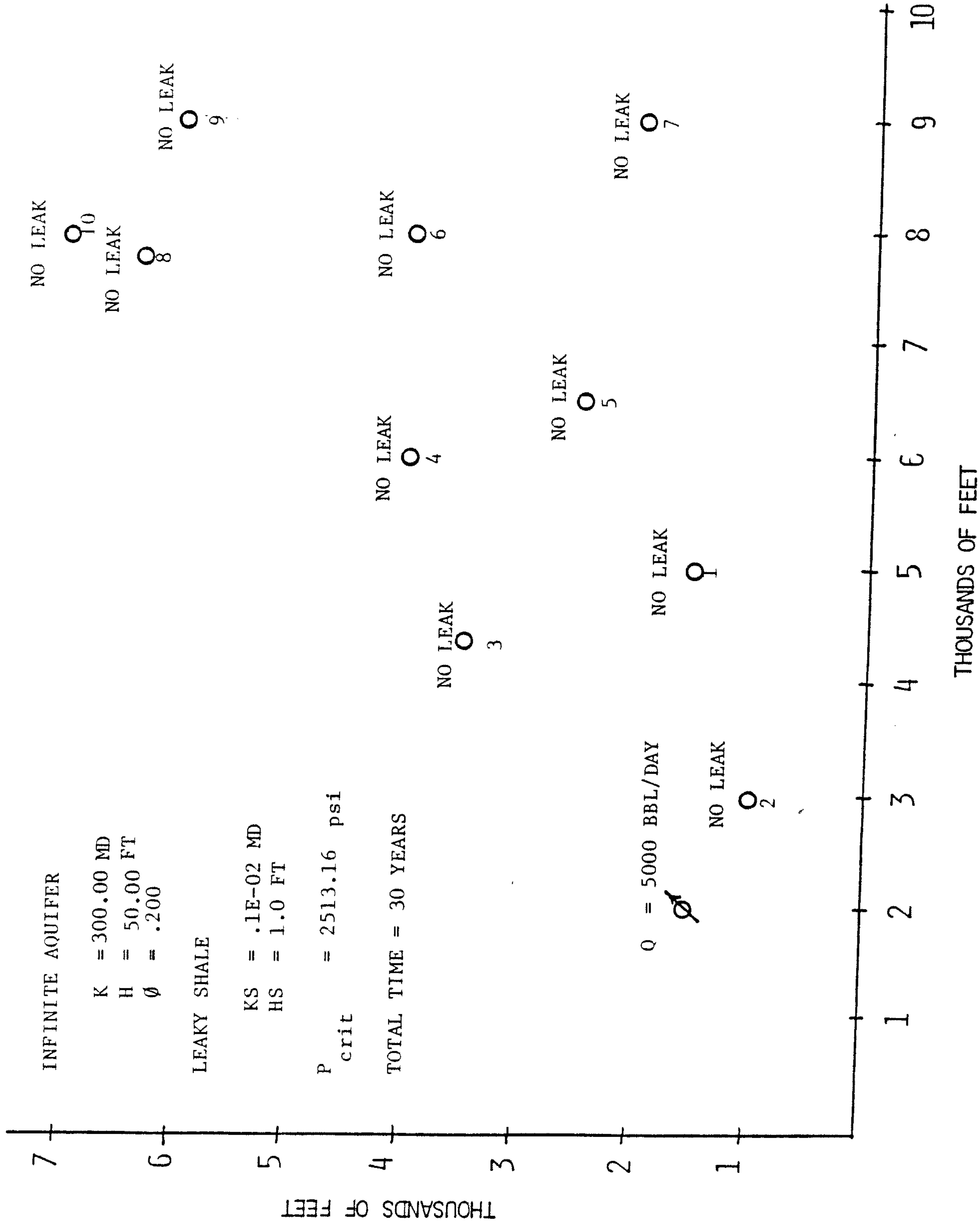
ABAN WELL	WELL DIAM IN	DEPTH TO DISP ZONE FT	DEPTH TO H2O ZONE FT	MUD DENSITY LB/GAL	GEL STRENGTH LB/100FT2	CRITIC PRESSU PSI
1	9.6	5000.00	600.0	9.000	100.00	2513.16
2	9.6	5000.00	600.0	9.000	100.00	2513.16
3	9.6	5000.00	600.0	9.000	100.00	2513.16
4	9.6	5000.00	600.0	9.000	100.00	2513.16
5	9.6	5000.00	600.0	9.000	100.00	2513.16
6	9.6	5000.00	600.0	9.000	100.00	2513.16
7	9.6	5000.00	600.0	9.000	100.00	2513.16
8	9.6	5000.00	600.0	9.000	100.00	2513.16
9	9.6	5000.00	600.0	9.000	100.00	2513.16
10	9.6	5000.00	600.0	9.000	100.00	2513.16

COORDINATES OF THE ABANDONED WELLS

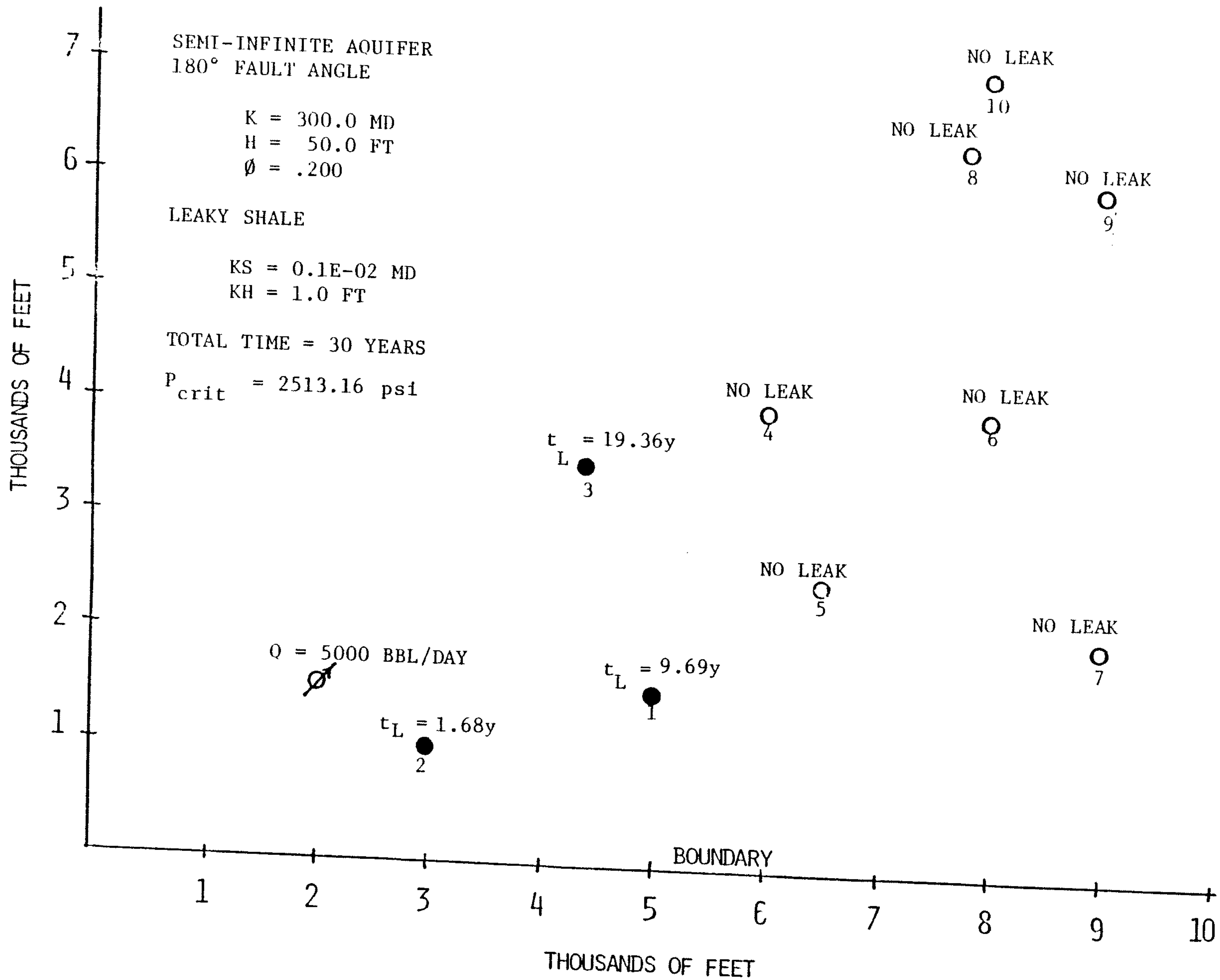
WELL #	X FT.	Y FT.
1	5000.000	1500.000
2	3000.000	1000.000
3	4400.000	3600.000
4	6000.000	4000.000
5	6500.000	2500.000
6	8000.000	4000.000
7	9000.000	2000.000
8	7800.000	6400.000
9	9000.000	6000.000
10	8000.000	7000.000

COORDINATES OF THE INJECTION WELL

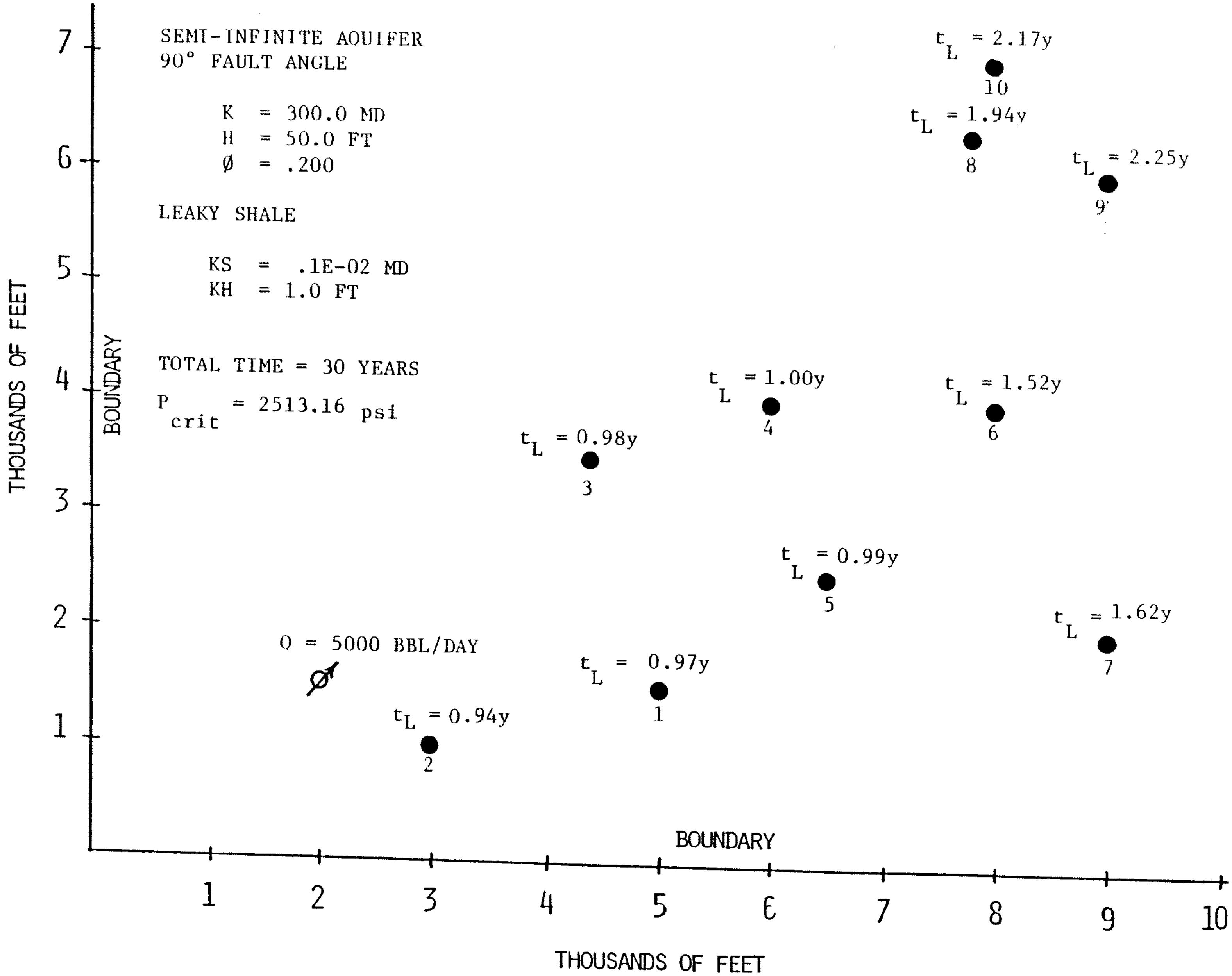
X= 2000.000 Y= 1500.000 FT.
INJECTION RATE =5000. BBL/DAY



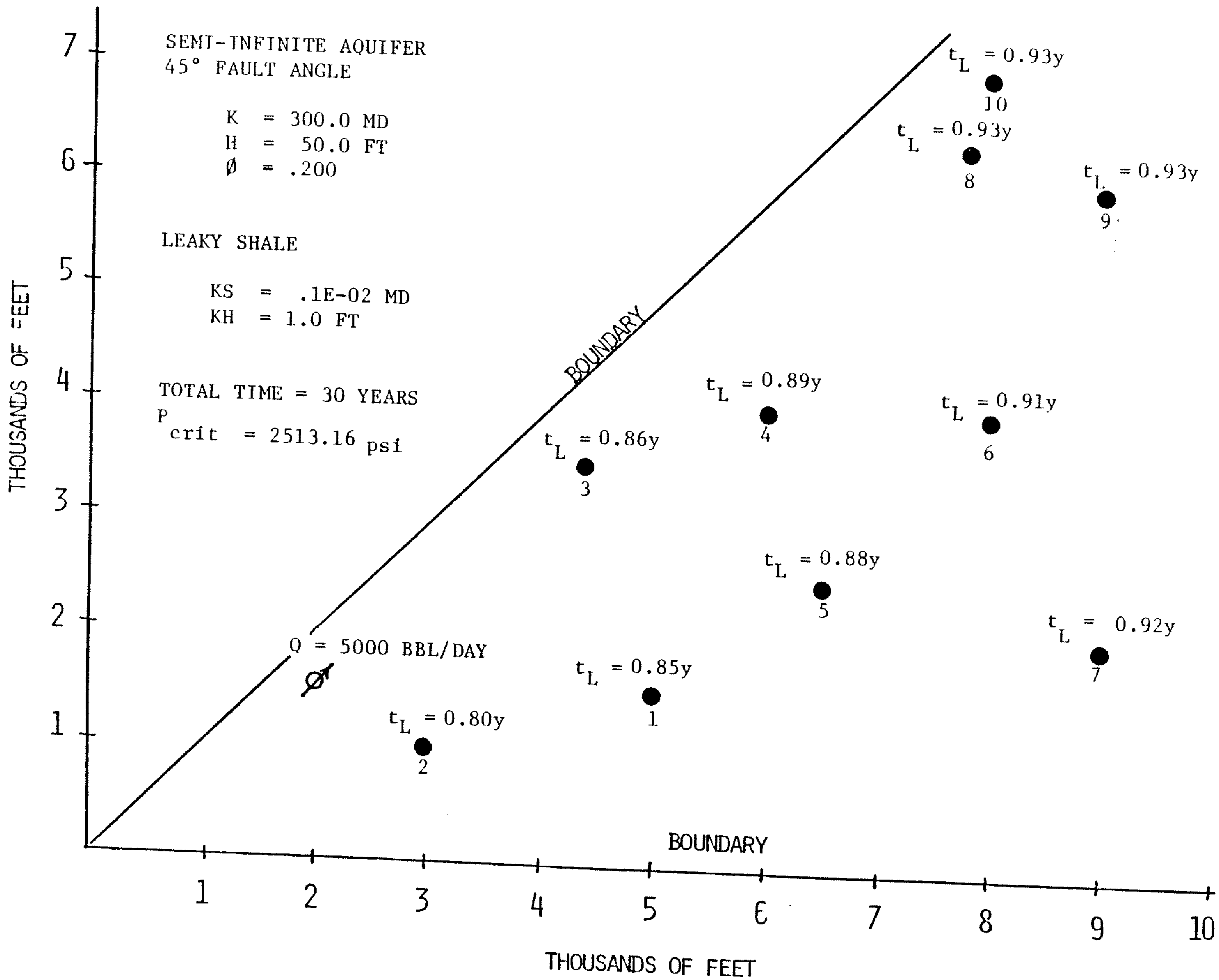
E IV, GROUP 4, NO. 1



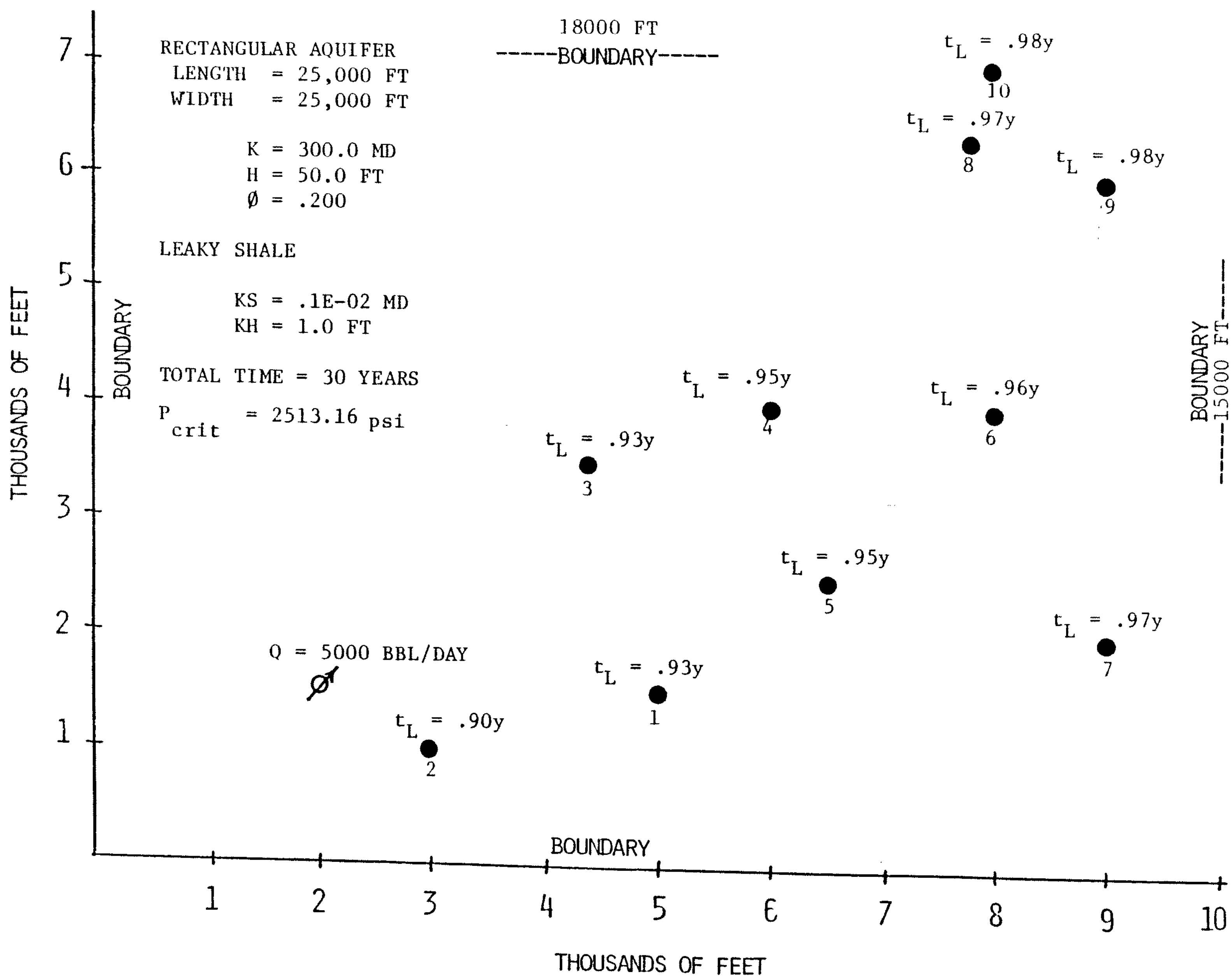
CASE IV, GROUP 4, NO. 2



E IV, GROUP 4, NO. 3



CASE IV, GROUP 4, NO. 4



SE IV, GROUP 4, NO. 5

CASE IV, GROUP 5

PROPERTIES OF THE DISPOSAL ZONE

****

COMPRESSIBILITY = 0.500E-05 1/PSI
PERMEABILITY = 300.000 MD
VISCOSITY = 1.000 CP
THICKNESS = 50.0 FT
POROSITY =0.200

****

PROPERTIES OF THE SHALE LAYER

****

SHALE PERMEABILITY =0.10000E-02 MD
SHALE THICKNESS = 1.00000 FT

PROPERTIES OF ABANDONED HOLES

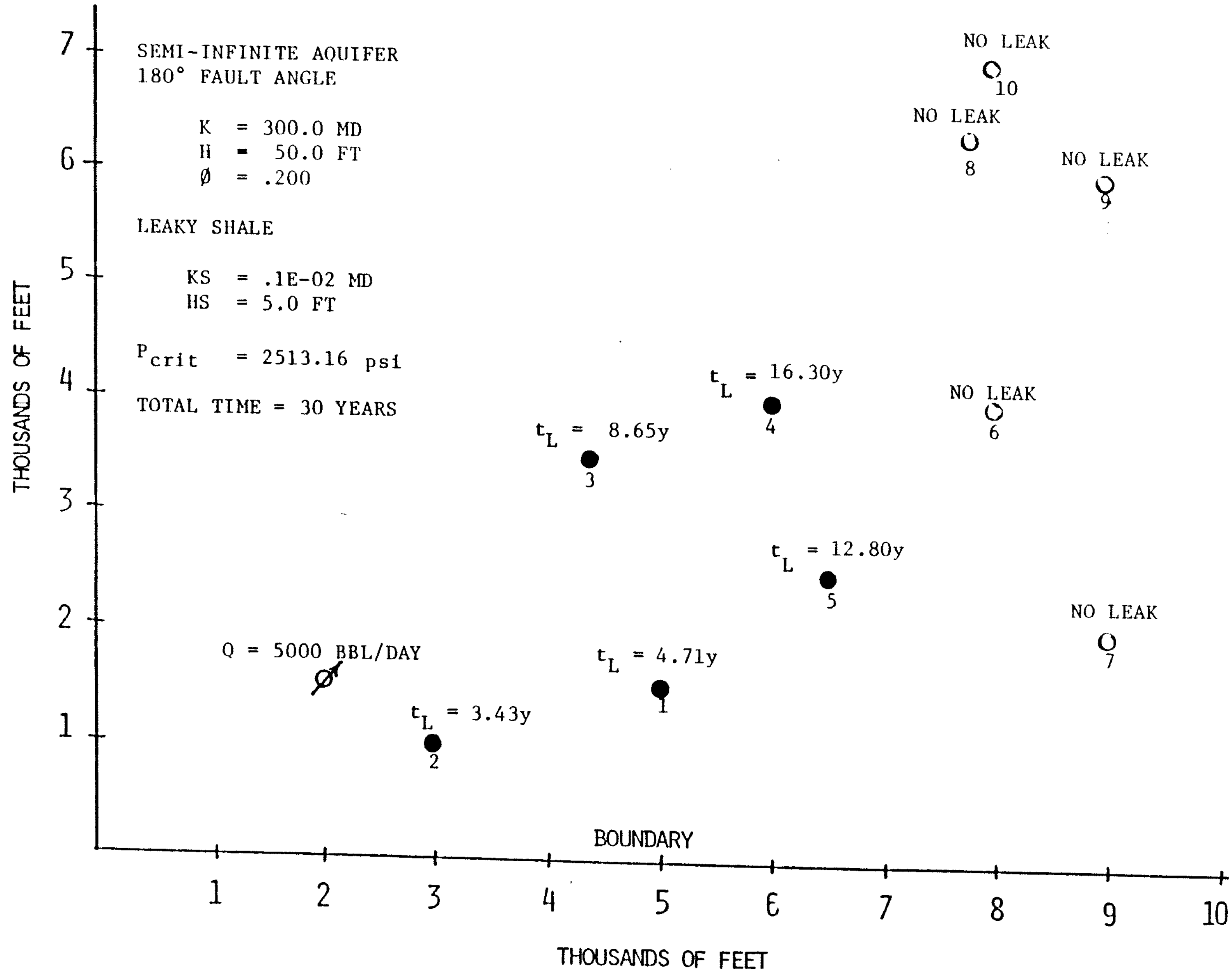
ABAN WELL	WELL DIAM IN	DEPTH TO DISP ZONE FT	DEPTH TO H2O ZONE FT	MUD DENSITY LB/GAL	GEL STRENGTH LB/100FT2	CRITIC PRESSU PSI
1	9.6	5000.00	600.0	9.000	100.00	2513.16
2	9.6	5000.00	600.0	9.000	100.00	2513.16
3	9.6	5000.00	600.0	9.000	100.00	2513.16
4	9.6	5000.00	600.0	9.000	100.00	2513.16
5	9.6	5000.00	600.0	9.000	100.00	2513.16
6	9.6	5000.00	600.0	9.000	100.00	2513.16
7	9.6	5000.00	600.0	9.000	100.00	2513.16
8	9.6	5000.00	600.0	9.000	100.00	2513.16
9	9.6	5000.00	600.0	9.000	100.00	2513.16
10	9.6	5000.00	600.0	9.000	100.00	2513.16

COORDINATES OF THE ABANDONED WELLS

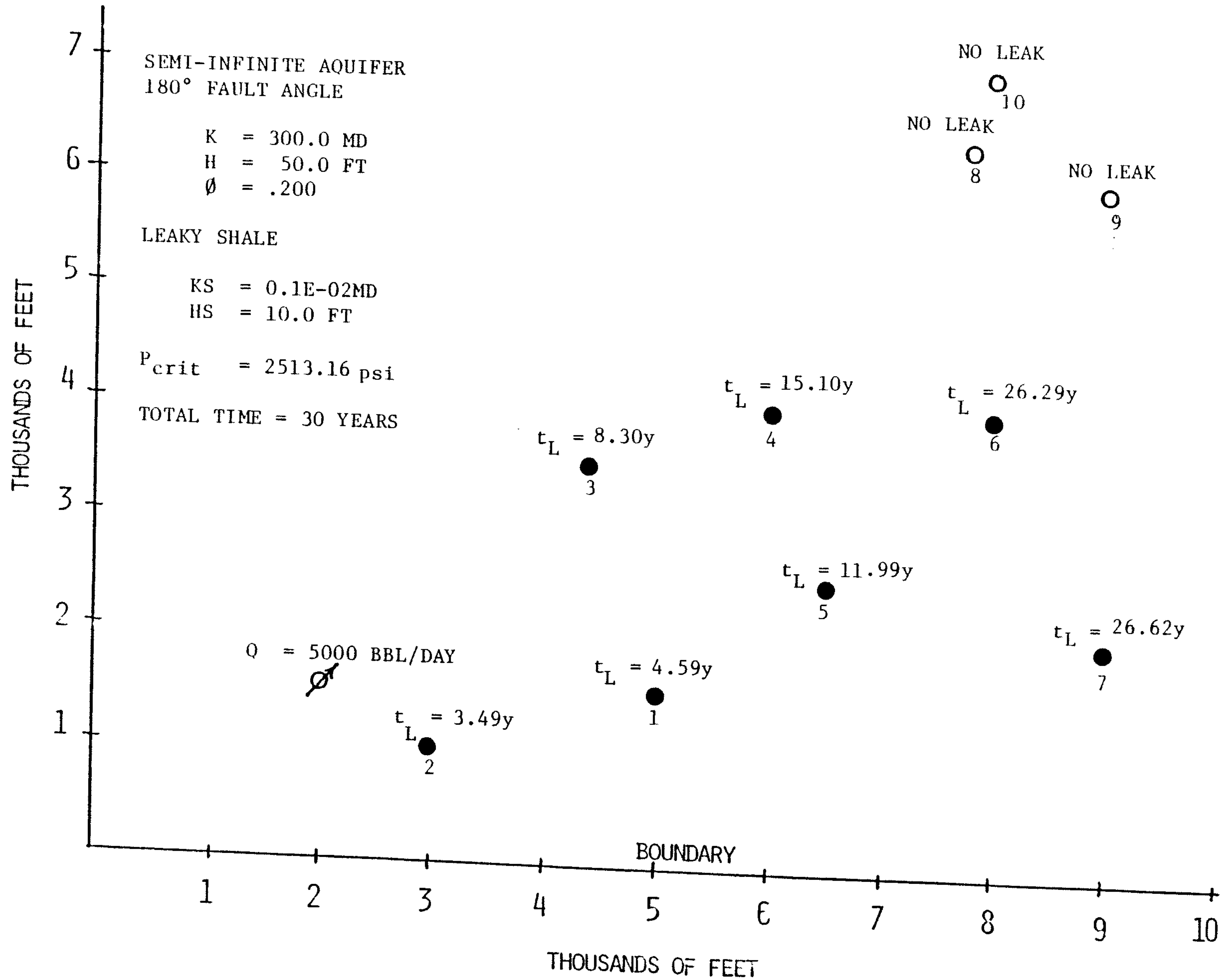
WELL #	X FT.	Y FT.
1	5000.000	1500.000
2	3000.000	1000.000
3	4400.000	3600.000
4	6000.000	4000.000
5	6500.000	2500.000
6	8000.000	4000.000
7	9000.000	2000.000
8	7800.000	6400.000
9	9000.000	6000.000
10	8000.000	7000.000

COORDINATES OF THE INJECTION WELL

X= 2000.000 Y= 1500.000 FT.
INJECTION RATE =5000. BBL/DAY



E IV, GROUP 5, NO. 1



CASE IV, GROUP 5, NO. 2

CASE IV, GROUP 6

PROPERTIES OF THE DISPOSAL ZONE
****
COMPRESSIBILITY = 0.500E-05 1/PSI
PERMEABILITY = 300.000 MD
VISCOSITY = 1.000 CP
THICKNESS = 50.0 FT
POROSITY =0.200
****

PROPERTIES OF THE SHALE LAYER
****

SHALE PERMEABILITY =0.10000E-02 MD
SHALE THICKNESS = 1.00000 FT

PROPERTIES OF ABANDONED HOLES

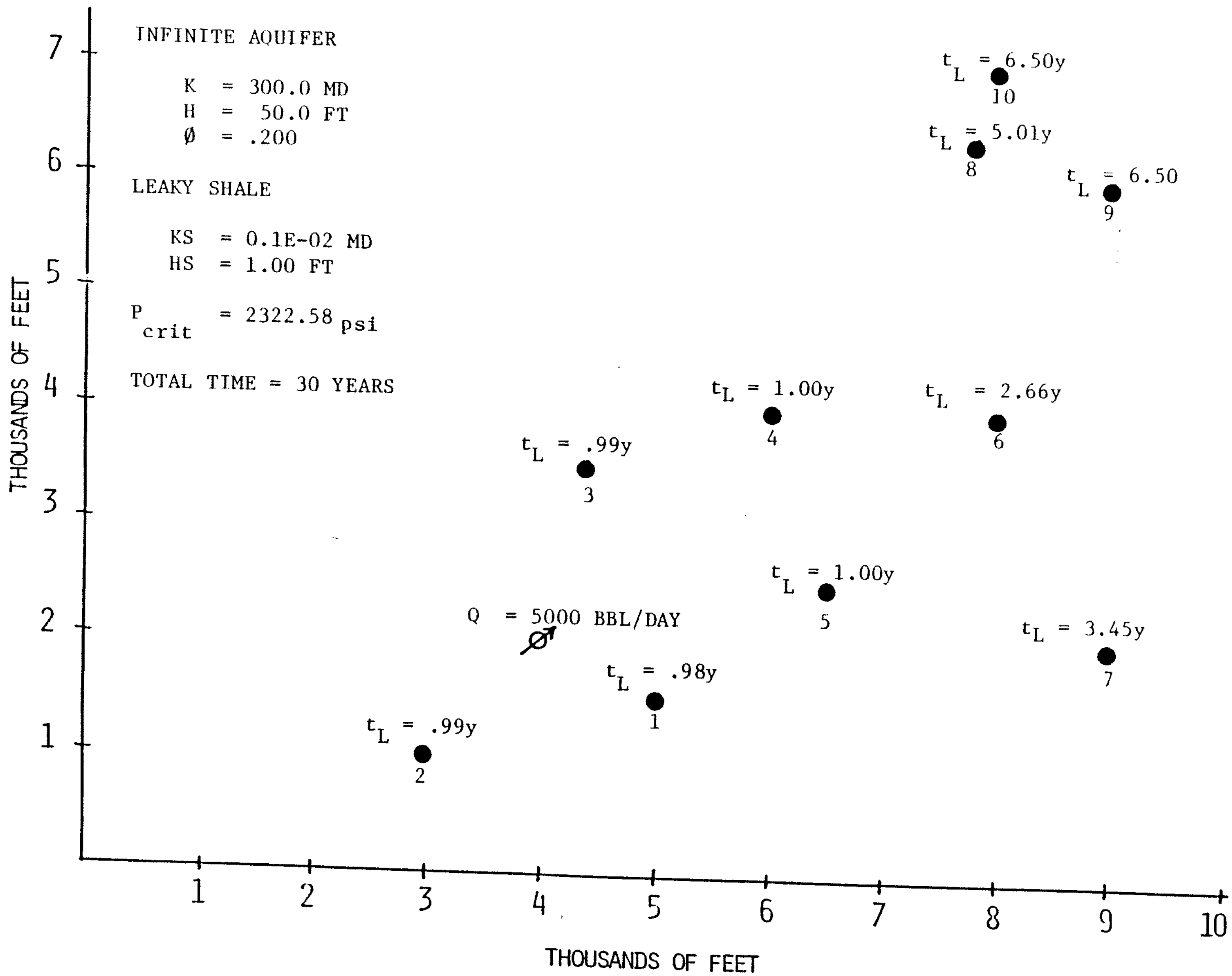
ABAN WELL	WELL DIAM IN	DEPTH TO DISP ZONE FT	DEPTH TO H2O ZONE FT	MUD DENSITY LB/GAL	GEL STRENGTH LB/100FT2	CRITIC PRESSU PSI
1	9.6	5000.00	600.0	8.600	50.00	2322.58
2	9.6	5000.00	600.0	8.600	50.00	2322.58
3	9.6	5000.00	600.0	8.600	50.00	2322.58
4	9.6	5000.00	600.0	8.600	50.00	2322.58
5	9.6	5000.00	600.0	8.600	50.00	2322.58
6	9.6	5000.00	600.0	8.600	50.00	2322.58
7	9.6	5000.00	600.0	8.600	50.00	2322.58
8	9.6	5000.00	600.0	8.600	50.00	2322.58
9	9.6	5000.00	600.0	8.600	50.00	2322.58
10	9.6	5000.00	600.0	8.600	50.00	2322.58

COORDINATES OF THE ABANDONED WELLS

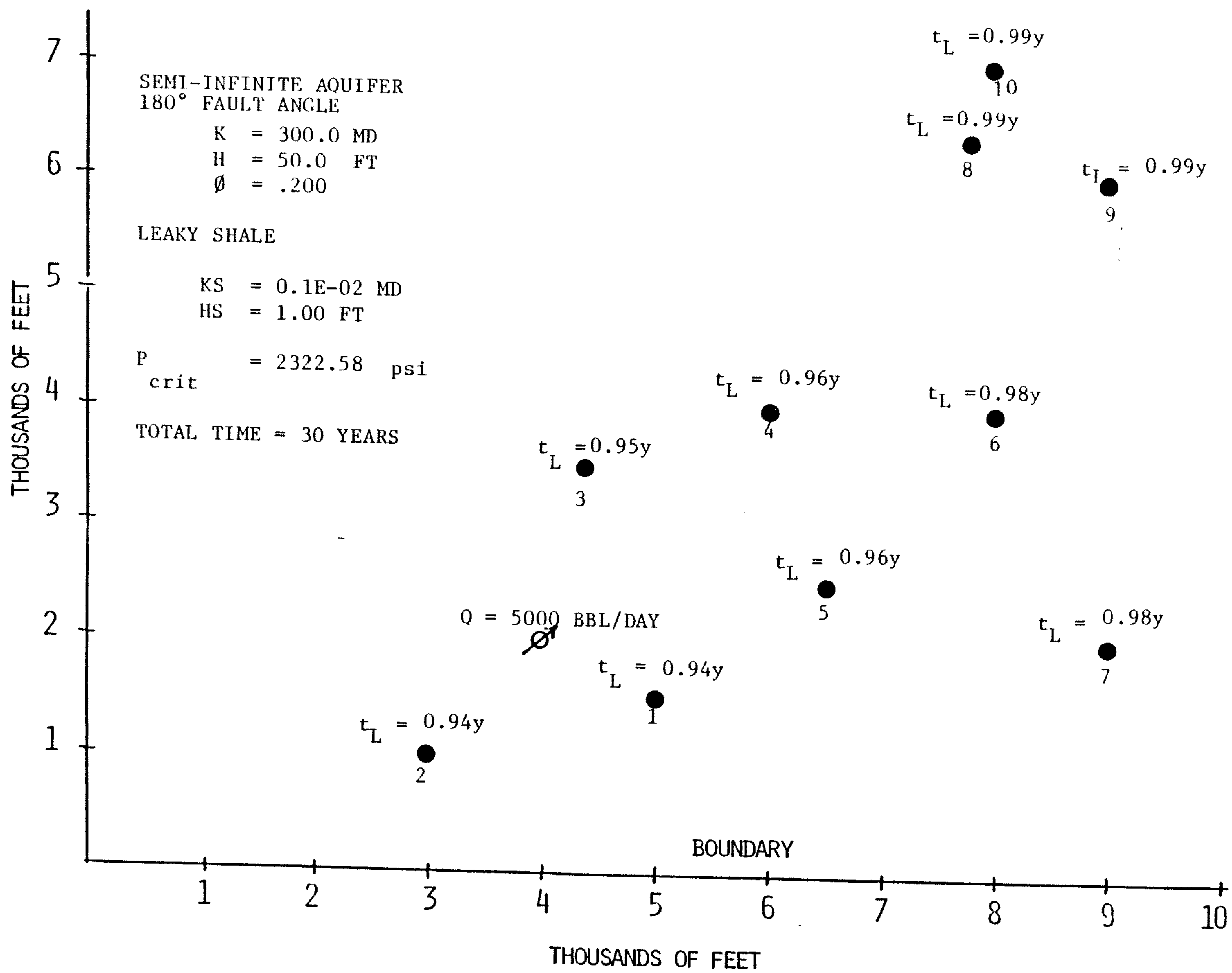
WELL # ******	X FT.	Y FT.
1	5000.000	1500.000
2	3000.000	1000.000
3	4400.000	3600.000
4	6000.000	4000.000
5	6500.000	2500.000
6	8000.000	4000.000
7	9000.000	2000.000
8	7800.000	6400.000
9	9000.000	6000.000
10	8000.000	7000.000

COORDINATES OF THE INJECTION WELL

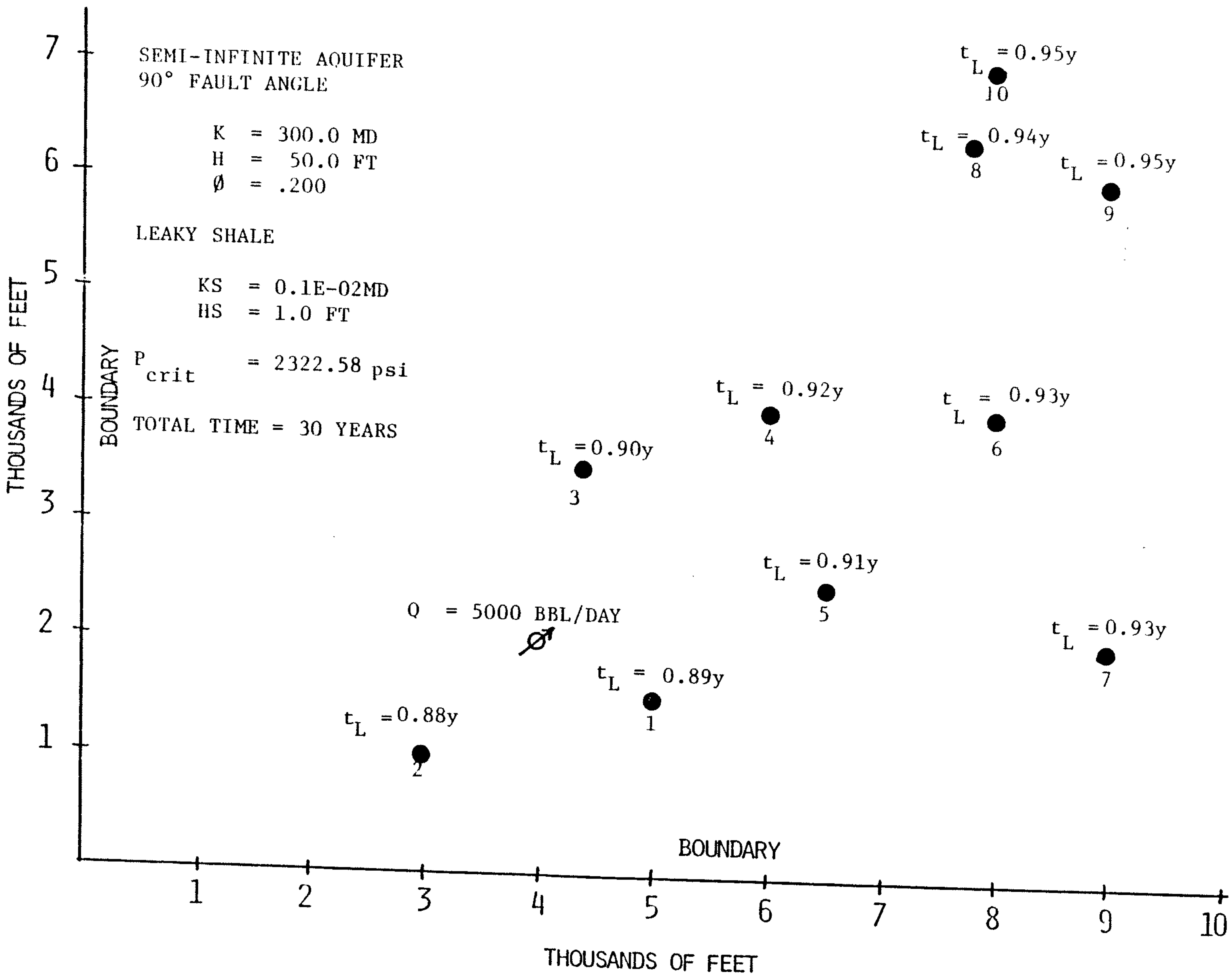
X= 4000.000 Y= 2000.000 FT.
INJECTION RATE =5000. BBL/DAY



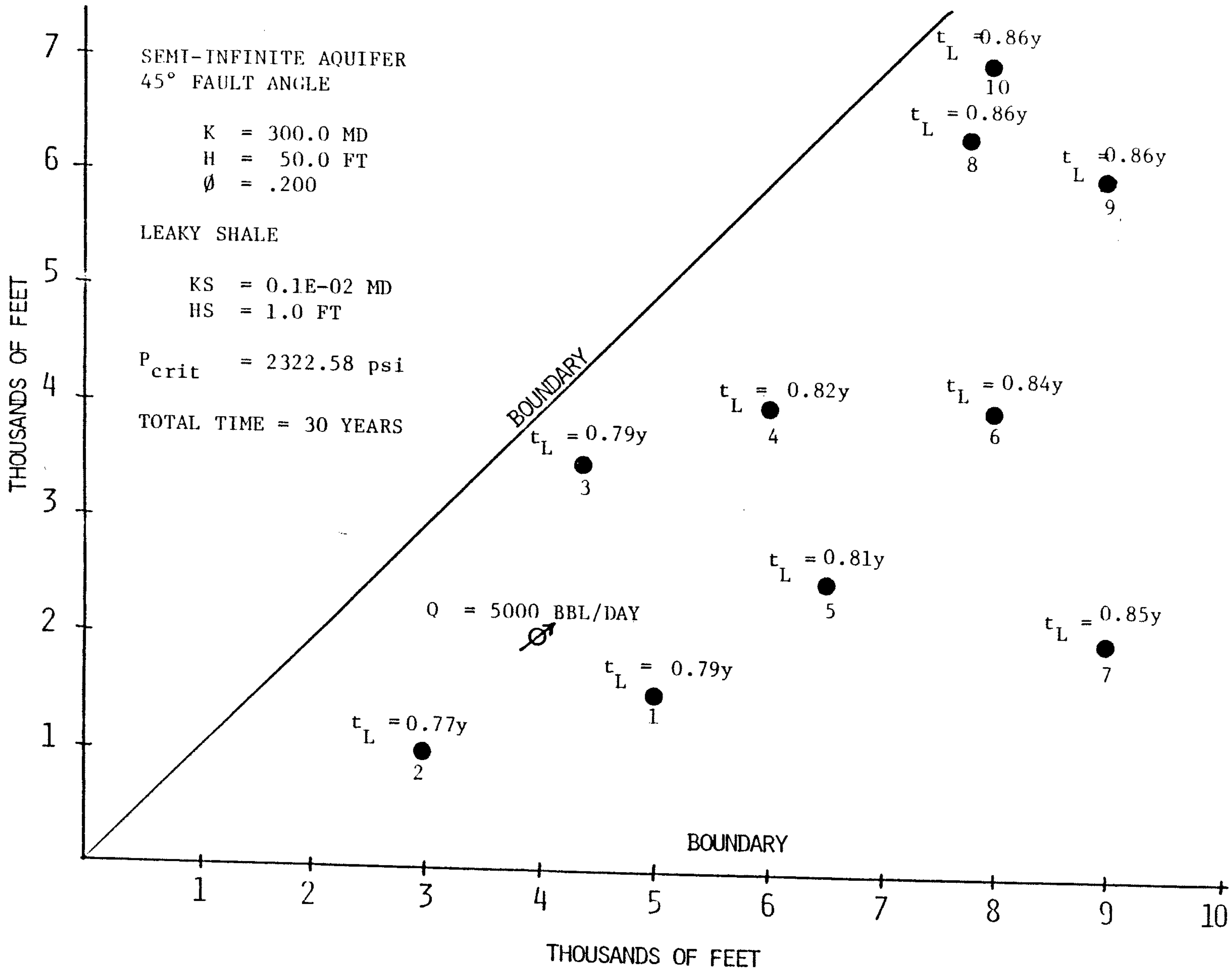
CASE IV, GROUP 6, NO. 1



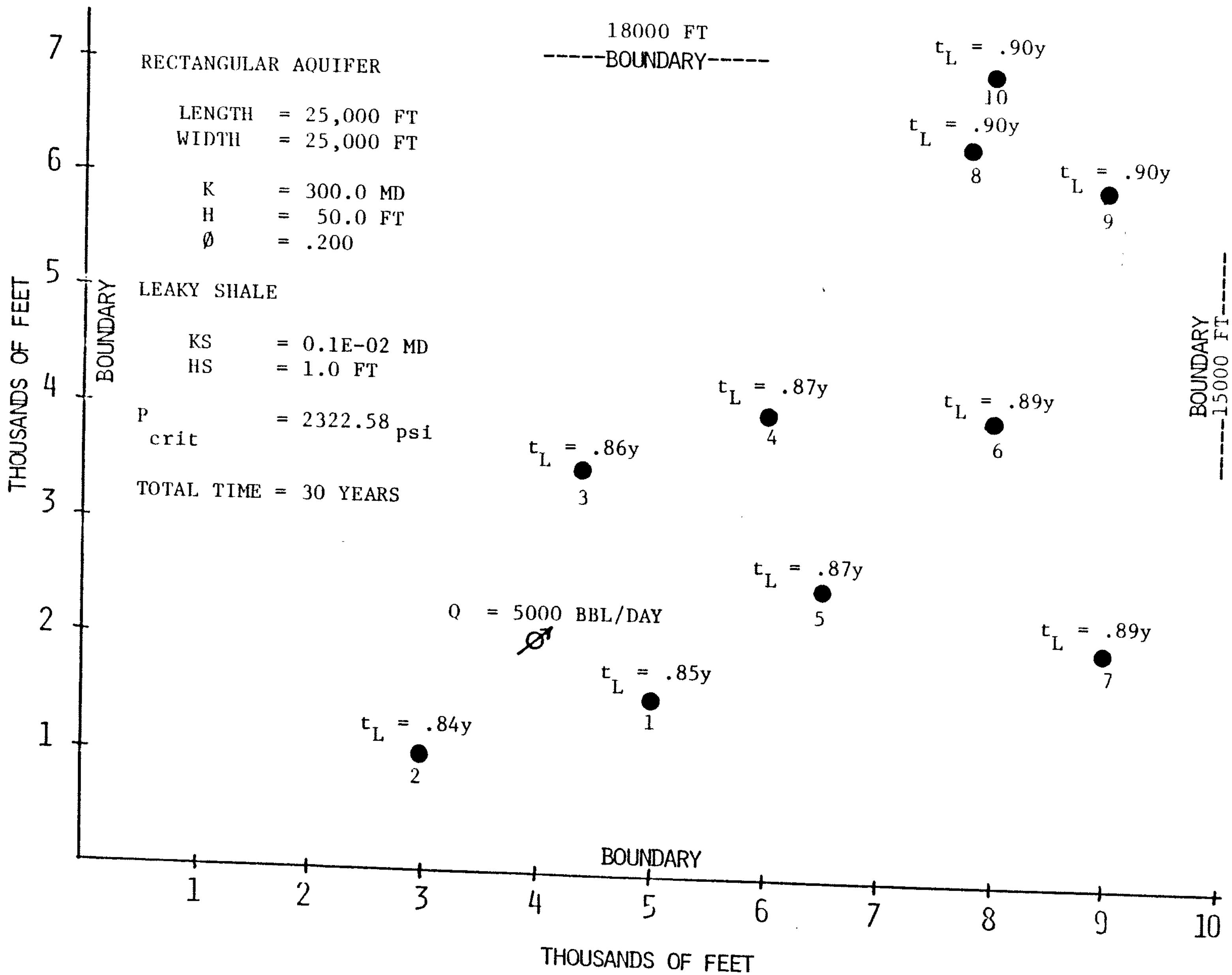
CASE IV, GROUP 6, NO. 2



CASE IV, GROUP 6, NO. 3



CASE IV, GROUP 6, NO. 4



CASE IV, GROUP 6, NO. 5

CASE IV, GROUP 7

PROPERTIES OF THE DISPOSAL ZONE

```
**********************************
COMPRESSIBILITY = 0.500E-05 1/PSI
   PERMEABILITY = 300.000   MD
      VISCOSITY = 1.000     CP
      THICKNESS =  50.0     FT
       POROSITY =0.200
**********************************
```

PROPERTIES OF THE SHALE LAYER

```
*****************************

SHALE PERMEABILITY =0.10000E-02 MD
   SHALE THICKNESS =  1.00000  FT
```

PROPERTIES OF ABANDONED HOLES

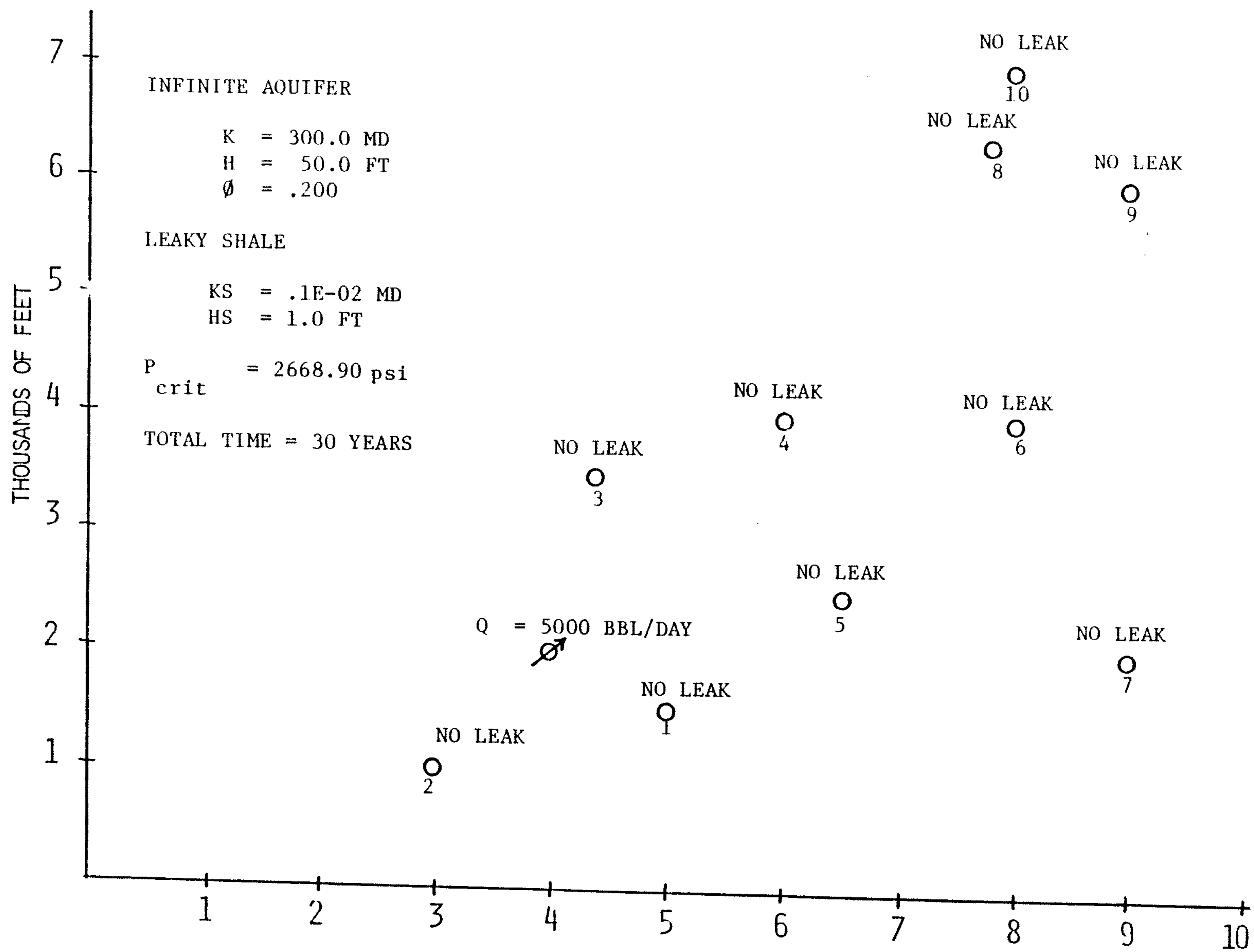
ABAN WELL	WELL DIAM IN	DEPTH TO DISP ZONE FT	DEPTH TO H2O ZONE FT	MUD DENSITY LB/GAL	GEL STRENGTH LB/100FT2	CRITIC PRESSU PSI
1	9.6	5000.00	600.0	8.600	250.00	2668.90
2	9.6	5000.00	600.0	8.600	250.00	2668.90
3	9.6	5000.00	600.0	8.600	250.00	2668.90
4	9.6	5000.00	600.0	8.600	250.00	2668.90
5	9.6	5000.00	600.0	8.600	250.00	2668.90
6	9.6	5000.00	600.0	8.600	250.00	2668.90
7	9.6	5000.00	600.0	8.600	250.00	2668.90
8	9.6	5000.00	600.0	8.600	250.00	2668.90
9	9.6	5000.00	600.0	8.600	250.00	2668.90
10	9.6	5000.00	600.0	8.600	250.00	2668.90

COORDINATES OF THE ABANDONED WELLS

WELL #	X FT.	Y FT.
1	5000.000	1500.000
2	3000.000	1000.000
3	4400.000	3600.000
4	6000.000	4000.000
5	6500.000	2500.000
6	8000.000	4000.000
7	9000.000	2000.000
8	7800.000	6400.000
9	9000.000	6000.000
10	8000.000	7000.000

COORDINATES OF THE INJECTION WELL

X= 4000.000 Y= 2000.000 FT.
INJECTION RATE =5000. BBL/DAY



CASE IV, GROUP 7, NO. 1

CASE V

EFFECTS OF ANISOTROPIC PERMEABILITY

Illustrating effect of anisotropy for two cases; a sealing fault and a partially sealing fault. In each case an isotropic run $K_x/K_y = 1$ is contrasted with a run for $K_x/K_y = 0.25$.

CASE V

PROPERTIES OF THE DISPOSAL ZONE

COMPRESSIBILITY =	0.500E-05	1/PSI
PERMEABILITY =	300.000	MD
VISCOSITY =	1.000	CP
THICKNESS =	50.0	FT
POROSITY =	0.200	

PROPERTIES OF ABANDONED HOLES

ABAN WELL	WELL DIAM IN	DEPTH TO DISP ZONE FT	DEPTH TO H2O ZONE FT	MUD DENSITY LB/GAL	GEL STRENGTH LB/100FT2	CRITIC PRESSU PSI
1	9.6	5000.00	600.0	9.000	100.00	2513.16
2	9.6	5000.00	600.0	9.000	100.00	2513.16
3	9.6	5000.00	600.0	9.000	100.00	2513.16
4	9.6	5000.00	600.0	9.000	100.00	2513.16
5	9.6	5000.00	600.0	9.000	100.00	2513.16

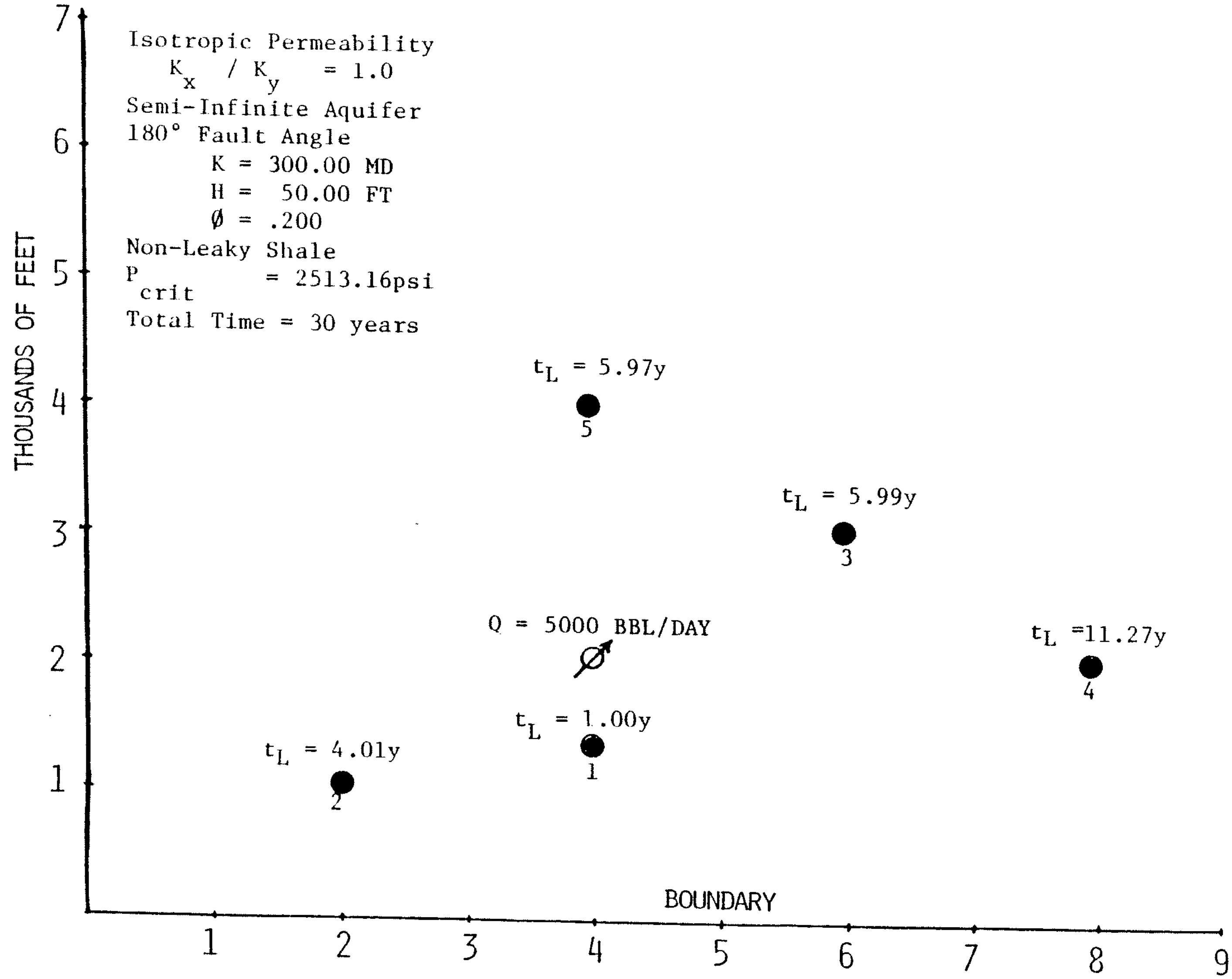
COORDINATES OF THE ABANDONED WELLS

WELL #	X FT.	Y FT.
1	4000.000	1500.000
2	2000.000	1000.000
3	6000.000	3000.000
4	8000.000	2000.000
5	4000.000	4000.000

COORDINATES OF THE INJECTION WELL

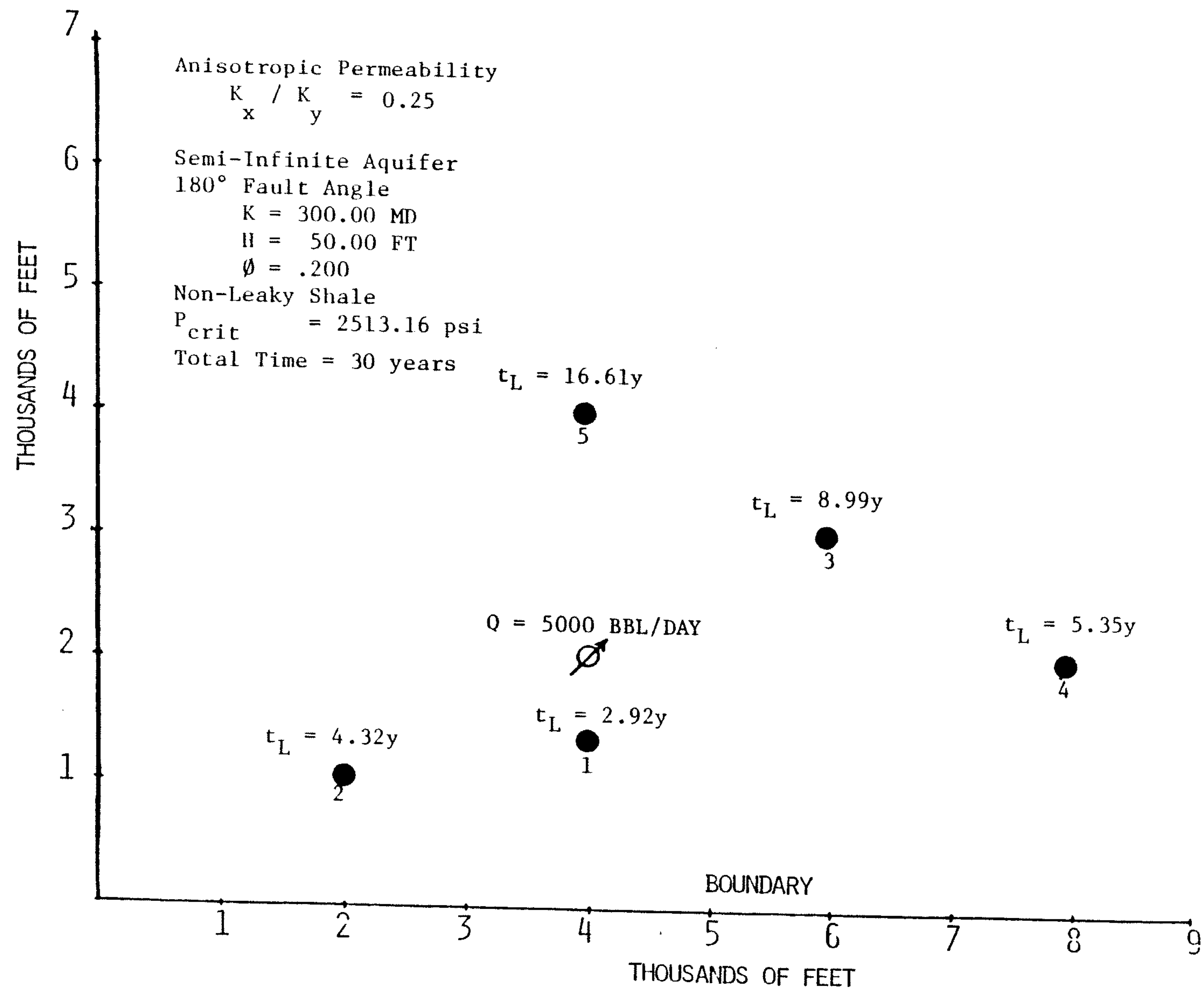
X= 4000.000 Y= 2000.000 FT.

INJECTION RATE =5000. BBL/DAY

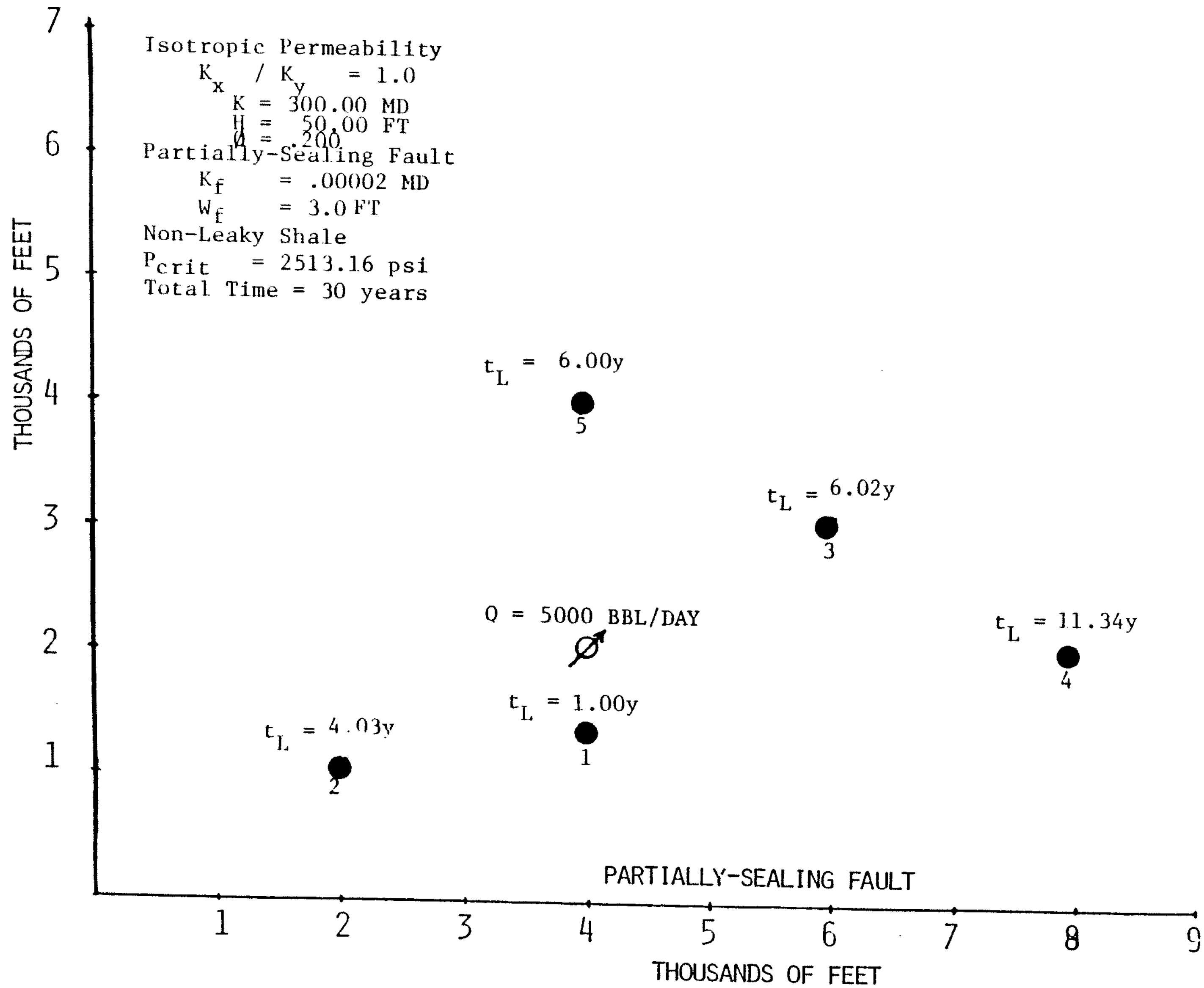


Isotropic Permeability
$K_x / K_y = 1.0$
Semi-Infinite Aquifer
180° Fault Angle
K = 300.00 MD
H = 50.00 FT
Ø = .200
Non-Leaky Shale
P_{crit} = 2513.16psi
Total Time = 30 years
t_L = 5.97y
5
t_L = 5.99y
3
Q = 5000 BBL/DAY
t_L =11.27y
4
t_L = 1.00y
1
t_L = 4.01y
2
BOUNDARY
THOUSANDS OF FEET
THOUSANDS OF FEET
1
2
3
4
5
6
7
8
9

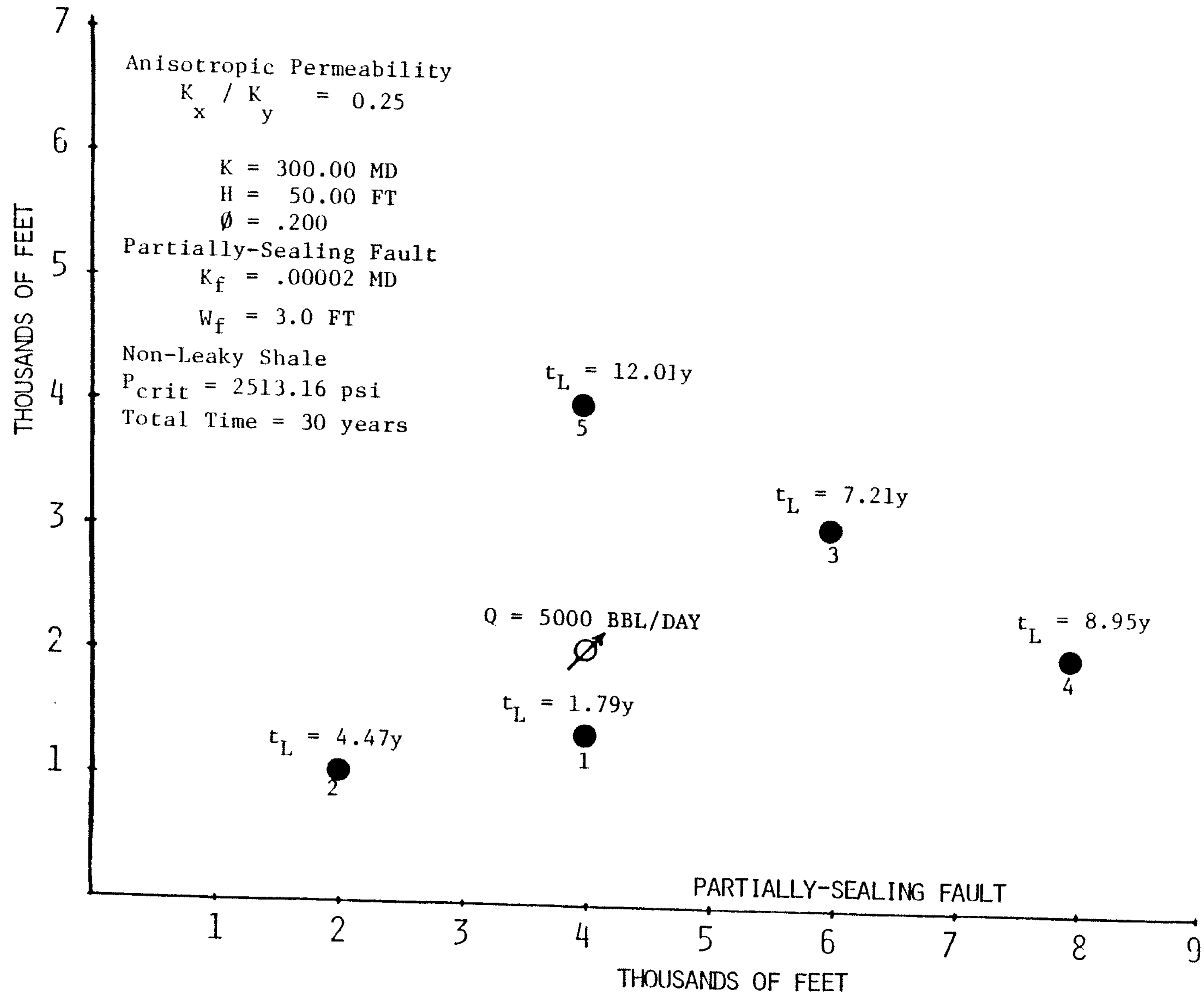
CASE V, NO. 1


Anisotropic Permeability
$K_x / K_y = 0.25$
Semi-Infinite Aquifer
180° Fault Angle
K = 300.00 MD
H = 50.00 FT
Ø = .200
Non-Leaky Shale
P_{crit} = 2513.16 psi
Total Time = 30 years
t_L = 16.61y
5
t_L = 8.99y
3
Q = 5000 BBL/DAY
t_L = 5.35y
4
t_L = 2.92y
1
t_L = 4.32y
2
BOUNDARY
THOUSANDS OF FEET
THOUSANDS OF FEET
1
2
3
4
5
6
7
8
9

CASE V. NO. 2


Isotropic Permeability
K_x / K_y = 1.0
K = 300.00 MD
H = 50.00 FT
Ø = .200
Partially-Sealing Fault
K_f = .00002 MD
W_f = 3.0 FT
Non-Leaky Shale
P_{crit} = 2513.16 psi
Total Time = 30 years
t_L = 6.00y
5
t_L = 6.02y
3
Q = 5000 BBL/DAY
t_L = 11.34y
4
t_L = 4.03y
2
t_L = 1.00y
1
PARTIALLY-SEALING FAULT
THOUSANDS OF FEET
THOUSANDS OF FEET
1
2
3
4
5
6
7
8
9
1
2
3
4
5
6
7

CASE V, NO. 3


Anisotropic Permeability
$K_x / K_y = 0.25$
K = 300.00 MD
H = 50.00 FT
Ø = .200
Partially-Sealing Fault
K_f = .00002 MD
W_f = 3.0 FT
Non-Leaky Shale
P_{crit} = 2513.16 psi
Total Time = 30 years
t_L = 12.01y
5
t_L = 7.21y
3
Q = 5000 BBL/DAY
t_L = 8.95y
4
t_L = 1.79y
1
t_L = 4.47y
2
PARTIALLY-SEALING FAULT
THOUSANDS OF FEET
THOUSANDS OF FEET

CASE V, NO. 4

CASE VI

EFFECTS OF FINITE RESERVOIR VOLUME

A series of runs for a reservoir of square side length 25000 ft. illustrating effects of values of P_{crit}, K_s/h_s, K and h on the time for on-set of leaking in abandoned wells.

CASE VI, NO. 1

PROPERTIES OF THE DISPOSAL ZONE

****

COMPRESSIBILITY = 0.500E-05 1/PSI
PERMEABILITY = 100.000 MD
VISCOSITY = 1.000 CP
THICKNESS = 300.0 FT
POROSITY =0.200

****

PROPERTIES OF ABANDONED HOLES

ABAN WELL	WELL DIAM IN	DEPTH TO DISP ZONE FT	DEPTH TO H2O ZONE FT	MUD DENSITY LB/GAL	GEL STRENGTH LB/100FT2	CRITIC PRESSU PSI
1	9.6	5000.00	600.0	9.000	100.00	2513.16
2	9.6	5000.00	600.0	9.000	100.00	2513.16
3	9.6	5000.00	600.0	9.000	100.00	2513.16
4	9.6	5000.00	600.0	9.000	100.00	2513.16
5	9.6	5000.00	600.0	9.000	100.00	2513.16
6	9.6	5000.00	600.0	9.000	100.00	2513.16
7	9.6	5000.00	600.0	9.000	100.00	2513.16
8	9.6	5000.00	600.0	9.000	100.00	2513.16
9	9.6	5000.00	600.0	9.000	100.00	2513.16
10	9.6	5000.00	600.0	9.000	100.00	2513.16

COORDINATES OF THE ABANDONED WELLS

WELL #	X FT.	Y FT.
1	5000.000	1500.000
2	3000.000	1000.000
3	4400.000	3600.000
4	6000.000	4000.000
5	6500.000	2500.000
6	8000.000	4000.000
7	9000.000	2000.000
8	7800.000	6400.000
9	9000.000	6000.000
10	8000.000	7000.000

COORDINATES OF THE INJECTION WELL

X= 2000.000 Y= 1500.000 FT.
INJECTION RATE =5000. BBL/DAY

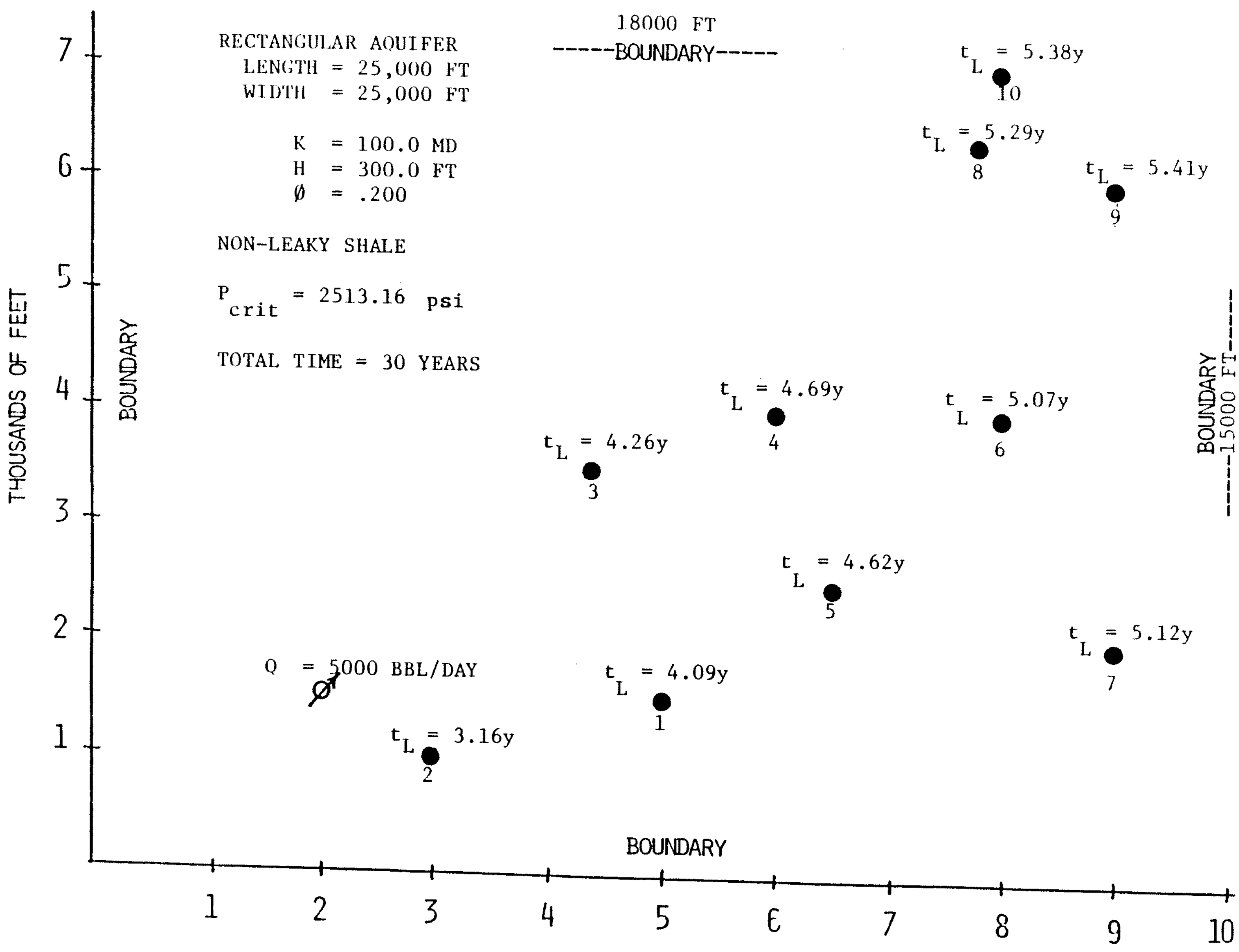
SYSTEM CONFIGURATION

NON-LEAKY SHALE

BOUNDED AQUIFER
. LENGTH = 25000. FT
. WIDTH = 25000. FT
. AREA =14348.025 ACRES

TIME OF INVESTIGATION= 30.00 YEARS

ABANDON WELL #	CRITICAL PRESSURE PSI	LEAKING ?	TIME TO LEAK YEAR
1	2513.16	YES	4.09
2	2513.16	YES	3.16
3	2513.16	YES	4.26
4	2513.16	YES	4.69
5	2513.16	YES	4.62
6	2513.16	YES	5.07
7	2513.16	YES	5.12
8	2513.16	YES	5.29
9	2513.16	YES	5.41
10	2513.16	YES	5.38


RECTANGULAR AQUIFER
LENGTH = 25,000 FT
WIDTH = 25,000 FT
K = 100.0 MD
H = 300.0 FT
Ø = .200
NON-LEAKY SHALE
P_{crit} = 2513.16 psi
TOTAL TIME = 30 YEARS
18000 FT
BOUNDARY
BOUNDARY
BOUNDARY
BOUNDARY
15000 FT
Q = 5000 BBL/DAY
t_L = 3.16y
t_L = 4.09y
t_L = 4.26y
t_L = 4.69y
t_L = 4.62y
t_L = 5.07y
t_L = 5.12y
t_L = 5.29y
t_L = 5.38y
t_L = 5.41y
1
2
3
4
5
6
7
8
9
10
THOUSANDS OF FEET
THOUSANDS OF FEET

CASE VI, NO. 1

CASE VI, NO. 2

PROPERTIES OF THE DISPOSAL ZONE

COMPRESSIBILITY = 0.500E-05 1/PSI
PERMEABILITY = 100.000 MD
VISCOSITY = 1.000 CP
THICKNESS = 300.0 FT
POROSITY =0.200

PROPERTIES OF THE SHALE LAYER

SHALE PERMEABILITY =0.10000E-02 MD
SHALE THICKNESS = 1.00000 FT

PROPERTIES OF ABANDONED HOLES

ABAN WELL	WELL DIAM IN	DEPTH TO DISP ZONE FT	DEPTH TO H2O ZONE FT	MUD DENSITY LB/GAL	GEL STRENGTH LB/100FT2	CRITIC PRESSU PSI
1	9.6	5000.00	600.0	9.000	100.00	2513.16
2	9.6	5000.00	600.0	9.000	100.00	2513.16
3	9.6	5000.00	600.0	9.000	100.00	2513.16
4	9.6	5000.00	600.0	9.000	100.00	2513.16
5	9.6	5000.00	600.0	9.000	100.00	2513.16
6	9.6	5000.00	600.0	9.000	100.00	2513.16
7	9.6	5000.00	600.0	9.000	100.00	2513.16
8	9.6	5000.00	600.0	9.000	100.00	2513.16
9	9.6	5000.00	600.0	9.000	100.00	2513.16
10	9.6	5000.00	600.0	9.000	100.00	2513.16

COORDINATES OF THE ABANDONED WELLS

WELL #	X FT.	Y FT.
1	5000.000	1500.000
2	3000.000	1000.000
3	4400.000	3600.000
4	6000.000	4000.000
5	6500.000	2500.000
6	8000.000	4000.000
7	9000.000	2000.000
8	7800.000	6400.000
9	9000.000	6000.000
10	8000.000	7000.000

COORDINATES OF THE INJECTION WELL

X= 4000.000 Y= 2000.000 FT.
INJECTION RATE =5000. BBL/DAY

SYSTEM CONFIGURATION

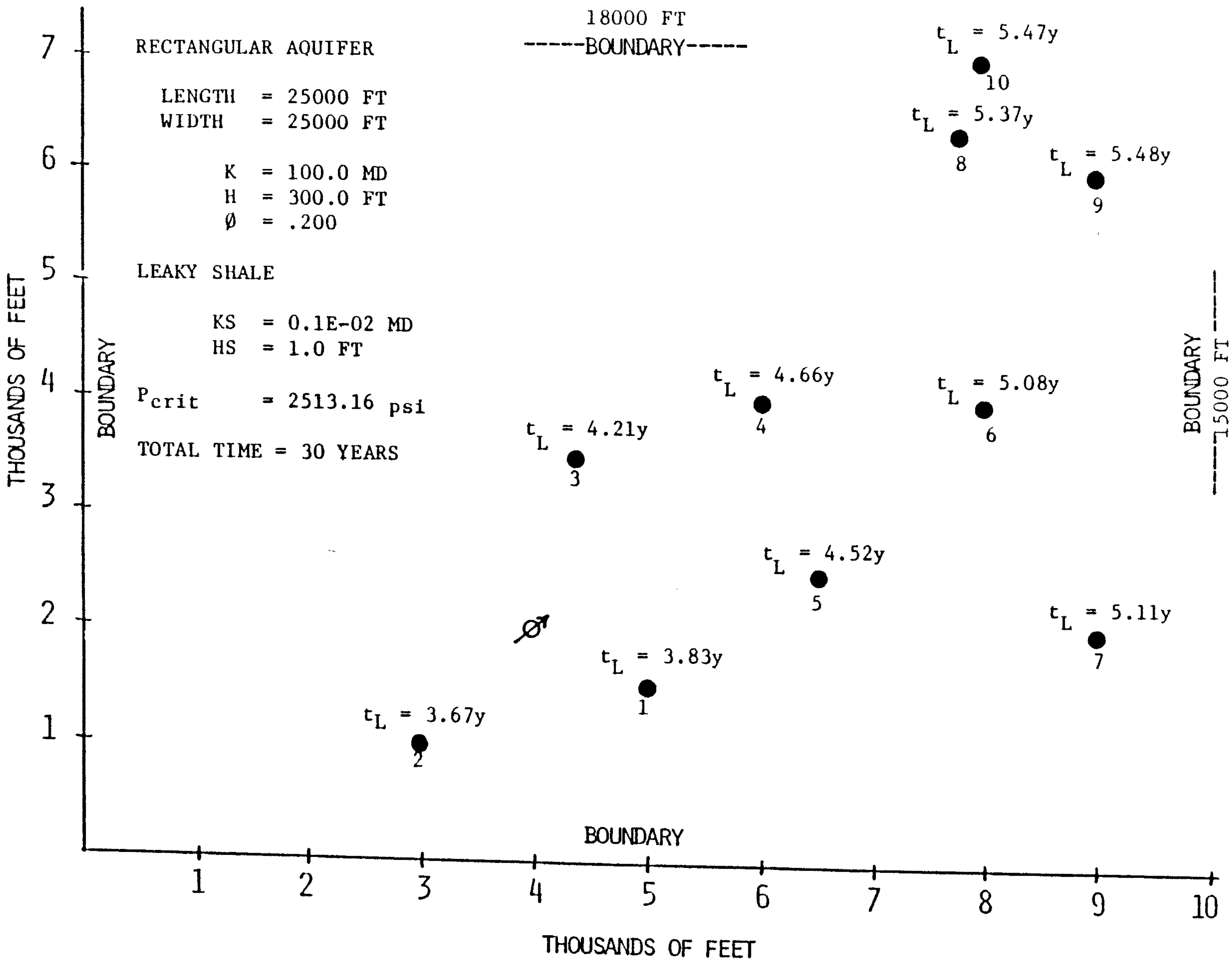
LEAKY SHALE LAYER

BETA/ALPHA=.44E+05 DAYS

BOUNDED AQUIFER
- LENGTH = 25000. FT
- WIDTH = 25000. FT
- AREA =14348.025 ACRES

TIME OF INVESTIGATION= 30.00 YEARS

ABANDON WELL #	CRITICAL PRESSURE PSI	LEAKING ?	TIME TO LEAK YEAR
1	2513.16	YES	3.83
2	2513.16	YES	3.67
3	2513.16	YES	4.21
4	2513.16	YES	4.66
5	2513.16	YES	4.52
6	2513.16	YES	5.08
7	2513.16	YES	5.11
8	2513.16	YES	5.37
9	2513.16	YES	5.48
10	2513.16	YES	5.47



18000 FT
BOUNDARY
RECTANGULAR AQUIFER
LENGTH = 25000 FT
WIDTH = 25000 FT
K = 100.0 MD
H = 300.0 FT
Ø = .200
LEAKY SHALE
KS = 0.1E-02 MD
HS = 1.0 FT
Pcrit = 2513.16 psi
TOTAL TIME = 30 YEARS
BOUNDARY
BOUNDARY
15000 FT
BOUNDARY
tL = 5.47y
10
tL = 5.37y
8
tL = 5.48y
9
tL = 4.66y
4
tL = 5.08y
6
tL = 4.21y
3
tL = 4.52y
5
tL = 5.11y
7
tL = 3.83y
1
tL = 3.67y
2
THOUSANDS OF FEET
THOUSANDS OF FEET
1
2
3
4
5
6
7
8
9
10

CASE VI, NO. 2

CASE VI, NO. 3

PROPERTIES OF THE DISPOSAL ZONE
****
COMPRESSIBILITY = 0.500E-05 1/PSI
PERMEABILITY = 100.000 MD
VISCOSITY = 1.000 CP
THICKNESS = 300.0 FT
POROSITY =0.200
****

PROPERTIES OF THE SHALE LAYER
****

SHALE PERMEABILITY =0.10000E-02 MD
SHALE THICKNESS = 1.00000 FT

PROPERTIES OF ABANDONED HOLES

ABAN WELL	WELL DIAM IN	DEPTH TO DISP ZONE FT	DEPTH TO H2O ZONE FT	MUD DENSITY LB/GAL	GEL STRENGTH LB/100FT2	CRITIC PRESSU PSI
1	9.6	5000.00	600.0	9.000	100.00	2513.16
2	9.6	5000.00	600.0	9.000	100.00	2513.16
3	9.6	5000.00	600.0	9.000	100.00	2513.16
4	9.6	5000.00	600.0	9.000	100.00	2513.16
5	9.6	5000.00	600.0	9.000	100.00	2513.16
6	9.6	5000.00	600.0	9.000	100.00	2513.16
7	9.6	5000.00	600.0	9.000	100.00	2513.16
8	9.6	5000.00	600.0	9.000	100.00	2513.16
9	9.6	5000.00	600.0	9.000	100.00	2513.16
10	9.6	5000.00	600.0	9.000	100.00	2513.16

COORDINATES OF THE ABANDONED WELLS

WELL #	X FT.	Y FT.
1	5000.000	1500.000
2	3000.000	1000.000
3	4400.000	3600.000
4	6000.000	4000.000
5	6500.000	2500.000
6	8000.000	4000.000
7	9000.000	2000.000
8	7800.000	6400.000
9	9000.000	6000.000
10	8000.000	7000.000

COORDINATES OF THE INJECTION WELL

X= 2000.000 Y= 1500.000 FT.
INJECTION RATE =5000. BBL/DAY

SYSTEM CONFIGURATION

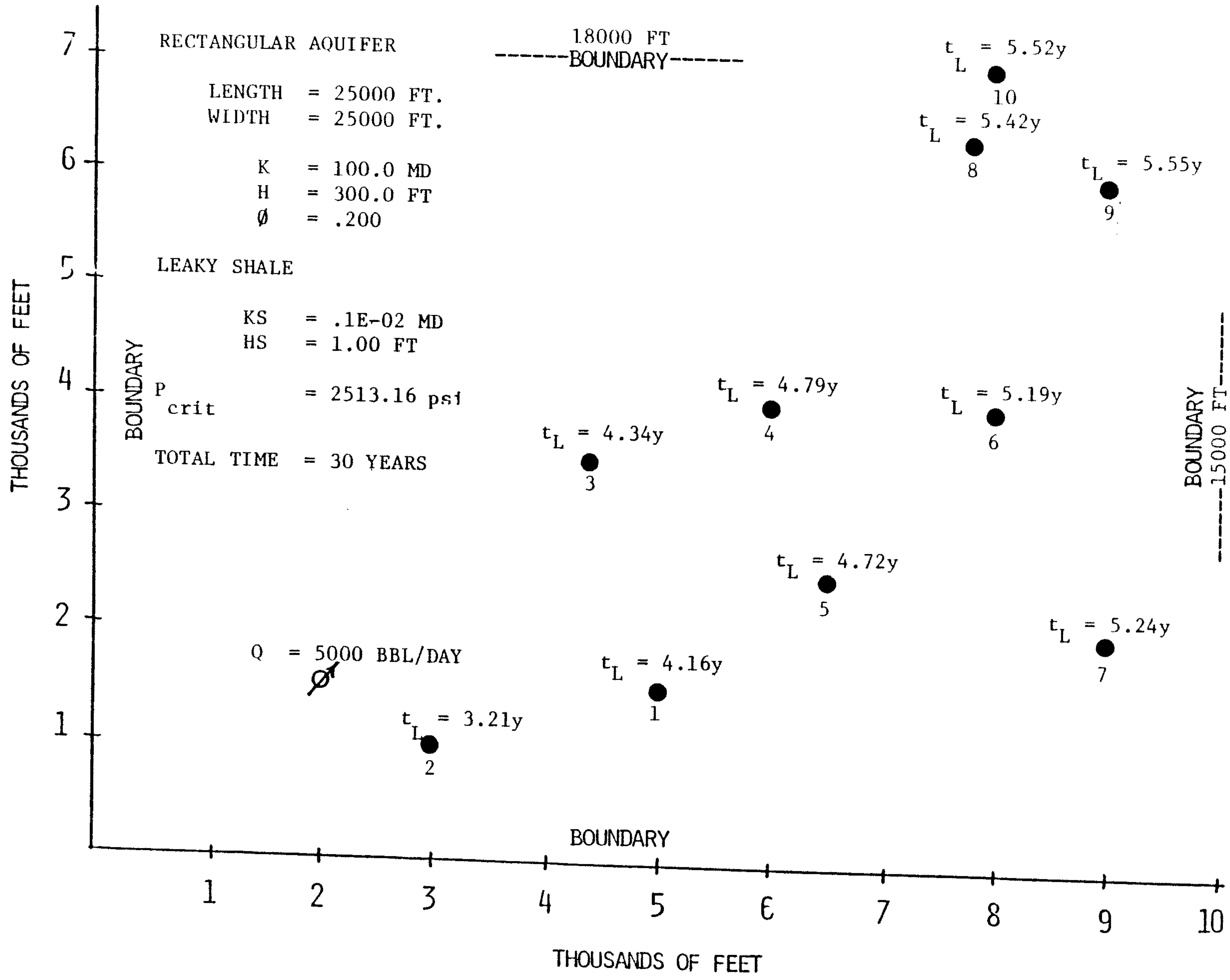
LEAKY SHALE LAYER

BETA/ALPHA=.44E+05 DAYS

BOUNDED AQUIFER
. LENGTH = 25000. FT
. WIDTH = 25000. FT
. AREA =14348.025 ACRES

TIME OF INVESTIGATION= 30.00 YEARS

ABANDON WELL #	CRITICAL PRESSURE PSI	LEAKING ?	TIME TO LEAK YEAR
1	2513.16	YES	4.16
2	2513.16	YES	3.21
3	2513.16	YES	4.34
4	2513.16	YES	4.79
5	2513.16	YES	4.72
6	2513.16	YES	5.19
7	2513.16	YES	5.24
8	2513.16	YES	5.42
9	2513.16	YES	5.55
10	2513.16	YES	5.52



RECTANGULAR AQUIFER
LENGTH = 25000 FT.
WIDTH = 25000 FT.
K = 100.0 MD
H = 300.0 FT
Ø = .200
LEAKY SHALE
KS = .1E-02 MD
HS = 1.00 FT
P crit = 2513.16 psi
TOTAL TIME = 30 YEARS
18000 FT
BOUNDARY
BOUNDARY
BOUNDARY
15000 FT
BOUNDARY
Q = 5000 BBL/DAY
tL = 3.21y
2
tL = 4.16y
1
tL = 4.34y
3
tL = 4.79y
4
tL = 4.72y
5
tL = 5.19y
6
tL = 5.24y
7
tL = 5.42y
8
tL = 5.52y
10
tL = 5.55y
9
THOUSANDS OF FEET
THOUSANDS OF FEET
1
2
3
4
5
6
7
8
9
10

CASE VI, NO. 3

CASE VI, NO. 4

PROPERTIES OF THE DISPOSAL ZONE

COMPRESSIBILITY = 0.500E-05 1/PSI
PERMEABILITY = 300.000 MD
VISCOSITY = 1.000 CP
THICKNESS = 50.0 FT
POROSITY =0.200

PROPERTIES OF THE SHALE LAYER

SHALE PERMEABILITY =0.10000E-02 MD
SHALE THICKNESS = 1.00000 FT

PROPERTIES OF ABANDONED HOLES

ABAN WELL	WELL DIAM IN	DEPTH TO DISP ZONE FT	DEPTH TO H2O ZONE FT	MUD DENSITY LB/GAL	GEL STRENGTH LB/100FT2	CRITIC PRESSU PSI
1	9.6	5000.00	600.0	9.000	100.00	2513.16
2	9.6	5000.00	600.0	9.000	100.00	2513.16
3	9.6	5000.00	600.0	9.000	100.00	2513.16
4	9.6	5000.00	600.0	9.000	100.00	2513.16
5	9.6	5000.00	600.0	9.000	100.00	2513.16
6	9.6	5000.00	600.0	9.000	100.00	2513.16
7	9.6	5000.00	600.0	9.000	100.00	2513.16
8	9.6	5000.00	600.0	9.000	100.00	2513.16
9	9.6	5000.00	600.0	9.000	100.00	2513.16
10	9.6	5000.00	600.0	9.000	100.00	2513.16

COORDINATES OF THE ABANDONED WELLS

WELL #	X FT.	Y FT.
1	5000.000	1500.000
2	3000.000	1000.000
3	4400.000	3600.000
4	6000.000	4000.000
5	6500.000	2500.000
6	8000.000	4000.000
7	9000.000	2000.000
8	7800.000	6400.000
9	9000.000	6000.000
10	8000.000	7000.000

COORDINATES OF THE INJECTION WELL

X= 4000.000 Y= 2000.000 FT.
INJECTION RATE =5000. BBL/DAY

SYSTEM CONFIGURATION

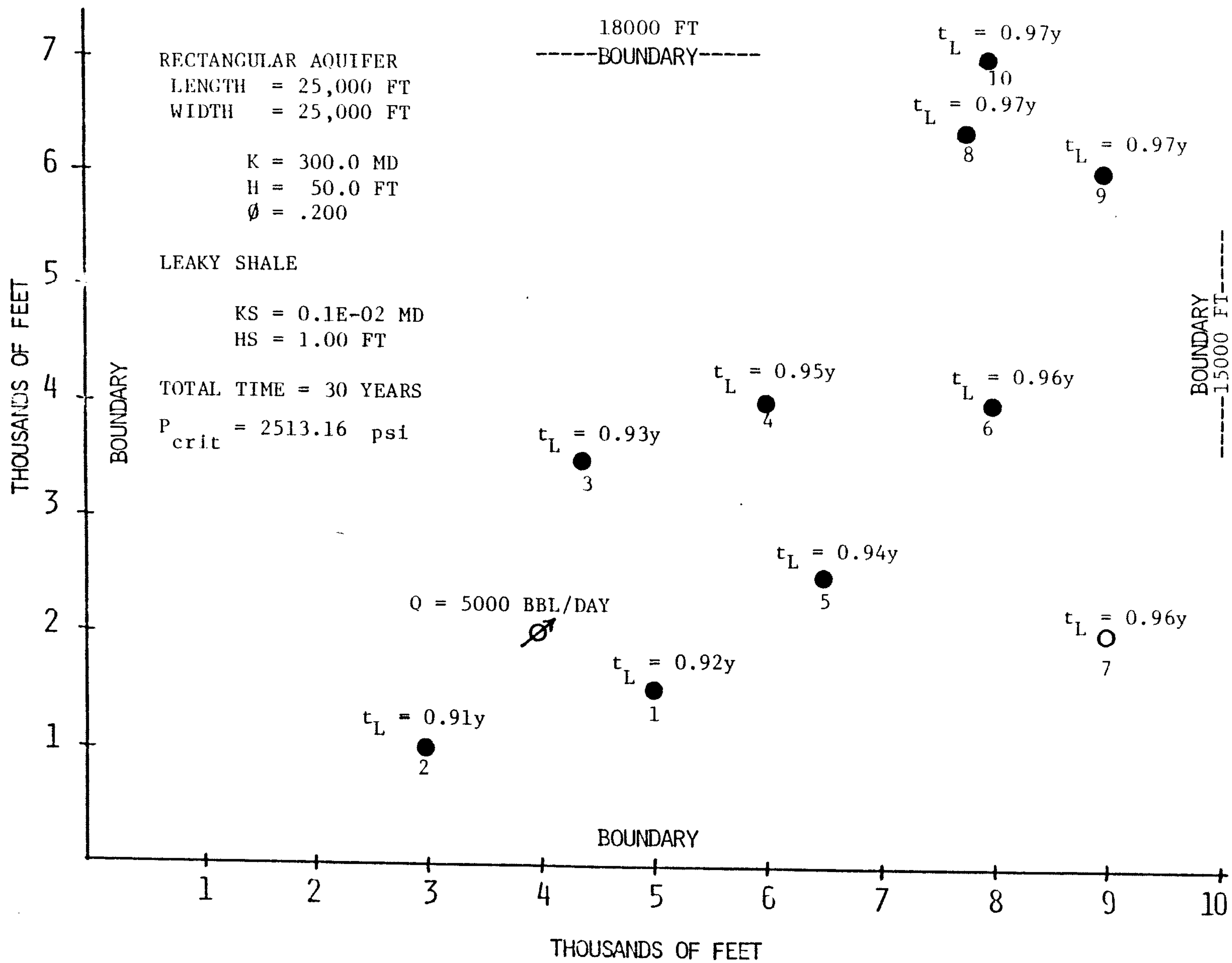
LEAKY SHALE LAYER

BETA/ALPHA=.73E+04 DAYS

BOUNDED AQUIFER
- LENGTH = 25000. FT
- WIDTH = 25000. FT
- AREA =14348.025 ACRES

TIME OF INVESTIGATION= 30.00 YEARS

ABANDON WELL #	CRITICAL PRESSURE PSI	LEAKING ?	TIME TO LEAK YEAR
1	2513.16	YES	0.92
2	2513.16	YES	0.91
3	2513.16	YES	0.93
4	2513.16	YES	0.95
5	2513.16	YES	0.94
6	2513.16	YES	0.96
7	2513.16	YES	0.96
8	2513.16	YES	0.97
9	2513.16	YES	0.97
10	2513.16	YES	0.97


RECTANGULAR AQUIFER
LENGTH = 25,000 FT
WIDTH = 25,000 FT
K = 300.0 MD
H = 50.0 FT
Ø = .200
LEAKY SHALE
KS = 0.1E-02 MD
HS = 1.00 FT
TOTAL TIME = 30 YEARS
P crit = 2513.16 psi
18000 FT
BOUNDARY
BOUNDARY
15000 FT
BOUNDARY
BOUNDARY
Q = 5000 BBL/DAY
tL = 0.91y
2
tL = 0.92y
1
tL = 0.93y
3
tL = 0.95y
4
tL = 0.94y
5
tL = 0.96y
6
tL = 0.96y
7
tL = 0.97y
8
tL = 0.97y
9
tL = 0.97y
10
THOUSANDS OF FEET
THOUSANDS OF FEET
1
2
3
4
5
6
7
8
9
10

CASE VI, NO. 4

CASE VI, NO. 5

PROPERTIES OF THE DISPOSAL ZONE

COMPRESSIBILITY =	0.500E-05	1/PSI
PERMEABILITY =	300.000	MD
VISCOSITY =	1.000	CP
THICKNESS =	50.0	FT
POROSITY =	0.200	

PROPERTIES OF ABANDONED HOLES

ABAN WELL	WELL DIAM IN	DEPTH TO DISP ZONE FT	DEPTH TO H2O ZONE FT	MUD DENSITY LB/GAL	GEL STRENGTH LB/100FT2	CRITIC PRESSU PSI
1	9.6	5000.00	600.0	8.600	100.00	2409.16
2	9.6	5000.00	600.0	8.600	100.00	2409.16
3	9.6	5000.00	600.0	8.600	100.00	2409.16
4	9.6	5000.00	600.0	8.600	100.00	2409.16
5	9.6	5000.00	600.0	8.600	100.00	2409.16
6	9.6	5000.00	600.0	8.600	100.00	2409.16
7	9.6	5000.00	600.0	8.600	100.00	2409.16
8	9.6	5000.00	600.0	8.600	100.00	2409.16
9	9.6	5000.00	600.0	8.600	100.00	2409.16
10	9.6	5000.00	600.0	8.600	100.00	2409.16

COORDINATES OF THE ABANDONED WELLS

WELL #	X FT.	Y FT.
1	5000.000	1500.000
2	3000.000	1000.000
3	4400.000	3600.000
4	6000.000	4000.000
5	6500.000	2500.000
6	8000.000	4000.000
7	9000.000	2000.000
8	7800.000	6400.000
9	9000.000	6000.000
10	8000.000	7000.000

COORDINATES OF THE INJECTION WELL

X= 6000.000 Y= 3000.000 FT.
INJECTION RATE =5000. BBL/DAY

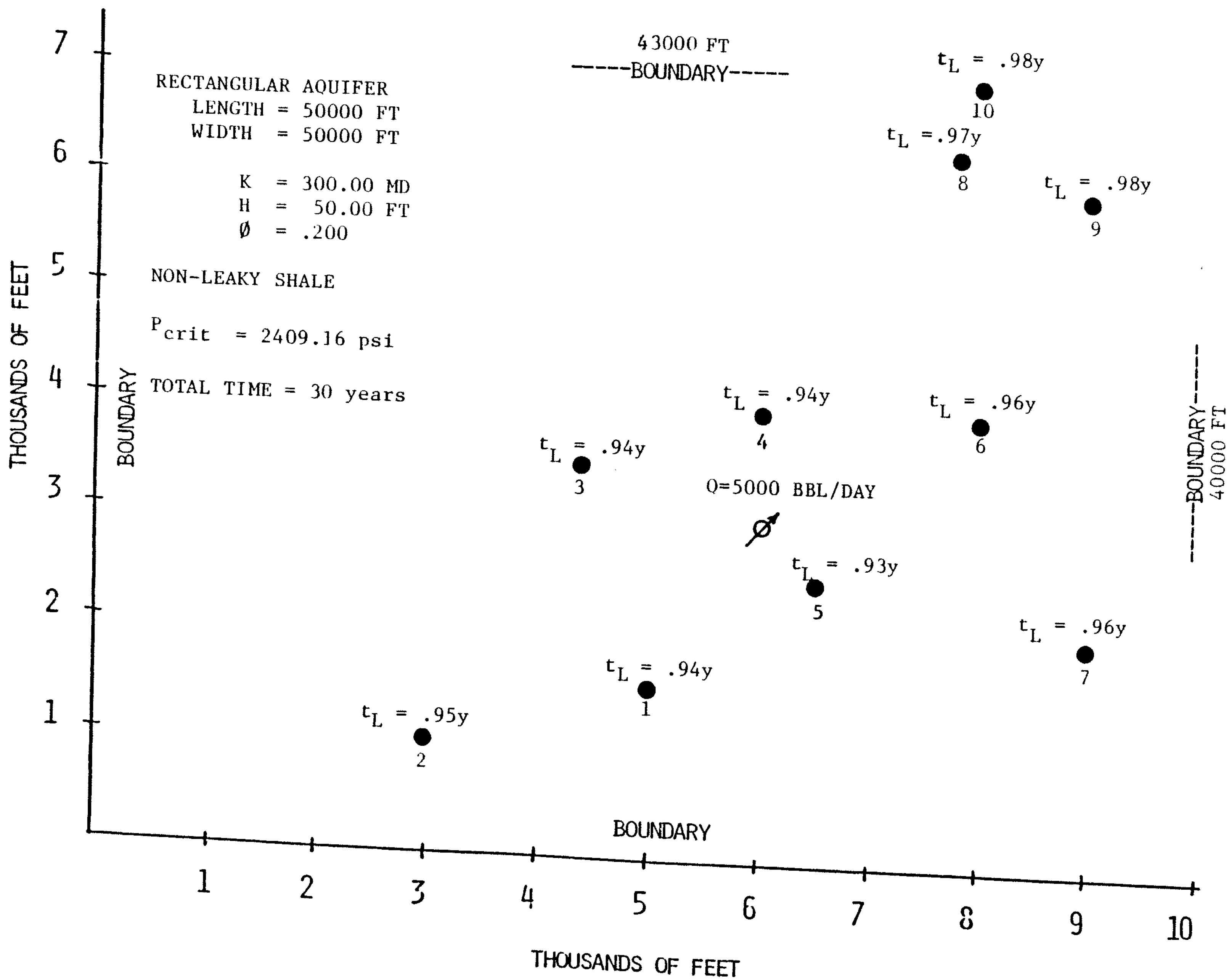
SYSTEM CONFIGURATION

NON-LEAKY SHALE

BOUNDED AQUIFER
. LENGTH = 50000. FT
. WIDTH = 50000. FT
. AREA =57392.102 ACRES

TIME OF INVESTIGATION= 30.00 YEARS

ABANDON WELL #	CRITICAL PRESSURE PSI	LEAKING ?	TIME TO LEAK YEAR
1	2409.16	YES	0.94
2	2409.16	YES	0.95
3	2409.16	YES	0.94
4	2409.16	YES	0.94
5	2409.16	YES	0.93
6	2409.16	YES	0.96
7	2409.16	YES	0.96
8	2409.16	YES	0.97
9	2409.16	YES	0.98
10	2409.16	YES	0.98


RECTANGULAR AQUIFER
LENGTH = 50000 FT
WIDTH = 50000 FT
K = 300.00 MD
H = 50.00 FT
Ø = .200
NON-LEAKY SHALE
P_{crit} = 2409.16 psi
TOTAL TIME = 30 years
43000 FT
-----BOUNDARY-----
BOUNDARY
40000 FT
BOUNDARY
BOUNDARY
Q=5000 BBL/DAY
t_L = .95y 2
t_L = .94y 1
t_L = .94y 3
t_L = .94y 4
t_L = .93y 5
t_L = .96y 6
t_L = .96y 7
t_L = .97y 8
t_L = .98y 9
t_L = .98y 10
THOUSANDS OF FEET
THOUSANDS OF FEET
1 2 3 4 5 6 7 8 9 10
1 2 3 4 5 6 7

CASE VI, NO. 5

CASE VI, NO. 6

PROPERTIES OF THE DISPOSAL ZONE

COMPRESSIBILITY	=	0.500E-05	1/PSI
PERMEABILITY	=	300.000	MD
VISCOSITY	=	1.000	CP
THICKNESS	=	50.0	FT
POROSITY	=	0.200	

PROPERTIES OF ABANDONED HOLES

ABAN WELL	WELL DIAM IN	DEPTH TO DISP ZONE FT	DEPTH TO H2O ZONE FT	MUD DENSITY LB/GAL	GEL STRENGTH LB/100FT2	CRITIC PRESSU PSI
1	9.6	5000.00	600.0	8.600	100.00	2409.16
2	9.6	5000.00	600.0	8.600	100.00	2409.16
3	9.6	5000.00	600.0	8.600	100.00	2409.16
4	9.6	5000.00	600.0	8.600	100.00	2409.16
5	9.6	5000.00	600.0	8.600	100.00	2409.16
6	9.6	5000.00	600.0	8.600	100.00	2409.16
7	9.6	5000.00	600.0	8.600	100.00	2409.16
8	9.6	5000.00	600.0	8.600	100.00	2409.16
9	9.6	5000.00	600.0	8.600	100.00	2409.16
10	9.6	5000.00	600.0	8.600	100.00	2409.16

COORDINATES OF THE ABANDONED WELLS

WELL #	X FT.	Y FT.
1	5000.000	1500.000
2	3000.000	1000.000
3	4400.000	3600.000
4	6000.000	4000.000
5	6500.000	2500.000
6	8000.000	4000.000
7	9000.000	2000.000
8	7800.000	6400.000
9	9000.000	6000.000
10	8000.000	7000.000

COORDINATES OF THE INJECTION WELL

X= 6000.000 Y= 3000.000 FT.
INJECTION RATE =5000. BBL/DAY

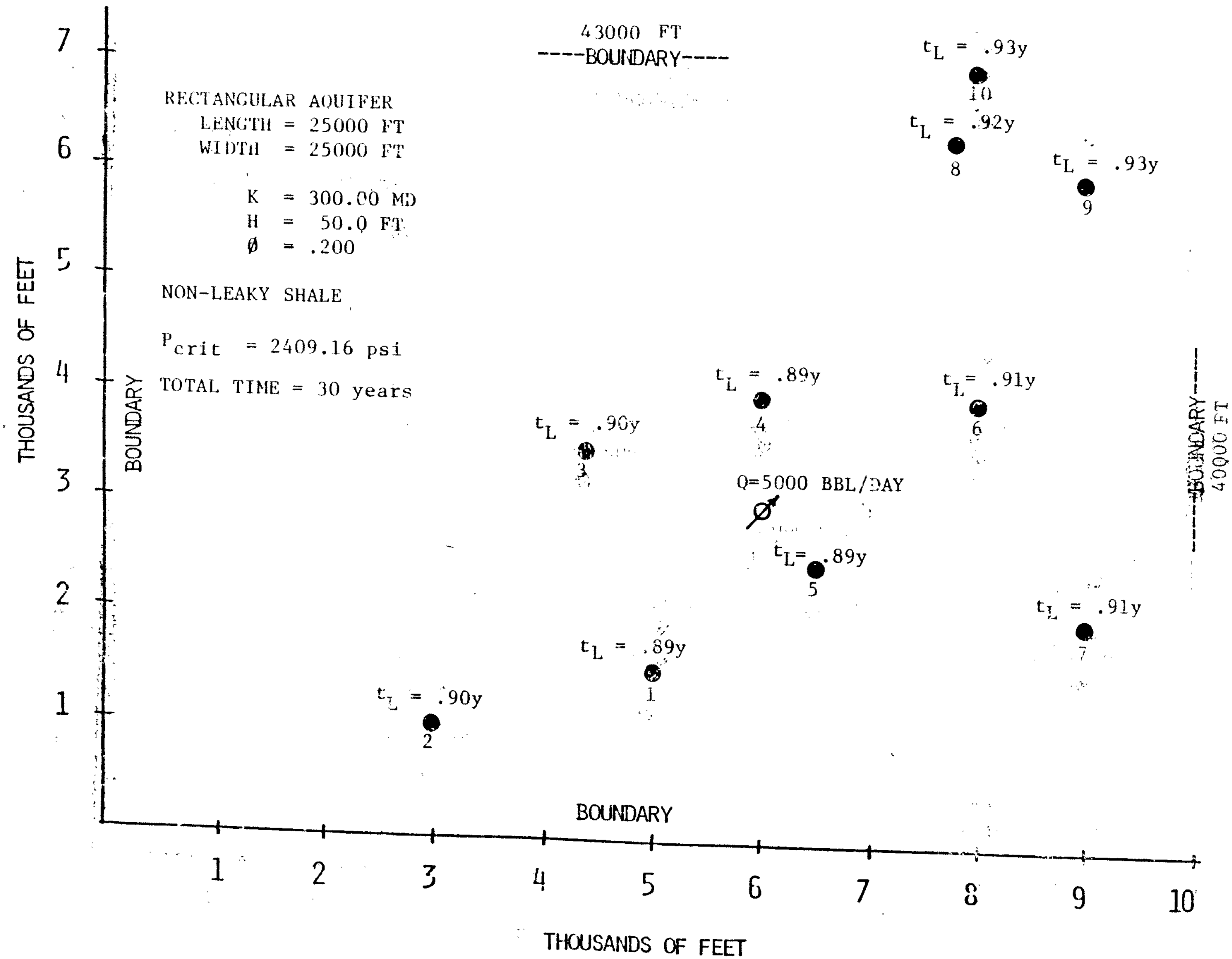
SYSTEM CONFIGURATION

NON-LEAKY SHALE

BOUNDED AQUIFER
- LENGTH = 25000. FT
- WIDTH = 25000. FT
- AREA =14348.025 ACRES

TIME OF INVESTIGATION= 30.00 YEARS

ABANDON WELL #	CRITICAL PRESSURE PSI	LEAKING ?	TIME TO LEAK YEAR
1	2409.16	YES	0.89
2	2409.16	YES	0.90
3	2409.16	YES	0.90
4	2409.16	YES	0.89
5	2409.16	YES	0.89
6	2409.16	YES	0.91
7	2409.16	YES	0.91
8	2409.16	YES	0.92
9	2409.16	YES	0.93
10	2409.16	YES	0.93


43000 FT
----BOUNDARY----
RECTANGULAR AQUIFER
LENGTH = 25000 FT
WIDTH = 25000 FT
K = 300.00 MD
H = 50.0 FT
Ø = .200
NON-LEAKY SHALE
Pcrit = 2409.16 psi
TOTAL TIME = 30 years
tL = .93y
10
tL = .92y
8
tL = .93y
9
tL = .89y
4
tL = .91y
6
tL = .90y
3
Q=5000 BBL/DAY
tL= .89y
5
tL = .91y
7
tL = .89y
1
tL = .90y
2
BOUNDARY
BOUNDARY
BOUNDARY
40000 FT
THOUSANDS OF FEET
THOUSANDS OF FEET
1
2
3
4
5
6
7
8
9
10

CASE VI NO. 6

Drilling Mud as a Hydraulic Seal in Abandoned Wellbores

DRILLING MUD AS A HYDRAULIC SEAL IN ABANDONED WELLBORES

R. E. Collins and D. Kortum
Research & Engineering Consultants, Inc., Englewood, Colorado 80111

Abstract

Results of a series of laboratory experiments are presented which exhibit the contribution of mud gel strength to the hydraulic sealing characteristics of mud filling an abandoned well. The apparatus consisted of a small scale, simulated wellbore fitted with a sandstone core plug at the lower end. Mud filling this wellbore was allowed to gel for a fixed time, then the brine pressure required for initiation of brine entry through the brine saturated core plug was measured. These data, together with measured properties of the mud, and geometry of the simulated wellbore constituted the experimental data.

These data indicate that in most circumstances the gel character of the mud contributes as much to the minimum fluid entry pressure as does the hydrostatic head of the mud. In fact, in many cases the gel might contribute more to sealing pressure than hydrostatic head by a factor of three or <u>more</u>. Furthermore it has been found that non-uniformities in hole diameter appear to cause an even greater contribution of mud gel to hole sealing by mud.

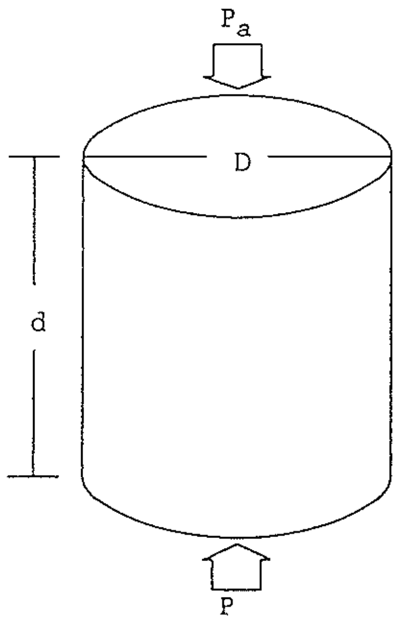
This study lends support to the viewpoint that abandoned wells pose very little threat as a path for contamination of any USDW in deep well injection operations if these wells are filled with gelled mud. However, these experiments are not truly scaled and it is proposed that properly scaled experiments are needed. A parallel study is also called for to characterize the properties of old muds in abandoned wells.

DRILLING MUD AS A HYDRAULIC SEAL IN
ABANDONED WELLBORES

R. E. Collins and D. Kortum
Research & Engineering Consultants, Inc., Englewood, Colorado 80111

Introduction

That a column of drilling mud remaining in an uncased well at abandonment provides a hydrostatic pressure against fluid entry from penetrated strata is generally accepted, but it has not been generally accepted that the gel property of the mud contributes an increment to this pressure that may be significant. Barker (1981) was evidently the first investigator to propose that both hydrostatic and gel contributions be included when estimating the threshold of aquifer pressure at which fluid from the aquifer could enter a mud-filled abandoned well. Specifically Barker estimated this threshold pressure from a balance of forces as in Figure 1.



$$\text{Net Pressure force, up} = \frac{\pi D^2}{4} (P - P_a)$$

$$\text{Weight force, down} = \frac{\pi D^2}{4} d\rho_m$$

$$\text{Shear force at wall, down} = \pi DdG$$

FIGURE 1

Here a straight, cylindrical well of diameter D and depth d to an aquifer is filled with mud of weight density ρ_m and gel strength G. At depth d a uniform pressure P exists over the cross-section of the well. If the upward force of this pressure exceeds the sum of the downward forces due to the atmosphere, weight of the mud, and the shear force at the wall of the hole then the column could be displaced upward by this pressure. Since pressure must be uniform in any horizontal plane within continuous fluid at rest, P is also the pressure of the brine in the aquifer at depth d. Thus Barker's criterion for no brine entry into the mud-filled well is

$$(1) \qquad \frac{\pi D^2}{4} P < \frac{\pi D^2}{4} d\rho_m + \pi DdG + P_a$$

where P_a is atmospheric pressure. This explicitly assigns the shear force per unit area on the wall of the hole as the gel strength G.

If the original, pre-injection pressure of the injection interval, $P_a + \rho_B gd$, is subtracted there results the criterion for admissible pressure increase in the aquifer, ΔP, with no brine entry into the abandoned well. Here ρ_B is the depth-averaged brine density from surface to the aquifer at depth d. In oil field units this gives the criterion as

$$(2) \qquad \Delta P \leq 0.052\ (\rho_m - \rho_B)d + 3.33 \times 10^{-3}\ \frac{Gd}{D}$$

For a minimum mud weight, about 9.0 lb./gal. for Bentonite mud, having a gel strength of 50 lb./(100 ft.^{2}) for a fresh water mix, and an average ρ_B of 8.4 lb./gal. this yields for a 5000 ft., 9-5/8" diameter hole

$$(3) \qquad \Delta P < 130 + 86.5 = 216.5 \text{ psi}$$

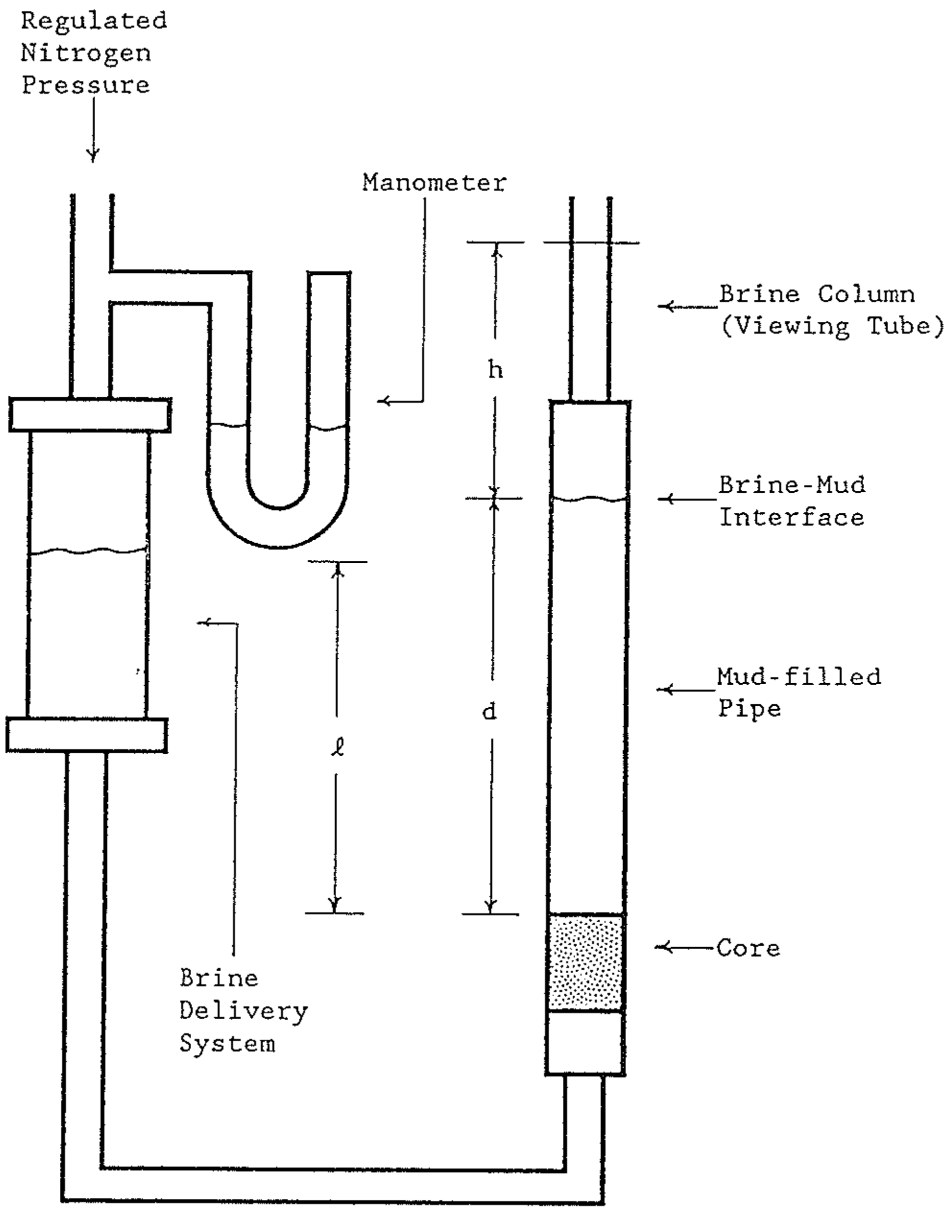
Thus gel contributes about 40% of the hole-sealing pressure of the mud in the hole. Clearly then it is important that this entry pressure criterion be validated.

Although this threshold pressure assignment is plausible it has not been confirmed experimentally. Thus we undertook a few simple experiments directed to such a demonstration. These are described here together with the rather surprising results that were obtained.

General Description of Apparatus and Procedure

This study actually included nine different experiments using the same basic apparatus with only minor alterations. Figure 2 shows the general configuration of laboratory equipment. A core was epoxied into a nipple and then attached to a pipe joint below the core which in turn was attached to a line carrying brine from a salt water reservoir. The pressure at this reservoir was recorded using a gauge or mercury manometer. Pressure was supplied to the brine using compressed nitrogen and a pressure regulator. Brine was pushed through the brine delivery system until no air existed in the lines and the rock was saturated with the brine. At this point, a pipe was attached to the core nipple and a column of bentonite mud (20 ppb bentonite with 3 ppb salt in Experiment No. 1 and 30 ppb bentonite in all other experiments)* was placed in the pipe over the core.

*ppb = pounds per barrel



(not to scale)

GENERAL DESCRIPTION OF EQUIPMENT

FIGURE 2

A sample of this mud was also placed in a Fann viscometer cup to remain quiescent. A small diameter transparent tube was attached to the top of the mud column and filled with brine to provide a volumetrically sensitive detection for movement of the mud column. The mud was allowed to gel for approximately 12 hours, at which time pressure was slowly applied to the brine delivery system until fluid movement was noted in the viewing tube at the top of the column. Concurrently, the gel strength of the mud sample in the viscometer cup was measured using a Fann V-G meter. Note that the relevant distances to calculate pressures are indicated by ℓ, h, and d in Figure 1. All physical dimensions of this apparatus are given in the appendix together with physical properties of the fluids used.

Data Reduction

The data reduction scheme in these experiments required calculation of the brine pressure, P_c, at the face of the core contacting the mud column. From Figure 1 this is (gauge value)

(4) $$P_c = P_m + \rho_B g \ell$$

where P_m is the pressure read on the manometer of the brine chamber. Also the hydrostatic pressure at the core face (gauge value), P_h, due to the brine column in the sight tube and the mud column is

(5) $$P_h = \rho_m g d + \rho_B g h$$

Thus the difference in these two pressures, $P_c - P_h$, is the measured excess brine pressure in the core plug required solely to "break the gel" and initiate fluid entry. Specifically our Eq.(1) is now expressed in terms of these pressures as

(6) $$\frac{\pi D^2}{4} (P_c - P_h) \geq \pi D d G$$

Now the first experiment indicated that a significant discrepancy existed between the measured pressure difference, $P_c - P_h$, as obtained using Eqs.(4) and (5) and the value implied by the equality in Eq.(6). That is, a value for $P_c - P_h$ can be computed from the measured value for G in the Fann instrument using Eq.(6). Specifically the measured value of $P_c - P_h$ was more than five times as large as that computed in this way. Thus these data implied that mud gel was contributing much more to the threshold brine entry pressure than one computes from the Fann measured value for G.

After some deliberation a hypothesis was formed to account for this discrepancy and this guided the design of subsequent experiments. It was conjectured that the excess pressure required to break the gel arose from the non-uniform diameter of the simulated wellbore. Specifically there was a narrowing of the diameter immediately above the core and abrupt "shoulders" of about 1/16" at the coupling. Also there was a "shoulder" of about 1/4" at the sight tube connection. It was believed that stress concentrations at these sharp corners caused a much greater applied stress to be required to shear the mud in the column.

Subsequent experiments were designed to test this hypothesis by introducing specific shape irregularities in the simulated wellbore. Then in each experiment an apparent gel strength was computed from measured pressures, P_c and P_h, using Eq.(6) as

$$G' = \frac{D}{4d} (P_c - P_h) \tag{7}$$

This is then compared to G determined in the Fann instrument as the ratio

$$R = \frac{G'}{G} \tag{8}$$

Following is a description of specific experiments in which R was determined for various geometries.

Description of Experiments

Exps. 1 & 2

The geometries for the various experimental runs are shown in Figure 3. In the first two runs, the pipe size was small (refer to Appendix). Two 1/16" shoulders were located along the length of the pipe, one just above the core and one midway up the length of the pipe. In addition, a fairly severe constriction occurred at the top of the column where the viewing tube was substantially smaller (diameter = 1/8") than the pipe itself and mud actually extended into this tube. Therefore, three constrictions existed along the mud column. The 1/16" shoulders were fairly large relative to the total diameter of the pipe.

Exp. 3

A large pipe was substituted for the small pipe (see Appendix). The pipe contained only one 1/8" shoulder located above the core. The adapter with brine viewing tube on top was used as shown in inset of Figure 3.

Exp. 4

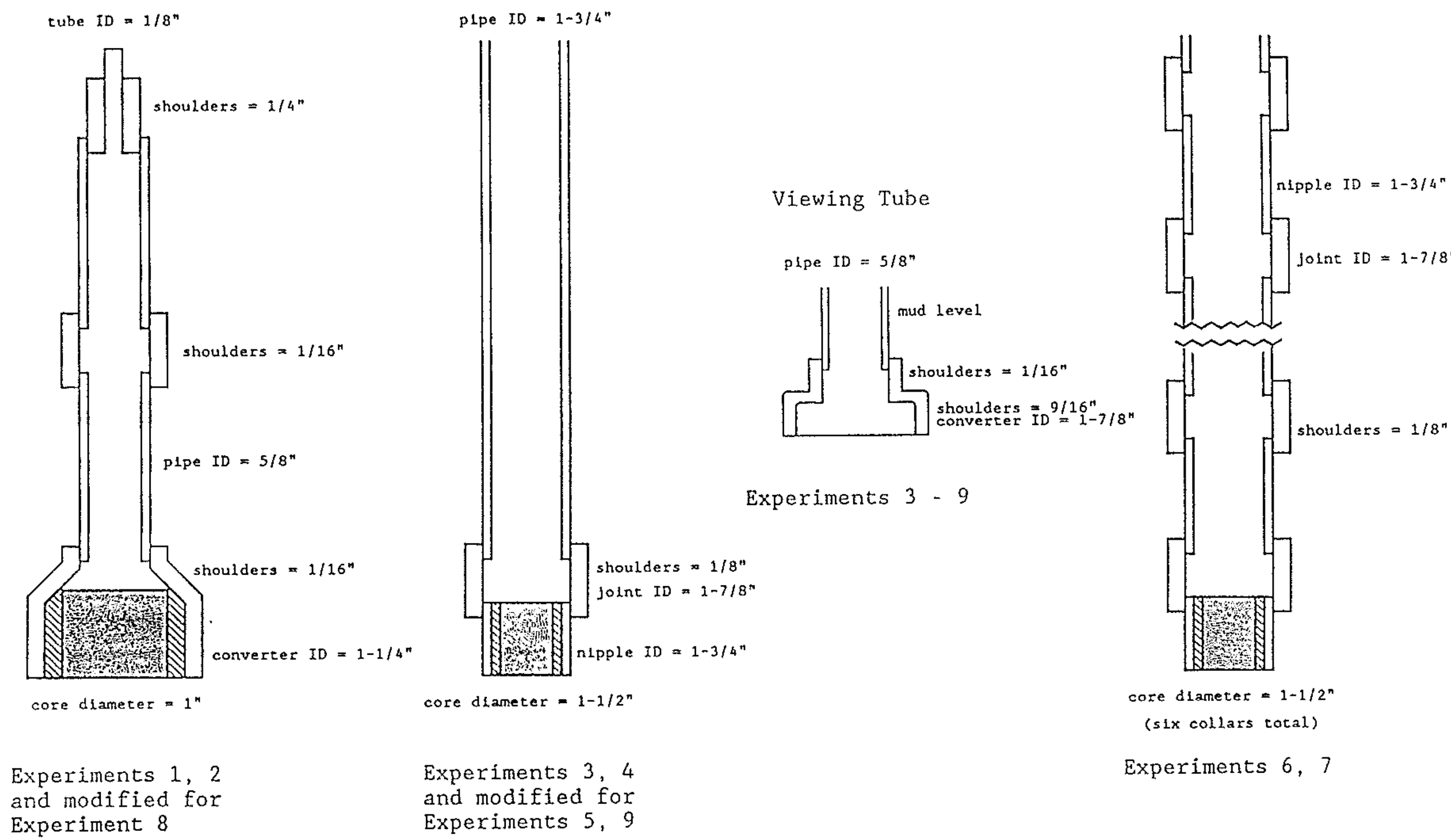
The same set-up as Exp. 3 was used; however, the pipe had an oily film over its entire inner surface. No specific data were collected since fluid movement occurred immediately and no apparent gel strength was observed. i.e. $P_c - P_h$ was zero.

Exp. 5

Exp. 5 was similar to Exp. 3 except that an additional constriction was placed on the mud column and the mud column extended into the smaller pipe on top and into the brine viewing tube (see Figure 3 inset).

Exps. 6 & 7

Experiments 6 and 7 were identical. These were identical to Exp. 3 but instead of a smooth pipe being used, a series of five joints and nipples (in addition to the one located above the core mentioned in Exp. 3) were located along the length of the pipe (see Figure 3).



(not to scale)

FIGURE 3

Exp. 8
This experiment employed the small pipe as in Exps. 1 and 2 but in this case the mud did not extend into the small viewing tube initially. The mud level was in the 5/8" ID pipe.

Exp. 9
This experiment was intended to test behavior in a pipe of uniform dimensions with no constrictions anywhere. A PVC pipe was mounted into the nipple containing the core used in Exps. 3 and 4 with the pipe inserted flush to the core plug face. Thus no "shoulders" were present in the mud-filled pipe. The adapter with the brine-filled viewing tube was mounted on top but the mud level was in the uniform diameter pipe.

Results and Discussion

Values for all parameters and data collected in these experiments are listed in the appendix and here we summarize values determined for R, the ratio of apparent to actual gel strength in Table I.

TABLE I

Exp. No.	1	2	3	4	5	6	7	8	9
R	5.11	5.05	1.68	0.00	2.77	3.83	3.61	5.76	1.99

The results of Exps. 1 and 2 indicate non-uniform geometry profoundly influences the apparent gel strength. Apparently the relative size of diameter constrictions in relation to the cylinder in which the mud stands produced the larger increases in apparent gel strength observed in Exps. 1 and 2 as compared to other experiments.

In Exp. 3, the one shoulder in the large pipe produced, approximately, a 68% increase in apparent gel strength over the Fann measured value. In Exps. 6 and 7, it would be reasonable to assume that the increase in apparent gel strength should be about six times the 68% value observed in Exp. 3 since 6 shoulders are present. This would produce an R value of 1 + (0.68 x 6) or 5.08 which is larger than the apparent values actually observed in Exps. 6 and 7.

Exp. 5 provides further evidence that geometric irregularities produce increases in apparent gel strength. With the constriction on the top of the pipe (along with the shoulder of Exp. 3), the apparent gel strength is increased by nearly three-fold over the Fann measured value.

Exp. 4 demonstrates that when the mud column is detached from the pipe structure by an oily film, either the brine flows up the pipe around the mud column or the column provides little or no gel strength since it is, in effect, not bonded to the pipe.

Exp. 8 was to test whether the very large value of G observed in Exps. 1 and 2 was due in part to the fact that mud extended into the small diameter viewing tube at the top of the 5/8" ID pipe. Since the observed value of R in Exp. 8 was even larger, this is not the case.

The objective in Exp. 9 was to determine whether a tube free of <u>any</u> non-uniformities in diameter of the mud column would yield a G value comparable to that measured in the Fann viscometer. Since the apparent G value in this case was almost double the Fann determined value, this is not the case. Thus, there are <u>other factors involved besides non-uniform diameter of hole</u> which cause the high apparent G values.

We can <u>speculate</u> on the implications of the data obtained in the above experiments:

(1) There is clearly an increase in the contribution of mud gel strength to the threshold pressure for brine entry arising from constrictions or non-uniformities in pipe (simulated bore-hole) diameter. A factor of about 2 - 5 was observed.

(2) There is another contribution to threshold brine entry pressure not associated with hole geometry. We speculate that this may be due to gelled mud in the pores of the core plug. Also it is possible that upon standing with mud pressure on the core plug, some particulates could enter the larger pores of the core plug. This might account for the results in Exps. 8 and 9.

Regardless of the ultimate resolution of these questions one fact is certain and this is that the gel strength of mud in an abandoned well does indeed contribute significantly to the threshold pressure for fluid entry to the well.

<u>Conclusions</u>

The experiments described here confirm that the gel characteristics of drilling mud do contribute substantially to the threshold pressure required for brine entry from an aquifer into a mud-filled wellbore. Specifically the threshold pressure for fluid entry computed by Eq.(1) above, using an <u>average</u> hole diameter D and a laboratory measured G value, will always be significantly conservative. The data presented have suggested that irregularities in hole diameter can cause the true gel contribution to be four to five times greater than that calculated for a uniform diameter. However, since these experiments were not properly scaled direct application of this result to actual wells should be used with caution. Further experiments and analysis could resolve this issue of effects of hole diameter irregularities. Other questions raised in these experiments might be explained in part by prior studies on particulate transport in porous media [Gruesbeck and Collins (1982)] but the effect of gelling of colloidal clay which invades the porous rock calls also for additional experiments.

Appendix

Data and Results
(see Nomenclature at end)

Experiment 1

Geometry	in.	cm.
Core Diameter	1.0	2.54
Pipe I.D.	0.625	1.488
Length, ℓ	24.409	62.0
Length, d	11.5	29.2
Length, h	4.53	11.5

Pressures	psi	in. Hg
P_m	3.0	
P_s	+0.8937	+1.8
P_h	0.5966	1.2
P_c	3.89	7.9

Gel Strength	psi	lbs./100 ft.^{2} (12 hrs.)
G		125.0
G′	0.04475	644.0

$G'/G = R = 5.11$

Experiment 2

Geometry	in.	cm.
Core Diameter	1.0	2.54
Pipe I.D.	0.625	1.488
Length, ℓ	14.6	37.0
Length, d	12.0	30.5
Length, h	3.94	10.0

Pressures	psi	in. Hg
P_m	7.859	16.0
P_s	-0.533	-1.1
P_h	0.5966	1.2
P_c	7.326	14.9

Gel Strength	psi	lbs./100 ft.^{2} (12 hrs.)
G		250.0
G′	0.08763	1262.0

$G'/G = R = 5.05$

Experiment 3

Geometry	in.	cm.
Core Diameter	1.5	3.82
Pipe I.D.	1.625	4.12
Length, ℓ	11.4	29.0
Length, d	26.0	66.0
Length, h	6.5	16.5

Pressures	psi	in. Hg
P_m	3.438	7.0
P_s	-0.418	-0.851
P_h	1.218	2.48
P_c	3.02	6.15

Gel Strength	psi	lbs./100 ft.^{2} (12 hrs.)
G		250.0
G′	0.02816	405.0

G′/G = R = 1.68

Experiment 5

Geometry	in.	cm.	
Core Diameter	1.5	3.82	
Pipe I.D.	1.625	4.12	small pipe
Length, ℓ	12.2	31.0	radius =
Length, d	33.9	86.0	0.3125 in.
Length, h	3.54	9.0	(see sketch)

Pressures	psi	in. Hg
P_m	4.91	10.0
P_s	-0.4476	-0.91
P_h	1.4059	2.86
P_c	4.4643	9.1

Gel Strength	psi	lbs./100 ft.^{2} (12 hrs.)
G		210.0
G′	0.04042	582.0

G′/G = R = 2.77

Experiment 6

Geometry	in.	cm.
Core Diameter	1.5	3.82
Pipe I.D.	1.625	4.12
Length, ℓ	13.8	35.0
Length, d	26.0	66.0
Length, h	6.3	16.0

Pressures	psi	in. Hg
P_m	3.93	8.0
P_s	-0.5044	-1.28
P_h	1.21	2.46
P_c	3.425	6.97

Gel Strength	psi	lbs./100 ft.^{2} (12 hrs.)
G		130.0
G′	0.03460	498.0

$G'/G = R = 3.83$

Experiment 7

Geometry	in.	cm.
Core Diameter	1.5	3.82
Pipe I.D.	1.625	4.12
Length, ℓ	13.8	35.0
Length, d	26.0	66.0
Length, h	6.3	16.0

Pressures	psi	in. Hg
P_m	4.13	8.4
P_s	-0.5044	-1.28
P_h	1.21	2.46
P_c	3.6214	7.373

Gel Strength	psi	lbs./100 ft.^{2} (12 hrs.)
G		150.0
G′	0.03768	542.0

$G'/G = R = 3.61$

Experiment 8
(small pipe - no top constriction)

Geometry	in.	cm.
Core Diameter	1.0	2.54
Pipe I.D.	0.625	1.876
Length, ℓ	21.65	55.0
Length, d	9.84	25.0
Length, h	3.05	7.75

Pressures	psi	in. Hg
P_m	6.1886	12.6
P_s	-0.7925	-1.6135
P_h	0.4827	0.9828
P_c	5.396	10.98

Gel Strength	psi	lbs./100 ft.^{2} (12 hrs.)
G		195.0
G′	0.078	1123.0

G′/G = R = 5.76

Experiment 9
(large pipe, PVC - no shoulders)

Geometry	in.	cm.
Core Diameter	1.5	3.82
Pipe I.D.	1.5	3.82
Length, ℓ	20.866	53.0
Length, d	22.441	57.0
Length, h	5.906	15.0

Pressures	psi	in. Hg
P_m	3.438	7.0
P_s	-0.7637	-1.555
P_h	1.062	2.162
P_c	2.674	5.444

Gel Strength	psi	lbs./100 ft.^{2} (12 hrs.)
G		195.0
G′	0.02694	388.0

G′/G = R = 1.99

Fluid Properties

	Density (g/cc)	lb./gal.	psi/ft.	psi/in.	psi/cm.
Salt	1.0147	8.45	0.4394	0.0366	0.01441
Mud (Exp. 1)	1.0396	8.65	0.4498	0.0375	0.01476
Mud (Exps. 2 - 9)	1.0444	8.70	0.4520	0.0377	0.01484

Mud Composition:

Exp. 1: 20 ppb bentonite, 3 ppb salt
Exps. 2 - 9: 30 ppb bentonite

Nomenclature

ℓ, d, h	Vertical Dimensions of Experimental Set-Up
r_c	Core Radius
r_p	Pipe Radius
h_p	Pipe Length
P_m	Manometer Pressure
P_s	Hydrostatic Pressure of Brine Reservoir
P_h	Hydrostatic Head of Mud/Brine Over Core
P_c	Pressure at Core Face

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Daeman and Ran 1968 Bentonite as a Waste Isolation Pilot Plan Shaft Sealing Material

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Bentonite as a Waste Isolation Pilot Plant Shaft Sealing Material

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Bentonite as a Waste Isolation Pilot Plant Shaft Sealing Material

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ABSTRACT

Current designs of the shaft sealing system for the Waste Isolation Pilot Plant (WIPP) propose using bentonite as a primary sealing component (DOE/WIPP, 1995). The shaft sealing designs anticipate that compacted bentonite sealing components can perform through the 10,000-year regulatory period and beyond. To evaluate the acceptability of bentonite as a sealing material for the WIPP, this report identifies references that deal with the properties and characteristics of bentonite that may affect its behavior in the WIPP environment.

This report reviews published studies that discuss using bentonite as sealing material for nuclear waste disposal, environmental restoration, toxic and chemical waste disposal, landfill liners, and applications in the petroleum industry. This report identifies the physical and chemical properties, stability and seal construction technologies of bentonite seals in shafts, especially in a saline brine environment. This report focuses on permeability, swelling pressure, strength, stiffness, longevity, and densification properties of bentonites.

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1. INTRODUCTION

The US Department of Energy (DOE) is developing the Waste Isolation Pilot Plant (WIPP) in southeastern New Mexico as a full-scale, mined geologic repository to demonstrate the safe management, storage, and disposal of transuranic (TRU) radioactive wastes that result from defense programs of the US Government. The WIPP underground facility is located in the brine-bearing, bedded salt of the Salado Formation at about 655 m below the ground surface.

Before disposing of radioactive wastes in the WIPP, the DOE must evaluate the repository based on various regulatory criteria for disposal of the waste components, and the US Environmental Protection Agency (EPA) must certify that compliance has been satisfactorily demonstrated. The regulations in 40 CFR 191.14 (d) (EPA, 1995a) require using both engineered and natural barriers to isolate waste from the accessible environment. The engineered and natural system should (1) limit the flow of fluid (water/brine and gas) through or into the repository over the designed lifetime and (2) limit radionuclide migration to the accessible environment below the acceptable level. Quantitative requirements for potential releases of radioactive and other hazardous materials from the repository system are specified in 40 CFR 191 and 40 CFR 268 (EPA, 1995b). Current designs of the shaft seal system for the WIPP propose to use bentonite as a primary sealing component (DOE/WIPP, 1995). The shaft sealing designs predict that compacted bentonite sealing components can last through the 10,000-year regulatory period and beyond.

Repository sealing requires that the sealing barriers have a low permeability, a long lifetime, a high resistance to erosion, mechanical and chemical stability, and compatibility with host rocks or materials. Bentonite has been used widely as a sealing material for waste containment structures such as landfills (Rowe et al., 1995; Daniel, 1993). Bentonite has excellent sealing performance and has been selected as a principal sealing component for numerous nuclear waste repositories. Bentonite has an extremely low hydraulic conductivity, is self-healing, and has good chemical stability that would provide effective long-term sealing (Gnirk, 1988). Bentonite can penetrate rock fractures either by viscous flow or by expansion (Pusch, 1978). Bentonite suspensions can form barriers at low solids concentrations (Ran and Daemen, 1991, 1992; Ran, 1993).

Bentonite as sealing component in the repository access excavations provides barriers to block fluid flow into or out of the repository. Bentonite can generate swelling pressure when water or brine penetrates the clay. Swelling of the seals increases the internal supporting pressure in the shaft and fractures and should accelerate healing of any disturbed rock zone (DRZ). Swelling of bentonite also can assist in sealing fractures caused by structural damage or by rock block displacement by self penetration into the fractures; it should also help in obtaining tightness between seals and host materials.

Bentonite has been studied as a sealing material in several nuclear waste repository programs. Extensive studies on sealing with bentonite have been conducted for the Swedish, Swiss, Canadian, German, and French programs (IAEA, 1990; Pusch and Bergstrom, 1980; Pusch, 1994; Coulon et al., 1987; Brenner, 1988; Bucher et al., 1986; Dixon et al., 1985).

Extensive studies also have been conducted within the context of the WIPP program, both from a sealing and from a backfill perspective (Butcher, 1994; Pfeifle, 1990).

For the purpose of evaluating the acceptability of bentonite as a sealing material for WIPP we have identified references that deal with the properties and characteristics of bentonite that may affect its behavior in the WIPP environment.

This report reviews published studies of bentonite used as sealing material for nuclear waste disposal, environmental restoration, toxic and chemical waste disposal, liners, and applications in the petroleum industry. This report identifies the physical and chemical properties, stability, and seal construction technologies of bentonites, especially in a brine/ salt environment. This report focuses on permeability, swelling pressure, strength, stiffness, longevity, and the densification properties of bentonites. All information about bentonite on which this report is based is archived in a computerized database system (ClayInfo), and can be obtained from the authors or from the Sandia WIPP Central Files.

2. RELATED REPOSITORY STUDIES

2.1 Waste Isolation Pilot Plant

The WIPP has investigated bentonite as a sealing and as a backfill material. Pfeifle (1990) investigated consolidation, permeability, and strength of crushed-salt/bentonite mixes. Pfeifle and Brodsky (1991) investigated the swelling pressure, water uptake, and permeability of 70%/30% crushed-salt/bentonite mixes.

2.2 Office of Nuclear Waste Isolation

The Office of Nuclear Waste Isolation (ONWI), Battelle Memorial Institute, Columbus, OH, has evaluated the use of clays for sealing nuclear waste repositories. A summary report (Meyer and Howard, 1983) includes these favorable characteristics: low hydraulic conductivity, high sorptivity, high compressibility, and, in some cases, high swelling capacity. Also stressed with respect to the use of clays as sealing materials is the potential of clays and clay minerals to provide long-term sealing, inferred from their geologic persistence, low solubility in repository-like environments, and slow reaction kinetics.

2.3 Swedish Studies

By far the most comprehensive, in-depth, and detailed study of bentonite as a repository sealant has been conducted within the Swedish repository program. The results of this work have been summarized in numerous publications (Pusch, 1978, 1979, 1980, 1994; Pusch et al., 1982, 1985; Pusch and Bergstrom, 1980; Pusch and Carlsson, 1985; Pusch and Güven, 1990; Pusch and Karnland, 1990; Nilsson, 1985). Only the most directly applicable of these reports are referenced here.

2.4 Swiss Studies

The Swiss nuclear waste disposal program has studied bentonite as a sealing material. For geochemical and hydrological reasons (i.e., because of the presence of a rather large concentration of Ca ions in the groundwater at the most likely candidate repository sites) the program has focused primarily on Ca bentonites.

2.5 Canadian Studies

The Canadian nuclear waste disposal program has conducted extensive studies on mixtures of bentonite and sand or crushed rock (granite), primarily for the purpose of evaluating the performance of such mixtures as backfill (Dixon et al., 1985, 1987, 1991, 1992a; Chapuis, 1990; Kjartanson et al., 1992; Yong et al., 1986). Only a few of the large number of publications generated by this work are referenced here.

2.6 Basalt Waste Isolation Project

The Basalt Waste Isolation Project (BWIP) has investigated the use of mixtures of crushed basalt and sodium bentonite as a waste packing material. A summary of BWIP studies is given by Allen and Wood (1988).

3. METHODOLOGY

In this study, two main lines of approach were pursued to identify relevant information:

1. computerized data searches,
2. use of personal documentation files and manual follow-up of references.

The search focused on (1) clay sealing for nuclear waste disposal and nonnuclear waste isolation, and (2) clay applications in petroleum and civil engineering. While researching the use of clay/bentonite for nuclear waste repository sealing, the focus of inquiry was on flow and the chemical and physical properties of bentonite, especially in salt, brine, or saline environments.

Six data bases were searched:

1. COMPENDEX (Electronic Engineering Index), Engineering Information, Inc. (1986 to 1995);
2. NTIS (National Technical Information Service), National Technical Information Service (1975 to 1995);
3. Dissertation Abstracts Ondisc, UMI, University Microfilms International (1861 to 1995);
4. GEOREF (Geological Reference File), American Geological Institute (1785 to 1995);
5. GEOBASE, Elsevier Science, (1980 to 1995)
6. INIS (International Nuclear Information System), International Atomic Energy Agency (1976 to 1995, outside USA only).

The data bases listed above were searched using the following terms as keywords or identifiers (except for the INIS and NTIS from 1975 to 1983, as specified below):

- bentonite,
- montmorillonite,
- smectite,
- clay and waste disposal,
- clay and permeability or hydraulic conductivity,
- clay and brine or salt or saline,
- soil and erosion or piping.

For the INIS data base and NTIS data base from 1975 to 1983, the following search terms were used:

- bentonite,
- montmorillonite,
- clay or bentonite or montmorillonite and salt or brine or saline,
- not in the United States (INIS only).

A total of 11,906 references has been located. As is common with computerized literature searches, the results present a mixed picture: A vast number of references were obtained that have marginal, if any, interest to the study at hand. Conversely, a number of important references were identified that otherwise would have been missed. Still, considerable uncertainty remains about the completeness of the searches because some important references we are familiar with did not show up on the searches. Nevertheless, we believe we have completed a fairly comprehensive search of the available literature.

An extensive experimental data base exists for the permeability of sodium bentonites under a variety of conditions. Many other properties of sodium bentonite (such as strength, stiffness, and chemical stability) also have been investigated in detail. The complexity of the material is such, however, that considerable uncertainty remains about its performance (Rowe et al., 1995, pp. 5, 108).

Abstracts of the references that appear relevant have been reviewed by the authors of the present report. Complete copies of the references have been obtained and reviewed to the extent possible within the allowed time frame.

4. BENTONITE COMPOSITION

The composition of a typical commercial sodium bentonite (e.g., Volclay, granular sodium bentonite) contains over 90% montmorillonite and small portions of feldspar, biotite, selenite, etc. A typical sodium bentonite has the chemical composition shown in Table 1.

Table 1. Chemical Composition of Volclay Sodium Bentonite

Elements	Composition (%)
SiO_2	63.02
Al_2O_3	21.05
Fe_2O_3	3.02
FeO	0.35
MgO	2.67
Na_2O	2.57
CaO	0.65
H_2O	5.64
Trace Elements	0.72

Source: Technical Data Sheet, American Colloid Company, 1995.

Sodium bentonite has a three-layer expanding mineral structure of approximately $(Al\ Fe_{1.67}\ Mg_{0.33})\ Si_4O_{10}\ (OH_2)\ Na^+Ca^{++}{}_{0.33}$. Specific gravity of the sodium bentonite is from about 2.5 to 2.8. The dry bulk density of granular bentonite is about 1.04 to 1.24 g/cm^3.

Sodium bentonite has a specific surface area of about 800 m^2/g; when unconfined it can swell to at least 12 mL/g. Densely compacted bentonite (1.75g/cm^3), when confined, can generate a swelling pressure up to 20 MPa when permeated by water (IAEA, 1990, p. 13). The magnitude of the swelling pressure depends on the mineral composition of bentonite and on the chemistry of the permeating water. Bentonite compacted to high bulk densities (>1.7 g/cm^3) has very promising thermal conductivity and thermal stability. Because of the special composition of bentonite, mixtures of bentonite and water can range in rheological characteristics from a virtually Newtonian fluid to a stiff solid, depending on water content. Bentonite can form stiff seals at low moisture content and can penetrate fractures and cracks at higher moisture-content values. Under the latter conditions it can fill spaces in seals and DRZs.

At the WIPP, compacted clay is being considered as a shaft sealing material. Columns of compacted clay will be emplaced in the WIPP shafts during repository closure. A number of optional materials have been investigated for use as the WIPP shaft sealing material. Because the term *clay* includes a large variety of materials, it is possible that some clay materials might satisfy the WIPP sealing requirements. A recurring problem with the use of the term clay is its imprecision and ambiguity, which can cause confusion as to what is intended for sealing purposes.

A standard soil mechanics engineering definition of clays is "fine-grained soil or the fine-grained portion of soil that can be made to exhibit plasticity (putty-like properties) within a range of water contents, and that exhibits considerable strength when air-dry" (ASTM D 653). A long-standing engineering practice has been to define clays as soil particles with a size smaller than a specified size (e.g., 0.002 mm), although ASTM D 653 explicitly recommends against such a definition based on particle size only. The widely (but not exclusively) used Unified Soil Classification System (USCS) (ASTM D 2487, D 2488) defines clay following the above ASTM definition and combining particle size with behavioral aspects.

A second cause of confusion regarding clay terminology is that clay can be defined purely mineralogically (i.e., on the basis of mineral composition) rather than on the basis of size and/or mechanical behavior only. Different investigators propose different definitions:

- "The term clay implies an earthy, fine-grained material which develops plasticity when mixed with a limited amount of water. Chemical analysis of clays shows that they are made up of hydrous aluminosilicates, frequently with appreciable amounts of iron, magnesium, calcium, sodium, and potassium" (Berry and Mason, 1959, pp. 502-503).
- "As a mineral term, it (i.e. clay) refers to specific clay minerals, which are distinguished by (1) small particle size, (2) a net negative electrical charge, (3) plasticity when mixed with water, and (4) high weathering resistance. These minerals are primarily hydrous aluminum silicates, with magnesium or iron occupying all or part of the aluminum positions in some minerals, and with alkalis (e.g., sodium, potassium) or alkaline earths (e.g. calcium) also present in some of them (Grim 1962, 1968)" (Mitchell, 1993, p. 18).
- "As used in this report, 'clay' refers to any fine-grained, earthen, generally plastic material containing a substantial proportion of clay minerals" (Meyer and Howard, 1983, p. 1).

A variety of clays could be considered for nuclear repository sealing purposes. For WIPP, as for most nuclear waste repository projects, bentonite has been and continues to be a prime candidate as a clay type sealing material. "Bentonite clay is chosen here because of its overwhelming positive sealing characteristics" (DOE/WIPP, 1995, p. 43). Bentonite is a highly plastic swelling clay material (e.g., Mitchell, 1993, p. 31), consisting predominantly of smectite minerals (e.g., IAEA, 1990, p. 11). Montmorillonite, the predominant smectite mineral in most bentonites, has the typical platelike structural characteristics of most clay minerals. It has an extremely large surface area, and this in turn directly explains many of the characteristics of bentonite (notably those of importance for sealing performance):

- "Many ... soil properties are attributable to surface phenomena. These properties can be correlated—they are even approximately proportional—to the specific surface area of the solid phase" (Koorevaar et al., 1983, p. 11).
- "The specific surface area of clay minerals, which governs many soil properties, varies from one mineral to another" (Koorevaar et al., 1983, p. 15).

The fundamental structural component of the phyllosilicate minerals, to which clay minerals belong, is the silica (SiO_4) tetrahedron. These tetrahedrons occur in sheets. Octahedral layers of cations (e.g., aluminum) occur parallel to the tetrahedral sheets. In montmorillonite, both surfaces of an octahedral sheet are shared with a tetrahedral sheet, resulting in a three-layer clay mineral. In general, the chemical composition of montmorillonite can be written as $(Na,Ca)_{0.33}(Al,Mg)_2\ Si_4O_{10}(OH)_2 \times H_2O$ (Berry et al., 1983, p. 424). The three-layer sheets are loosely bonded with dipolar water molecules and cations. The weakness of the bond between the sheets allows for ready separation and resulting volume changes. The idealized structure as described here is more theoretical than actual, however, as various isomorphous substitutions are common. The weak bonding explains the high cation exchange capacity of montmorillonites.

Virtually all the physical and mechanical attributes of bentonite will depend on the as-emplaced conditions. Hence such attributes will be a function of the primary design and the specified construction variables, e.g., density (or void ratio) and water content. They possibly are a function of the composition of the water with which the bentonite is prepared.

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5. BENTONITE PROPERTIES AND CHARACTERISTICS OF PARTICULAR RELEVANCE TO WIPP SEALING

A number of bentonite properties and characteristics are important from a sealing perspective. A primary characteristic is permeability or hydraulic conductivity. Although bentonite is known to have extremely low permeability under many conditions, it also is known to be a rather complex material. Its properties, specifically its permeability, are affected by many factors. A major objective of the data base assembled here is to identify the likely permeability of bentonite under WIPP conditions, or, conversely, to determine bentonite seal design specifications that will meet the minimum WIPP sealing requirements.

5.1. Permeability/Hydraulic Conductivity

A variable of primary interest with respect to repository sealing is the hydraulic conductivity of the seal material. The hydraulic conductivity of bentonite depends on numerous factors, e.g., the emplaced density, the chemical composition of the permeant, the bentonite structure, and the hydraulic gradient.

The permeability of dense bentonite is about 1×10^{-16} to 1×10^{-21} m^2 (1×10^{-9} to 1×10^{-14} m/s). Table 2 and Figures 1 and 2 give reported permeabilities of bentonite and bentonite mixtures. Figure 2 contains all data in Table 2.

5.1.1 Permeability to Water/Brine

Bentonite is widely used as a sealant; as a result, an extensive data base exists with reference to the permeability of bentonite. Bentonite has been researched extensively within the context of the Swedish and Canadian nuclear waste disposal programs, in conjunction with international cooperative programs. Within the context of nuclear waste disposal, the sealing properties of bentonite have been studied in considerable detail, i.e. with attention to the numerous factors that may influence bentonite behavior. Hence results obtained in the nuclear waste disposal context may be more complete and more reliable than results obtained in conventional sealing applications, where investigations may not be as detailed or complete. Figures 1 and 2 show the permeability of typical bentonite and bentonite mixture seals at varied dry density as a function of bentonite content.

Westsik et al. (1982) as quoted by Allen and Wood (1988) measured hydraulic conductivities in the range of 4.6 to 6.7×10^{-20} m^2 for sodium bentonite compacted to a high density (2.1 g/cm^3 dry) with a synthetic basalt groundwater utilizing various hydraulic gradients and heads.

Table 2. Reported Hydraulic Conductivity of Compacted Bentonite and Bentonite Mixtures

Material	Composition (%)	Density	Hydraulic Conductivity (m/s)	T (°C)[†]	Pressure Gradient	Test Type	Permeant	Reference
Bentonite/shale	12:88	1.765	2.01×10^{-10}		24	triaxial, lab	4 M NaCl	Haug et al., 1988
Bentonite/shale	12:88	1.765	1.65×10^{-10}		61	triaxial, lab	4 M NaCl	Haug et al., 1988
Bentonite/shale	12:88	1.765	1.58×10^{-10}		121	triaxial, lab	4 M NaCl	Haug et al., 1988
Bentonite/fly ash/sand	12:3:85	1.6	4.0×10^{-10}			triaxial, lab	4 M NaCl	Haug et al., 1988
Bentonite/sand	15:85	1.865	1.0×10^{-9}		14	triaxial, lab	4 M NaCl	Haug et al., 1988
Bentonite/sand	15:85	1.865	2.0×10^{-9}		28.8	triaxial, lab	4 M NaCl	Haug et al., 1988
Bentonite/sand	15:85	1.865	6.3×10^{-10}		115	triaxial, lab	4 M NaCl	Haug et al., 1988
Bentonite	100	0.6	$6.1\text{x } 10^{-9}$		3000		DDW	Bucher et al., 1986
Bentonite	100	0.6	7.0×10^{-8}		3000		1.2 M Saline	Bucher et al., 1986
Bentonite	100	1.02	2.6×10^{-13}		460		DDW	Dixon et al., 1987
Bentonite	100	1.02	6.3×10^{-13}		1700		DDW	Dixon et al., 1987
Bentonite	100	1.12	4.5×10^{-14}		1550		DDW	Dixon et al., 1987
Bentonite	100	1.12	$1.6\text{x } 10^{-12}$		3100		DDW	Dixon et al., 1987
Bentonite	100	1.12	4.5×10^{-14}		>3100		DDW	Dixon et al., 1987
Bentonite	100	1.22	3.7×10^{-13}		1580		DDW	Dixon et al., 1987
Bentonite	100	1.22	$\sim3.1\times10^{-13}$		>3100		DDW	Dixon et al., 1987
Bentonite	100	1.24	1.0×10^{-13}		1560		Saline	Dixon et al., 1987
Bentonite	100	1.24	5.0×10^{-13}		1560		DDW	Dixon et al., 1987
Bentonite	100	1.24	3.5×10^{-13}		3120		DDW	Dixon et al., 1987
Bentonite	100	1.24	3.2×10^{-13}		>3120		DDW	Dixon et al., 1987
Bentonite	100	1.42	1.9×10^{-13}		2000		DDW	Pusch, 1980
Bentonite	100	1.42	2.1×10^{-13}		5000-10000		DDW	Pusch, 1980
Bentonite	100	1.43	$\sim1.8\times10^{-13}$		1700-3400		DDW	Dixon et al., 1987
Bentonite	100	1.46	1.8×10^{-13}		1600-8000		Saline	Dixon et al., 1987
Bentonite	100	1.5	1.9×10^{-13}		2000		DDW	Dixon et al., 1987
Bentonite	100	1.8	9.0×10^{-14}		2000		DDW	Pusch, 1980
Bentonite	100	1.8	1.1×10^{-13}		500-10000		DDW	Pusch, 1980
Bentonite/sand	50:50	1.21	4.2×10^{-12}	25				Dixon et al., 1987
Bentonite/sand	50:50	1.21	3.7×10^{-12}	50				Dixon et al., 1987
Bentonite/sand	50:50	1.21	8.0×10^{-12}	75				Dixon et al., 1987
Bentonite/sand	50:50	1.32	2.0×10^{-14}	25				Dixon et al., 1987
Bentonite/sand	50:50	1.32	1.6×10^{-13}	50				Dixon et al., 1987
Bentonite/sand	50:50	1.32	3.0×10^{-13}	75				Dixon et al., 1987
Bentonite/fly ash			$1.9\text{-}32\times10^{-11}$					Edil et al., 1987
Bentonite/soil			$2\times10^{-6} - 5.0\times10^{-11}$					Chapuis, 1982
Bentonite/soil			$3\times10^{-6} - 1.0\times10^{-11}$					Lundgren, 1981

[†] T= temperature (room temperature unless otherwise specified); * = mixed with saltwater; DDW = distilled deionized water. Blank cells indicate that information is not available.

Table 2. Reported Hydraulic Conductivity of Compacted Bentonite and Bentonite Mixtures

Material	Composition (%)	Density	Hydraulic Conductivity (m/s)	T (°C)†	Pressure Gradient	Test Type	Permeant	Reference
Bentonite/soil			3.0×10^{-9} - 1.4×10^{-12}					Haile, 1985
Bentonite/soil			1.6×10^{-9} - 1.4×10^{-11}					Gipson, 1985
Bentonite/soil			2.5×10^{-11} - 1.2×10^{-12}					Pusch & Alstermark, 1985
Bentonite/soil			2×10^{-6} - 8.0×10^{-11}					Holopainen, 1985
Bentonite/soil			2×10^{-8} - 7.0×10^{-10}					Jessberger et al., 1985
Bentonite/soil			5×10^{-9} - 8.0×10^{-12}					Haxo et al., 1985
Bentonite/soil			1×10^{-9} - 6.3×10^{-10}					Haug, 1985
Bentonite/soil			2.7×10^{-7} - 1.6×10^{-11}					Garlanger et al., 1987
Bentonite/soil			1×10^{-5} - 1.0×10^{-12}					Kenney et al., 1992
Bentonite/soil			2.7×10^{-8} - 2.9×10^{-9}					Stockmeyer, 1992
Bentonite/sand	4	1.65	8.1×10^{-10}			Consolidation cell	DDW	Kenney et al., 1992
Bentonite/sand	4	1.65	2.1×10^{-9}			Consolidation cell	0.7 M NaCl	Kenney et al., 1992
Bentonite/sand	4	1.65	5.0×10^{-10}			Consolidation cell	DDW	Kenney et al., 1992
Bentonite/sand	4	1.65	1.0×10^{-9}			Consolidation cell	0.7 M NaCl	Kenney et al., 1992
Bentonite/sand	4	1.65	6.4×10^{-9}			Consolidation cell	DDW	Kenney et al., 1992
Bentonite/sand	4	1.65	1.2×10^{-9}			Consolidation cell	0.7 M NaCl	Kenney et al., 1992
Bentonite/sand	8	1.51	2.1×10^{-9}			Consolidation cell	DDW	Kenney et al., 1992
Bentonite/sand	8	1.51	4.8×10^{-9}			Consolidation cell	0.7 M NaCl	Kenney et al., 1992
Bentonite/sand	8	1.49	2.2×10^{-9}			Consolidation cell	DDW	Kenney et al., 1992
Bentonite/sand	8	1.49	5.4×10^{-9}			Consolidation cell	0.7 M NaCl	Kenney et al., 1992
Bentonite/sand	8	1.51	2.1×10^{-9}			Consolidation cell	DDW	Kenney et al., 1992
Bentonite/sand	8	1.51	5.5×10^{-10}			Consolidation cell	0.7 M NaCl	Kenney et al., 1992
Bentonite/sand	8	1.56	9.2×10^{-11}			Consolidation cell	DDW	Kenney et al., 1992
Bentonite/sand	8	1.56	1.5×10^{-10}			Consolidation cell	0.7 M NaCl	Kenney et al., 1992
Bentonite/sand	12	1.47	6.1×10^{-11}			Consolidation cell	DDW	Kenney et al., 1992
Bentonite/sand	12	1.47	9.1×10^{-11}			Consolidation cell	0.7 M NaCl	Kenney et al., 1992
Bentonite/sand	8	1.72	6.4×10^{-9}			Consolidation cell	0.7 M NaCl	Kenney et al., 1992
Bentonite/sand	8	1.72	1.2×10^{-9}			Consolidation cell	DDW	Kenney et al., 1992
Bentonite/sand	16	1.71	6.8×10^{-11}			Consolidation cell	0.7 M NaCl	Kenney et al., 1992
Bentonite/sand	16	1.71	3.2×10^{-11}			Consolidation cell	DDW	Kenney et al., 1992
Bentonite	100	0.43	2.1×10^{-11}				DDW	Kenney et al., 1992
Bentonite	100	0.57	5.9×10^{-12}				DDW	Kenney et al., 1992
Bentonite	100	0.74	5.2×10^{-12}				DDW	Kenney et al., 1992
Bentonite	100	0.38	5.7×10^{-11}				DDW	Kenney et al., 1992
Bentonite	100	0.38	1.1×10^{-10}				0.7 M NaCl	Kenney et al., 1992
Bentonite	100	0.46	3.1×10^{-11}				DDW	Kenney et al., 1992

† T= temperature (room temperature unless otherwise specified); * = mixed with saltwater; DDW = distilled deionized water. Blank cells indicate that information is not available.

Table 2. Reported Hydraulic Conductivity of Compacted Bentonite and Bentonite Mixtures

Material	Composition (%)	Density	Hydraulic Conductivity (m/s)	T (°C)[†]	Pressure Gradient	Test Type	Permeant	Reference
Bentonite	100	0.46	4.7×10^{-11}				0.7 M NaCl	Kenney et al., 1992
Bentonite	100	0.31	1.6×10^{-10}				DDW	Kenney et al., 1992
Bentonite	100	0.31	3.7×10^{-10}				0.7 M NaCl	Kenney et al., 1992
Bentonite	100	0.27	2.9×10^{-10}				DDW	Kenney et al., 1992
Bentonite	100	0.27	4.7×10^{-10}				0.7 M NaCl	Kenney et al., 1992
Bentonite*		0.66	8.7×10^{-10}				0.7 M NaCl	Kenney et al., 1992
Bentonite*		0.69	6.4×10^{-10}				0.7 M NaCl	Kenney et al., 1992
Bentonite*		0.79	2.8×10^{-10}				0.7 M NaCl	Kenney et al., 1992
Bentonite*		0.91	9.7×10^{-11}				0.7 M NaCl	Kenney et al., 1992
Bentonite*		1.11	2.1×10^{-11}				0.7 M NaCl	Kenney et al., 1992
Bentonite*		0.58	1.3×10^{-9}				0.7 M NaCl	Kenney et al., 1992
Bentonite*		0.68	4.4×10^{-10}				0.7 M NaCl	Kenney et al., 1992
Bentonite*		0.78	2.0×10^{-10}				0.7 M NaCl	Kenney et al., 1992
Bentonite*		0.78	2.9×10^{-11}				DDW	Kenney et al., 1992
Bentonite*		0.58	1.1×10^{-9}				0.7 M NaCl	Kenney et al., 1992
Bentonite*		0.58	2.8×10^{-11}				DDW	Kenney et al., 1992
Bentonite*		0.63	3.7×10^{-9}				0.7 M NaCl	Kenney et al., 1992
Bentonite*		0.63	3.8×10^{-11}				DDW	Kenney et al., 1992
Na-bentonite		2.1	2.2×10^{-14}	25		Oedometer		Pusch, 1982
Na-bentonite		1.94	7.8×10^{-14}	25		Oedometer		Pusch, 1982
Na-bentonite		1.94	1.1×10^{-13}	25		Oedometer		Pusch, 1982
Na-bentonite		1.89	1.1×10^{-13}	25		Oedometer		Pusch, 1982
Na-bentonite		1.89	1.2×10^{-13}	25		Oedometer		Pusch, 1982
Na-bentonite		1.92	1.28×10^{-13}	25		Oedometer		Pusch, 1982
Na-bentonite		2.06	1.28×10^{-13}	75		Oedometer		Pusch, 1982
Na-bentonite		1.89	1.4×10^{-13}	75		Oedometer		Pusch, 1982
Na-bentonite		1.94	1.5×10^{-13}	75		Oedometer		Pusch, 1982
Na-bentonite		1.94	1.67×10^{-13}	75		*Oedometer*		*Pusch, 1982*
Na-bentonite		1.8-2.1	2.3×10^{-13}				10^4	Pusch, 1982
Na-bentonite		1.8-2.1	2.0×10^{-13}				2×10^3	Pusch, 1982
Na-bentonite		1.8-2.1	1.9×10^{-13}				10^3	Pusch, 1982
Bentonite	100	1.4	1.3×10^{-12}					Mingarro et al., 1991
Bentonite	100	1.6	7.7×10^{-13}					Mingarro et al., 1991
Bentonite	100	1.8	3.3×10^{-13}					Mingarro et al., 1991
Bentonite	100	2.0	8.1×10^{-14}					Mingarro et al., 1991
Bentonite/granite	75:25	1.46	8.3×10^{-12}					Mingarro et al., 1991

[†] T= temperature (room temperature unless otherwise specified); * = mixed with saltwater; DDW = distilled deionized water. Blank cells indicate that information is not available.

Table 2. Reported Hydraulic Conductivity of Compacted Bentonite and Bentonite Mixtures

Material	Composition (%)	Density	Hydraulic Conductivity (m/s)	T (°C)[†]	Pressure Gradient	Test Type	Permeant	Reference
Bentonite/granite	75:25	1.63	5.9×10^{-12}					Mingarro et al., 1991
Bentonite/granite	75:25	1.83	9.0×10^{-13}					Mingarro et al., 1991
Bentonite/granite	75:25	2.00	1.3×10^{-13}					Mingarro et al., 1991
Bentonite/granite	50:50	1.40	1.4×10^{-9}					Mingarro et al., 1991
Bentonite/granite	50:50	1.60	5.4×10^{-10}					Mingarro et al., 1991
Bentonite/granite	50:50	1.80	6.3×10^{-11}					Mingarro et al., 1991
Bentonite/granite	50:50	2.00	3.4×10^{-11}					Mingarro et al., 1991
Bentonite/granite	25:75	1.41	3.5×10^{-8}					Mingarro et al., 1991
Bentonite/granite	25:75	1.65	1.4×10^{-8}					Mingarro et al., 1991
Bentonite/granite	25:75	1.80	9.5×10^{-9}					Mingarro et al., 1991
Bentonite/granite	25:75	2.00	4.4×10^{-9}					Mingarro et al., 1991
Bentonite/sands	10	1.46	5.1×10^{-8}					Chapuis, 1990
Bentonite/sands	10	1.71	7.4×10^{-9}					Chapuis, 1990
Bentonite/sands	15	1.52	1.4×10^{-11}					Chapuis, 1990
Bentonite/sands	5	1.15	5.7×10^{-10}					Chapuis, 1990
Bentonite/sands	10	1.28	2.0×10^{-8}					Chapuis, 1990
Bentonite/sands	5	1.34	2.8×10^{-8}					Chapuis, 1990
Bentonite/sands	10	1.19	3.2×10^{-8}					Chapuis, 1990
Bentonite/sands	5	1.22	1.0×10^{-7}					Chapuis, 1990
Bentonite/sands	10	0.92	9.1×10^{-10}					Chapuis, 1990
Bentonite/sands	5	1.47	1.0×10^{-8}					Chapuis, 1990
Bentonite/sands	10	1.36	2.1×10^{-9}					Chapuis, 1990
Bentonite/sands	20	1.32	2.6×10^{-11}					Chapuis, 1990
Bentonite/sands	2	1.31	8.0×10^{-7}					Chapuis, 1990
Bentonite/sands	3	1.52	2.0×10^{-7}					Chapuis, 1990
Bentonite/sands	4	1.36	6.0×10^{-9}					Chapuis, 1990
Bentonite/sands	6	1.78	9.8×10^{-8}					Chapuis, 1990
Bentonite/sands	8	1.77	2.9×10^{-8}					Chapuis, 1990
Bentonite/sands	7	1.85	1.2×10^{-9}					Chapuis, 1990
Bentonite/sands	7	1.85	6.9×10^{-8}					Chapuis, 1990
Bentonite/sands	7	1.83	1.2×10^{-7}					Chapuis, 1990
Bentonite/sands	3	1.79	2.2×10^{-9}					Chapuis, 1990
Bentonite/sands	6	1.75	6.0×10^{-10}					Chapuis, 1990
Bentonite/sands	3	1.75	2.2×10^{-8}					Chapuis, 1990
Bentonite/sands	6	1.74	1.2×10^{-8}					Chapuis, 1990
Bentonite/sands	25	1.43	2.6×10^{-11}					Chapuis, 1990

[†] T= temperature (room temperature unless otherwise specified); * = mixed with saltwater; DDW = distilled deionized water. Blank cells indicate that information is not available.

Table 2. Reported Hydraulic Conductivity of Compacted Bentonite and Bentonite Mixtures

Material	Composition (%)	Density	Hydraulic Conductivity (m/s)	T (°C)†	Pressure Gradient	Test Type	Permeant	Reference
Bentonite/sands	33.3	1.29	1.2×10^{-11}					Chapuis, 1990
Bentonite/sands	33.3	1.3	4.9×10^{-11}					Chapuis, 1990
Bentonite/sands	20	1.57	9.7×10^{-11}					Chapuis, 1990
Bentonite/sands	2.5	1.91	2.2×10^{-9}					Chapuis, 1990
Bentonite/sands	3	1.93	8.3×10^{-10}					Chapuis, 1990
Bentonite/sands	4.7	1.75	1.4×10^{-6}					Chapuis, 1990
Bentonite/sands	5.8	1.74	6.4×10^{-7}					Chapuis, 1990
Bentonite/sands	6.4	1.78	2.1×10^{-7}					Chapuis, 1990
Bentonite/sands	7.5	1.81	1.1×10^{-8}					Chapuis, 1990
Bentonite	100	2.1	1.5×10^{-14}	Room				Pusch & Carlsson, 1985
Bentonite	100	2.0	2.0×10^{-14}	Room				Pusch & Carlsson, 1985
Bentonite	100	1.9	3.0×10^{-14}	Room				Pusch & Carlsson, 1985
Bentonite	100	1.8	5.0×10^{-14}	Room				Pusch & Carlsson, 1985
Bentonite	100	1.7	8.0×10^{-14}	Room				Pusch & Carlsson, 1985
Bentonite	100	2.1	1.5×10^{-13}	70				Pusch & Carlsson, 1985
Bentonite	100	2.0	2.0×10^{-13}	70				Pusch & Carlsson, 1985
Bentonite	100	1.9	5.0×10^{-13}	70				Pusch & Carlsson, 1985
Bentonite	100	1.8	8.0×10^{-13}	70				Pusch & Carlsson, 1985
Bentonite	100	1.7	1.0×10^{-12}	70				Pusch & Carlsson, 1985
Bentonite	100	1.13	2.6×10^{-12}					Dixon et al., 1992a
Bentonite	100	1.20	9.2×10^{-13}					Dixon et al., 1992a
Bentonite	100	1.31	6.3×10^{-13}					Dixon et al., 1992a
Bentonite	100	1.30	8.2×10^{-13}					Dixon et al., 1992a
Bentonite	100	1.35	3.7×10^{-13}					Dixon et al., 1992a
French clay		1.40	3.0×10^{-13}					Atabek et al., 1990
French clay		1.50	1.0×10^{-13}					Atabek et al., 1990
French clay		1.60	8.0×10^{-14}					Atabek et al., 1990
French clay		1.70	5.0×10^{-14}					Atabek et al., 1990
Bentonite/crushed granite	25:75	1.88	2.1×10^{-11}		30.2			Radhakrishna & Chan, 1982
Bentonite/crushed granite	25:75	1.88	3.7×10^{-11}		277.0			Radhakrishna & Chan, 1982
Bentonite/crushed granite	50:50	1.56	3.7×10^{-12}		90.3			Radhakrishna & Chan, 1982
Bentonite/crushed granite	50:50	1.56	1.8×10^{-12}		967.5			Radhakrishna & Chan, 1982
Bentonite/crushed granite	50:50	1.59	7.8×10^{-12}		70.3			Radhakrishna & Chan, 1982
Bentonite/crushed granite	50:50	1.59	9.2×10^{-11}		70.3			Radhakrishna & Chan, 1982
Na-bentonite		1.09	3.07×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.17	9.92×10^{-13}				DDW	Dixon et al., 1987

† T= temperature (room temperature unless otherwise specified); * = mixed with saltwater; DDW = distilled deionized water. Blank cells indicate that information is not available.

Table 2. Reported Hydraulic Conductivity of Compacted Bentonite and Bentonite Mixtures

Material	Composition (%)	Density	Hydraulic Conductivity (m/s)	T (°C)[†]	Pressure Gradient	Test Type	Permeant	Reference
Na-bentonite		1.2	9.67×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.23	6.02×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.25	3.07×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.32	8.54×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.28	6.65×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.3	5.05×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.55	9.43×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.43	9.01×10^{-14}				DDW	Dixon et al., 1987
Na-bentonite		1.57	1.81×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.5	1.34×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.48	9.96×10^{-14}				DDW	Dixon et al., 1987
Na-bentonite		1.47	5.89×10^{-14}				DDW	Dixon et al., 1987
Na-bentonite		1.59	1.78×10^{-14}				DDW	Dixon et al., 1987
Na-bentonite		1.73	1.91×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		2.07	2.11×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.88	9.24×10^{-14}				DDW	Dixon et al., 1987
Na-bentonite		1.69	7.57×10^{-14}				DDW	Dixon et al., 1987
Na-bentonite		1.68	7.76×10^{-14}				DDW	Dixon et al., 1987
Na-bentonite		1.81	4.59×10^{-14}				DDW	Dixon et al., 1987
Na-bentonite		1.86	3.49×10^{-14}				DDW	Dixon et al., 1987
Na-bentonite		1.8	1.91×10^{-14}				DDW	Dixon et al., 1987
Na-bentonite		1.92	7.05×10^{-15}				DDW	Dixon et al., 1987
Na-bentonite		2.12	6.54×10^{-15}				DDW	Dixon et al., 1987
Na-bentonite		2.2	5.35×10^{-15}				DDW	Dixon et al., 1987
Na-bentonite		0.501	1.06×10^{-9}				DDW	Dixon et al., 1987
Na-bentonite		1.25	2.99×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.3	2.84×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.32	2.84×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.34	2.06×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.34	1.68×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.43	3.14×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.41	1.91×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.41	1.38×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.44	1.16×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.52	2.45×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.5	1.77×10^{-13}				DDW	Dixon et al., 1987

[†] T= temperature (room temperature unless otherwise specified); * = mixed with saltwater; DDW = distilled deionized water. Blank cells indicate that information is not available.

Table 2. Reported Hydraulic Conductivity of Compacted Bentonite and Bentonite Mixtures

Material	Composition (%)	Density	Hydraulic Conductivity (m/s)	T (°C)[†]	Pressure Gradient	Test Type	Permeant	Reference
Na-bentonite		1.5	1.10×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.52	1.38×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.4	2.01×10^{-14}				DDW	Dixon et al., 1987
Na-bentonite		1.71	3.07×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.88	3.56×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.78	9.47×10^{-14}				DDW	Dixon et al., 1987
Na-bentonite		1.68	9.71×10^{-14}				DDW	Dixon et al., 1987
Na-bentonite		1.66	7.20×10^{-14}				DDW	Dixon et al., 1987
Na-bentonite		1.75	5.89×10^{-14}				DDW	Dixon et al., 1987
Na-bentonite		1.78	4.05×10^{-14}				DDW	Dixon et al., 1987
Na-bentonite		1.83	2.79×10^{-14}				DDW	Dixon et al., 1987
Na-bentonite		1.9	3.16×10^{-14}				DDW	Dixon et al., 1987
Na-bentonite		2.04	7.79×10^{-15}				DDW	Dixon et al., 1987
Na-bentonite		2.17	6.71×10^{-15}				DDW	Dixon et al., 1987
Na-bentonite		2.23	6.87×10^{-15}				DDW	Dixon et al., 1987
Na-bentonite		0.67	6.22×10^{-9}				DDW	Dixon et al., 1987
Na-bentonite		1.17	1.24×10^{-12}				DDW	Dixon et al., 1987
Na-bentonite		1.36	6.14×10^{-12}				DDW	Dixon et al., 1987
Na-bentonite		1.31	6.96×10^{-12}				DDW	Dixon et al., 1987
Na-bentonite		1.37	3.71×10^{-11}				DDW	Dixon et al., 1987
Na-bentonite		1.19	1.47×10^{-11}				DDW	Dixon et al., 1987
Na-bentonite		1.1	1.63×10^{-11}				DDW	Dixon et al., 1987
Na-bentonite		1.2	3.20×10^{-11}				DDW	Dixon et al., 1987
Na-bentonite		1.17	3.81×10^{-11}				DDW	Dixon et al., 1987
Na-bentonite		1.14	5.14×10^{-11}				DDW	Dixon et al., 1987
Na-bentonite		1.15	9.12×10^{-11}				DDW	Dixon et al., 1987
Na-bentonite		1.07	5.14×10^{-11}				DDW	Dixon et al., 1987
Na-bentonite		1.04	3.36×10^{-11}				DDW	Dixon et al., 1987
Na-bentonite		0.887	2.49×10^{-11}				DDW	Dixon et al., 1987
Na-bentonite		1.03	1.47×10^{-10}				DDW	Dixon et al., 1987
Na-bentonite		1.08	2.36×10^{-10}				DDW	Dixon et al., 1987
Na-bentonite		1.05	2.30×10^{-10}				DDW	Dixon et al., 1987
Na-bentonite		1.03	2.48×10^{-10}				DDW	Dixon et al., 1987
Na-bentonite		1.02	1.33×10^{-10}				DDW	Dixon et al., 1987
Na-bentonite		0.884	2.55×10^{-11}				DDW	Dixon et al., 1987
Na-bentonite		0.989	4.19×10^{-10}				DDW	Dixon et al., 1987

[†] T= temperature (room temperature unless otherwise specified); * = mixed with saltwater; DDW = distilled deionized water. Blank cells indicate that information is not available.

Table 2. Reported Hydraulic Conductivity of Compacted Bentonite and Bentonite Mixtures

Material	Composition (%)	Density	Hydraulic Conductivity (m/s)	T (°C)[†]	Pressure Gradient	Test Type	Permeant	Reference
Na-bentonite		0.904	1.79×10^{-10}				DDW	Dixon et al., 1987
Na-bentonite		0.877	1.93×10^{-10}				DDW	Dixon et al., 1987
Na-bentonite		0.87	4.29×10^{-10}				DDW	Dixon et al., 1987
Na-bentonite		0.836	6.73×10^{-10}				DDW	Dixon et al., 1987
Na-bentonite		0.792	4.29×10^{-10}				DDW	Dixon et al., 1987
Na-bentonite		0.609	1.98×10^{-10}				DDW	Dixon et al., 1987
Na-bentonite		2.34	2.28×10^{-14}				1.2 M NaCl	Dixon et al., 1987
Na-bentonite		2.1	1.45×10^{-13}				1.2 M NaCl	Dixon et al., 1987
Na-bentonite		1.99	3.08×10^{-14}				1.2 M NaCl	Dixon et al., 1987
Na-bentonite		2.08	8.75×10^{-13}				1.2 M NaCl	Dixon et al., 1987
Na-bentonite		1.73	5.47×10^{-14}				1.2 M NaCl	Dixon et al., 1987
Na-bentonite		1.54	1.60×10^{-13}				1.2 M NaCl	Dixon et al., 1987
Na-bentonite		1.39	2.77×10^{-13}				1.2 M NaCl	Dixon et al., 1987
Na-bentonite		1.32	2.16×10^{-13}				1.2 M NaCl	Dixon et al., 1987
Na-bentonite		1.33	4.81×10^{-13}				1.2 M NaCl	Dixon et al., 1987
Na-bentonite		1.34	6.17×10^{-13}				1.2 M NaCl	Dixon et al., 1987
Na-bentonite		1.31	6.49×10^{-13}				1.2 M NaCl	Dixon et al., 1987
Na-bentonite		1.32	1.10×10^{-12}				1.2 M NaCl	Dixon et al., 1987
Na-bentonite		1.28	2.21×10^{-12}				1.2 M NaCl	Dixon et al., 1987
Na-bentonite		1.27	3.64×10^{-12}				1.2 M NaCl	Dixon et al., 1987
Na-bentonite		1.19	1.89×10^{-11}				1.2 M NaCl	Dixon et al., 1987
Na-bentonite		1.12	3.28×10^{-11}				1.2 M NaCl	Dixon et al., 1987
Na-bentonite		0.894	1.75×10^{-11}				1.2 M NaCl	Dixon et al., 1987
Na-bentonite		0.918	4.00×10^{-11}				1.2 M NaCl	Dixon et al., 1987
Na-bentonite		0.935	6.27×10^{-11}				1.2 M NaCl	Dixon et al., 1987
Na-bentonite		1.12	1.17×10^{-10}				1.2 M NaCl	Dixon et al., 1987
Na-bentonite		1.07	1.84×10^{-10}				1.2 M NaCl	Dixon et al., 1987
Na-bentonite		1.07	3.18×10^{-10}				1.2 M NaCl	Dixon et al., 1987
Na-bentonite		1.12	9.75×10^{-9}				1.2 M NaCl	Dixon et al., 1987
Na-bentonite		0.681	6.85×10^{-8}				1.2 M NaCl	Dixon et al., 1987

[†] T= temperature (room temperature unless otherwise specified); * = mixed with saltwater; DDW = distilled deionized water. Blank cells indicate that information is not available.

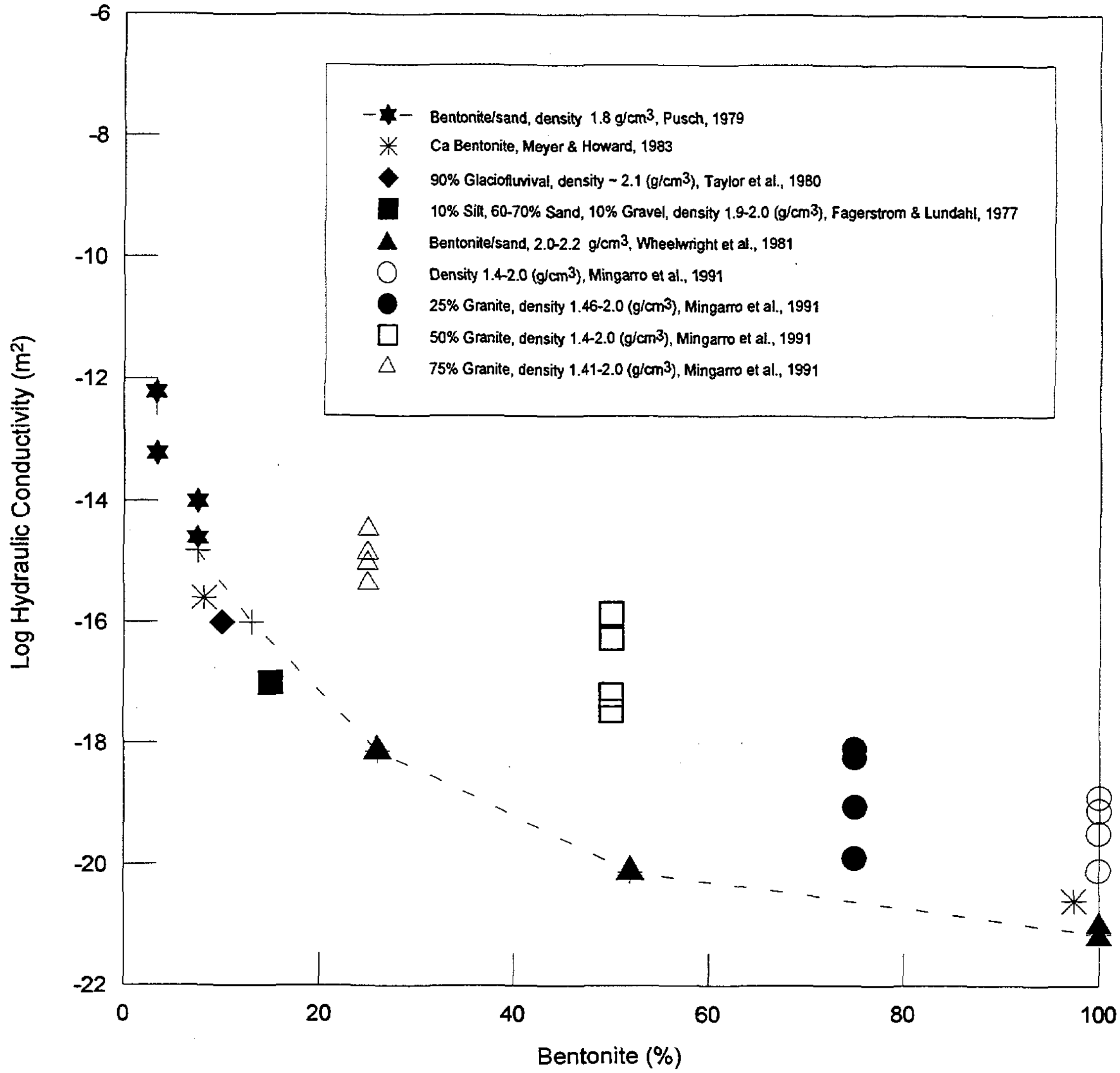

Figure 1. Hydraulic conductivity of compacted mixtures of bentonite with sand, crushed granite, or soils as a function of bentonite content (after Meyer and Howard, 1983; Mingarro et al., 1991).

Influence of Compaction/Density

Figure 2 shows the reported permeability of compacted bentonite and of bentonite mixtures with sand, crushed rock, and fly ash. The permeability of a bentonite seal relates to the void space or density. At the same density, pure bentonite has much lower permeability than bentonite mixtures. Compacted bentonite has fewer pore spaces for fluid flow. It is not necessary that materials with the same density have the same void space because the specific gravity of materials varies significantly. The specific gravity of bentonite varies from 2.4 to 2.8, which makes significant difference in terms of the void ratio for seals with the same dry density.

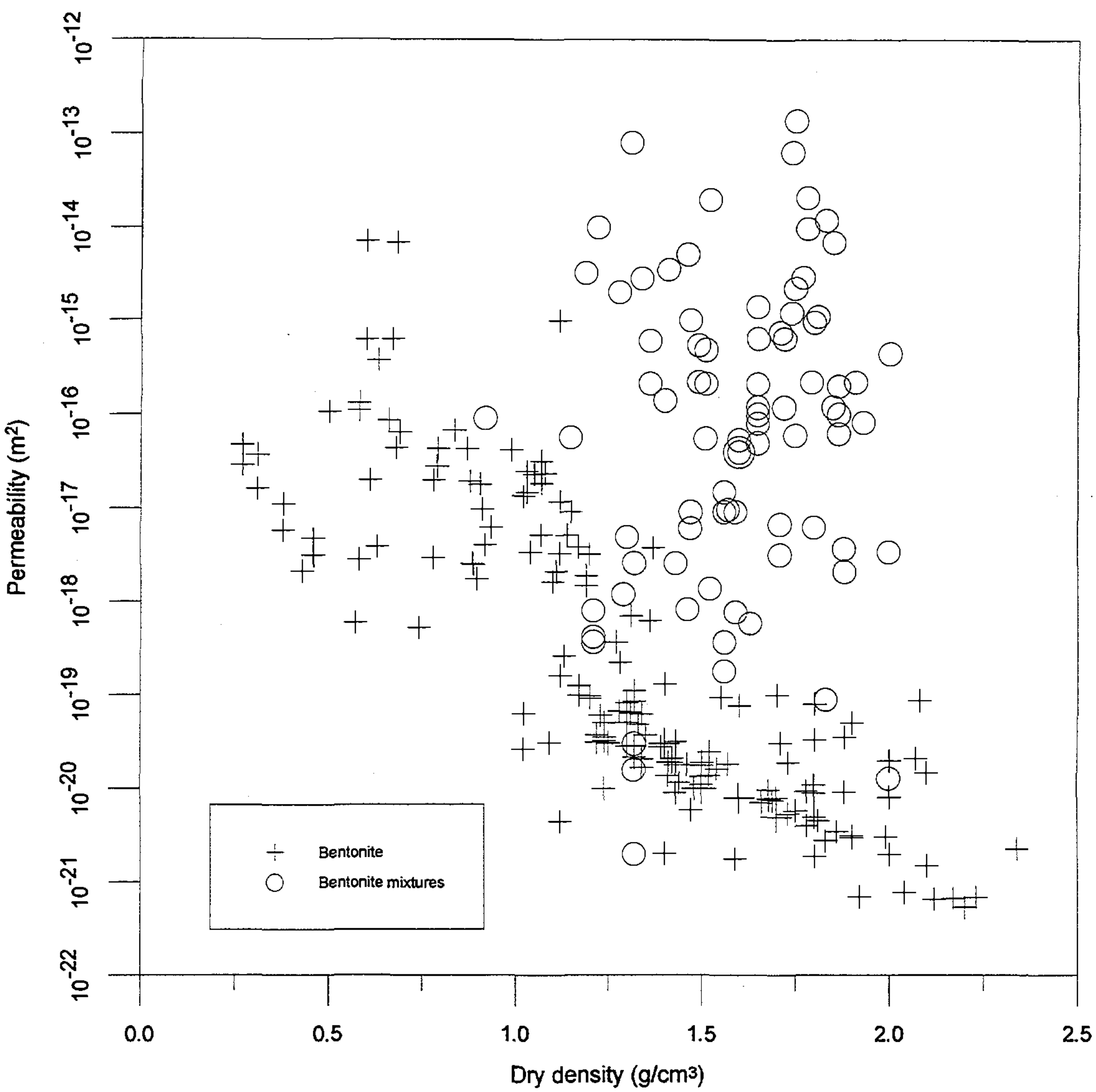

Figure 2. Reported hydraulic conductivity of compacted bentonite and bentonite mixtures as a function of dry density.

Influence of Permeant Chemistry/Brine

Alther (1982) summarized the influence of solution chemistry on sodium bentonite permeability (see Table 3). Calcium chloride, calcium sulfate, and calcium phosphates cause an increase in viscosity (i.e., flocculation or gelling) and hence increase permeability drastically. Acids dissolve part of the lattice over longer time periods. In the short term, they also flocculate the clay and cause an increase in permeability. High concentrations of Ca, Mg and total salts also increase permeability. Sodium salts decrease the permeability at certain percentages but increase it at higher percentages because competition for space between the sodium ions takes place, resulting in overcrowding and gelling.

Table 3. The Influence of Permeant Chemistry on Bentonite Permeability

Permeant Chemistry	Filter Cake	Soil Bentonite Backfill
Ca^{++} or Mg^{++} @ 1,000 ppm	N	N
Ca^{++} or Mg^{++} @ 10,000 ppm	M	M
NH_4NO_3 @ 10,000 ppm	M	M
HCl (1%)	N	N
H_2SO_4 (1%)	M	N
HCl	M/H*	M/H*
NaOH (1%)	M	M
CaOH (1%)	M	M
NaOH (5%)	M	M/H*
Sea Water	N/M	N/M
Brine (G_s=1.2)	M	M
Acid Mine Drainage $FeSO_4$ (pH=3)	N	N
Lignin (in Ca^{++} solution)	N	N
Alcohol	H(failure)	M/H

Data from D'Appolonia (1980).
N = No significant effect; permeability increase by about a factor of 2 or less at steady state.
M = Moderate effect; permeability increase by about a factor of 2 to 5 at steady state.
H = permeability increase by a factor of 5 to 10.
* = Significant dissolution likely.

Kenney et al. (1991) observed that the "hydraulic conductivity of mixtures containing high-swell bentonite, when permeated with a strong saline solution, increased by only a small amount, indicating that the fabric of bentonite enclosed within the framework was little influenced by this change of system chemistry."

Peterson and Kelkar (1983) observed a slight decrease in the hydraulic conductivity of bentonite samples when flow tested with a brine rich in Na^+ and Mg^{+2} (compared to flow tests with deionized water), from about 2 to 3×10^{-13} m/s to about 1.1 to 2×10^{-13} m/s.

Barbour (1987) presents data that show an increase by a factor of five for the permeability of a sand/Ca-bentonite sample after permeation with a 4.0 M NaCl brine. Barbour argues persuasively, although with limited support from experimental data, that the confining pressure may be a determining factor on whether the permeability will increase or not as a result of brine penetration. This topic may deserve further attention for WIPP shaft sealing, where shaft creep closure is expected to provide an active confining pressure.

Barbour (1987) and Sego et al. (1987) reference work by Ridley (1985) and Ridley et al. (1983) to raise some serious concerns about the validity of a widely used method for measuring permeability, namely rigid wall permeameters for studying the influence of brine on permeability. A rigid wall permeameter may not be appropriate to obtain true permeability measurements because it does not compensate for the shrinkage that may occur in field situations. Fernandez and Quigley (1988) present results that tend to support this concern. Their results of permeability tests on clays using water-soluble organic liquids show that an even rather modest stress applied to the clay largely eliminates the large permeability increases that are observed in unpressured samples. Fernandez and Quigley note that even a modest stress (about 160 kPa) suffices to prevent permeability increases.

Almanza and Lozano (1990) subjected Ca-montmorillonite to flow tests with fresh water and with NaCl brine of 60% saline saturation at 50°C. The permeability was essentially the same for the two permeants. The authors conclude that a Ca-montmorillonite may be a better sealant against Na brine flow than a Na bentonite, even through it has a much smaller swelling capacity, because the exchange of one Ca^{++} ion by two Na^{+} ions results in a permeability decrease.

For sodium bentonite, the permeability increases when saline solutions (0.7 to 1.2 *M* NaCl) are the permeate (Figure 3). Kenney et al. (1992) conducted hydraulic conductivity tests on compacted bentonite/sand mixtures using distilled water and 0.7 mol/L salt water as the permeants. Samples with dry density of 1.5, 1.65, or 1.85 g/cm^3 and with bentonite to sand ratios of 0.05 to 0.25 were tested. The hydraulic conductivity of bentonite permeated with salt water is about two orders of magnitude higher than that permeated with distilled water. Kenney et al. (1992) also found that bentonite samples mixed with brine and permeated with 0.7 *M* brine can have a hydraulic conductivity about two orders of magnitude higher than samples mixed with distilled water and permeated with 0.7 *M* brine.

Yang and Barbour (1992) studied the influence of brine on clay permeability. Fresh water and brine (5.0 *M* NaCl) were permeated through static-compacted, kneading-compacted, or slurry samples of Regina Clay (45.2 % montmorillonite, calcium based). Yang and Barbour found that brine increases the hydraulic conductivity of the clay 2 to 6 times at confining pressures less than 10 kPa, and about 2 times when the confining pressure is higher than 50 kPa. Haug et al. (1990) obtained test results from which they concluded that a NaCl brine had an insignificant effect on the hydraulic conductivity of illite/bentonite mixes under high confining stresses. Under low confining pressures, hydraulic conductivity increases significantly. Yang and Barbour (1992) concluded that brine permeation through clays does not change the microstructure of the clay significantly; it does, however, increase the size of interaggregate pores.

According to Mitchell (1976, p. 112), NaCl concentration influences the interlayer thickness, which dominates the swelling pressure and hydraulic conductivity of bentonite when it is saturated. For a montmorillonite clay with a specific surface of 800 m^2/g and a cation exchange capacity of 83 meq/100 g, the thickness of the interlayer is 333 Å when saturated with a solution of 0.83×10^{-4} *M* NaCl, and 1.25 Å when saturated with a solution of 6 *M* NaCl (Figure 4). The decreased thickness of interlayers reduces the swelling capacity of montmorillonite and increases the hydraulic conductivity. It seems that salt/brine has significant influence on the swelling and flow properties of bentonite. However, the bentonite seal should retain its original physical and chemical properties if the emplaced bentonite is never penetrated by brine. For high density bentonite under low injection pressure, the low hydraulic conductivity and higher swelling pressure developed in the bentonite layer adjacent to the permeant source can resist further brine penetration. It is necessary to understand how brine penetrates the bentonite to fully understand the performance of bentonite seals emplaced in salt/brine environment.

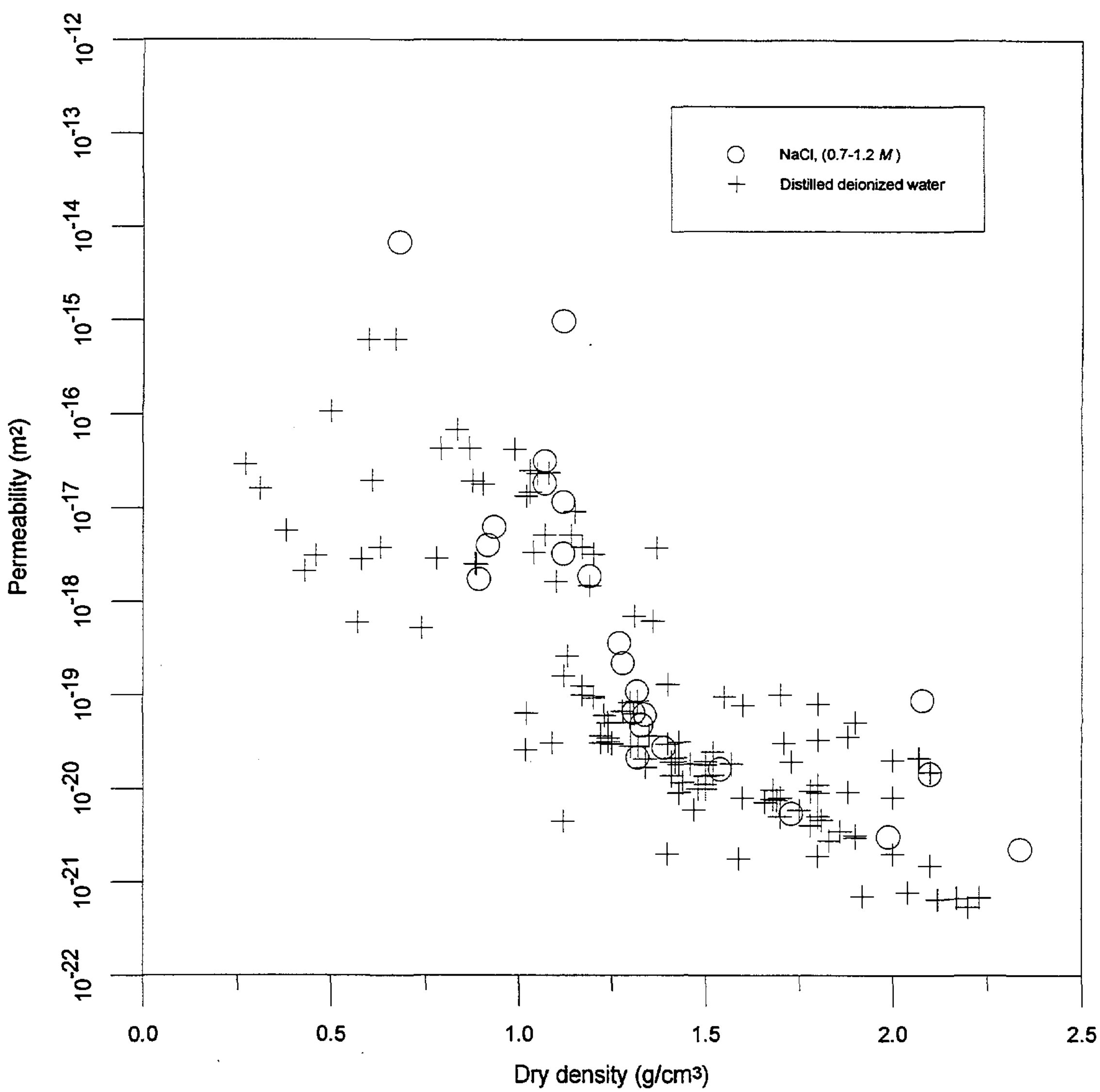

Figure 3. Reported permeability as a function of dry density for permeant with distilled deionized water and brine.

Sodium bentonite that is hydrated and permeated only with relatively fresh water will be effective indefinitely. The interlayer sodium cation can be exchanged with cations that have higher replacing power during hydration and permeation. Cation exchange greatly reduces the amount of water that bentonite can hold in the interlayer, resulting in decreased swell capacity. The loss of swell usually causes increasing porosity and increasing hydraulic conductivity. Mitchell (1976, p. 130) notes that Li^+, K^+, Rb^+, Cs^+, Mg^{2+}, Ca^{2+}, Ba^{2+}, Cu^{2+}, Al^{2+}, Fe^{3+} and Th^{4+} have higher replacing power to replace Na^+ in interlayers of bentonite. Li^+, K^+ and Ca^{2+} in brine tend to replace Na^+ in bentonite during hydration and permeation, hence increasing its hydraulic conductivity.

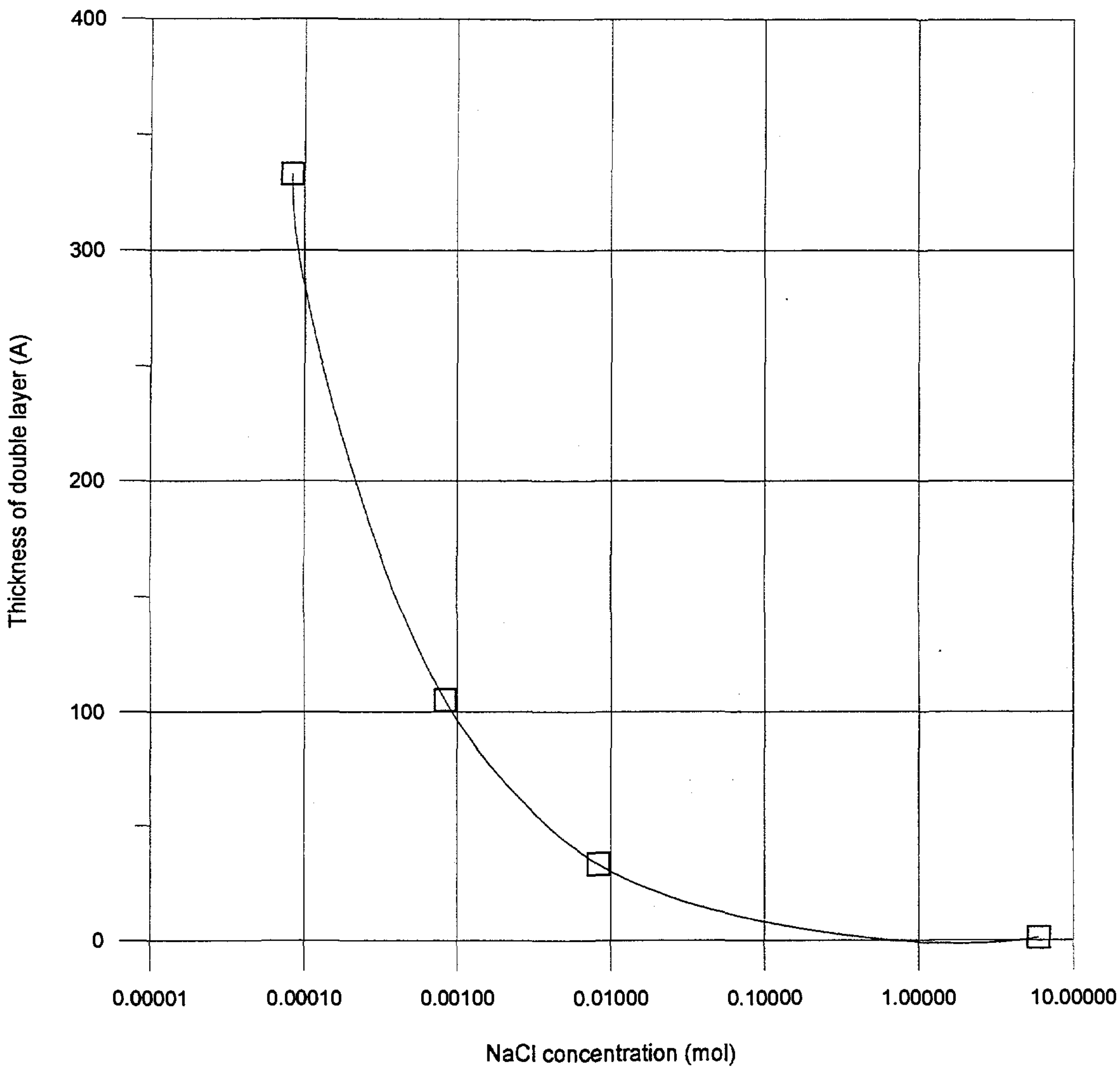

Figure 4. The thickness of interlayer as a function of NaCl concentration in solutions (calculation based on Equation 7.28 in Mitchell, 1976, p. 125).

Size Effects

Permeability may also vary with sample size. The permeability of bentonite measured in the laboratory may differ from that measured in the field. It is generally recognized that permeability increases when samples become larger, because defects or nonuniform density statistically have a better chance of being present in larger samples (Olson and Daniel, 1981). For pure bentonite, such size influence may not be as significant as for other materials, such as soil and mixtures of clay and sand/crushed rock, because of relatively uniform particle size and material components.

Boynton and Daniel (1985) conducted hydraulic conductivity tests for clays with sample-size diameters from 3.8 to 15 cm (1.5 to 6 in.). They concluded that the effect of sample size on permeability depends on water content at time of compaction. For samples compacted slightly dry of optimum, permeability is essentially independent of sample diameter. When samples are compacted drier or wetter than optimum, the permeability increases with increasing sample diameter.

Olson and Daniel (1981) compared the hydraulic conductivity data of clays from 72 sites where field and laboratory hydraulic conductivities have both been measured. The range in the ratio of field permeability to laboratory hydraulic conductivity is from 0.3 to 46,000. However, for nearly 90% of the cases the ratio is from 0.38 to 64.

Daniel (1984) compared hydraulic conductivity results of laboratory and field tests from four projects where soil/bentonite liners were used. The ratio of permeability measured in laboratories to the permeability measured in the field is from 5 to 100,000. Daniel (1984) concluded that the actual hydraulic conductivities of the clay liners were generally 10 to 1,000 times higher than values obtained from laboratory tests. However, many of the factors cited by Daniel (1984) as causes for the discrepancies between laboratory and field testing should not apply for WIPP shaft sealing, or they should be avoidable: Discrepancies seem largest for relatively thin layers (less than 0.6 m [24 in.] thick), desiccation has affected most of the liners where large differences were measured, and construction inspection was not as extensive as it might have been. Benson et al. (1994), in a very careful analysis of size effects including consideration of multiple case studies, essentially conclude that laboratory size permeability tests can be representative of *in situ* compacted clay, on condition that *in situ* compaction is conducted with extreme care.

5.1.2 Gas Permeability

According to Brenner (1988, p. 26) gas flow through saturated compacted bentonite requires displacement of "free" water in the larger pores or, in extremely dense bentonite, a displacement of clay particles. According to Pusch et al. (1985) as quoted by Brenner (1988), a critical gas pressure exists above which a sudden rapid increase in gas flow is observed. This critical gas pressure increases with density and is a material characteristic.

Pusch et al. (1985) conducted experiments in a swelling oedometer on samples of MX-80 bentonite that were 50 mm in diameter and 20 mm thick. The saturated density ranged from 1.70 to 2.14 g/cm^3 (dry density was 1.4 to 1.79 g/cm^3). The samples were saturated with a Nagra water fairly rich in salts. The critical (breakthrough) gas pressure, measured with both nitrogen and hydrogen, ranged from 1.6 to 21 MPa. The ratio of the breakthrough gas pressure to swelling pressure ranged from 0.2 to 0.9, with most typical values in the range of 0.5 to 0.7. The ratio was smaller when the gas pressure increased more rapidly. A mechanistic model explaining the observed gas flow behavior, based on the likely pore structure, is given by Pusch and Hokmark (1990). The macroscopic hydraulic conductivity to gas appears to be of the same order of magnitude as that of water, i.e. about 10^{-13} m/s for dry densities of about 1.7 to 1.8 g/cm^3.

5.2 Porosity

Because the entire pore volume is not available for water flow, the effective porosity (the ratio of the interconnected pore volume to the total volume of the medium) is used to characterize the fluid flow in porous media or clay (Bear, 1972, p. 44; Gillott, 1987, p. 390). The pore properties (size, size distribution, shape, and structures) of clay are affected by moisture content, pore water chemistry, and confining pressure. A portion of the water adsorbed or retained on solid clay particles is unable to flow freely, and the space occupied by such water is not available for water flow. The amount of water attached on the solid particles depends on the surface area of the solids and the thickness of the diffuse double layer. Chapuis (1990) introduced the term "efficient porosity" to describe the water flow in clay. Efficient porosity is measured by determining the portion of bound water adsorbed on the solid particles and subtracting that portion from the effective porosity. The portion of space (slow-moving water on particles) not available for water flow ranges about 20 to 50% of the total porosity. Chapuis (1990) reports the results of 45 laboratory tests on the porosity of bentonite and of soil bentonite mixtures. The average efficient porosity is 53% of primary porosity. Figure 5 shows the correlation between efficient porosity and total porosity.

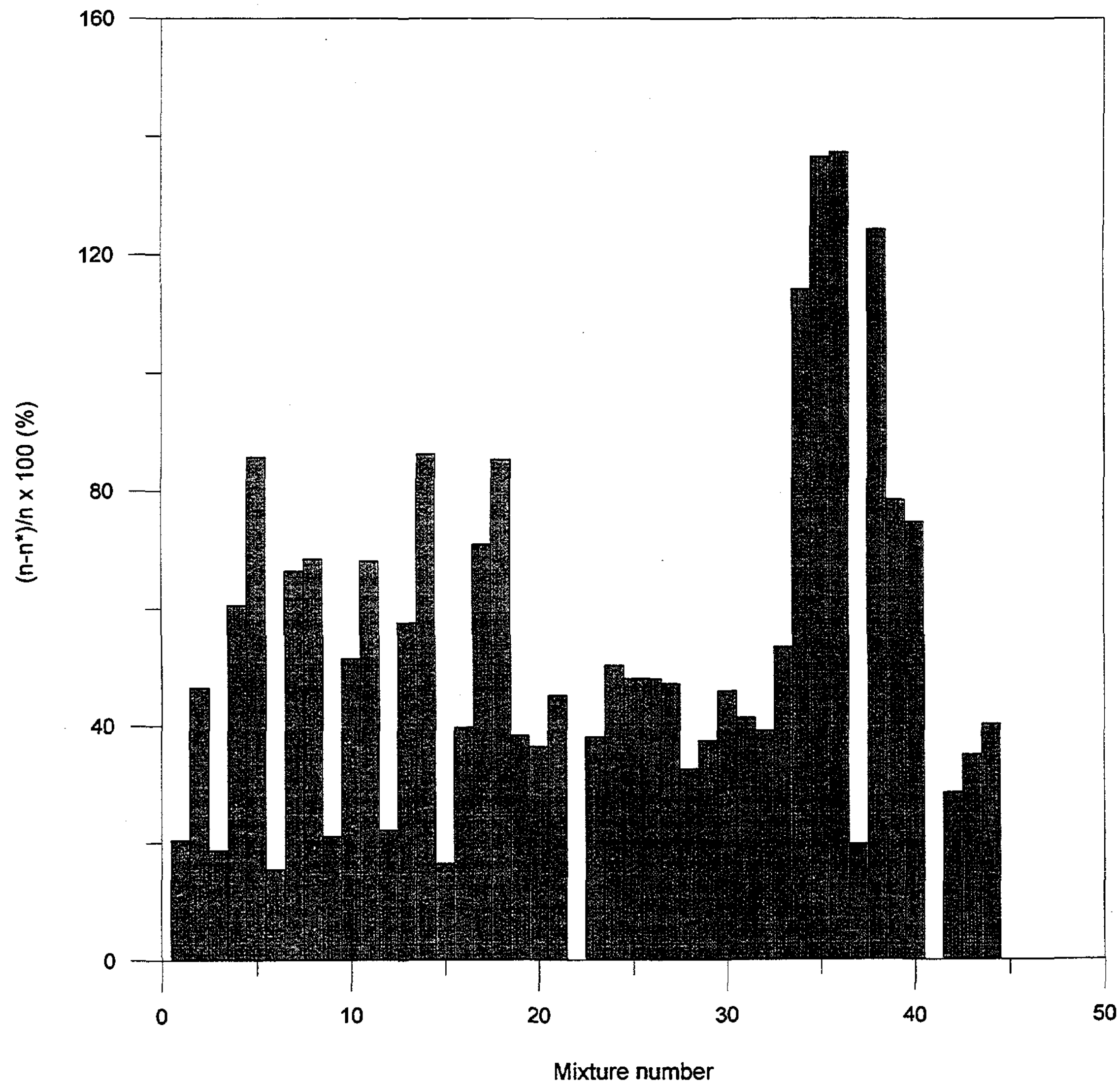

Figure 5. Correlation between total porosity (n) and efficient porosity (n^*) of bentonite/ sand mixtures (data reported by Chapuis, 1990).

The primary or total porosity n is given by the expression:

$$n = \frac{e}{1+e} \qquad (1)$$

where e is the void ratio, which can be calculated from the specific gravity (G_s) of bentonite, the dry density (ρ_d) of the bentonite seal, and the density of water (ρ_w), i.e.:

$$e = G_s \frac{\rho_w}{\rho_d} - 1 \qquad (2)$$

The specific gravity of bentonite is about 2.4 to 2.8. For Volclay GPG-30, the specific gravity is 2.5 (American Colloid Company, 1995). The efficient porosity should vary with moisture content and salt concentration. Diamond (1970) measured the effective porosity of montmorillonite as 35% less than the calculated or primary or total porosity. Figure 6 shows dry density plotted as a function of porosity.

The efficient porosity (n^*), defined here as the porosity actually available to water flow, is less than the total porosity because a thin water film adheres to smectite surfaces and is essentially immobile. Chapuis (1990) found no direct correlation between hydraulic conductivity and total or primary porosity, but a correlation exists with efficient porosity.

5.3 Volumetric Behavior: Swelling and Shrinkage

The volumetric behavior of clay sealants may affect waste isolation. Shrinkage could enhance releases, especially of gaseous products. Swelling is likely to tighten the bond between seal and host rock, but swelling must not be so large as to enhance the permeability of the host rock, particularly any unfavorably oriented discontinuities in the host rock.

5.3.1 Swelling

Bentonite is widely considered a desirable repository sealing material because of its swelling capacity. Swelling pressure of bentonite varies significantly, from 50 kPa to more than 58 Mpa (Westsik et al., 1982; Pusch, 1982), depending on the chemical components of the saturation fluid and its material composition. The methods used to measure swelling pressure may also cause variations in measured swelling pressure. An extremely long time is required to saturate the bentonite and to develop swelling pressure. During swelling pressure measurement, if the bentonite is never fully saturated, the measured swelling pressure at that condition may not be representative; it may be much lower than the actual maximum possible.

As shown in Table 4 and Figure 7, the swelling pressure of bentonite saturated with salt water at low density is 3 to 10 times lower than that saturated with fresh water. Pusch (1980) concluded that the swelling pressure of bentonite saturated with brine is identical to that of bentonite saturated with fresh water for densities close to or greater than 2.1 g/cm^3. This may be true when the bentonite has never been saturated. It is clear that this conclusion is applicable for WIPP when the WIPP brine contains up to or more than 5 M NaCl.

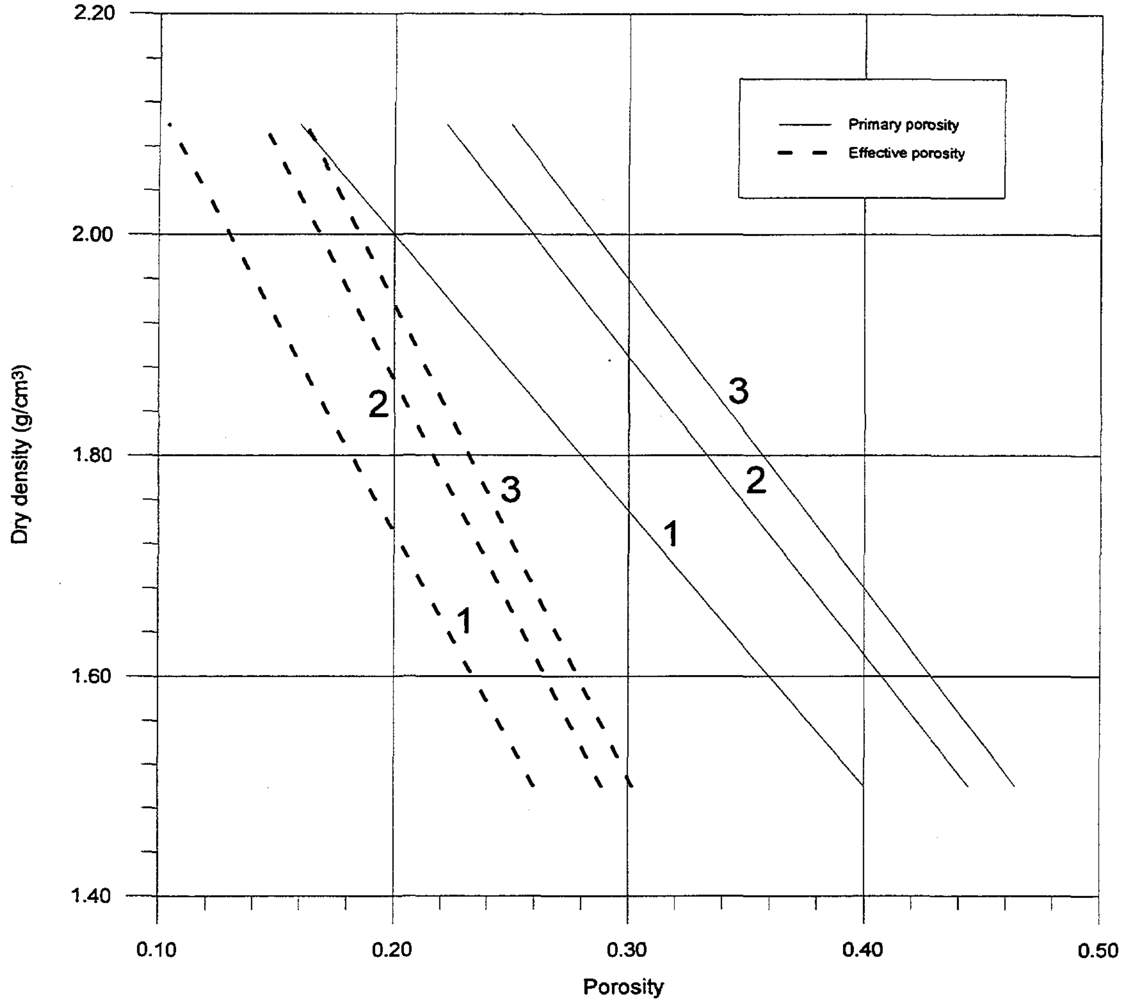

Figure 6. Dry density of bentonite as a function of porosity, where 1: $G_s = 2.5$, 2: G_s=2.7 and 3: G_s=2.8. Effective porosity = 65% of primary porosity (Equations 1 and 2).

Westsik et al. (1982), as recounted by Allen and Wood (1988), measured swelling pressures of 57 to 58 MPa for a pure bentonite at high density, which is in good agreement with pressures reported by Pusch (1979).

According to Brenner (1988, p. 21) the influence of water ions on swelling pressure is negligible: No significant difference was observed in terms of swelling behavior for two bentonites when either demineralized water or water rich in sodium was used.

Table 4. Reported Swelling Pressures of Bentonite and Bentonite Mixtures

Material	Composition (%)	Density	Swelling Pressure (MPa)	Permeant	Reference
Bentonite/sand	10	2.1	0.15		Nilsson, 1985
Bentonite/sand	10	1.9	0.02		Nilsson, 1985
Bentonite/sand	20	2.0	0.13		Nilsson, 1985
Bentonite/sand	20	1.8	0.02		Nilsson, 1985
Na-bentonite		1.4	0.10	Low electrolyte fluid	Pusch, 1994
Na-bentonite		1.8	0.80	Low electrolyte fluid	Pusch, 1994
Na-bentonite		2.1	10.00	Low electrolyte fluid	Pusch, 1994
Ca-bentonite		1.8	0.50	Low electrolyte fluid	Pusch, 1994
Ca-bentonite		2.1	10.00	Low electrolyte fluid	Pusch, 1994
Na-bentonite		1.8	0.30	High electrolyte fluid	Pusch, 1994
Na-bentonite		2.1	10.00	High electrolyte fluid	Pusch, 1994
Ca-bentonite		1.8	0.05	High electrolyte fluid	Pusch, 1994
Ca-bentonite		2.1	10.00	High electrolyte fluid	Pusch, 1994
French clay		1.4	0.9		Atabek et al., 1990
French clay		1.5	2.0		Atabek et al., 1990
French clay		1.6	4.5		Atabek et al., 1990
French clay		1.7	8.0		Atabek et al., 1990
Na-bentonite		0.907	0.092		Oscarson et al., 1990
Na-bentonite		1.02	0.080		Oscarson et al., 1990
Na-bentonite		0.86	0.155		Oscarson et al., 1990
Na-bentonite		0.869	0.259		Oscarson et al., 1990
Na-bentonite		0.955	0.310		Oscarson et al., 1990
Na-bentonite		1.085	0.455		Oscarson et al., 1990
Na-bentonite		1.119	0.451		Oscarson et al., 1990
Na-bentonite		1.164	0.514		Oscarson et al., 1990
Na-bentonite		1.083	0.576		Oscarson et al., 1990
Na-bentonite		1.194	0.591		Oscarson et al., 1990
Na-bentonite		0.975	0.128		Oscarson et al., 1990
Na-bentonite		1.020	0.300		Oscarson et al., 1990
Na-bentonite		0.964	0.679		Oscarson et al., 1990
Na-bentonite		0.993	0.774		Oscarson et al., 1990
Na-bentonite		0.991	0.812		Oscarson et al., 1990
Na-bentonite		1.033	0.860		Oscarson et al., 1990
Na-bentonite		1.022	0.964		Oscarson et al., 1990
Na-bentonite		1.115	0.867		Oscarson et al., 1990
Na-bentonite		1.236	0.941		Oscarson et al., 1990
Na-bentonite		1.164	1.173		Oscarson et al., 1990
Na-bentonite		1.241	1.524		Oscarson et al., 1990
Na-bentonite		1.281	1.884		Oscarson et al., 1990
Na-bentonite		1.273	2.062		Oscarson et al., 1990
Na-bentonite		1.293	2.201		Oscarson et al., 1990
Na-bentonite		1.335	2.591		Oscarson et al., 1990
Na-bentonite		1.146	0.806		Oscarson et al., 1990
Na-bentonite		1.173	1.722		Oscarson et al., 1990
Na-bentonite		1.214	1.794		Oscarson et al., 1990
Na-bentonite		1.234	2.012		Oscarson et al., 1990
Na-bentonite		1.223	2.028		Oscarson et al., 1990

Table 4. Reported Swelling Pressures of Bentonite and Bentonite Mixtures

Material	Composition (%)	Density	Swelling Pressure (MPa)	Permeant	Reference
Na-bentonite		1.281	2.488		Oscarson et al., 1990
Na-bentonite		1.333	3.338		Oscarson et al., 1990
Na-bentonite		1.403	3.393		Oscarson et al., 1990
Na-bentonite		1.309	3.899		Oscarson et al., 1990
Na-bentonite		1.335	4.028		Oscarson et al., 1990
Na-bentonite		1.353	3.963		Oscarson et al., 1990
Na-bentonite		1.40	0.677		Mingarro et al., 1991
Na-bentonite		1.57	2.354		Mingarro et al., 1991
Na-bentonite		1.80	3.543		Mingarro et al., 1991
Na-bentonite		2.13	31.883		Mingarro et al., 1991
Bentonite/sand	75:25	1.42	0.128		Mingarro et al., 1991
Bentonite/sand	75:25	1.60	0.795		Mingarro et al., 1991
Bentonite/sand	75:25	1.81	3.541		Mingarro et al., 1991
Bentonite/sand	75:25	2.04	24.525		Mingarro et al., 1991
Bentonite/sand	50:50	1.38	0.284		Mingarro et al., 1991
Bentonite/sand	50:50	1.60	0.471		Mingarro et al., 1991
Bentonite/sand	50:50	1.80	2.747		Mingarro et al., 1991
Bentonite/sand	50:50	2.00	15.267		Mingarro et al., 1991
Bentonite/sand	25:75	1.41	0.049		Mingarro et al., 1991
Bentonite/sand	25:75	1.58	0.334		Mingarro et al., 1991
Bentonite/sand	25:75	1.81	0.589		Mingarro et al., 1991
Bentonite/sand	25:75	2.03	5.886		Mingarro et al., 1991
Na-bentonite		1.917	1.399	0.3 M $CaCl_2$	Pusch, 1980
Na-bentonite		2.000	1.854	0.3 M $CaCl_2$	Pusch, 1980
Na-bentonite		1.989	3.259	0.3 M $CaCl_2$	Pusch, 1980
Na-bentonite		2.081	19.178	0.3 M $CaCl_2$	Pusch, 1980
Na-bentonite		2.151	46.833	0.3 M $CaCl_2$	Pusch, 1980
Na-bentonite		1.751	0.705	Distilled water	Pusch, 1980
Na-bentonite		1.801	1.034	Distilled water	Pusch, 1980
Na-bentonite		1.832	1.746	Distilled water	Pusch, 1980
Na-bentonite		1.888	3.007	Distilled water	Pusch, 1980
Na-bentonite		1.998	6.464	Distilled water	Pusch, 1980
Na-bentonite		2.009	16.995	Distilled water	Pusch, 1980
Na-bentonite		2.079	24.421	Distilled water	Pusch, 1980
Na-bentonite		2.189	73.927	Distilled water	Pusch, 1980
Na-bentonite		1.818	0.863	Ground water	Pusch, 1980
Na-bentonite		1.846	0.993	Ground water	Pusch, 1980
Na-bentonite		1.819	1.055	Ground water	Pusch, 1980
Na-bentonite		2.003	5.502	Ground water	Pusch, 1980
Na-bentonite		2.036	15.999	Ground water	Pusch, 1980
Na-bentonite		2.112	38.034	Ground water	Pusch, 1980
Na-bentonite		2.189	65.513	Ground water	Pusch, 1980
Na-bentonite		1.859	0.780	0.6 M NaCl	Pusch, 1980
Na-bentonite		1.913	1.055	0.6 M NaCl	Pusch, 1980
Na-bentonite		2.003	3.194	0.6 M NaCl	Pusch, 1980
Na-bentonite		2.059	24.917	0.6 M NaCl	Pusch, 1980
Na-bentonite		2.151	55.764	0.6 M NaCl	Pusch, 1980

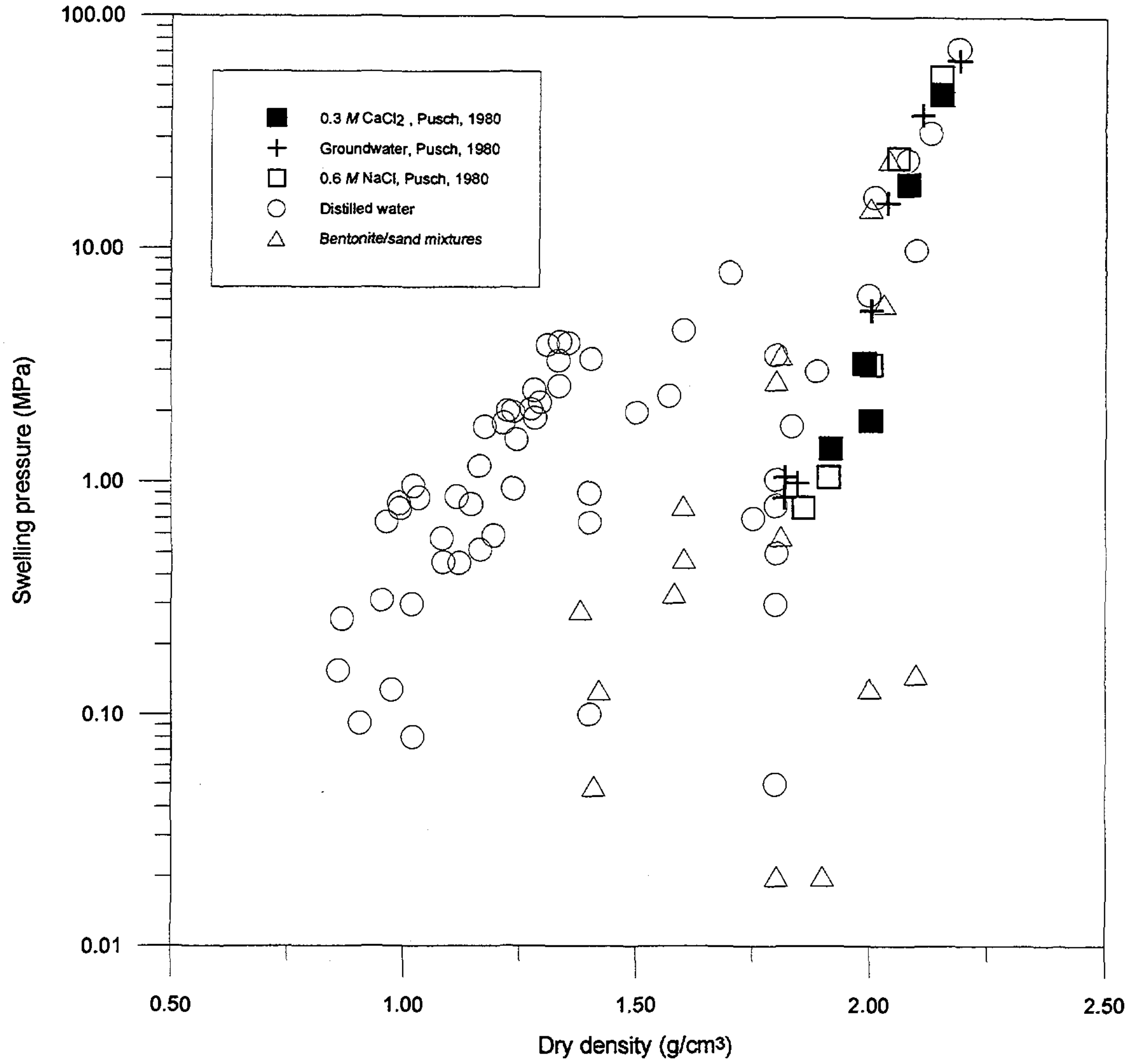

Figure 7. Reported swelling pressure as a function of dry density of bentonite and bentonite mixtures.

Allison et al. (1990) conducted swelling pressure measurements on bentonites and measured swelling pressures significantly lower than those reported by Pusch (1980), as shown in Figure 8. Allison et al. (1990) attribute the differences to inconsistency in measurement methods, and they describe the measurement methods used by Pusch (1980) as unrealistic or as not representative of actual conditions. The merits of the argument are not necessarily obvious. It is clear, however, that (1) swelling pressures may vary significantly depending on the details of the method used to measure the swelling pressure and (2) the most representative or realistic method (i.e., the method that most appropriately simulates field conditions) is far from obvious.

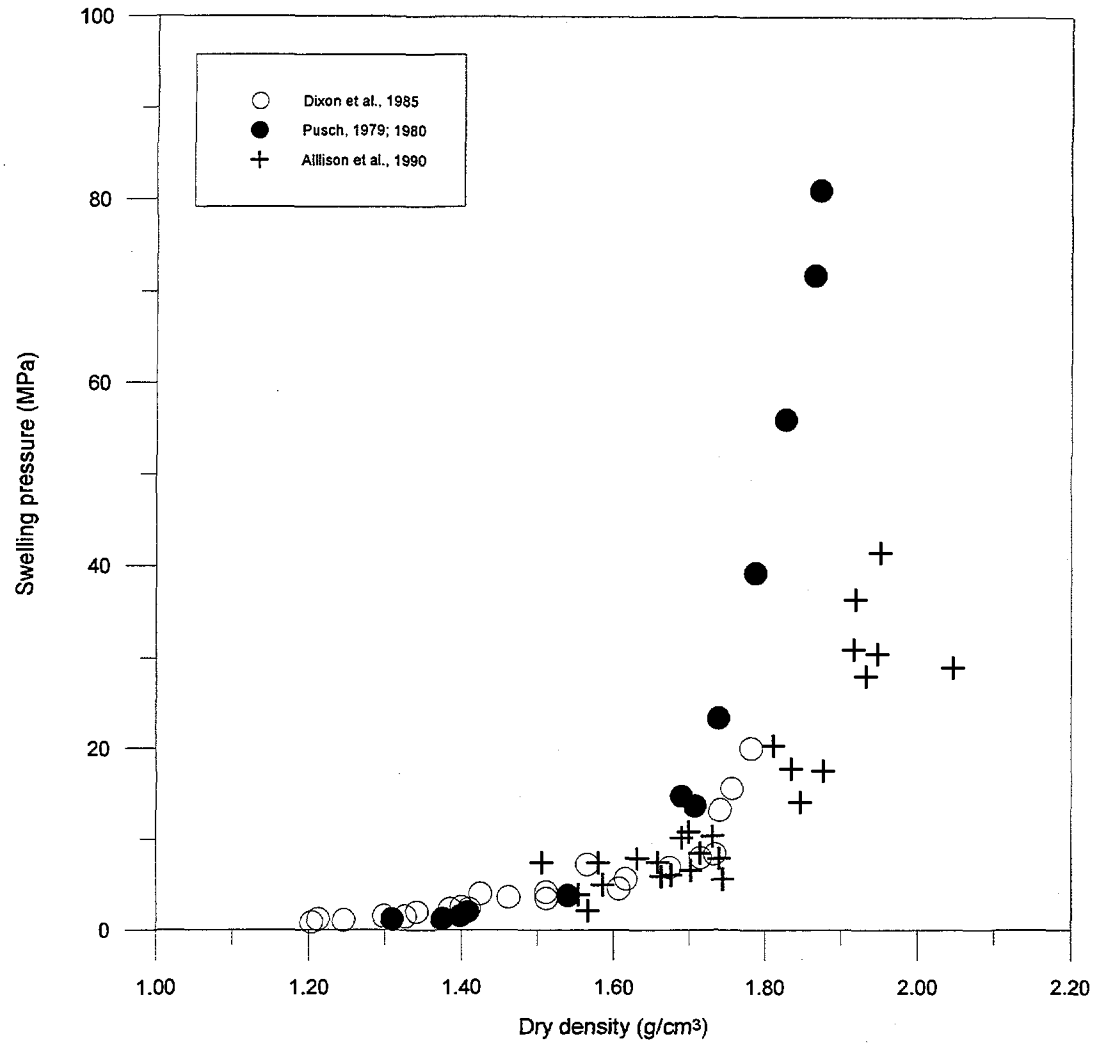

Figure 8. Comparison of swelling pressure for Na-bentonite from various researchers (after Allison et al., 1990).

Dixon et al. (1991) investigated three different methods for measuring the swelling pressure of highly compacted mixtures of sand and bentonite: triaxial consolidation, 1-D oedometer consolidation, and tests in a rigid constant-volume cell. They concluded that for tests on highly precompacted mixtures the results were largely independent of the test method used. Note that the materials tested generated relatively low swelling pressures, in the 1 to 3 MPa range.

5.3.2 Shrinkage

Compacted bentonite shrinks when it is dried to low water content. An increase in confining pressure reduces the volume of the compacted bentonite, especially when permeated by permeants containing numerous types of cations and electrolytes such as Na^+. Other factors (such as type of bentonite, temperature, fabric, and density) also change the volume of the compacted bentonite. The shrinkage of compacted bentonite caused by loss of moisture content is directly related to clay mineral composition. The thickness of the diffuse double layer varies with changes of the pore fluid chemistry. Haug et al. (1988) reported a 7% volume decrease for 20:80 sodium bentonite/sand mixtures when NaCl concentration increased from 0 to 4 mol/L and when a 200 kPa surcharge was applied. Barbour and Yang (1993) observed that, for clay initially remolded with distilled water, the clay always shrinks when the pore fluid is replaced by brine.

5.4 Mechanical Properties

Compacted clay seals in shafts also act as structural components to support the shaft walls, which prevents collapse and allows healing of the DRZ. To provide the necessary resistance, the bentonite seals should have enough mechanical stiffness and strength to resist shaft closure and prevent separation from the upper sealing columns, which may result from over shrinkage and subsidence. Although the mechanical properties of bentonite are as important to sealing as its fluid-conduction properties, few studies have focused on the mechanical properties of compacted bentonite.

5.4.1 Strength

Radhakrishna and Chan (1982) studied the strength and deformation characteristics of compacted Black Hills bentonite, Avonlea bentonite, and Pembina bentonite, as well as the attributes of bentonite mixtures with crushed granite or sand. The results of their investigations are given in Table 5.

Table 5. Mechanical Properties of Bentonite and Bentonite/Crushed Granite Mixtures

Sample	Bentonite Content (%)	As Compacted				After Saturation			
		Dry Density (g/cm^3)	Moisture Content (%)	Compressive Strength (MPa)	Young's Modulus (MPa)	Dry Density (kg/m^3)	Moisture Content (%)	Compressive Strength (MPa)	Young's Modulus (MPa)
CGBB	50	1.765	15.3	0.822	50.0	1.685	19.7	0.374	7.1
CGBB	50	1.655	22.5	0.358	19.6	1.585	24.7	0.136	6.2
CGBB	50	2.138	9.7	1.339	58.3	2.076	11.5	0.560	12.0
CGBB	50	2.015	12.0	0.872	21.6	1.976	12.5	0.360	2.0
BB	100	1.670	22.3	2.524	68.0	1.338	37.3	1.200	25.9
AVB	100	1.557	19.6	4.578	313.0	1.554	25.1	1.780	43.6
PB	100	1.443	25.5	2.948	352.0	1.435	34.1	2.104	108.6
CGAVB	50	1.784	18.2	1.956	98.0	1.797	18.9	1.768	87.1
CGBB	50	1.795	16.8	3.384	154.0	1.770	21.2	1.360	68.7
CGBB	50	1.883	13.1	1.230	31.9	1.897	16.5	0.876	25.8
CGBB	25	1.935	14.0	0.522	63.6	1.885	15.1	0.580	53.6

After Radhakrishna and Chan (1982).
CGBB = Mixture of Black Hills bentonite and crushed granite; BB = Black Hills bentonite;
AVB = Avonlea bentonite; PB = Pembina bentonite;
CGAVB = Mixture of Avonlea bentonite and crushed granite.

Di Maio and Fenelli (1994) investigated the residual strength of bentonite as a function of pore fluid chemistry. The residual friction angle of bentonite increases significantly when distilled water is replaced with a 1 *M* NaCl solution, and even more when a saturated sodium chloride solution is used (from 6° to 9° to 18°). Barbour (1987) quotes data from triaxial tests reported by Ho (1985) and Ho and Pufahl (1987) on Regina clay (a clay containing 45% montmorillonite, 28% illite, 18% kaolinite and 9% trichloride). After exposing the samples to a 4.0 *M* solution of NaCl brine, the friction angle increases from 33° to 37°. Mitchell (1993, p. 364) cites friction values from Kenney (1967), which show a significant increase for Na-montmorillonite when prepared with a NaCl brine as compared to fresh water: the residual friction angle increased from 6° to about 17°. Borgesson et al. (1995) conducted triaxial tests on MX-80 bentonite samples with wet density of 2.0 g/cm^3 and found that the friction angle is 12.9° and cohesion is 106 kPa when pore water with 3.5% NaCl is used. When blocks with a dry density of 1.8 g/cm^3 are used, the finished seal in shafts should have a dry density slightly less than 1.8 g/cm^3.

5.4.2 Stiffness

Bentonite and bentonite-based seals are likely to be characterized by highly complex, strongly nonlinear mechanical behavior. Yin et al. (1990) used a three-modulus hypoelastic constitutive model for compacted sand-bentonite mixtures.

Young's Modulus

Figure 9 shows the relationship between Young's modulus and minor principal stress, σ_3. The Young's modulus (E) of clay is given by Janbu (1963) in the formula:

$$E = Kp_a\left(\frac{\sigma_3}{p_a}\right)^n \qquad (3)$$

where K is a dimensionless modulus number that varies from about 300 to 2000 (Mitchell, 1993, p. 339); for saturated bentonite, the range probably is much narrower, about 100 to 300 or less. The variable n is an exponent usually in the range of 0.3 to 0.6 (Mitchell, 1993, p. 339). Pa is a unit constant equal to atmospheric pressure, and σ_3 is minor principal stress.

Yin et al. (1990) concluded that the Young's modulus of a 50:50 bentonite sand mixture can be calculated as:

$$E = kp' \qquad (4)$$

where k is a constant: $k = 80$ for 50:50 bentonite sand mixture; p' is the effective mean stress: $p' = 1/3\ (\sigma_1' + 2\sigma_3')$.

The Young's modulus of bentonite should be lower than that of a bentonite/sand mixture. Highly compacted and relatively dry bentonite (2.0 g/cm^3 with 10% water content) has a Young's modulus up to 300 MPa, which decreases with the uptake of water (Meyer and Howard, 1983).

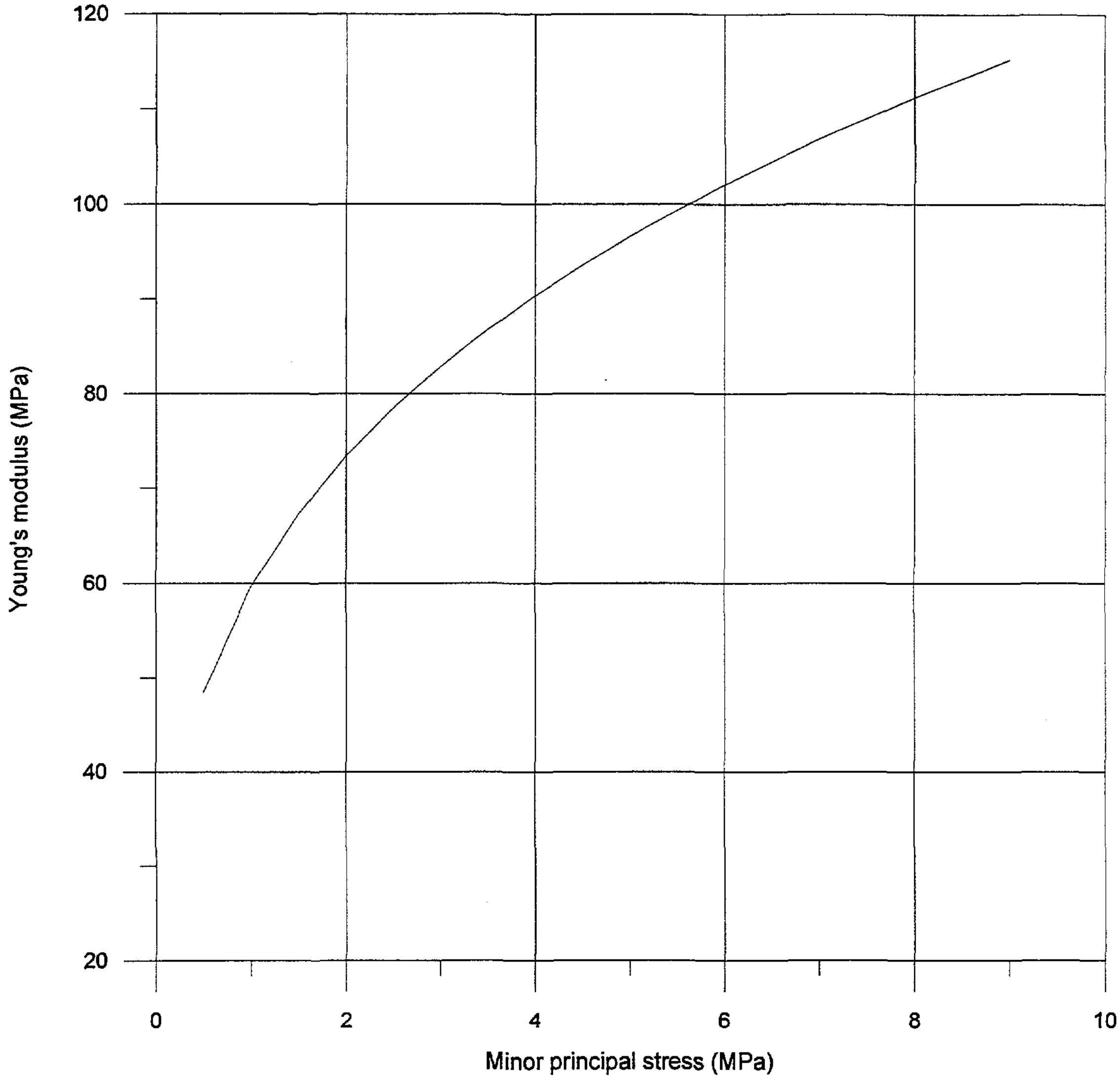

Figure 9. Young's modulus of clay as a function of minor principal stress with $K = 300$, $P_a = 14.4$ psi, and $n = 0.3$ in Equation 3 (after Janbu, 1963).

Bulk Modulus

Yin at al. (1990) concluded that the bulk modulus of a 50:50 bentonite/sand mixture is 13.7 p'. Again, for pure bentonite, the bulk modulus is almost certainly lower.

Poisson's Ratio

Meyer and Howard (1983) reported that for highly compacted and relatively dry bentonite (2.0 g/cm^3 with 10% water content), the Poisson's ratio is about 0.15. For soft clay, the Poisson's ratio should be about 0.375, according to Dunn et al. (1980, p. 113). Saturated bentonite is known to be extremely plastic; therefore Poisson's ratio is expected to be larger, i.e., at least 0.4 and probably 0.45 or larger.

Mechanical Behavior

The preceding extremely brief description of bentonite stiffness in terms of single isotropic elastic constants is at best extremely simplistic and at worst rather misleading. More complete and complex mechanical behavior models have been developed for clays. Barbour (1987) summarizes numerous references in a model that explicitly includes a solid phase, a pore fluid phase, and a diffuse double layer phase. A constitutive model including these phases clearly is far more realistic for describing relations between stress and strain, including for example the effects of salt migration. It is unclear whether or not sufficient information is available yet to implement such a model.

5.5 Sorption

Ion exchange, or sorptive retardation of radionuclides, is one of the main reasons that clays, specifically bentonites, have been selected as backfill and sealing materials for many repositories. An extensive literature exists on sorptive and retardation studies of radionuclides in clays. Although many references for this topic are included in the computerized data bases accompanying this document, no effort was made to review and summarize those references. One example may suffice to show that sorption studies on clay, specifically bentonite, have been conducted within the context of most repository programs.

Brodda and Merz (1983) describe experimental investigations of the sorption of strontium and cesium on six clay types, including two bentonites. The authors observe that sorption efficiency is greatly reduced when saline brines flow through the clays.

5.6 Index Properties

The liquid and plastic limits of bentonite depend greatly on the type of the adsorbed cations (Mitchell, 1976). The range of reported index properties of bentonite are given in Table 6. The plastic limit of bentonite is 50 to 100 (Mitchell, 1976, p. 173) or 83 to 250 (Grim and Güven, 1978, p. 218). The liquid limit of bentonite ranges from 100 to 900 (Mitchell, 1976, p. 173) and from 160 to 500 (Grim and Güven, 1978, p. 218).

Table 6. Reported Index Properties of Bentonite

Material	Liquid Limit	Plastic Limit	Free Swell*	Fluid	References
Bentonite	500	40	25	DDW	Kenney et al., 1992
Bentonite	105	35	5.4	0.7 *M* NaCl	Kenney et al., 1992
Ca-bentonite	75.5	24.3			Yang and Barbour, 1992
Na-bentonite	250				Dixon et al., 1992a
Bentonite	355	55			Yong and Cabral, 1992
Bentonite	100-900	50-100			Mitchell, 1976, p. 173
Bentonite	160-500	83-250			Grim and Güven, 1978, pp. 218-220

* = Void ratio; DDW = Distilled deionized water

The liquid limit increases with increasing amounts of exchangeable sodium cations; the liquid limit does not relate to size fraction of bentonite (Sridharan et al., 1986). For sodium bentonite, the liquid limit is 250 and the plastic limit is 49 (Dixon et al., 1991).

Kenney et al. (1992) report that the liquid limit of bentonite reduces from 500 to 105 when a 0.7 mol/L solution of NaCl is used for saturation instead of distilled water. The plastic limit of bentonite reduces also, from 40 to 35, when a 0.7 mol/L solution of NaCl is introduced.

For clay liners affected by landfill leachate, Bowders et al. (1985) recommend that the index properties of clay be determined for clay mixed with fresh water and for clay mixed with leachate. If no significant differences in the index properties are measured, it is then likely that the permeability will not be affected significantly. Bagchi (1994, p. 142) indicates that this relation between index properties and permeability was recognized by Terzaghi (1936).

5.7 Longevity

The argument that clays, particularly bentonites, have persisted in nature over long geologic times has frequently been invoked as a primary criterion for their selection as sealing materials. Detailed studies have been conducted within the framework of many repository programs to evaluate the likely longevity of clays, specifically bentonites, particularly for backfill studies. When used as a backfill component in a high-level waste repository, clay will likely be exposed to much higher temperatures than when used as a seal component; it may also be exposed to high radiation levels. WIPP is not a heated repository. Nevertheless, data about alteration at elevated temperature may be relevant or applicable, to the extent that such results can be considered representative as accelerated tests.

The longevity of bentonite seals is directly related to the stability of smectites under installed and site conditions (Güven, 1990). The conversion of montmorillonite to hydrous mica is one of the changes that can influence the stability of bentonite seals. In a brine environment, excess sodium may decrease the swelling ability and increase the permeability of the bentonite seal. Several methodologies have been adopted to study the longevity of bentonite seals, including montmorillonite conversion, microstructure changes, observation of long-term permeability, and comparison of the swelling pressure and permeability of processed and unprocessed bentonites.

The primary longevity requirement is stability: the performance of compacted clay seals should not deteriorate excessively over time. Krumhansl (1986) conducted an extensive scoping investigation of the long-term stability of bentonite in a saline environment. Because the investigation was designed to improve understanding of the long-term stability of bentonite when used as a backfill for high-level waste (HLW) packages, he subjected bentonite to environments far more severe than those likely to be encountered by WIPP shaft seals. Krumhansl (1986, p. 3) reported that

> "...most experiments were done at the most extreme conditions likely to occur in a commercial HLW repository. These experiments can also be considered as accelerated tests (or "overtests") for repositories isolating cooler forms of waste, such as the defense

> wastes.... These results make a strong case that bentonite is sufficiently stable to warrant the additional research required to fully demonstrate bentonite backfill feasibility.

In a technical report on underground repository sealing, the International Atomic Energy Agency (IAEA) summarized the results from a number of studies on the longevity of clay seals. The IAEA (1990, p. 58) concluded that

> ...for highly compacted clays, within the range of values expected in a repository, even in the near field, temperature and ionic concentration in the groundwater should not significantly affect swelling potential or hydraulic conductivity.

Pusch and Karnland (1990) studied the conversion of montmorillonite to illite when potassium is available. The conversion of smectite to illite takes place in the environment either at high effective pressure and at temperature exceeding about 60°C or drying (Pusch, 1994, p. 352). Pusch and Güven (1990) studied the microstructure of Na-bentonite with a bulk density of 2.0 g/cm^3 under temperatures from 150 to 200°C for six months. The microstructure of the bentonite changed, with an enlargement of the pores. No mineralogical and chemical changes were observed. Howard and Roy (1985) conducted laboratory studies of sodium-saturated bentonite to investigate smectite alteration at 150 to 250°C for 30 to 180 days. They found that potassium transfers smectite into illite. The rate of transformation depends on temperature, potassium content, and fluid composition. Although WIPP salt only contains 0.151 to 0.232% potassium (Brodsky, 1994), the smectite to illite transformation may occur.

Oscarson et al. (1990) compared the swelling pressures and hydraulic conductivity of processed and unprocessed bentonites to identify the longevity of the bentonite seal. They found that processed bentonite has higher swelling capacity and lower permeability for bentonites with dry densities from 0.9 to 1.4 g/cm^3. Unprocessed bentonite maintains a significantly high swelling capacity and low permeability after millions of years of water erosion, thermal alteration, loading, and unloading.

Ran (1993) studied the flow properties of pure bentonite grout before and after healing from washing out some particles and channeling for over 200 days. After being washed out twice and subjected to varied pressure gradients for over 200 days, the bentonite can maintain low hydraulic conductivity.

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6. EMPLACEMENT/CONSTRUCTION

The major sealing characteristics of bentonites and clays (i.e., hydraulic conductivity and swelling behavior), as well as most other properties, are a strong function of emplacement density. Various emplacement options have been considered; among them are *in situ* compaction of powdered bentonite, emplacement in the form of precompacted blocks, and hydraulic or pneumatic emplacement.

In situ compaction with conventional compaction equipment is unlikely to produce acceptable densities if extremely low hydraulic conductivities are deemed necessary or desirable. Although one can conceptually visualize *in situ* static compaction equipment that could provide the pressures necessary to compact to high densities, such equipment would require design and construction.

A few emplacement investigations have been conducted for pure bentonite seals and for shaft sealing. Most investigations for seal emplacement technologies have focused on using sand or quartz bentonite mixtures to seal nuclear waste emplacement rooms. However, shaft sealing design can benefit from those investigations. Two emplacement methods have been investigated. One is the use of bentonite blocks, and another is *in situ* compaction.

The Canadian nuclear waste program has conducted extensive testing, both *in situ* and in large scale laboratory simulators, of the compaction of clay-based barrier materials with dynamic hydraulically powered impact hammers (e.g., Kjartanson et al., 1992). The Swedish program similarly has investigated field compaction of bentonite-based tunnel backfill by means of plate vibrators (e.g., Nilsson, 1985). Both studies demonstrated the feasibility of *in situ* compaction of bentonite-based materials to a high density. However, such manual backfill compaction might be excessively slow for the compaction of several hundred ft of shaft seals. Therefore the alternative of using sheepsfoot compactors is recommended, although it will require some modification of the driving systems for the compaction equipment. Heavy sheepsfoot rollers should allow the use of higher lifts than are possible with manual or semi-manual compaction, providing the kneading compaction that will minimize the permeability (Mitchell et al., 1965). They should also allow application of a large compaction energy in a reasonable amount of time.

Sheepsfoot roller compaction is widely used for construction of impervious liners for earth dams (Hilf, 1975) and for the construction of clay liners for waste disposal facilities (Daniel, 1993). Geotechnical textbooks and most experts interviewed recommend the use of sheepsfoot or tamping foot rollers for compacting cohesive (clay) soils to achieve low permeability (Goldman et al., 1990). The fundamental explanation for the effectiveness of sheepsfoot compaction in reducing permeability appears to be that kneading compaction and the associated large shear strains induce a dispersed structure that greatly reduces permeability (Mitchell et al., 1965). More detailed investigations of the soil structure resulting from sheepsfoot compaction are referenced by Seed and Chan (1959), according to Mitchell et al. (1965). Sufficient compaction passes will have to be made to assure that the required compaction energy is applied.

In Sweden, Nilsson (1985) conducted compaction tests of bentonite/sand mixtures in the field. The tests were conducted in a tunnel with six nuclear waste emplacement rooms. A dynamic roller (vibrator) was used to compact 10/90% or 20/80% bentonite/sand mixtures. The compaction after 25 runs resulted in dry densities of 1.59 to 1.71 g/cm^3 for the 10/90% bentonite/sand mixture, and 1.5 to 1.6 g/cm^3 for the 20/80% bentonite/sand mixture. The moisture content of the bentonite/sand mixture at compaction ranged from 8% to 16%.

In Germany, Bucher and Jedelhauser (1985) conducted laboratory compactions of quartz-sand/bentonite mixtures. The mixtures have Na-bentonite (MX-80) content from 17% to 33% or Ca-bentonite (Montigel) from 26% to 31% by weight. The mixtures were statically compacted in a compaction mold with 80 to 320 MPa compactive pressure. Their final density was 1.5 g/cm^3.

In Canada, Dixon et al. (1985) conducted laboratory compactions of bentonite and bentonite/sand mixtures. Standard Proctor molds and modified molds were used for compaction. The sand/bentonite mixtures had 25, 32.5, 40 and 75% bentonite contents. When the modified compactive energy was applied, the achieved dry density varied with bentonite content and moisture content. The compaction of the bentonite under the modified compactive effort was about 1.3 g/cm^3.

For bentonite/sand mixtures with more than 50% bentonite content, the modified compactive energy is insufficient to overcome the high shearing resistance of the water attached to the bentonite particles (Dixon et al., 1985). If the mixture has less than 50% bentonite content, greater compaction can be achieved (Nilsson, 1985; Dixon et al., 1985). However, Bucher and Jedelhauser (1985) note that the static pressure required to reach a given dry density of the bentonite filling the pores between sand grains is 10 to 20 times greater than that required to fill spaces between bentonite particles in a specimen of bentonite alone.

Highly compacted bentonite blocks were placed at the WIPP site. Bentonite blocks were produced in a block machine with 26.2 MPa (3800 psi) static pressure, and 1.8 g/cm^3 density was achieved (Howard, 1989). Pusch (1994) and Pusch et al. (1982) propose to use precompacted bentonite blocks to seal shafts. Bentonite blocks can be manufactured by uniaxial or three-dimensional compression. A dry density of 1.8 g/cm^3 with water content of 6% to 7% can be achieved by applying pressure up to 150 MPa (Pusch, 1994).

In situ compaction of clays is a widely used practice for many sealing applications, particularly, hazardous waste sites, heap leach pads, and similar engineered waste-containment structures. Emplacement, compaction, and verification methods are well established and readily available. Modifications of standard procedures may be required for emplacement in shafts, primarily because the equipment most likely to be recommended for clay compaction (i.e., sheepsfoot rollers) may not be readily available in sizes and weights desirable in shafts. Also, it seems quite likely that the required performance in WIPP shafts may be more stringent than the requirements for most other applications.

A potentially serious problem for *in situ* compaction may arise from the selected performance requirements. If the bentonite seals are designed for minimal hydraulic conductivity at emplacement, it is likely that the recommended moisture content will be wetter than optimum (e.g., Mitchell et al., 1965). A highly plastic clay such as bentonite is likely to be very sticky, as well as very soft, at such high moisture contents, which may result in operational difficulties (Daniel, 1993).

The performance of bentonitic seals depends on many variables. Main factors to be taken into account during design and construction include compaction procedures to be used, moisture content, density, and type of fluid (i.e., water composition) mixed with bentonite.

Three important considerations with regard to compaction are (1) the type of equipment to be used, (2) the amount of energy to be applied, and (3) procedures to be used to assure that no preferential flowpaths develop between lifts. It is highly desirable to achieve the lowest practically possible permeability; therefore a kneading type compaction will be prescribed, most probably in the form of sheepsfoot roller type compaction, assuming the equipment can be operated in a shaft.

It is probable that a large energy application will be prescribed, i.e., the application of multiple compaction passes. Special indentation/kneading type preparation of interfaces between lifts will be prescribed to assure the development of a tight interface between lifts.

The development of desiccation cracks in emplaced lifts must be prevented. Most likely, large quantities of dry air will be blown into the bottom of the shafts during seal emplacement. Thus consideration must be given to either assure that the airflow does not cause excessive drying of emplaced bentonite (e.g., by artificially increasing the moisture content of the air) or to provide surface protection on top of emplaced seal material.

In addition to technical concerns, it is necessary to implement close supervision and inspection procedures. Several clay liner failures have been attributed to lack of inspection (e.g., Daniel, 1984; 1993), presumably reflecting inadequate construction. Daniel (1990) summarizes construction quality control procedures for compacted soil liners, many of which would be applicable and appropriate for shaft seals.

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7. RESERVES, SUPPLIES, AND LONG-TERM AVAILABILITY

Because repository backfilling and sealing may not take place for several decades, concern exists about the long term availability of bentonite. According to Miles (1995) "High swelling sodium bentonite is rare... Lower grade sodium bentonite deposits stretch north from Wyoming, through Montana and into the Canadian Provinces. In contrast, high quality calcium bentonite occurs throughout the USA and the world."

The availability question has been investigated within the context of the Canadian nuclear waste disposal program. According to Dixon et al. (1992b) the proven reserves of North American sodium bentonite exceed 1.9×10^9 Mg, and vast supplies are known to exist, though they have not yet been proven. The Canadian reference repository would require, for backfill and sealing, some 2.5×10^6 Mg of bentonite. The Canadian conceptual disposal vault would require 6×10^4 Mg of sodium bentonite each year for forty years. The North American bentonite industry has an installed annual bentonite production capacity of 2×10^7 Mg. The Canadian repository therefore would require approximately 2% of industry capacity. The Canadian program has screened a number of commercial products for potential suitability as backfill material and has identified ten currently marketed bentonite products that meet the initial quality standards for the buffer/backfill material, as well as two noncommercial bentonites.

According to Rath (1986) a conservative estimate of the remaining Wyoming bentonite reserves is about 90 to 100 million tons. Hosterman and Patterson (1992) concluded that the bentonite reserves in the United States are 800 million tons. There is considerable uncertainty about these estimates, however, because most companies do not willingly reveal reserve figures. Moreover, the figures change significantly with economic conditions. "Geologically, there is considerably more bentonite available than is presently commercially mineable." (Rath, 1986). In recent years (i.e., 1989 through 1993) production of Wyoming sodium bentonite has been on the order of 2.5 to 3 million short tons per year (Arrington-Webb, 1994; Virta, 1994).

A conservative approximation of the bentonite required for WIPP shaft sealing can be made assuming that the total cross-sectional areas of the compacted clay seals for four shafts will be 100 m^2 (DOE/WIPP, 1995, p. D-5), the maximum total length of the seals will be 400 m, and the seals will be compacted to a maximum dry density of 2 g/cm^3. It is assumed that the bentonite from the manufacturer contains 10% water. Under these assumptions, for four shafts about 88,000 metric tons (96,976 short tons) of bentonite would be needed for the shaft seals. This quantity represents about 3% of the current annual US sodium bentonite production.

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8. CONCLUSIONS

Bentonite has been widely studied as a primary sealing material for nuclear waste repositories (IAEA, 1990; Pusch and Bergstrom, 1980; Pusch, 1994; Coulon et al., 1987; Brenner, 1988; Bucher et al., 1986; Dixon et al., 1985; Butcher, 1994; Pfeifle, 1990). The swelling, longevity, and flow properties of bentonites and bentonite mixtures with sand or crushed rock have been extensively characterized with distilled deionzied water as the permeate. A few studies (Pusch, 1980; Dixon et al., 1987; Kenney et al., 1992) have been conducted using brines with low NaCl concentration (from 0.7 to 1.2 *M*) as pore fluid.

The permeability of compacted sodium bentonite (from 0.5 to 2.2 g/cm^3) ranges from 1×10^{-16} to 1×10^{-21} m^2. The permeability of bentonite mixtures varies significantly with density depending on the bentonite content. The permeability of compacted sodium bentonite increases two to three orders of magnitude when saline solutions (0.7 to 1.2 *M* NaCl) are the permeate. NaCl concentration in permeation fluid has a slight influence on the permeability of Ca-bentonite. If the confining pressure is high enough to compress the increased pores, such influence may be reduced. The permeability of bentonite mixtures with sand or crushed rock does not closely relate to the density of the seal (see Figure 2), but more to the bentonite content (see Figure 1).

The gas permeability of compacted bentonite depends on the moisture content of the bentonite and its density. Gas penetration through bentonite requires displacing free water in pores; hence a breakthrough pressure is needed. The breakthrough pressure increases with increasing moisture content and density. For saturated compacted bentonite, the breakthrough pressure ranges from 1.6 to 21 MPa for dry densities from 1.4 to 1.79 g/cm^3 (Pusch and Hokmark, 1990). For WIPP shaft sealing, bentonite seals should maintain enough density and moisture content to limit gas migration to an acceptable level.

For compacted sodium bentonite, the swelling pressure ranges from 0.1 to 74 MPa for dry densities from 0.86 to 2.19 g/cm^3 (Pusch, 1980, 1994; Oscarson et al., 1990; and Mingarro et al., 1991). The swelling pressure for compacted bentonite with a dry density less than 1.0 g/cm^3 is less than 1.0 MPa. Certain cations (i.e., NaCl, $CaCl_2$, etc.) in the permeate fluid can significantly reduce the swelling capacity of bentonite (Mitchell, 1976). A bentonite seal in a NaCl-bearing environment may generate much less swelling pressure.

Bentonite has persisted in nature over geologic time scales. Geologic evidence, laboratory data, and theoretical analysis show that highly compacted bentonite can maintain physical, thermal, and chemical stability in environments other than Na^+ and Ca^+-rich ones. In the WIPP environment, two factors may potentially influence the stability of compacted bentonite. The first is cation exchanges, which lead to conversion of the sodium bentonite into other types of bentonites that have higher permeability. Illite may be an inevitable product of reaction of smectite with K^+-rich pore fluid. Calcium bentonite may be formed when the pore fluid is rich enough in Ca^{2+}. A second factor is that bentonite may decrease its volume when brine penetrates because NaCl in brine can reduce the thickness of the double layer.

The mechanical properties of compacted bentonite are not well characterized when the pore fluid contains a high NaCl concentration (i.e., similar to WIPP conditions of >5 *M*).

The shear strength of compacted bentonite increases significantly when distilled water is replaced by 1 *M* NaCl solution as pore fluid (Di Maio and Fenelli, 1994). The reported compressive strength ranges from 2.5 to 4.6 MPa for compacted dry bentonite, and reduces to 1.2 to 2.1 MPa after saturation (Radhakrishna and Chan, 1982). The Young's modulus of compacted bentonite decreases with water uptake, from 68 – 352 MPa to 26 – 109 MPa (Radhakrishna and Chan, 1982; Meyer and Howard, 1983).

In situ compaction with conventional equipment is unlikely to produce the desirable density for bentonite seal construction. Two technologies (dynamic compaction and precompacted blocks) have been studied for bentonite seal construction for Swedish, Canadian, German, and US nuclear waste programs. Dynamic compaction technology has been evaluated both in the laboratory and in the field for mixtures of bentonite with sand or crushed rock. *In situ* compaction using a dynamic impact hammer (Kjartanson et al., 1992) or a plate vibrator (Nilsson, 1985) can densify mixtures of bentonite and sand or crushed rock to a dry density of 1.75 to 2.0 g/cm^3. Dixon et al. (1985) and Yong et al. (1986) reported that a dry density of 1.3% can only be achieved by dynamic compaction for bentonite when the modified Proctor effort is applied. Howard (1989), Pusch (1994), and Pusch et al. (1982) report that bentonite blocks with a dry density higher than 1.8 g/cm^3 can be produced in a block machine under 26 to 150 MPa static compression pressure.

A conservative estimate of the remaining Wyoming bentonite reserves is about 90 to 100 million tons (Rath, 1986). The proven high quality sodium bentonite reserves are about 1900 million tons in North America (Dixon et al., 1992b). The North American bentonite industry has an annual production capacity of 20 million tons (Dixon et al., 1992b). The WIPP shaft sealing system requires only about 88,000 metric tons of bentonite, which is about 3% of the current annual US production.

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Draft Report a Review of Literature and Laboratory Data Concerning Mud Filled Holes

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DRAFT REPORT
A REVIEW OF LITERATURE
AND LABORATORY DATA CONCERNING
MUD FILLED HOLES

CHEMICAL MANUFACTURING ASSOCIATION
WASHINGTON, DC

ENVIROCORP PROJECT NO. 10-1302

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OCTOBER 1989

PREPARED BY

ENVIROCORP SERVICES & TECHNOLOGY, INC.
HOUSTON, TEXAS

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1.0 INTRODUCTION

The purpose of the Underground Injection Control (UIC) Regulations are to prevent the possible contamination of underground sources of drinking water (USDW). One possible avenue of contamination is through manmade wellbores. Native or other injected fluids may migrate up these wellbores and contaminate a USDW.

Several factors must be considered to determine the probability of upward fluid migration and thus the potential for USDW contamination. These include but are not limited to the following:

- The subsurface lithology penetrated.
- Drilling method used.
- Location and condition of casing.
- Location of mechanical and/or cement plugs.
- Type of fluid left in the well.

The static mud column or drilling fluid left in the hole will provide substantial resistance to upward migration or flow. Most mud systems develop a gel structure when allowed to remain quiescent. This gel strength provides resistance to migration or flow and helps maintain the density of the fluid by suspending barite, clay, and other drilled solids. The density of the mud column provides hydrostatic head or a pressure along the wellbore that also provides resistance to upward fluid flow or migration. These properties are additive, therefore the sum of these forces must be exceeded for flow and/or migration to occur. Additionally, other related factors, such as wellbore closure from collapse or other natural events, must also be considered.

2.0 PURPOSE OF THE REPORT

Some doubt has been expressed by the regulators, concerned citizen groups, and the owner/operators related to the conditions of abandoned wellbores and annular spaces and their ability to contain injected and native fluids. This concern is a result of a deficiency in the literature specifically addressing the factors related to wellbore closure and the effect on the prevention of fluid migration. This report provides data on the factors effecting the static mud column, in the wellbore or behind the casing in the casing/wellbore annulus, to provide significant resistance to upward fluid migration along these potential pathways. The area within the zone of endangering influence from nearby injection wells is the area of greatest concern.

The zone of endangering influence is defined as that area, the radius of which is the lateral distance in which pressures in the injection zone may cause the migration of the injection and/or formation fluid into an underground source of drinking water (USDW). In some cases, this zone may also include the area of potential plume migration. There are numerous factors that must be considered when determining the potential for USDW contamination, however, the purpose of this report is to only address those factors that are relevant to the properties of drilling and other fluids remaining in abandoned wellbores and those left in the casing/wellbore annulus of both abandoned and active wells.

3.0 SUMMARY

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4.0 SUMMARY OF KNOWN MUD PROPERTIES 0113265

The wellbore and annulus space are rarely empty and are filled with native water, brine, or drilling fluid. In the case of native waters or brine the fluids may have seeped into the wellbore or been left there by the original driller. If the well was originally drilled with a cable tool rig or rotary drilling rig using compressed air, the fluid in the hole is probably native water or brine. However, the vast majority of artificial penetrations are made exploring for oil, gas and other minerals. Virtually all the wells drilled along the Gulf Coast used drilling fluids. In other areas it is logical to conclude that most wellbores are mud filled since rotary drilling techniques using drilling fluid are predominately used when drilling oil and gas exploration and development wells and other mineral extraction wells. Upon completion of the drilling operation, if the well is not completed for production, the drillpipe is removed from the wellbore and the drilling mud used to drill the well will remain in the wellbore indefinitely. If the well is completed or casing is run and partially cemented across a portion of the wellbore, drilling mud would have been displaced ahead of the cement from the annular space between the casing and open hole. If cement was not circulated to the surface, then the annular space above the cemented section will be filled with drilling mud.

A fluid filled wellbore or annular space provides resistance to upwards fluid migration because of two opposing forces. Barker (1981) was evidently the first investigation to propose the effects of these forces on fluid migration. The first would be the hydrostatic head or downward force caused by the weight of the fluid column. This can be described as psi/foot of depth by taking the weight of one cubic foot of water and dividing it into 144 square inches one-foot high. A cubic foot of water weighs approximately 62.3 pounds, dividing by 144 square inches, we find that a column of water one-foot high exerts a downward pressure of 0.433 psi. Therefore a column of water 1000 feet deep would provide a downward force of 433 psi. If fluid were migrating upward, it would have to have a driving force in excess of 433 psi. This example used fresh water having a density of 8.33 lbs/gal. Rogers, (1963) prepared a graph (Figure 1) showing the relationship of hydrostatic pressure with depth for mud fluids of various densities ranging from 8.33 to 20 ppg.

Drilling fluid density is the only short-term property of a drilling mud which can prevent reservoir fluids from entering the wellbore. Fluid density is also the only mud property that can prevent formation collapse due to tectonic stresses or unconsolidation of the formation. In general, as indicated by Mitchell, Goodman, and Wood (1987), and by Gray and Darley (1980, p. 355) drillers commonly use a mud weight that will overbalance the highest formation fluid pressure encountered by a "safe margin" which will commonly range between 200 to 400 psi. The overbalanced mud weight is used to provide a conservative margin of error to prevent fluid flow into the wellbore.

Along the Gulf Coast, increased mud weight is also used to prevent the unconsolidated formation from sloughing into the well. As an example, a well recently drilled in the Upper Texas Coast under the supervision of

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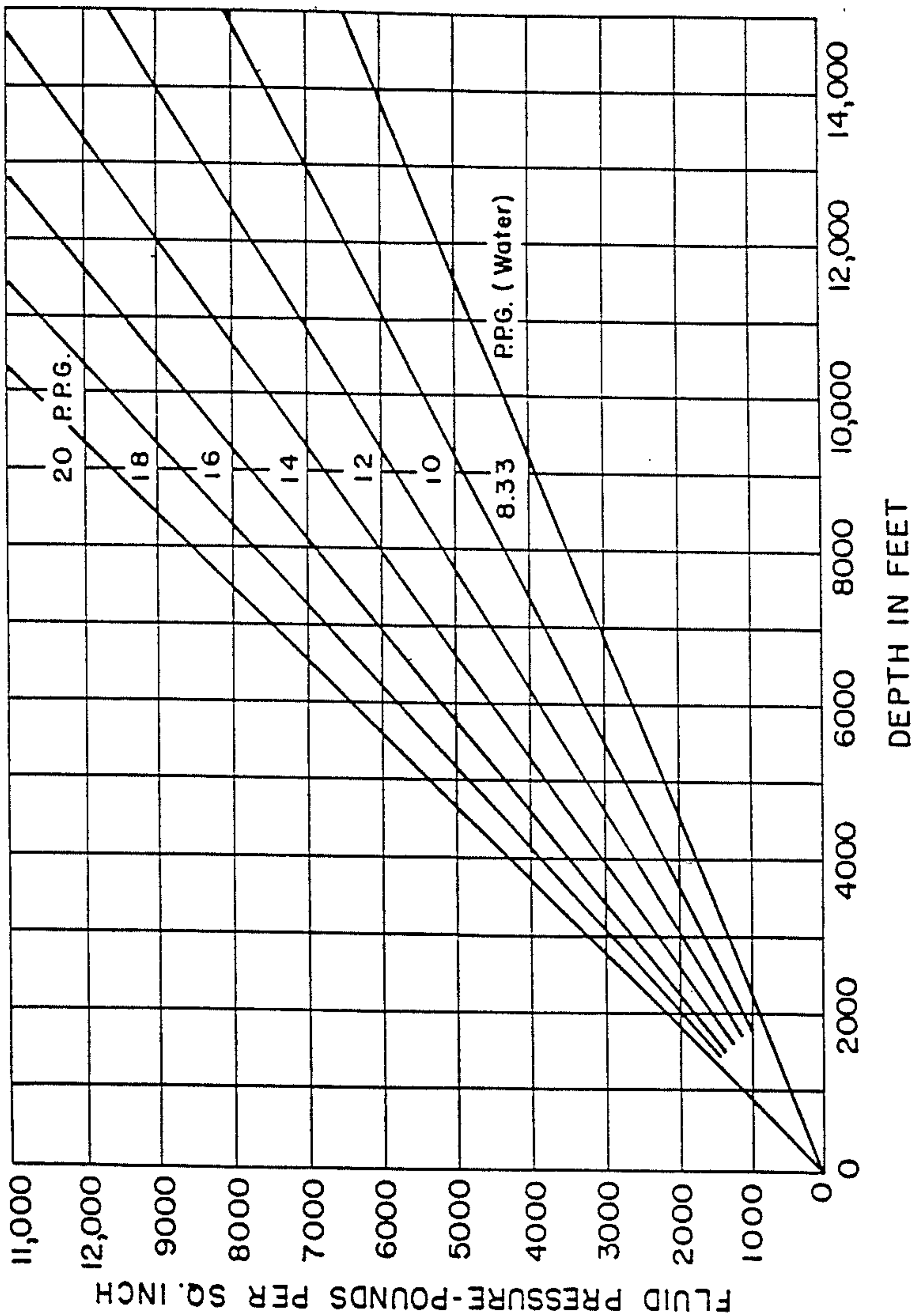

Hydrostatic pressure of mud fluids.

FIGURE 1

Envirocorp required an 8.8 pound/gallon (lb/gal) mud to balance the formation fluid pressure during a gravel pack operation. However, the mud weight needed to be increased above 9.4 lb/gal to prevent the sides of the open hole from sloughing into the wellbore.

The above example, and the data provided by Mitchell, Goodman, and Wood (1987) demonstrates that the original mud column will commonly overbalance the highest static reservoir pressure encountered by 100 psi or more. The average overbalance pressure indicated by the data provided by the above authors is approximately 350 psi. One should remember that this overbalance pressure or "safe margin" will eventually press the mud filtrate into the shale formations and increase the shale hydration force. This will increase the probability of wellbore closures across shale sections.

Dissolved and suspended solids are the reason mud fluids have densities higher than their base fluid. For example, the density of water can be increased from 8.33 ppg to 10.0 ppg by making a solution of common salt (sodium chloride). Likewise, mixtures of bentonite clay and barite (barium sulfate) can attain weights in excess of 20 ppg.

Mined barium sulfate, or simply barite, is the most common material used to increase the density of drilling mud. API barite (See Table 1) is specified to have a specific gravity of no less than 4.20. The average specific gravity for drilled solids is approximately 2.65.

TABLE 1
TYPICAL API BARITE PARTICLE SIZE DISTRIBUTION

VOLUME, %	SIZE PARTICLE, MICRONS
10	2.22
20	4.51
25	6.58
30	8.71
35	10.98
40	13.88
45	16.79
50	19.82
55	22.84
60	28.97
65	31.19
70	35.65
75	40.64
80	46.03
85	51.43
90	62.96

Gray, Darley, and Rogers, (1980) divided the particles suspended in mud into three groups according to size: (1) colloids, from about 0.005 to 1 micron (1 micron = 0.001 mm), which impart viscous and filtration properties; (2) silt and barite (sometimes called "inert solids"), 1 to 50 microns, which provide density; and, (3) sand, 50 to 420 microns, which generally does not significantly benefit the properties of the mud. NL Baroid, (1979) classified these same particles as follows: API sand, more than 74 microns, silt, 2-74 microns, barite 2-60 microns, and clays, less than 1 micron.

The relationship of particle size distribution to filtration rate is well known. Generally, muds with low filtration rates have a higher concentration of small particles than those with high filtration rates. Gates and Bowie, (1942) illustrated this relationship (Figure 2) by plotting the particle size distribution for both a low filter rate (0-20 ml/hr) mud and high filter rate (40-75 ml/hr) mud.

This relationship indicates that muds having low filtration rates would be more stable. The suspended solids would have less tendency to settle and therefore the density or mud weight would generally remain constant throughout the mud column in a wellbore or annular space.

The ability for the mud column to support its mixture of suspended solids is extremely important to maintain the integrity of the columns hydrostatic head. Pearce, (1989) showed that less than 3% of the barite has any potential to settle out of the mixture if minimal gel strengths (5.616/100 ft^2) are present.

The second opposing force that would act as a deterrent to fluid migration along a wellbore would be present only if the fluid filling the wellbore had gel strength. Most drilling fluids contain this characteristic. Collins and Kortum (1988) suggest gel strength contributes 40% of the hole-sealing pressure of the mud in the hole.

One of the primary functions of the drilling mud is the removal of drilled cuttings from the wellbore. The mud carries the cuttings from beneath the bit, transports them up the wellbore/drillpipe annulus and releases them at the surface. Since normal drilling operations require that mud circulation be stopped periodically to add another joint of drillpipe, the mud must have a property which acts to suspend the drilled cuttings in the static mud column. This property is known as gel strength. Gel strength is time dependent and increases as the mud column remains quiescent. Most drilling fluids are thixotropic and develop a gel structure like "Jello" when allowed to stand quiescent but become fluid when disturbed.

To determine the combined effect of both hydrostatic head and gel strength acting as a deterrent to fluid migration along a mud filled wellbore or annulus, we must first identify the forces acting on a wellbore and/or annulus existing in a static state. Figure 3 represents a vertical force diagram of a static mud column in an abandoned well that contains no uncemented casing. Figure 4 represents the forces acting on the static mud column in the annulus between the casing and open hole above the cemented interval.

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The equation for the force balance in Figure 3 takes the following form,

$$w + GS_w 2\pi r_w h = Pf\,\pi r^2_w - P_t \pi r^2_w \qquad (1)$$

where

$$w = r^2_{w\rho} h$$

and

- w = weight of mud column
- GS_w = gel strength of mud column acting on circumference area of wellbore
- P_t = pressure at top of well
- P_f = pressure at formation being contained
- r_w = radius of wellbore
- h = height of mud column in wellbore
- ρ = density of mud

Simplifying the force balance and adjusting for standard units, we obtain the following pressure equation,

$$P_f = P_t + 0.052\rho h + 3.33 \times 10^{-3 GSh/D} \qquad (2)$$

where

- P_f = pressure at the contained formation in psi
- P_t = pressure at the top of well in psi
- ρ = density of mud in lb/gal
- h = height of mud column in feet
- GS = gel strength in lb/100 ft^2
- D = diameter of wellbore in inches

The force balance equation for Figure 4 takes the form

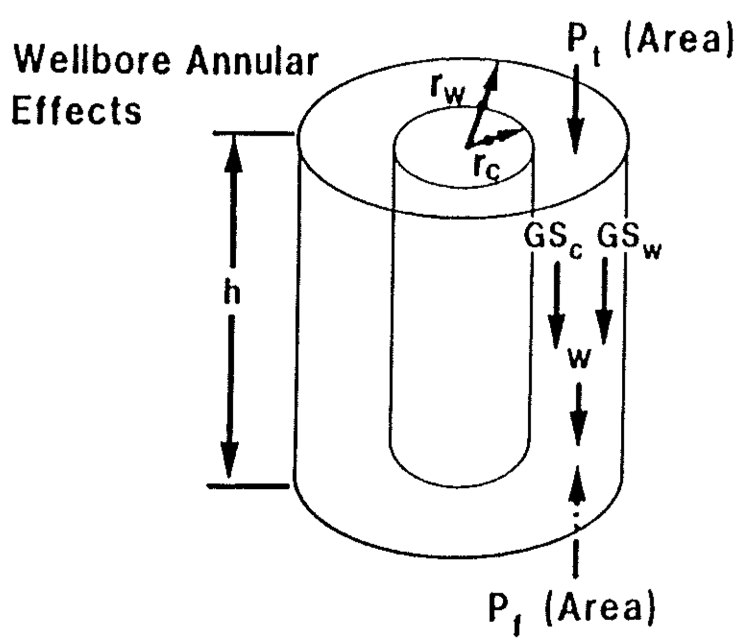
$$w + GS_c(2\pi r_c h) + GS_w(2\pi r_w h) = \qquad (3)$$

$$P_f \pi (r^2_w - r^2_c) - P_t \pi (r^2_w - r^2_c)$$

where

$$w = \rho h\,(r^2_w - r^2_c)$$

ANNULUS STATIC MUD COLUMN FORCE BALANCE DIAGRAM



P_t (Area) = Pressure at the Top of Well = $P_t \pi (r_w^z - r_c^2)$

W = Weight of Fluid Column = $\rho h \pi (r_w^2 - r_c^2)$

GS_w = Gel Stength of Mud Acting on Circumference Area of Well Bore = $GS_w (2 \pi r_w h)$

GS_c = Gel Stength of Mud Acting on Circumference Area Casing = $GS_c (2 \pi r_c h)$

P_f (Area) = Pressure at the Formation Being Contained = $P_f \pi (r_w^2 - r_c^2)$

Forces From Mud Column = Sum of Pressure Forces

$$w + GS_s (2 \pi r_c h) + GS_w (2 \pi r_w h) = P_f \pi (r_w^2 - r_c^2) - P_t \pi (r_w^2 - r_c^2)$$

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FIGURE 4

and

w = weight of mud column in annulus

GS = gel strength of mud acting on circumference area of both the wellbore (GS_W) and casing wall (GS_C) and $GS_W = GS_C$

P_t = pressure at top of well

P_f = pressure at formation being contained

r_W = radius of wellbore

r_C = outside radius casing

h = height of mud column in annulus

ρ = density of mud

Simplifying the force balance and adjusting for standard units, we obtain the following pressure equation,

$$P_f = P_t + 0.052\rho h + \frac{3.33 \times 10\text{-}3^{GSh}}{D_W - D_C} \tag{4}$$

where:

P_f = pressure at the contained formation in psi

P_t = pressure at top of well in psi

ρ = density of mud in lb/gal

h = height of mud column in feet

GS = gel strength of mud in lb/100 ft2

D_W = diameter of wellbore in lb/100 ft^2

D_C = outside diameter of casing in inches

It is generally recommended that the values required to calculate the flow resistance of a mud filled wellbore or annular space be obtained from the well records. The physical configuration of the well can usually be obtained from many sources. These include but are not limited to state libraries, geological surveys and other public information sources. The density of the drilling fluid used to drill the well is normally recorded on the geophysical log heading. The gel strength values may be more difficult to obtain. Mud properties are generally run while conditioning the mud to run casing and cement. These values are normally determined by the drilling fluid supplier or service company and are reported on standardized forms. These data are normally available from the owner/operator's well files or the service company. Also, it is frequently not necessary to find the well records of each well since wells drilled adjacent to each other frequently use the same or similar mud systems. Historical records are also a good source of obtaining conservative values for gel strengths of specific types of drilling fluid systems.

Since the gel strength of different types of mud systems varies, it is difficult to determine the exact gel strength of the mud in a particular wellbore. Collins and Kortum (1988) suggest that the configuration of the wellbore can increase the apparent gel strength six times the observed values. A review of the gel strength characteristics of various types of muds was made to evaluate the factors that effect the gel strength structure. No consideration was given to the hole configuration. The aim of this review was to provide sufficient information to determine the minimum gel strength structure that could be anticipated for any combination of formation, wellbore, and mud type.

Thixotropy is the property, exhibited by certain gels, of liquefying when stirred or shaken and then returning to their gelled state when allowed to stand quiescent. This property in drilling fluids is the result of various clay minerals being used as additives in drilling fluids. Generally, clay particles fall into the colloidal particle range. Colloidal systems used in drilling fluids include solids dispersed in liquids and liquid droplets dispersed in other liquids. These highly active colloidal particles comprise a small percentage of the total solids in drilling muds but act to form the dispersed gel forming phase of the mud that provides the desired viscosity, thixotropy, and wall cake properties.

Thixotropy is essentially a surface phenomenon which is characterized by gel strength measurements. The gel strength indicates the attractive forces between particles under static conditions. The strength of the gel structure which forms under static conditions is a function of the amount and type of clays in suspension, time, temperature, pressure, Ph, and the chemical treating agents used in the mud. Those factors which promote, the edge-to-edge and face-to-edge association of the clay particles defined as flocculation increase the gelling tendency of the mud and those factors which prevent the association decrease the gelling tendency.

Due to their size, colloidal particles remain indefinitely in suspension. When suspended in pure water the clay particles will not flocculate. When flocculation occurs the particles form clumps or flocs. These loosely associated flocs contain large volumes of water. If the clay concentration in the mud is sufficiently high, flocculation will cause formation of a continuous gel structure instead of individual flocs.

Gel strength is measured by a multispeed direct indicating viscometer by slowly turning the driving shaft by hand and observing the maximum deflections before the gel structure breaks. The gel strength is normally measured after quiescent periods of 10 seconds (initial gel strength) and 10 minutes. The measurements are taken at surface conditions of standard temperature and pressure. To determine the gel strength of the static mud column in an abandoned well it is necessary to determine the gel strength of the mud under the influence of borehole conditions. The initial and 10 minute gel strengths bear no direct relation to the ultimate gel strength of the mud at borehole conditions. To determine the ultimate gel strength of a mud it is necessary to discuss the factors which act to influence the initial gel strength at borehole conditions.

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Once the drilling operation is completed and the well is abandoned the mud is subjected to conditions vastly different from those encountered at the surface. In the range of formation depths utilized for disposal of industrial wastes the temperature would be expected to range from 80 to 300°F, the pressure from 1500 to 5000 psi and time from days to several years. Several studies have been conducted to determine the impact of conditions. The information obtained from this research should provide a means of determining a reasonable minimum gel strength value for the abandoned wells which exist in the range of formations described above.

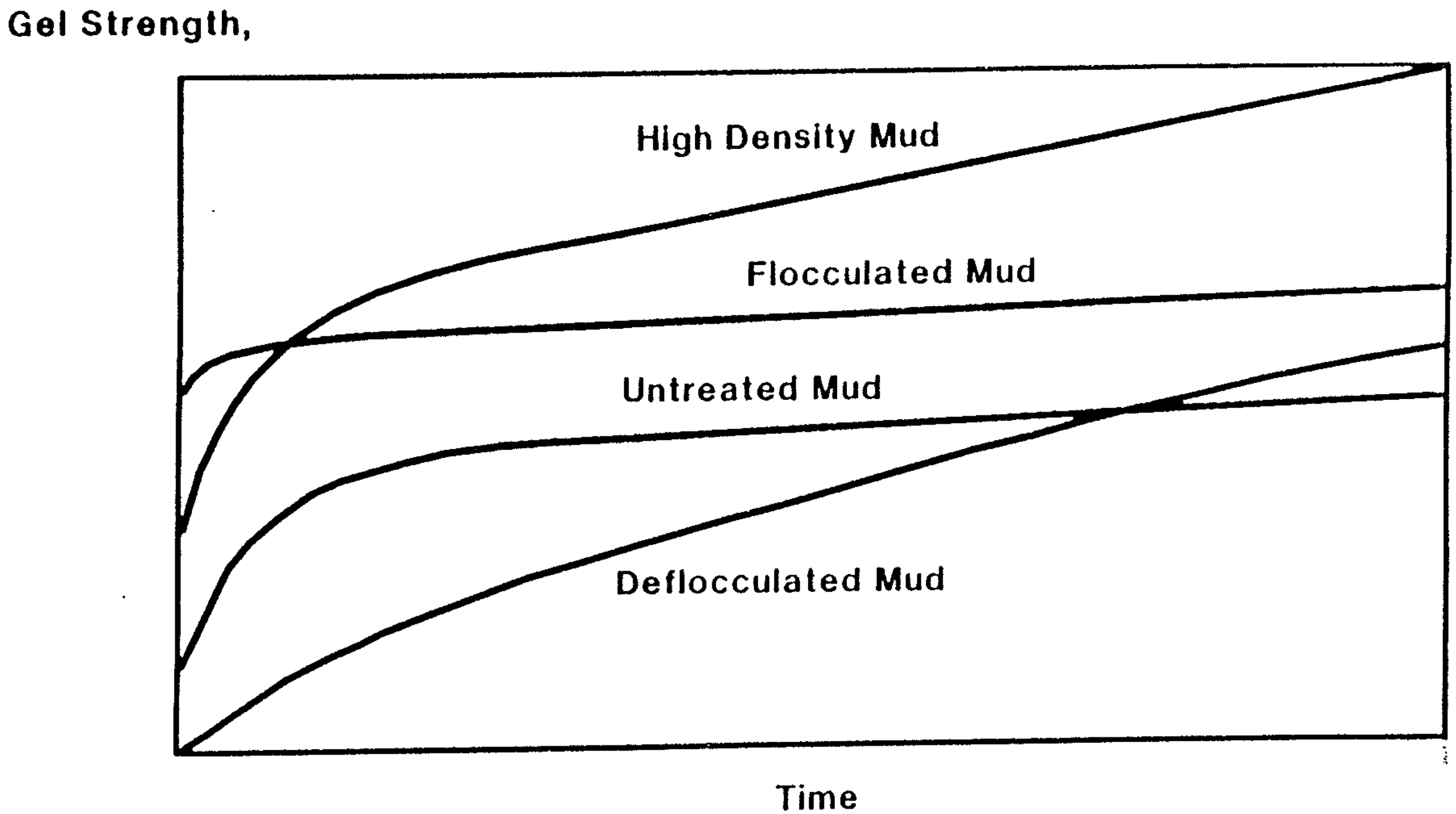
It is observed that common used water-base muds develop high gel strengths after prolonged periods of quiescence. The relationship between gel strength and time varies widely from mud to mud, depending on the composition, degree of flocculation, temperature, pH, solids, and pressure. Figure 5 (Gray, Darley, and Rogers, 1980) indicates the increase in gel strength with time for various mud types and reveals that there is no well established means of predicting long-term gel strengths with time. It is noted in all cases that the gel strength is observed to increase.

Annis (1976) noted that when a bentonite mud is quiescent, the gelling process depends on both temperature and time. Annis compared the effect of temperature on the initial and 30 minute gel strength of an 18 ppb bentonite suspension. Figure 6 indicates that the 30 minute gel strength of the 18 ppb suspension is at any temperature approximately six times the initial gel strength. The dependence of gel strength on time at different temperatures, as noted by Annis, is shown in Figure 7. Based on these and other tests of up to 18 hours Annis concluded that there is a strong indication that gel strength increases indefinitely with time.

The above works indicate that the ultimate gel strength of water-base muds is considerably higher than the values recorded for the initial and 10 minute gel strength. Although there is no direct relationship between gel strength and time, it is possible, based on available information, to conclude that the ultimate gel strength of a mud will be several times larger than the initial or 10 minute gel strength of the mud. In reference to the work by Garrison (1939), it is possible to consider the ultimate gel strength of a treated mud to be equivalent to that of a similar mud that was not treated, since the effect of the thinner is to decrease the rate of gelling and not the ultimate gel strength obtained.

In addition to time, temperature can have a major effect on the gel strength of water-based drilling fluids. Stini-Vasan (1957) studied the effects of temperature on the gel strength of several water-based drilling muds. In most of the cases investigated by Stini-Vasan it was noted that the gel strength leveled off after 160°F. The emulsion and lime treated muds showed no change in gel strength with increase of temperature. It was found that each mud had its own characteristic curve and no quantitative interpretation was possible. The work of Weintritt and Hughes (1965) on Table 2, indicates that emulsion Mud G experienced no change in gel strength in going from 75 to 180°F over a wide range of times. It is noted that although the gel strength did not vary with temperature, it went from an initial gel strength of 0 to a gel strength of 25 after 16 hours. These values are displayed graphically on Figure 8.

INCREASE IN GEL STRENGTH OF VARIOUS MUD TYPES WITH TIME



(From Gray, Darley, and Rogers)

Ken E. Davis Associates

FIGURE 5

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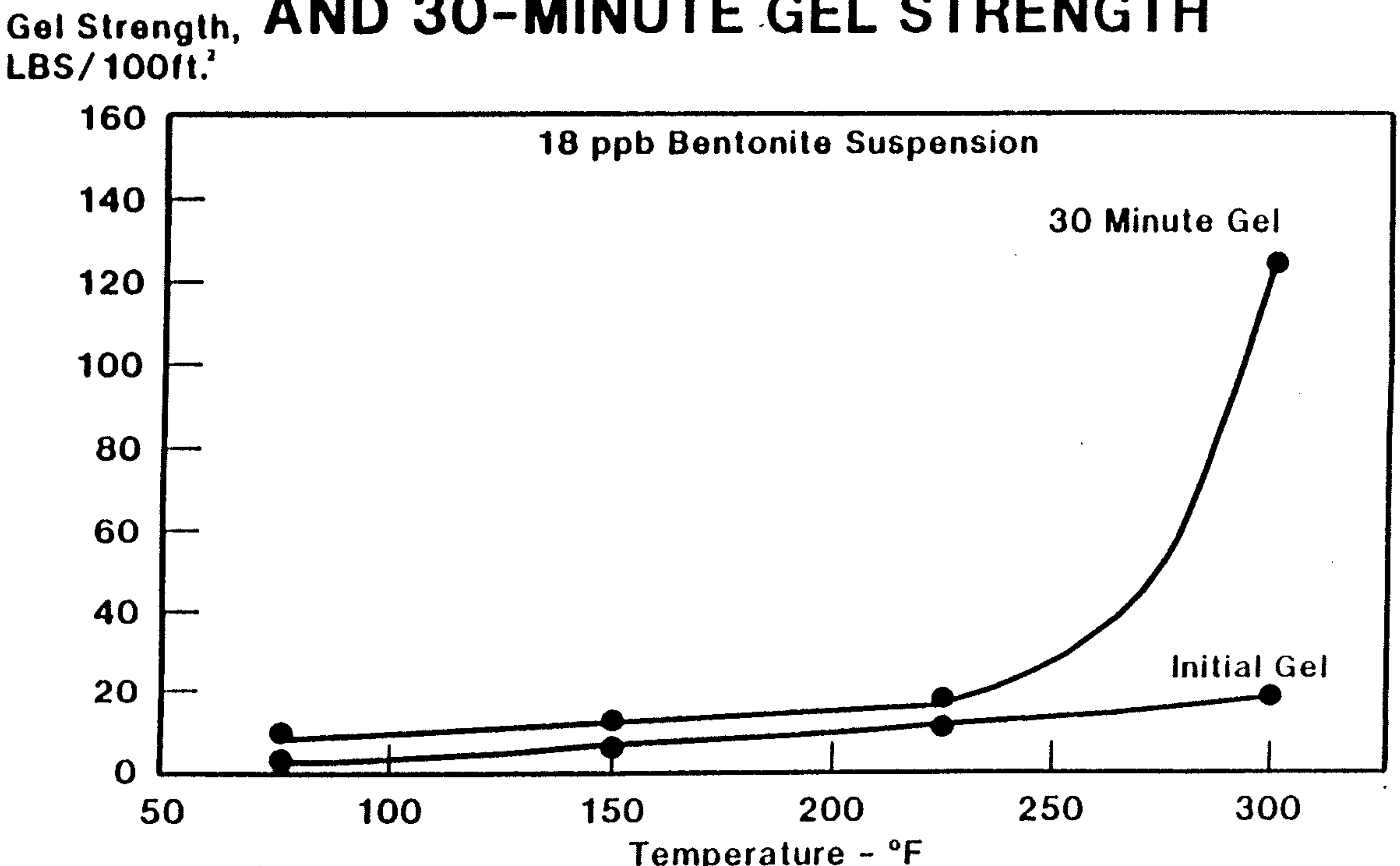
EFFECT OF TEMPERATURE ON INITIAL AND 30-MINUTE GEL STRENGTH

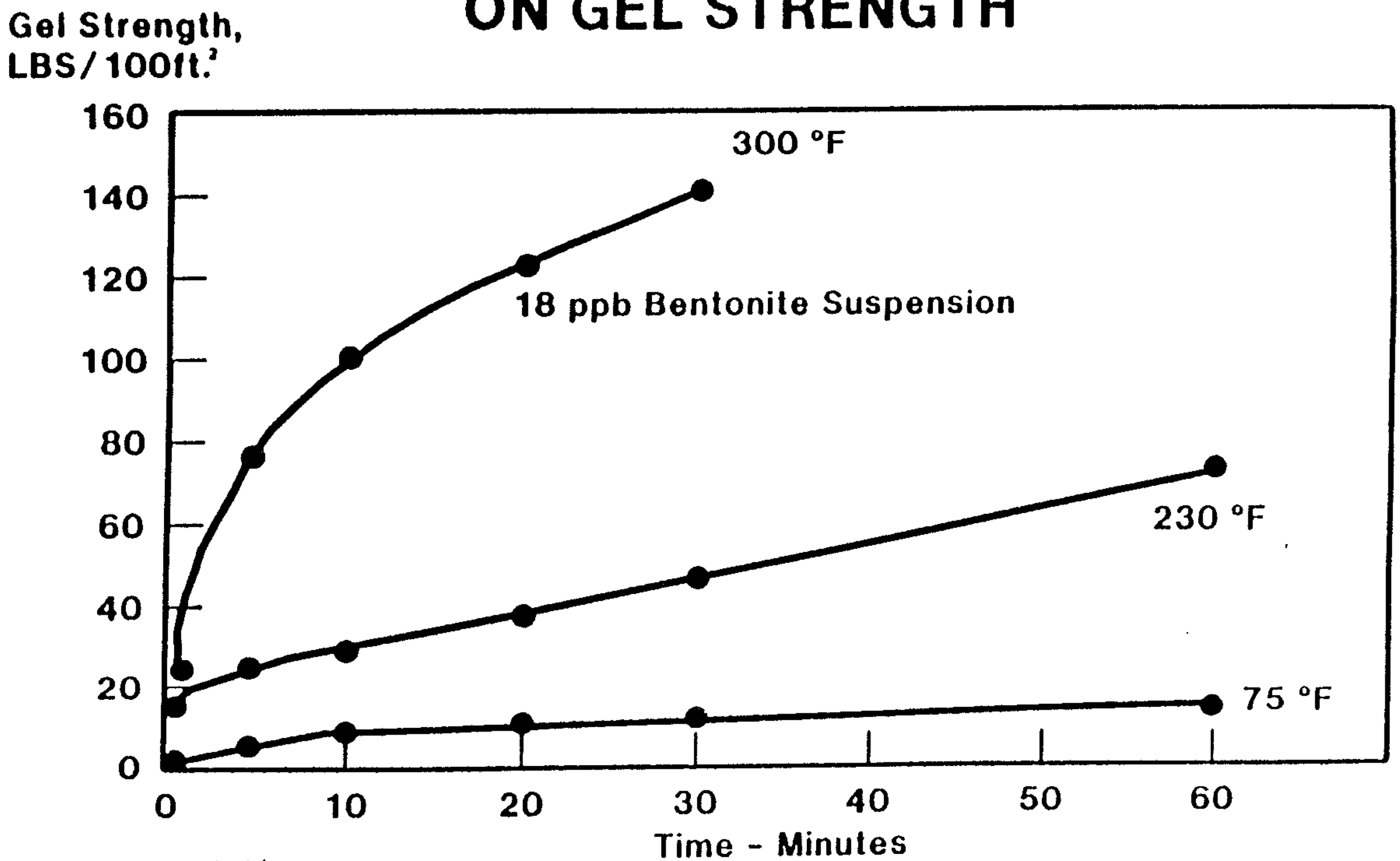


(From Annis 1976)

Ken E. Davis Associates

FIGURE 6

EFFECTS OF TIME AND TEMPERATURE ON GEL STRENGTH



(From Annis 1976)

Ken E. Davis Associates

FIGURE 7

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TABLE 2

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COMPARISON OF MUD PROPERTIES WITH PROGRESSIVE GEL-STRENGTH TESTS
GYP-FERROCHROME LIGNOSULFONATE EMULSION MUDS

	SAMPLE			
	Mud E	Mud F	Mud G	
			No Treatment	3 lb/bbl
Weight, unstirred, lb/gal	11.0	10.7	10.6	
Weight, stirred, lb/gal	11.0	10.3	10.7	
Plastic Viscosity, cp	14	23	16	15
Yield Point, lb/100 sq ft	3	6	2	1
10-sec gel, lb/100 sq ft	1	2	1	0
10-min gel, lb/100 sq ft	8	8	7	3
API filtrate,	6.2	3.3	5.2	2.9
pH	10.9	10.6	10.5	10.4
Composition:				
Water % by vol	76	63	75	
Oil, % by vol	5	11	9	
Solids, % by vol	19	16	16	
Solids, % by vol	39	36	37	
Solids, SG	2.7	2.9	3.0	
Filtrate Ion Analysis:				
Chlorides, ppm	3500	400	3000	
Sulfates, epm	250	300	130	
Carbonate, epm	24	28	12	
Bicarbonate, epm	12	160	12	
Calcium, epm	44	52	44	

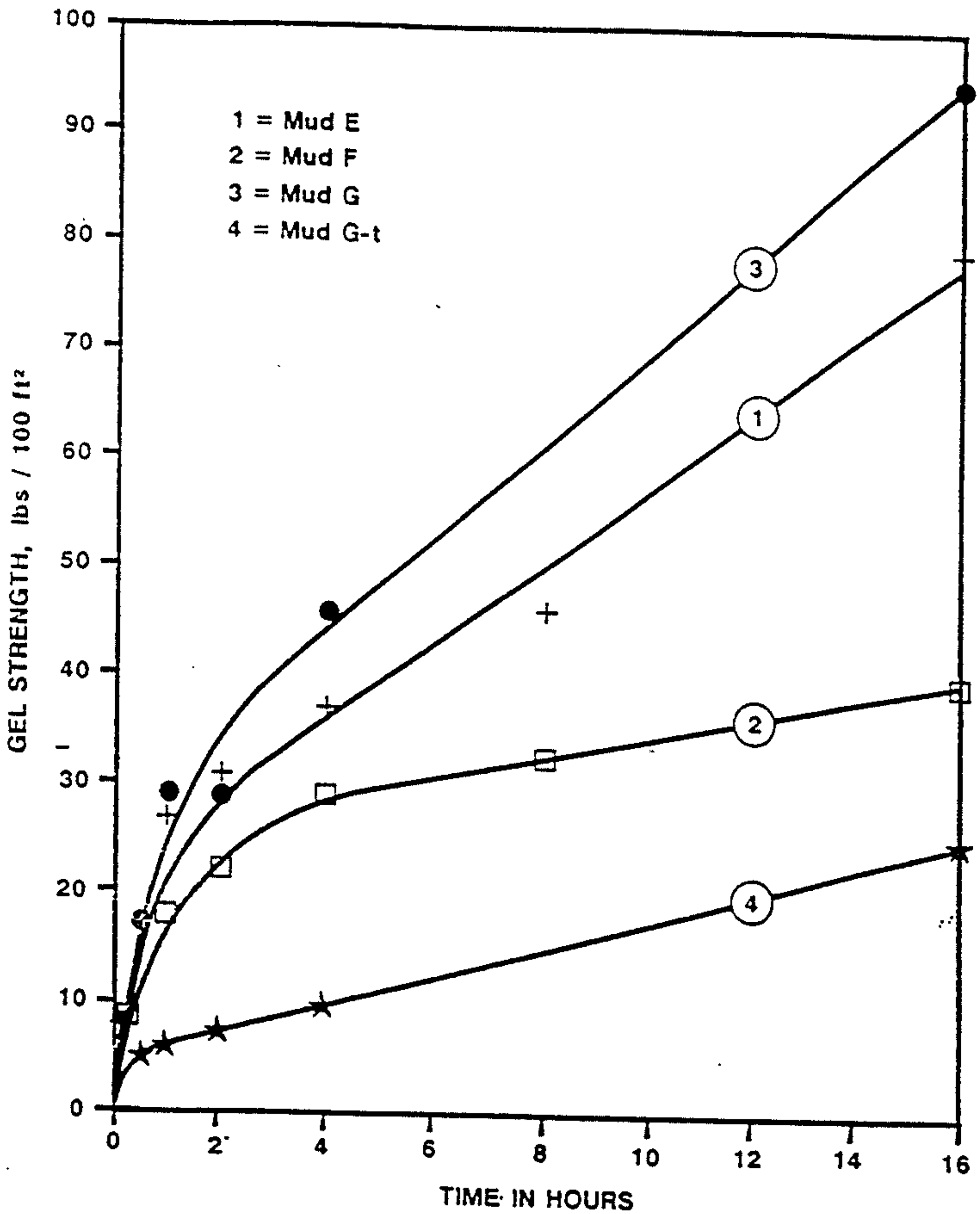
Progressive Gel Strengths
lb/100 sq ft

Temperature (°F) / Time	Mud E 75°	Mud E 180°	Mud F 75°	Mud F 180°	Mud G No Treatment 75°	Mud G No Treatment 180°	Mud G 3 lb/bbl 75°	Mud G 3 lb/bbl 180°
0 minutes	1	1	2	2	1	1	0	0
3 minutes	2	3	2	5	3	8	1	1
10 minutes	8	18	8	12	7	26	3	3
30 minutes	15	40	11	18	17	58	5	5
60 minutes	27	90	18	16	29	91	6	6
2 hours	31	145	22	22	29	104	7	7
4 hours	37	190	29	42	46	172	10	10
8 hours	46	190	33	42				
16 hours	80	320	40	57	95	320	25	25

(From Weintritt and Hughes, 1965)

FIGURE 8
EFFECT OF TIME ON
GEL STRENGTH OF THREE
FIELD MUDS AT 75°F
(FROM WEINTRITT AND HUGHES, 1965)

SEE TABLE 2



Annis (1976) was capable of investigating the gel strength up to temperatures of 350°F. Stini-Vasan (1957) observed that the gel strengths leveled off after 160°F but Annis noted that at higher temperatures a rapid increase in the gel strength was noted. Thus increased temperature, like increased bentonite concentration promotes flocculation. The temperature at which a rapid increase in gel strength occurs, represents the onset of flocculation. Therefore it is possible to expect the gel strength to increase significantly at some elevated temperature. However, Hiller (1963) noted that some clay suspensions display a decrease in gel strength with increased pressure, especially at high temperatures. He noted that the gel strength was reduced to 1/4 of its original value for a pressure increase form 300 to 8000 psi at a temperature of 302°F.

Although no direct means exists to determine the ultimate gel strength of a drilling mud at borehole conditions, it is possible to safely say that the gel strength developed in the borehole is considerably greater than that indicated by the initial and 10 minute gel strengths recorded for a given mud. These conclusions are substantially supported with subsequent lab tests run on the Fann 70 Consistometer under actual well conditions. Futher confirmation was obtained from the evaluation of a mud system taken from an abandoned well after 29 years. These data are presented in section 6.0.

Pearce (1989) made an estimation of the minimum gel strength required to suspend solid weighting material indefinitely in the drilling fluid. He said the gel strength required to prevent a spherical solid of radius r from settling can be estimated using the following equation:

$$(\rho_b - \rho_f)\, g\, (4\pi r^3/3) = G\, (\pi r^2) \qquad (5)$$

or

$$G = 4\, (\rho_b - \rho_f)\, gr/3$$

where:

P_b = density of barite (4.2 g/cm^3)

P_f = density of water (1.0 g/cm^3)

r = radius of barite particle (cm)

G = Gel Strength (dynes/cm^2)

If the maximum radius of barite is assumed to be 0.00635 cm (0.0025 inches) or larger, the largest 3% of the solids allowed in standard API barite (Gray, Darley, and Rogers, 1980, p. 533), the gel strength is calculated to be 26.6 dynes/cm^2 or 5.6 lbs/100 ft^2. This calculation shows that only minimal gel strength is required to keep over 97% of the barite weighting material suspended. Since barite density is 4.2 g/cm^3, bentonite density is 2.6 g/cm^3, and the density of sandstone is 2.65 g/cm^3, it is clear that the gel strength in the field muds will reach a value in excess of the gel strength required to maintain mud density in less than an hour. Only the larger drilled solids and the largest 3% of the barite have any potential for settling during this time period.

As indicated by the above calculation, a gel strength of 5.6 lbs/100 ft^2 is adequate to suspend the largest 3% of the barite particles in the mud. It should be noted that the development of sufficient gel strength to prevent barite from settling does not mean that drilled solids do not settle from the mud. An examination of the settled solids, as discussed later in this report, shows that the settled solids, are composed mainly of drilled solids that are significantly larger than the barite used for weight material. During the first twenty to thirty minutes of quiescence, these particles are usually large enough to settle to the bottom. In fact, the largest barite particles will also settle. However, the loss of these materials will not alter the mud weight significantly, since the large drill solids are removed at the surface, and are not included in the measured mud density. Furthermore, the largest barite particles with any potential to settle constitute less than 3% of the total barite in the mud. Therefore, the loss of these larger barite particles will not alter the mud density by more than 0.3%.

As an example consider a 10 lb/gal, mud system with the following formulation:

Component	Specific Gravity	Concentration (lbs/bbl)	Volume Percent
Bentonite	2.6	18	1.84
Barite	4.2	77	5.26
H_2O	1.0	325	92.9

A loss of 3% barite would lead to the following mud system:

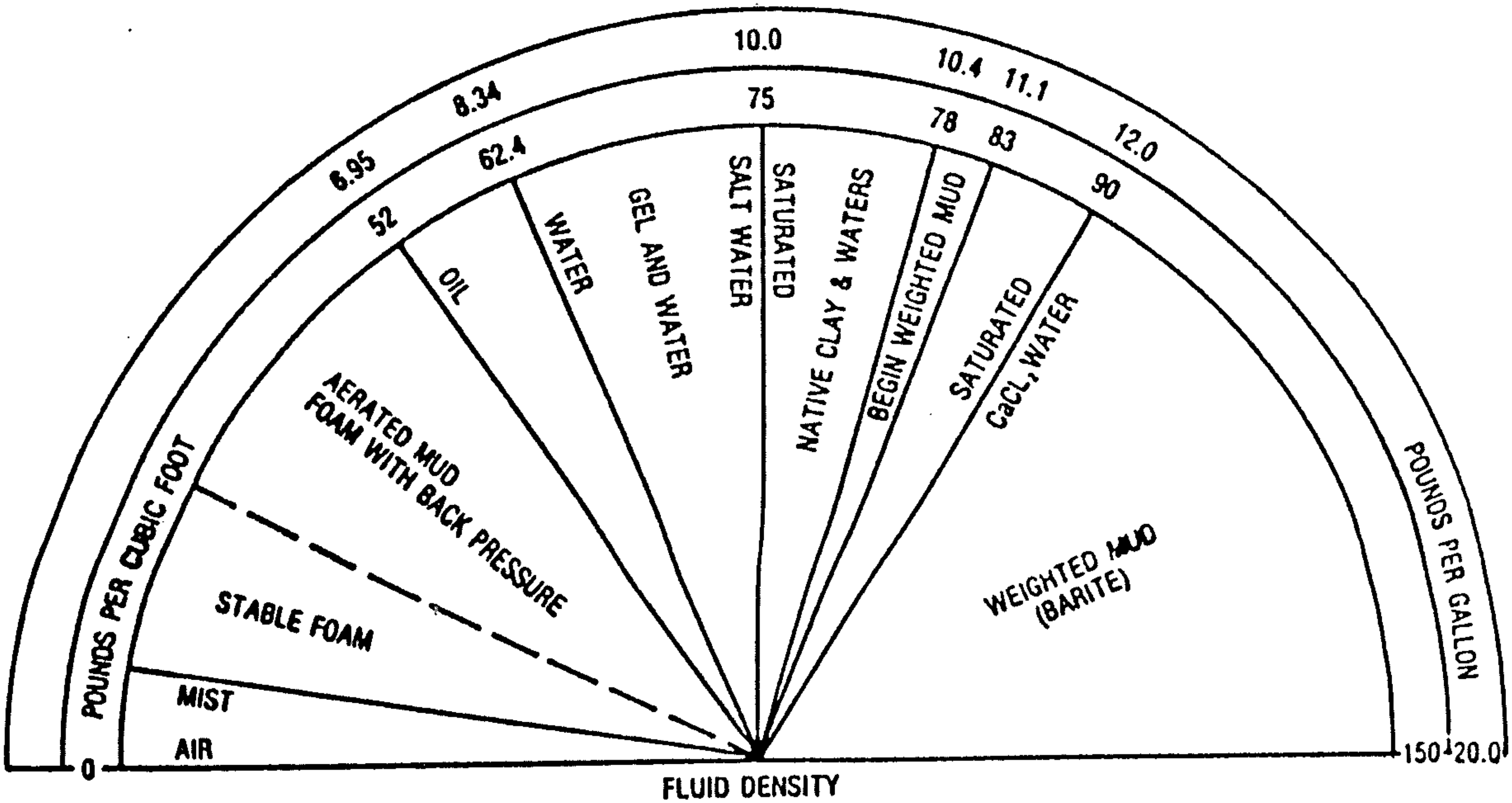
Component	Specific Gravity	Concentration (lbs/bbl)	Volume Percent
Bentonite	2.6	18.1	1.84
Barite	4.2	74.1	5.08
H_2O	1.0	326	93.1

The weight of this second systems is 9.97 lb/gal, which reflects a total reduction in mud weight of 0.3% or 4 psi per 1000 feet of mud column. This number is a conservative value since less than 3% of the barite is expected to settle, the radius of the largest particles has been over estimated, and the minimum gel strength required to prevent solids from settling will be reached in less than thirty minutes.

5.0 REQUIRED DRILLING MUD WEIGHTS

Hutchison and Anderson, (1974) developed the fan chart shown in Figure 9 to illustrate the range of densities that are available for use. The maximum mud weights that may be required in oil well drilling are determined by the pressure gradients (psi/ft of depth) of the formation fluids. The pressure on the pore fluids at any given depth very seldom exceeds the pressure exerted by the weight of the earth above the depth in question, i.e., the overburden pressure. Eaton, (1969) illustrated this phenomenon by plotting the overburden stress gradient against depth for Gulf Coast formations. This plot showed the gradient at 5000 feet is approximately 0.91

FAN CHART SHOWING DENSITY RANGE OF DRILLING FLUIDS



Drilling fluids can be prepared ranging in density from that of air to 2½ times that of water. (FROM HUTCHISON AND ANDERSON , 1974)

FIGURE 9

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psi/ft. This gradient would be equivalent to a mud weight of 17.5 lb/gal It would therefore be expected that the highest pore fluid pressure that could be generated by the weight of the overburden at 5000 feet would be contained by 17.5 lb/gal mud. However, it is well known that the fracture gradient for formations above 10,000 feet along the Gulf Coast rarely exceed 0.80 psi/ft and that the normal pressure gradient is approximately 0.467 psi/ft. The equivalent mud density for the normal gradient would be 8.99 lb/gal. Therefore, the mud weight on wells drilled to less than 10,000 feet along the Gulf Coast rarely exceed 12.0 lb/gal.

There is some variation in the densities required for certain drilling areas. Pressures in excess or overburden are sometimes encountered. In these cases, the pore fluids are being partially contained by the strength of the rock. The highest pore pressure found in the United States thus far was reported by Parker, (1973) as 1.06 psi/ft.

6.0 RELEVANT LABORATORY DATA

Laboratory testing technique and equipment have been developed that can simulate reservoir and/or well conditions. The equipment used for these tests can accelerate the natural effects of time, temperature, and pressure. The most common of these testing techniques use the Ultrasonic Cement Analyzer (UCA) autoclave developed by Halliburton and the Fann 70 Consistometer. Cheveron's Drilling Fluid Services Laboratory has performed laboratory tests on muds using this equipment. The work was done to simulate the condition of mud left in the wellbore and/or annular space between the wellbore and casing, above the cement column.

A mud was formulated using mud additives similar to those used in actual wells located in Mississippi. This mud was subjected to filtration losses for four hours in a cell at 175° F and 500 psi pressure to simulate bottom-hole conditions. The mud slurry was then transferred to an UCA autoclave and aged for two weeks under bottom--hole temperatures and pressures. The results of this test indicated the mud developed significant compressive strength during the testing period and could only be described as a mud plug. Due to the nature of this plug it would require substantial pressure to move the plug and/or energy to restore the plug to a moveable fluid. The gel strength was too high to measure with available equipment, however, the test clearly demonstrated the mud developed some structural integrity during a relatively short test period.

Subsequently, the aforementioned tests were repeated using an NL Baroid Fann 70 Viscometer (The same type of equipment as the consistometer mentioned above.). This "state-of-the-art" instrument is capable of measuring the viscosity and gel structure of muds under downhole conditions. During these tests, a lime-treated fresh water mud, similar to the mud used in the Mississippi wells was formulated. The mud composition and gel strengths are shown on Table 3.

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FANN 70 VISCOMETER GEL STRENGTH MEASUREMENTS ON A LABORATORY PREPARED LIME-QUEBRACHO MUD

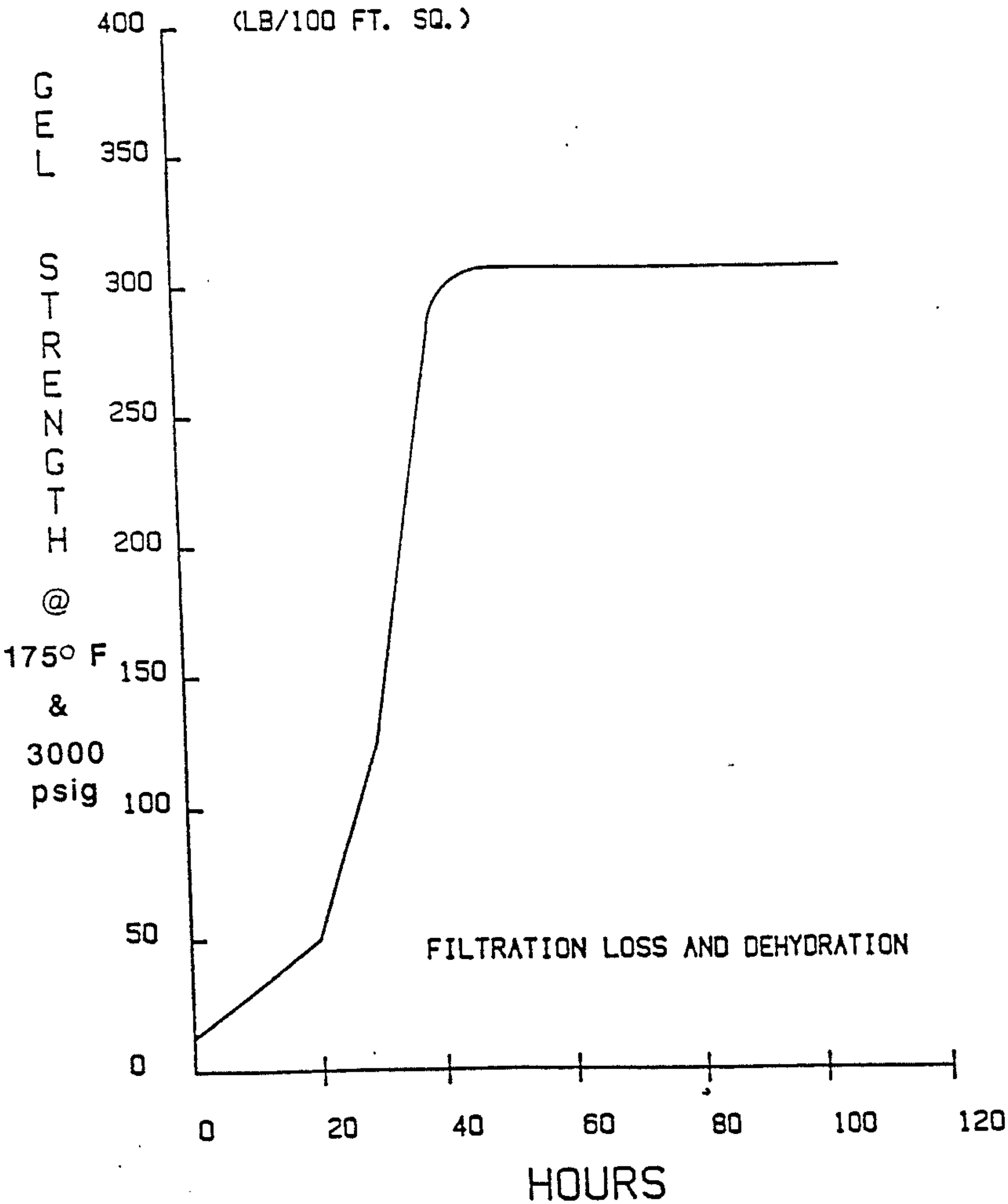

FIGURE 10

TABLE 4

PROPERTIES OF RECOVERED MUD FROM NORA SCHULZE NO. 2 0113265

SAMPLE NO.	DEPTH (ft)	MUD WEIGHT (lb/gal)	SHEAR STRENGTH (lbs/100 ft^2)	GEL STRENGTH (lbs/100 ft^2)
1	---	---	---	---
2	60	12.0	540	304
3	111	10.9	230	296
4	174	11.0	310	295
5	207	11.2	190	>320
6	240	10.9	170	284
7	273	10.7	180	237
8	306	10.9	285	254
9	339	10.5	190	288
10	372	10.9	245	272
11	405	11.1	280	220
12	438	11.1	255	222
13	471	11.1	301	292
14	504	11.1	300	230
15	537	11.0	490	292
16	570	11.0	225	217
17	603	10.9	240	236
18	636	11.3	650	>320
19	609	11.4	750	---
20	702	11.5	2100	---
21	719	10.9	4700	---
22	725	10.7	890	---
23	731	11.3	7000	---

Average mud weight using all samples - 11.1

Shear strength averaged for samples 3 through 17 - 260 lbs/100 ft^2

Average gel strength of samples 3 through 17 - 267 lbs/100 ft^2

Using the Fann 70 Viscometer, gel strengths of the mud were obtained under downhole conditions. The gel strengths were measured at intervals of 10 minutes, 30 minutes, 1, 2, 4, 8, 16, and 24 hours. During this period of time, the gel strength increased from 33 to 49 lbs/100 ft^2. A second test was performed using a mud with similar composition. The mud was first subjected to downhole conditions, such as filtration loss and temperature destabilization. Next, the gel properties of the mud were measured using the Fann 70 Viscometer at intervals up to 96 hours. In this test, the gel strengths increased to over 300 lbs/100 ft^2. Figure 10 is a graphic illustration of both these tests.

TABLE 3
RESULTS OF FANN 70 VISCOMETER TESTS
ON LABORATORY PREPARED LIME-QUEBRACHO MUD

MUD COMPOSITION

Water	.95 bbls
Aquagel	20 ppb
Rev Dust	60 ppb
Quebracho	3 ppb
Lime	2.0 ppb
Barite	36.8 ppb

Gel Strength at 175° F and 3,000 psig

Time	Pounds/100 Ft^2
10 minutes	33
30 minutes	33
1 hour	35
2 hours	43
4 hours	53
8 hours	45
16 hours	49
24 hours	50
48 hours	309
96 hours	310

Gray, Neznayko, and Gilkerson (1952) reported the thickening mechanism in lime-treated muds was the result of caustic and lime reacting with the clay minerals and silica to form hydrated alumino-silicates and silicates. These products resemble to some extent those involved in the setting of cement.

The first stage in the stiffening of limed muds is the development of a gel structure which is not significantly destroyed by mixing. Increased temperature causes a more ridged characteristic and as the cementing material concentration increases, all the liquid is retained in the solid mass. The quantity and composition of the suspended solids affect the rate of solidification and thus the strength of the gel structure. Although the concentration of organic thinner affects gel structure development, its effect becomes negligible because the organic thinner concentration appears to decrease as the mud sets.

E.L. Cook, in his response to the Gray, Neznayko, and Gilkerson report, suggests the reduction in the organic dispersants effectiveness was related to the loss of alkalinity. A certain degree of alkalinity is necessary to render organic dispersants soluble and effective in a mud. Therefore, the loss of alkalinity through precipitation, would cause a build-up in gel strength that is additive to the gelled structure occurring as a result of the reactions of clay and silica.

Increases in gel structure development have also been experienced in other types of mud containing both organic and inorganic thinners. The mechanism is very similar and usually related to hydrolysis or precipitation of the thinner or dispersant material.

7.0 CASE HISTORY ON LONG-TERM PROPERTIES OF WATER-BASE MUD

Pearce, (1989) tested samples of a mud taken from the Nora Schulze No. 2, an abandoned well located near Corpus Christi, Texas. This well was an exploratory oil and gas well that was abandoned in November, 1959.

The samples from the reentered well were obtained by forcing 2-7/8 inch tubing into the well with a special coring device attached to the driving edge of the tubing. From a depth of 120 feet to approximately 740 feet, the tubing had to be pushed into the wellbore, because the tubing weight alone did not apply sufficient force to move the tubing through the mud. At a depth of approximately 740 feet, the tubing could no longer be pushed into the wellbore. The tubing was pulled from the well at that point, and the mud in each joint was allowed to flow into a 5 gallon plastic pail which was quickly sealed. The bottom three pup joints, each 6 feet in length, were sealed for shipment back to the laboratory because the mud in these joints did not flow easily from the tubing. From ±740 feet to ±1100 feet, the mud could not be cored using the above techniques, and it was therefore necessary to drill and circulate the remaining drilling fluid out of the hole to check the cement plug placed at the bottom of the surface casing.

The data obtained from these samples are presented in Table 4. It shows the average density of the mud 11.1 lb/gal over the entire 740 foot section studied. The average gel strength was 267 lb/100 ft^2 and shear strength ranged from a low of 170 lb/100 ft^2 at 240 feet to a high of 7000 lb/100 ft^2 at 731 feet.

8.0 KNOWN FORMATION FACTORS AFFECTING MUD RESISTANCE TO VERTICAL MIGRATION

An abandoned wellbore and/or uncemented annular space is subjected to numerous forces that tend to close these potential pathways to fluid migration. Along the Gulf of Mexico coastline and in areas of similar sedimentary geology the shale or clay bearing formations tend to hydrate and swell across the wellbore opening or annular space. A similar closure can also result when the hydrostatic weight of the mud column is less than the formation overburden pressure and other factors. Gnirk, (1972) made calculations that wellbore pressures in excess of 5000 psi are required to inhibit wellbore closure.

Water wetting of shale can and usually does result in borehole blockage. The instability usually results primarily from overburden pressure, pore pressure, or tectonic stress. This is true regardless of whether the clay in the shale is largely expandable or non-expandable, or whether the shale in place is brittle or plastic. Moreover, shale dispersion, hole closure or sloughing from shale swelling are all attributable to adsorption of water by shale. Davis, (1986) gave examples of normally pressured stratum drilled at depths of 5000 and 10,000 feet along the Gulf Coast using mud weights of 9.5 pound per gallon (ppg). Under these relatively common conditions the pressure differential would be 125 and 250 psi respectively. These numbers represent the pressure that filtrate from the mud is being pressed into the formation by the overbalance of hydrostatic pressure over formation pore pressure. The matrix or shale hydration force created under those conditions will be 2530 and 5060 psi respectively.

9.0 CONCLUSIONS

In review the data presented within this report indicates the following expectations for the long-term properties of mud left in wellbore and in the casing/wellbore annulus.

1. The density of clay, water-based drilling fluids should not be altered by more than 0.3% over an extended period of time, since adequate gel strength will be developed to minimize solids settling.

2. The mud density will overbalance original formation pressure by at least 100 psi or more along the length of the wellbore.

3. Gel strength will reach a minimum of 25 lbs/100 ft^2 and will most likely exceed 100 lbs/100 ft^2 over an extended period of time.

4. For cased holes, the top of the mud column in abandoned wells will be close to the surface, since the mud will remain inside the casing and hole after it is abandoned.

5. The mud left in casingless wells drilled through an unsaturated zone, may be subject to dehydration and cracking along this interval if the formations are permeable. Dehydration of the mud below this level is highly improbable, if not impossible, due to the water absorption properties of the clay.

6. Moisture tends to restore dehydrated mud and will cause the clays to swell and close off any potential cracks in the dry cake. Therefore, fluid migration pathways will close when contacted by any migrating fluid.

7. In regions such as the Gulf Coast, the stresses in the exposed formations should load the mud column and increase the hydrostatic head with time. The expected increase in hydrostatic head is caused by the effects of time, temperature, and pressure decreasing the moisture content and/or increasing the gel strength.

8. The solids in the mud cannot be forced into the formation by means other than fracturing of the weakest exposed formation.

9. Loss of water to the formation due to wellbore closure will increase both mud density and gel strength. If total compaction of the fluid in the wellbore occurs, the permeability of the compacted column could approach 10^{-9} darcies.

10. An aqueous clay-based mud provides excellent sealing characteristics and is not susceptible to the development of a micro annulus. It has good gel shear strength and is less likely to separate with time and leave water suspended above the mud column.

In all cases, for the mud systems reviewed, the long-term mud properties are expected to be more resistant to vertical migration of the fluid than the original mud. Since the original mud density typically overbalances formation pore pressure, it is realistic to expect that mud filled wellbores will not provide a conduit for fluid flow into a USDW.

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FACTORS AFFECTING THE AREA OF REVIEW FOR HAZARDOUS EFFLUENT DISPOSAL WELLS

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FACTORS EFFECTING THE AREA OF REVIEW

FOR HAZARDOUS WASTE DISPOSAL WELLS

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Abstract

The area of review, for a hazardous waste disposal well, is defined as the radial distance from the receiving well in which the pressure, caused by injection, increases sufficiently to possibly cause migration of fluids into useable sources of drinking water (USDW). Among the potential conduits for fluid migration from the disposal formation are improperly plugged well bores, channeling behind the casing of the injection w faulted formations, solution channels, naturally fractured formation facies pinch-outs. Usually faults, solution channels and most other naturally occurring geological conduits are filled with native fluids and are frequently sealed from USDWs by secondary mineralization. This paper concerns itself with only those conduits that are man-made.

Man-made conduits such as old abandoned test holes or oil and gas wells are sealed with cement plugs and drilling mud. The static mud column provides substantial resistance to upward flow. Most mud systems develop a gel structure when allowed to remain quiescent. To initiate flow up an improperly abandoned well bore, the pressure in the disposal zone must exceed the sum of the static mud column pressure and the mud gel strength pressure. If the sum of these values is not exceeded during the life of a hazardous waste disposal well, there is no potential for contamination of USDWs. This paper presents a simplified procedure which can be used to calculate that effected area.

Introduction

The area of review, for a deep injection well, is determined by the zone of endangering influence for the life expectancy of that well. The zone of endangering influence is defined as that area the radius of which is the lateral distance in which pressures in the injection zone may cause the migration of the injection and/or formation fluid into an underg source of drinking water (USDW).

Factors affecting this area of review are the radial extent of ground water movement from the well bore, the rate of pressure build-up in the reservoir, through time, at various distances from the well bore and the potential for upward migration of fluids through man-made conduits.

The prediction of the probable rate of pressure increase and radial fluid movement in the disposal reservoir, resulting from the injection of fluids is a problem often confronted by injection well operators and regulatory agencies. Fluid injected into a formation which is already liquid filled will result in an increase in pressure in that formation. This injected fluid must be accommodated by either one or a combination of the following; expansion of the pore space in the matrix rock, compression of either or both the formation and injected fluids or expulsion of the formation water.

The resulting increase in pressure in the receiving formation due to the injection of fluids pose potential environmental threats to our USDWs if any man-made conduits exist within the area of review. Among the potential conduits for fluid migration from the disposal formation are improperly plugged well bores, channeling behind the casing of the injection well, faulted formations, solution channels, naturally fractured formations or facies pinch-outs.

Factors Effecting the Area of Review

Area of Review

The radius of the area of review for an injection well is determined either by calculating the zone of endangering influence or by using a fixed radius from the well bore which ever is less. The distance of the fixed radius varies from state to state. In states where the Environmental Protection Agency (EPA) has primacy, the fixed radius is 1/4 mile, while in primacy states or states that set their own regulatory standards so long as they meet or exceed EPA standards, the fixed radius varies from 1/4 mile to 2-1/2 miles.

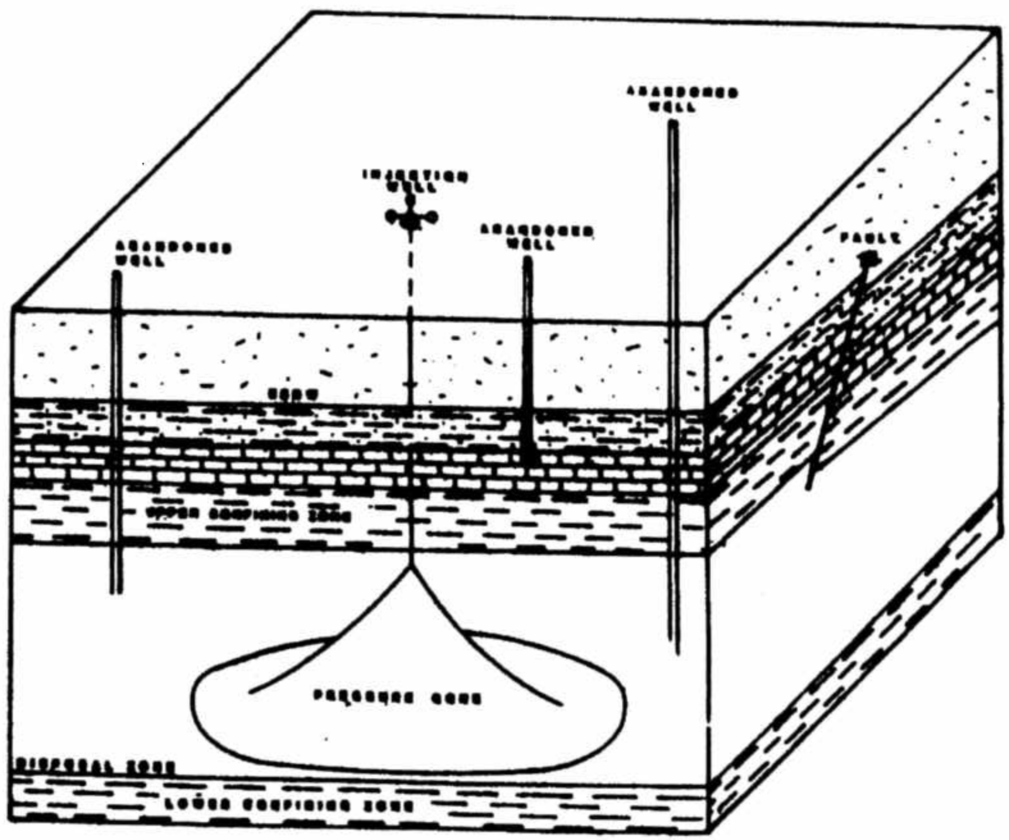
Computation of the zone of endangering influence should be calculated for an injection period equal to the expected life of the well. There are several equations that can be used for determining the area of review. The most notable and widely used is shown below (Barker, 1971; Ferris, et al, 1962; Kruseman and DeRidder, 1970; Lohman, 1972).

$$h = \frac{Q}{4\pi T}\left(-0.577216 - \log_e u + u - \ldots - \frac{u^2}{2 \times 2!} + \frac{u^3}{3 \times 3!} - \ldots\right) \quad (1)$$

where

$$h = \frac{r^2 S}{4Tt}$$

FIGURE 1
SCHEMATIC SHOWING FACTORS
AFFECTING THE AREA OF REVIEW



and

h = hydraulic head change at radius r and time t
Q = injection rate
T = transmissivity
S = storage coefficient
t = time since injection began
r = radial distance from well bore to point of interest.

For large values of time, small values of radius of investigation, or both, Equation 1 can be reduced to:

$$\Delta h = \frac{2.30Q}{4\pi T} \log \frac{2.25Tt}{r^2 S} \qquad (2)$$

Unfortunately, this equation does not address all the possible well configurations, multiple well systems, reservoir conditions, skin effects and other variables and combinations thereof. Warner, et al (1979) posed the use of several equations based on specific conditions of the system being evaluated. They indicated that an adequate approximation of the pressure build-up caused by injection into infinite confined reservoirs can be determined if we assume

1. Flow is horizontal.
2. Gravity effects are negligible.
3. The reservoir is homogeneous and isotropic.
4. The injected and reservoir fluids have a small and constant compressibility.
5. The receiving reservoir is infinite in areal extent and is completely confined above and below by impermeable beds.
6. Prior to injection the piezometric surface in the vicinity of the well is horizontal, or nearly so.
7. The volume of fluid in the well is small enough so that the effect of the wellbore can be neglected.
8. The injected fluid is taken into storage instantaneously. That is, pressure effects are transmitted instantaneously through the aquifer.

The basic differential equation for the unsteady radial flow of a slightly compressible fluid from an injection or other type well is (Matthews and Russell, 1967)

$$\frac{\partial^2 P}{\partial r^2} + \frac{1}{r}\frac{\partial P}{\partial r} = \frac{\phi u c}{k}\frac{\partial P}{\partial t} \qquad (3)$$

where:

Symbol	Parameter or Variable	Practical Units
c	compressibility	psi^{-1}
Q	porosity	decimal fraction
h	reservoir thickness	feet (ft)
k	permeability	millidarcies (m)
u	viscosity	centipoise (cp)

p	pressure	psi
q	flow rate	stock tank barrels/day (STB/I
r	radial distance	feet (ft)
t	time	days (D)

The pressure build-up equations used by Warner, et al (1979) wer written using dimensionless pressure (P_D) and dimensionless time (t_D). These dimensionless quantities are groups of variables that commonly occu in build-up equations and can be conveniently replaced by a single term Dimensionless time, for the units listed above is:

$$t_D = \frac{6.33 \times 10^{-3} kt}{\phi \mu c r^2} \qquad (4)$$

In unsteady state or transient flow equations, dimensionles pressure (P_D) is a function of dimensionless time and, perhaps, othe quantities, depending on the particular buildup solution. It is define for each equation in which it is used, throughout the Warner report.

The Warner equations presented all contain the variable β, th formation volume factor, which is the ratio of the volume of the flui being injected at reservoir pressure compared with the volume a standard conditions (520°R, 14.7 psi). For liquids, β can, fo practical purposes, be considered to be 1.0, as in all examples in thi report. However, β is quite variable when the injected fluid is gas When a highly compressible fluid is being injected, β should b evaluated at an average reservoir pressure. In cases where the pr ur is not known, enter a value of β = 1.0, obtain the approximate pre then evaluate β (Amyx, et al, 1960) and recalculate the pressure.

Multiple Well Effects

As indicated in Figure 2, if we assume a constant injection rate fo a single well penetrating the entire receiving aquifer, and adjust fo practical units, the differential equation, Equation 3, has a solution o the form

$$P_r = P_i + 70.6 \frac{q\mu\beta}{kh} \left[Ei \left(\frac{39.5\ \phi\mu c r^2}{kt}\right)\right] \qquad (5)$$

and for the case where $1/t_d < 0.01$. This is approximated as

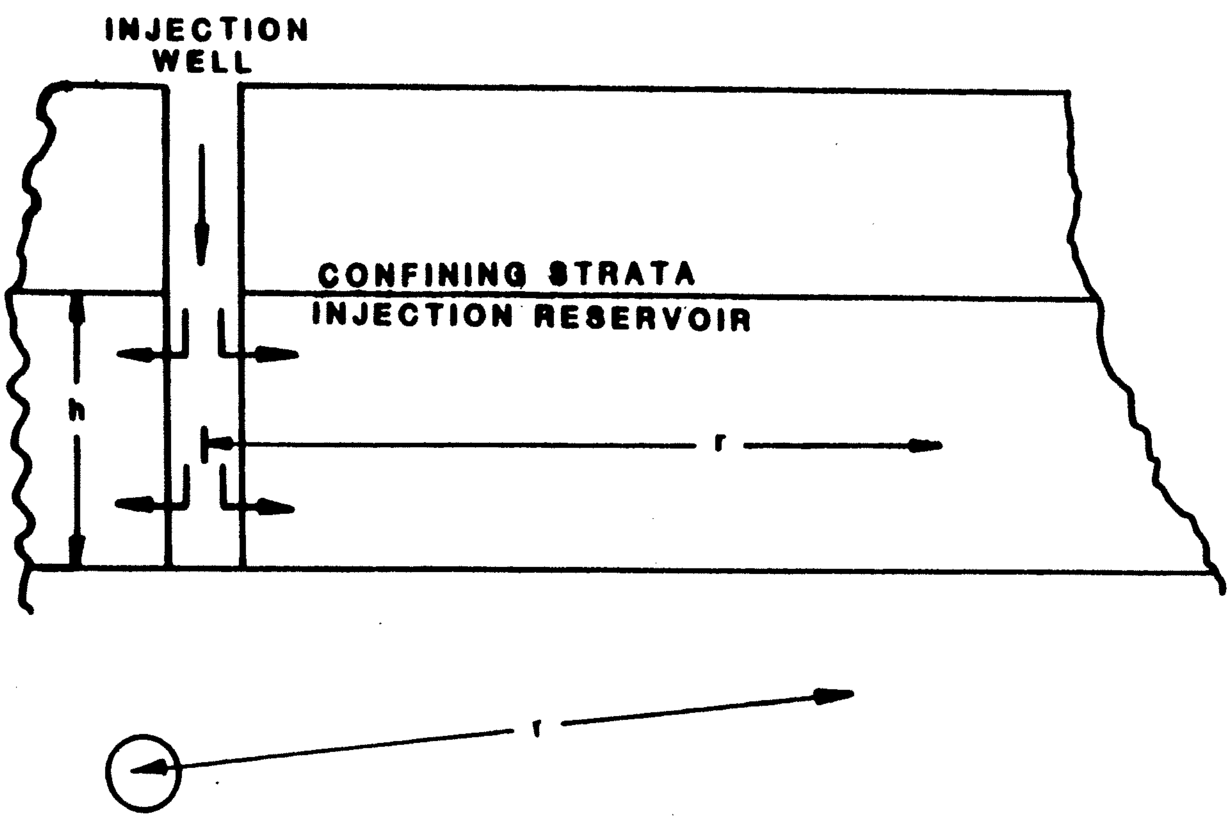
$$P_r = P_i + 162.6 \frac{q\mu\beta}{kh} \log \left(\frac{kt}{70.4\ \phi\mu c r^2}\right) \qquad (6)$$

where

FIGURE 2

PROFILE AND PLAN VIEWS OF A COMPLETELY PENETRATING WELL INJECTING INTO A CONFINED RESERVOIR. PRESSURE IS TO BE CALCULATED AT A POINT r DISTANCE FROM THE WELL.

(FROM WARNER, et.al. 1979)



Symbol	Parameter of Variable	Practical Units
β	formation volume factor	Std Stk Tank BBL (RB/STB)
P_r	reservoir pressure at radius r	psi
P_i	initial reservoir pressure	psi

A convenient characteristic of these equations (Warner, 1979) is that the effects of individual wells can be superimposed to obtain the combined effect of multiple wells. As indicated in Figure 3, the pressure at any given point in a reservoir can be evaluated by summing the pressures caused by each of the individual injection wells. Assuming the same criteria as in Equations 4 and 5 above, except for multiple wells, we have

$$P_r = P_i + 70.6 \left[\sum_{n=1}^{m} \frac{q_n \mu_n \beta_n}{k_n h_n} \, Ei \left(\frac{39.5 \, \phi_n \mu_n c_n r_n^2}{k_n t_n} \right) \right] \quad (7)$$

where n is the well number.

For cases where $1/t_d < 0.01$, an adequate approximation is

$$P_r = P_i + 162.6 \left[\sum_{n=1}^{m} \frac{q_n \mu_n \beta_n}{k_n h_n} \log \left(\frac{k_n t_n}{70.4 \, \phi_n \mu_n c_n r_n^2} \right) \right] \quad (8)$$

If we assume a variable injection rate for the same criteria as previously applied, the applicable equation is

$$P_r = P_i + 70.6 \left[\sum_{a=1}^{n} \frac{(q_a - q_{a-1}) \mu \beta}{kh} \, Ei \left(\frac{39.5 \, \phi \mu c r^2}{k(t - t_{a-1})} \right) \right] \quad (9)$$

For cases where $1/t_d < 0.01$

$$P_r = P_i + 162.6 \left[\sum_{a=1}^{n} \frac{(q_a - q_{a-1}) \mu \beta}{kh} \log \left(\frac{k(t - t_{a-1})}{70.4 \, \phi \mu c r^2} \right) \right] \quad (10)$$

where a is the time interval under consideration and q_a is the rate during that time interval.

These equations are based on the principle of superposition. That is, the pressure effects begin with the initial injection period t_1 and rate q_1. When a new rate q_2 is implemented, it is as if a new well begins to operate at that rate, with the effects superimposed on the original well, while the original well continues to operate at rate q_1. This performance is shown diagrammatically in Figure 4.

FIGURE 3

PROFILE AND PLAN VIEWS OF TWO COMPLETELY PENETRATING WELLS INJECTING INTO A CONFINED RESERVOIR. PRESSURE IS TO BE CALCULATED AT A POINT AT RADII r_1 AND r_2 FROM WELLS 1 AND 2 RESPECTIVELY.

(FROM WARNER, et.al. 1979)

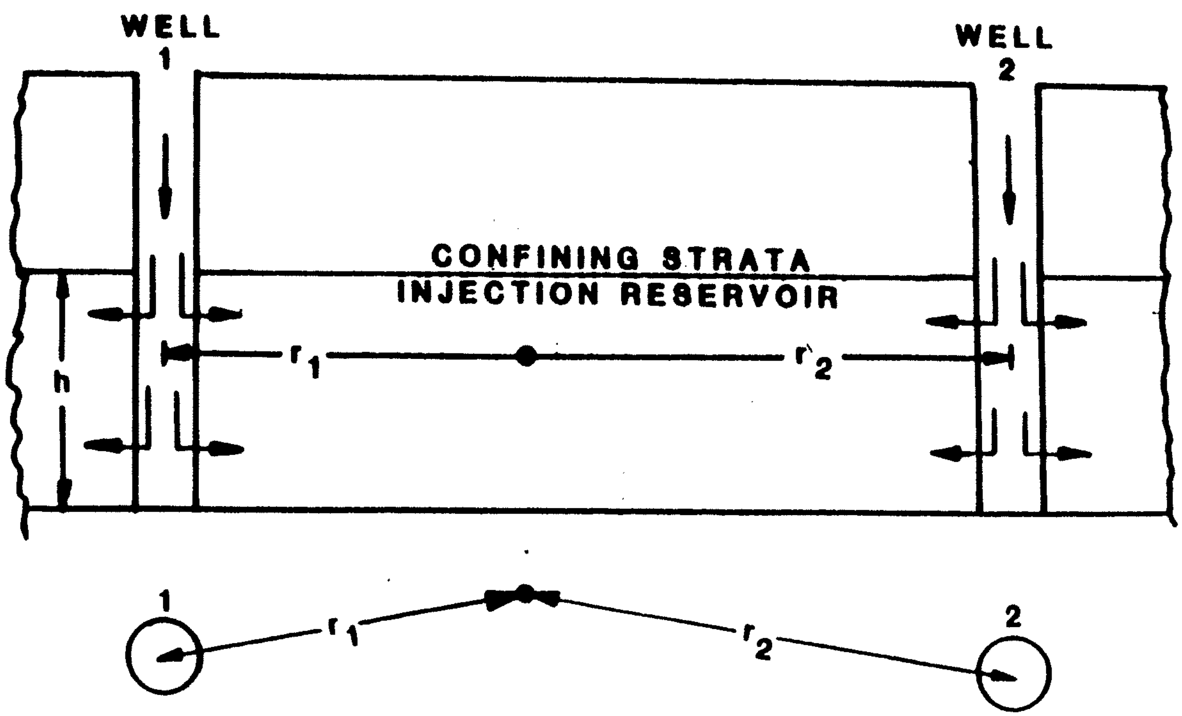
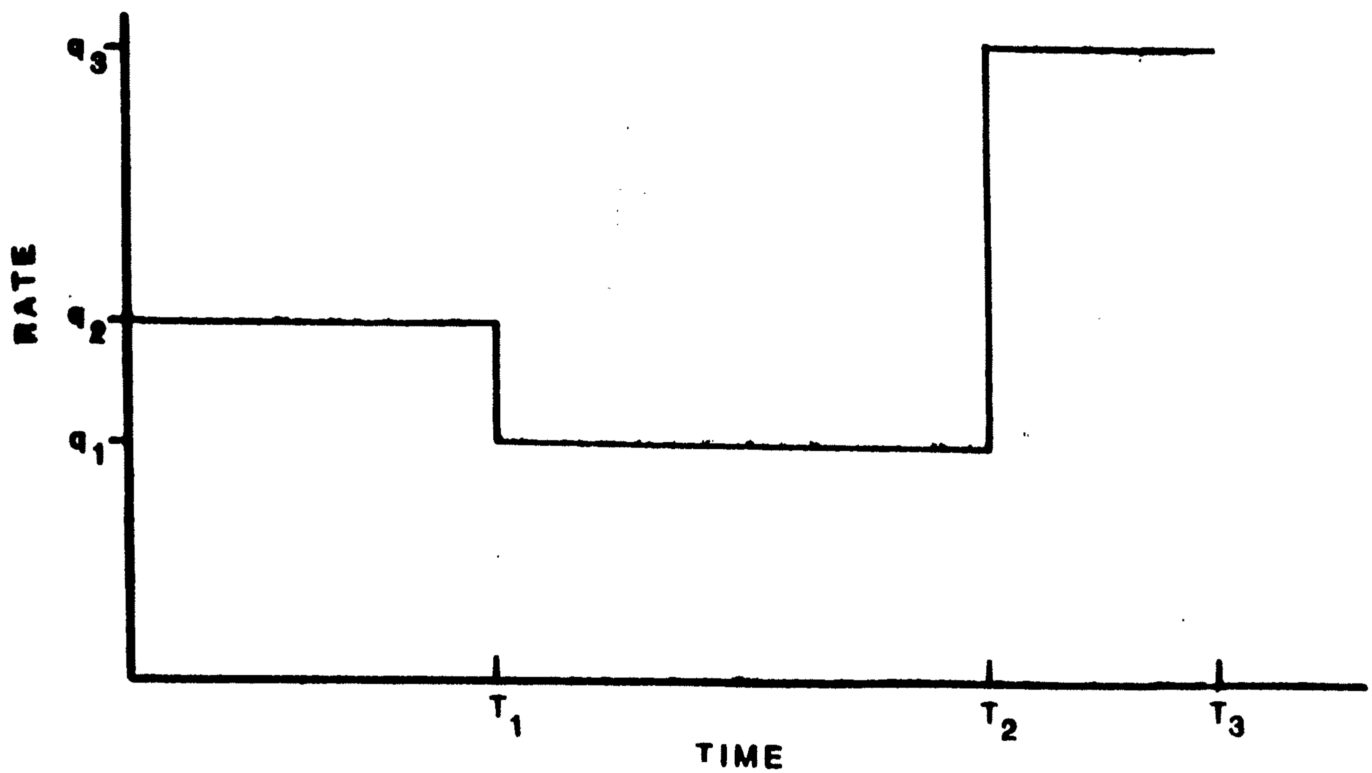


FIGURE 4

DIAGRAMMATIC REPRESENTATION OF THE INJECTION HISTORY OF AN INJECTION WELL OPERATING AT A VARIABLE RATE,

(FROM WARNER, et.al. 1979)



In computing the pressure buildup caused by multiple injection wells operating at variable rates, the principle of superposition is applied twice, once for computation of the pressure effects of each well and a second time in summing the effects of the individual wells. Figure 2 depicts two wells whose effects must be summed and Figure 3 shows a possible pattern of variable rate injection that might exist.

The applicable equation is:

$$P_r = P_i + \left[\sum_{b=1}^{m} \sum_{a=1}^{n} \frac{70.6(q_{ba} - q_{b(a-1)})}{k_b h_b} \, Ei \left(\frac{39.5 \phi_b \mu_b c_b r_b^2}{k_b(t_b - t_{b(a-1)})} \right) \right] \qquad (11)$$

Where b is the well number, a is the time interval under consideration for well b, and q_{ba} is the rate for well b during time interval a. For cases where $1/t_d < 0.01$, an adequate approximation is:

$$P_r = P_i + \left[\sum_{b=1}^{m} \sum_{a=1}^{n} \frac{162.6(q_{ba} - q_{b(a-1)})}{k_b h_b} \, \log \left(\frac{k_b(t_b - t_{b(a-1)})}{70.4 \phi_b \mu_b c_b r_b^2} \right) \right] \qquad (12)$$

In summary, these two equations state and perform the calculation for each well, as done for the single-well variable-rate case and then sum the effects of the wells.

Skin Effects

Warner, et. al. (1979) also addressed the effects of skin damage. Injection wells may suffer permeability loss in the vicinity of the wellbore during construction or operation or they may experience permeability gain. Permeability loss can result from drilling mud invasion, clay-mineral reactions, chemical reactions between injected and aquifer water, bacterial growth, etc. Permeability gain can result from chemical treatment such as acidization or from hydraulic fracturing and other mechanical stimulation methods. These permeability changes, which occur in the immediate vicinity of the wellbore are called "skin effects" by the petroleum industry and are described by a "skin factor" (van Everdingen, 1953; Hurst, 1953). The skin factor (s) is positive for permeability loss and negative for permeability gain.

The skin factor can vary from about -5 for a hydraulically fractured well to + ∞ for a well that is completely plugged (Earlougher, 1977). The incremental pressure difference caused by the skin effect is described by:

$$\Delta P_s = s \frac{q}{2\pi kh} \qquad (13)$$

Equation 13 is applied by combining it with equations that are derived for pressure buildup without skin effects. For example, Equation 5 is rewritten below to include skin effects:

$$P_r = P_i + \frac{70.6 q\mu\beta}{kh} \left[Ei\left(\frac{39.5\phi\mu c r^2}{kt}\right) + 2s\right] \quad (14)$$

When $1/t_d < 0.01$, an adequate approximation of Equation 14 is:

$$P_r = P_i + 70.6 \frac{q\mu\beta}{kh} \left[\ln\left(\frac{kt}{70.4\phi\mu c r^2}\right) + 2s\right] \quad (15)$$

Equations 14 and 15 are only valid at the wellbore. No equations are presented here for calculation of pressure buildup near the wellbore, in the zone of damage or improvement, because this zone is relatively thin and because the calculations are of relatively limited applicaton. Outside of the skin zone, the standard equations can be applied with no correction (Earlougher, 1977). The thickness of the skin is determined by (Hawkins, 1956):

$$r_s = r_w e^{s\ k_s/k-k_s} \quad (16)$$

Seldom if ever, will k_s be known. Reasonable estimates of k_s can, however, be made to allow calculation of the range of possible skin thicknesses. Consideration of the sources of permeability reduction around a wellbore indicates that, in the case of wellbore damage, r_s would seldom be greater than a few feet. The radius of permeability improvement can be greater, in the tens of feet for an ordinary hydraulic fracturing program, but probably less than 100 feet as the maximum r_s except in cases of massive hydraulic fracturing.

It should be noted that these equations can only be used for pressure buildup at the well. As discussed above, s is assumed to be zero and the ordinary buildup equations should be applied for points outside of the skin zone, which is estimated by Equation 16 or assumed to be less than 100 feet, if Equation 16 can not be used.

It is generally assumed, in estimating the pressure effects of injection wells, that the wells will be drilled completely through the injection reservoir. This will usually be true, since it maximizes the injection efficiency of the well. However, for mechanical or geological reasons, drilling is sometimes stopped before complete penetration of the reservoir has been achieved. Such wells are described as partially penetrating. In other cases, a well may be drilled completely through the reservoir, but only a part of the reservoir is completed for injection. Figure 5 depicts partially penetrating and partially completed wells. The equation for pressure buildup as a result of injection into (pumping from) such a well (Hantush, 1964; Witherspoon, et al, 1967) is:

$$P_r = P_i + P_{DPP}\left(\frac{141.2 q\mu\beta}{\phi\mu c r^2}\right) \quad (17)$$

where:

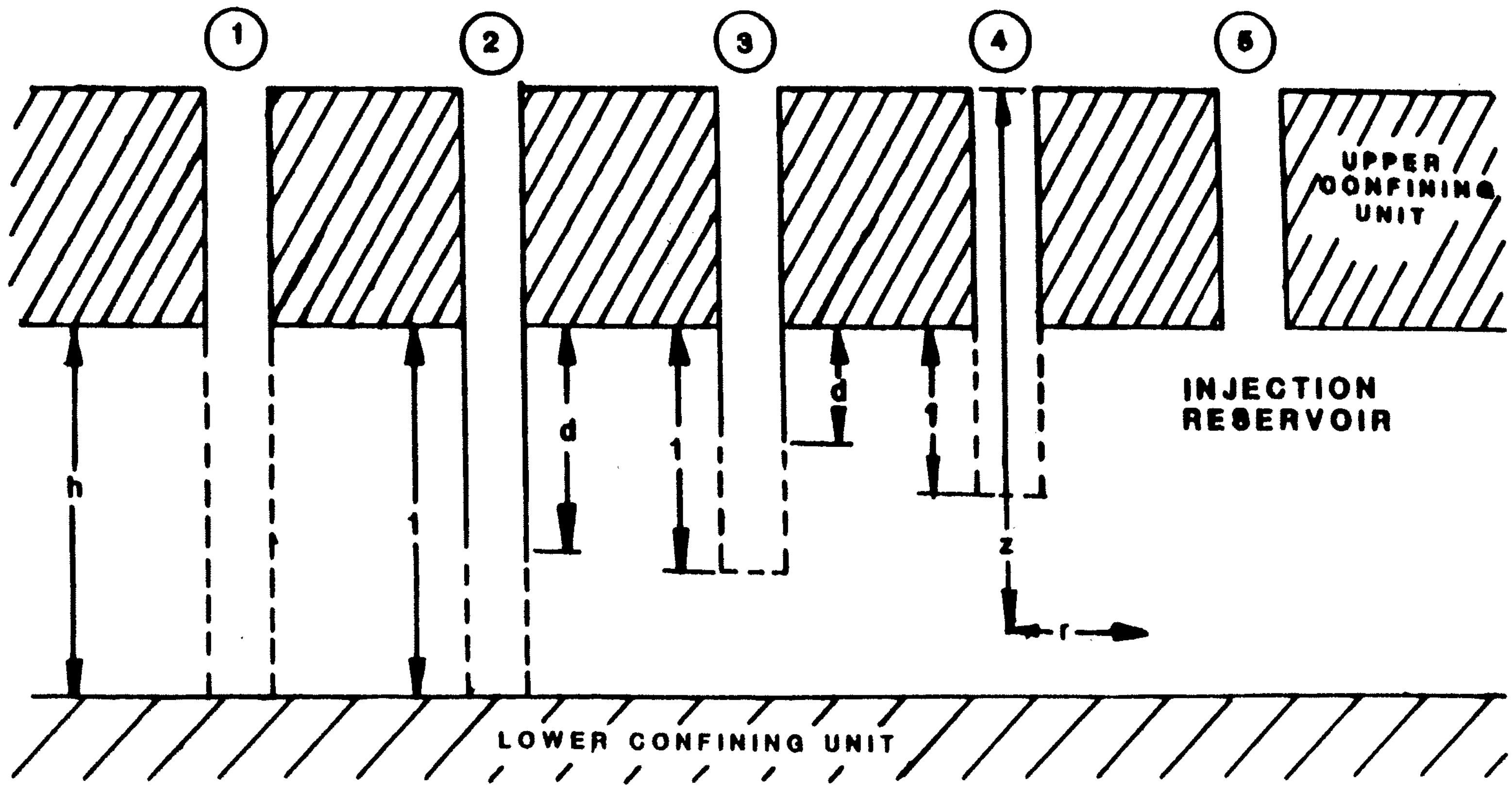
$$P_{DPP} = \frac{1}{2}\left[Ei\left(\frac{1}{4t_D}\right) + f(r, h, l, d, z)\right]$$

FIGURE 5

WELLS WITH VARYING DEGREES OF PENETRATION AND COMPLETION

1. FULLY PENETRATING FULLY COMPLETED WELL.
2. FULLY PENETRATING PARTIALLY COMPLETED WELL.
3. PARTIALLY PENETRATING PARTIALLY COMPLETED WELL.
4. PARTIALLY PENETRATING FULLY COMPLETED WELL.
5 NON-PENETRATING WELL.

(FROM WARNER, et.al. 1979)



Partial penetration results in greater pressure buildup (decline) a and near the wellbore than would be experienced in a fully penetr-ir well for the same injection (pumping) rate. The magnitude of diff depends on the degree of penetration, l; the ratio of the radiu investigation to aquifer thickness, r/h; the length of the complete interval, l-d; and the vertical point of investigation, z. The expande form of Equation 17 is too complex for practical use by hand and th number of variables so large that is is impractical to provide tables fo evaluation of P_{DPP}. Computer programs have been developed to solv Equation 17 by Warner, et al (1979).

Warner, et al (1979) also addressed the effects of fracture reservoirs, infinite semiconfined reservoirs, bounded reservoirs reservoirs with variable permeability, reservoirs with radially varyin permeability and fluids of variable viscosity. Although all thes possibilities may effect pressure buildup within a reservoir an therefore, the area of review, their specific values are rarely known Normally these values can only be determined through well testin utilizing pressure buildup and fall off or step rate injection testing Reasonable estimates can normally be made with the aforementione equations and adjusted for these parameters after operating the system fo a reasonable period of time.

Criteria for Eliminating Potential USDW Contamination through Geologica Barriers

Geohydrological Factors

Several geohydrological factors must be considered when studying th area of review for deep well injection. The subsurface environment is complex physical and chemical system. Before the injection of fluids int this system can be permitted, it must be evaluated for its ability t contain the wastes. Upward migration of wastes can occur through eithe natural geologic or man-made pathways. Natural geologic conduits such a faults, solution channels or fractures are usually filled with nati fluids and are frequently sealed from USDWs by secondary mineralizatior Man-made conduits such as old abandoned test holes or oil and gas wel] are sealed with cement plugs and drilling muds. However, the chemica effects of the injected waste on the formation rock and conduits, if an must also be evaluated. When evaluating these phenomena, we must remembe that chemical reactions in the subsurface are normally very slow ar equilibrium is reached very quickly. Since fluid movement in th subsurface is very slow, diffusion is the primary mixing factor ar provides additional support to waste containment near the well bore. we consider all the rocks that are commonly penetrated when a well drilled, the rock most susceptible to blocking both artificial and natur conduits is shale. Both sandstones and carbonate rocks can beco unstable, and fill a well bore or annular space when subjected to tecton stresses or when the hydrostatic mud pressure is lower than the pressu on the fluids within the rocks, particularly when the permeability is lo The instability of shale, on the other hand, is compounded t extraordinary manner that this rock is affected when exposed to wat

Reaction of Shales and Clays

Shales are essentially rocks that contain clay. Shale rocks are formed by the compaction of sediments. Water is squeezed out as sediments are buried deeper by layers deposited progressively during geologic time. The degree of compaction of the sediments is proportional to the depth of burial, provided the water is able to escape easily to permeable strata. The younger sediments soften and disperse when mixed with water. The older shales usually have undergone diagenesis, may remain hard and are less easily dispersed into water. The term shale is applied to everything from clays to lithified materials such as slate. Soft clays are extremely reactive with water while slates are relatively inert. Because the various shales behave differently upon exposure to drilling fluids when penetrated by the bit, it is useful to classify shales so that instability may be approached in a somewhat systematic manner. Such a classification is shown in Table I.

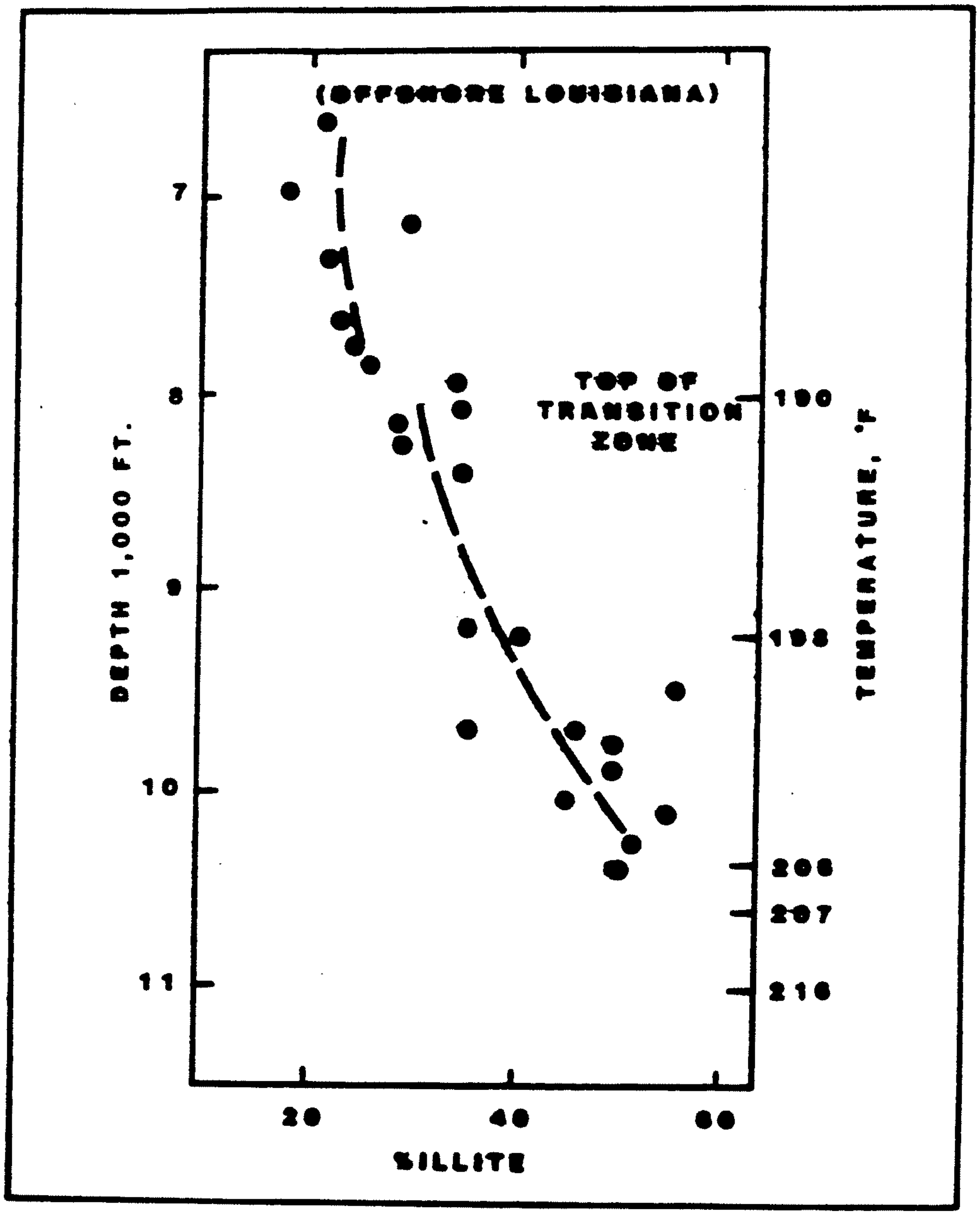
The amount of clay, the type of clay, the depth of burial, and the amount of water in a given shale all relate to the stability of the shale. The amount of clay in a given shale depends on the composition of the shale sediments at the time of deposition. The type of clay in a given shale depends not only on sediment composition at the time of deposition, but also on changes that may occur in the clay after burial.

From the view point of effect on hole stability, clays may be classified broadly as expandable and non-expandable. Expandable clays exhibit a high degree of swelling when wetted with water. Expandable clays as a group are called smectites. Montmorillonite (bentonite) is a high-swelling member of the smectite group. The non-expandable clay most commonly found in shales is illite. Chlorite and kaolinite are non-expandable clays often found in shales as well. Non-expandable clays swell much less than expandable clayes on being wetted with water. The degree of swelling of both clay types varies greatly with the type and amount of salt dissolved in the water with which the clay is wetted (R.E. Grim, 1968).

The type of clay in younger sediments depends in large part on the temperature at depth of burial. A change in clay mineralogy with depth is illustrated in Figure 6 (W.H. Fertl and D.J. Timko, 1970). The increasing percentage of illite with depth is attributable to alteration of smectite to illite. The alteration phenomenon is called "diagenesis". Some water of crystallization is released from the expandable clay during diagenesis. Illite differs from montmorillonite structurally in that some of the silicons in the outer silicate layers (R.E Grim, 1968) of illite are always replaced by aluminums, and the resultant charge deficiency is balanced by potassium ions (R.E. Grim, 1968). Temperature, rather than pressure, is thought to be the critical variable in the reaction through which this change is brought about.

The amount of water in a given shale depends on the depth of burial and the type of clay in the shale. Loosely bound water is squeezed out of the shale by pressure exerted by the weight of the overburden of the earth at depth of burial. A good approximation of the magnitide of overburden pressure is 1 psi/ft of depth. A laboratory experiement that illustrates

FIGURE 6
LATTICE MIXING
(FROM FERTLAND AND TIMKO)



this phenomenon is presented graphically in Figure 7 (H.C.H. Darley, 1969). Both bentonites in this illustration are expandable clays, and the Ventura shale contains mostly non-expandable clays. Most of the free water that can be easily squeezed out of the expandable clays is freed with a effective pressure of 2500 to 2000 psi. A matrix (grain to grain) stress of this magnitude would be expected in the crust of the earth at a depth of about 4500 to 5500 feet. Additional water is released as the swelling clays are subjected to even greater effective pressures.

Causes of Shale Instability

Shale instability may result from the following forces, either singly or in combination:

1. Overburden pressure
2. Pore pressure
3. Tectonic forces
4. Water adsorption
   a. Dispersion
   b. Swelling

Various forms of hole instability arise when the stress relief of overburden pressure occasioned by drilling exceeds the yield strength of the formation. A well-known example of this phenomenon is the plastic flow that occurs in geopressured shales. The water content and the plasticity of the shale are abnormally high relative to the overburden load, and the shale is extruded into the hole in plastic flow.

When the pressure of the drilling fluid is less than the pressure of the fluids within the pores of the rock being drilled, the pressure differential toward the hole tends to induce fragments of rock to fall into the hole. Such caving is more likely to occur when the rock is relatively impermeable. The strength of the rock is a factor in this process as well.

Tectonic forces result from stresses imposed on a given stratum by deformation of the crust of the earth. Such deformation is commonly described as folding and faulting, and is a normal result of the formation of mountains. Stresses thus created are relieved quickly in shale that is readily deformable, but tend to remain in rocks that are brittle. Even a small amount of water adsorption can cause sufficient stress to induce shales to flake off in fragments and slough into the hole.

Shale Classifications

Reference to a shale classification like the one given in Table I is helpful for a description of the effect of water absorption on shale stability. Because the number of combinations of physical and chemical properties of rocks called "shale" is so large, a classification of some kind is necessary for a logical and organized approach to predict the probability of occurrence. For purposes of illustration, a description follows of how shales of Class A through E behave upon wetting with fresh water. Obviously the behavior of the different classes of shale would be different in various salt solutions.

FIGURE 7

WATER RETAINED UDER LOAD

(FROM DARLEY)

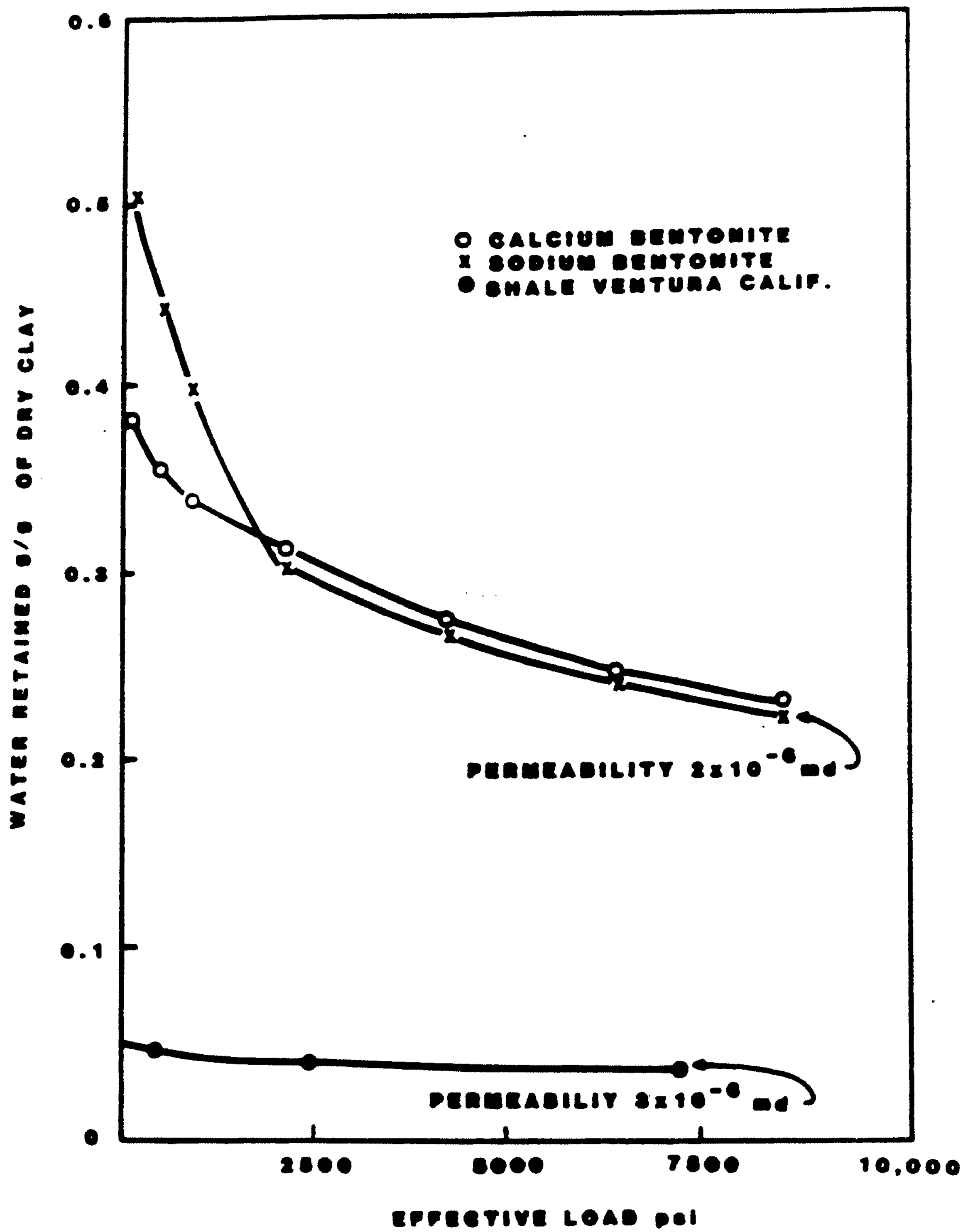


TABLE 1

A GENERAL SHALE CLASSIFICATION

Class	Texture	Methylene blue capacity (me/100g)	Water Content	Wt% Water	Clay Content	Wt% Clay	Density g/cc
A	Soft	20-40	Free and bound	25-70	Montmorillonite and illite	20-30	1.2-1.5
B	Firm	10-20	Bound	15-25	Illite and mixed layer montmorillonite-illite	20-30	1.5-2.2
C	Hard	3-10	Bound	5-15	Trace of montmorillonite high in illite	20-30	2.2-2.5
D	Brittle	0-3	Bound	2-5	Illite, kaolin chlorite	5-30	2.5-2.7
E	Firm-hard	10-20	Bound	2-10	Illite and mixed layer montmorillonite-illite	20-30	2.3-2.7

(From Mondshine 1969)

Class-A shale is characterized primarily by high-water content an relatively high expandable clay content. The word montmorillonite as use in Table I denotes expandable clays as identified by the methylene test. The word smectite is now a more widely accepted group Montmorillonite is a member of the smectite group. Shale of this qua..t is often found at shallow depth where the overburden load is still to small to have squeezed more water from the sediments during compaction and the temperature too low to have induced diagenesis. The same shal may also be found at greater depth when permeable avenues for the escap of connate water did not exist, and where conditions were not right fo montmorillonite to have been altered to illite (see Figure 6). When stil more water is added to Class A shale, it would be expected that th compaction process would be to a degree reversed. In the higher wate content range, this shale could also be squeezed into the hole from th pressure created by the weight of the overburden. The lower the mu weight, the more likely it would be for this phenomenon to occur.

Class-B shale would respond to adsorption of fresh water mainly b becoming more plastic or less firm. Water would penetrate slowly from th borehole into the shale body. Capillary adsorption of water into beddin planes would occur nominally if at all, because of the smectite clays i the shale. Abnormal pore pressure in shale of this description i possible. Aside from possible pressure effects, Class-B shale woul usually remain rather stable after being penetrated.

Class-C shale would be more likely to slough into the hole tha either Class A or B. This type of shale would be found in sediment similar to those that constituted Class-B shale, but at greater d h Some softening would occur upon adsorption of fresh water. Very l there would be sections where the shale would still be hard after wate adsorption and some swelling, so that some fragments would disengage fro the matrix and fall into the hole. The mechanism of fragmentation coul be the result of either capillary adsorption along bedding planes, o simply penetration of water into the shale body away from the hole.

Class D shale may be found at both shallow and great depths, but i likely to be quite old geologically. Brittle shale subdivides into smal particles when immersed in water, but swells and softens very little if a all. It is believed that cleavage takes place along old fracture plane that are held together by attractive forces that act over short distance only. Hydration when contacted by an aqueous drilling fluid cause separation at the old fracture planes.

Class E shales are likely to be found quite deep, and are usuall abnormally pressured. Occurrence of this type of shale is sometime thought to be anomalous, even though it is found quite often in sediment of tertiary age. This shale would have a strong tendency to slough upo adsorption of fresh water. In interbedded smectite-illite intervals illite ledges may be borken off by the unequal degree of swelling of th two different shales.

Shale Hydration

Water wetting of shale can and usually does result in borehole blockage. The instability usually results primarily from overburden pressure, pore pressure, or tectonic stress. This is true regardless or whether the clay in the shale is largely expandable or non-expandable, or whether the shale in place is brittle or plastic. Moreover, shale disperson, hole closure or sloughing from shale swelling are all attributable to adsorption of water by shale.

The forces that cause shale to absorb water are attributable to the clay in the shale. It should also be emphasized at the outset that these forces through which clay adsorbs, imbibes, draws or sucks water into itself can be very great. By comparison the force with which mud filtrate may be pressed into the formation by the differential between the hydrostatic pressure of the mud column and the pore pressure of the formation is very small. For example, if a normally pressured stratum at 5000 or 10,000 feet on the Gulf Coast is drilled with 9.5 ppg mud, the pressure differential would be about 125 and 250 psi respectively. This figure represents the pressure with which filtrate from the mud is being pressed into the formatio by the overbalance of hydrostatic pressure over pore pressure. The text following will illustrate that the water adsorption forces of shale are much greater.

Hydration of shale depends upon a number of factors such as the hydration energy of the interlayer cations on the clays present and the charge density on the surface of the clay crystals. A reasonable estimate of the shale hydration force can be made by considering the compaction forces involved in subsurface burial of a given shale stratum during geologic time. For well drilling purposes, the hydration force is calculated conveniently in this way. The effective compaction stress on a shale section at any given depth can be represented by the equation, $s = S - P$, where s is the intergranular or matrix stress (W.R. Mathews and J. Kelly, 1967), S is the overburden pressure (approximately 1 psi/ft), and P is the pressure on the fluid in the pores of the rock.

As a given layer of shale is buried deeper, progressively more water is squeezed out of the shale by the weight of the overburden. The force with which water is being expelled from the shale in the compaction process equals the intergranular or matrix stress. The adsorption (or suction) force of the clay acts in opposition to the water expulsion force of compaction. This compacting force is relieved on the borehole face when the shale is penetrated by the bit. Consequently, a hydration force equal to the degree of relief develops. Since the compaction force equals the matrix stress, then:

$$\text{SHALE HYDRATION FORCE}_{psi} = \text{OVERBURDEN}_{psi} - \text{PORE PRESSURE}_{psi}$$

For example, assuming again a normally pressured shale (9 lb/gal mud weight equivalent) at 10,000 ft on the Gulf Coast:

$$OVERBURDEN_{psi} = 1\ psi/ft = 10{,}000\ psi$$

$$MATRIX\ STRESS_{psi} = OVERBURDEN_{psi} - PORE\ PRESSURE_{psi}$$

$$= 10{,}000\ psi - (9 \times 0.052 \times 10{,}000)\ psi$$

$$= 5320\ psi$$

The shale hydration force at 10,000 feet in normal pore pressure is therefore 5320 psi.

Drilling Fluids

Artificial penetrations in the area of review or zone of endangering influence can provide potential conduits to USDWs if improperly plugged when abandoned, improperly cemented when constructed or a combination thereof. Artificial penetrations are usually man-made holes used for the exploration of oil and gas or other minerals and water. These holes are rarely empty and are fluid filled with native water, brine or drilling fluid. In the case of native waters or brine the fluids may have seeped into the well bore or been left there by the original driller. If the well was originally drilled with a cable tool rig or rotary drilling rig using compressed air, the fluid in the hole is probably native water or brine. However, the vast majority of artificial penetrations are made exploring for oil and gas. Therefore, it is logical to conclude that most well bores are mud filled since rotary drilling techniques using drilling fluid are predominately used when drilling oil and gas exploration and development wells. Upon completion of the drilling operation, if the well is not completed for production, the drill pipe is removed from the bore and the drilling mud used to drill the well will remain in the bore indefinitely. If the well is completed or casing is run and partially cemented across a portion of the well bore, drilling mud would have been displaced ahead of the cement from the annular space between the casing and open hole. If cement was not circulated to the surface, then the annular space above the cemented section will be filled with drilling mud.

A fluid filled well bore or annular space provides resistance to upwards fluid migration because of two opposing forces. The first would be the hydrostatic head or downward force caused by the weight of the fluid column. This can be described as psi/foot of depth by taking the weight of one cubic foot of water and dividing it into 144 square inches one-foot high. A cubic foot of water weighs approximately 62.3 pounds dividing by 144 square inches, we find that a column of water one-foot high exerts a downward pressure of 0.433 psi. Therefore a column of water 1000 feet deep would provide a downward force of 433 psi. If fluid were migrating upward, it would have to have a driving force in excess of 433 psi. This example used fresh water having a density of 8.33 lbs/gal. The second opposing force that would act as a deterent to fluid migration along a well bore would be present only if the fluid filling the well bore had gel strength. Most drilling fluids contain this characteristic.

One of the primary functions of the drilling mud is the removal of drilled cuttings from the well bore. The mud carries the cuttings from beneath the bit, transports them up the well bore/drill pipe annulus and releases them at the surface. Since normal drilling operations require that mud circulation be stopped periodically to add another joint of drill pipe, the mud must have a property which acts to suspend the drilled cuttings in the static mud column. This property is known as gel strength. Gel strength is time dependent and increases as the mud column remains quiescent. Most drilling fluids are thixotropic and develop a gel structure like "Jello" when allowed to stand quiescent but become fluid when disturbed.

To determine the combined effect of both hydrostatic head and gel strength acting as a deterrent to fluid migration along a mud filled well bore or annulus, we must first identify the forces acting on a well bore and/or annulus existing in a static state. Figure 8 represents a vertical force diagram of a static mud column in an abandoned well that contains no uncemented casing. Figure 9 represents the forces acting on the static mud column in the annulus between the casing and open hole above the cemented interval.

The equation for the force balance in Figure 8 takes the following form,

$$w + GS_w\left(2\pi r_w h\right) = P_f\left(\pi r^2_w\right) - P_t\left(\pi r^2_w\right) \tag{18}$$

where

$$w = r^2_w \rho h$$

and

w = weight of mud column
GS_w = gel strength of mud column acting on circumference area of well bore
P_t = pressure at top of well
P_f = pressure at formation being contained
r_w = radius of well bore
h = height of mud column in well bore
ρ = density of mud

Simplifying the force balance and adjusting for standard units, we obtain the following pressure equation,

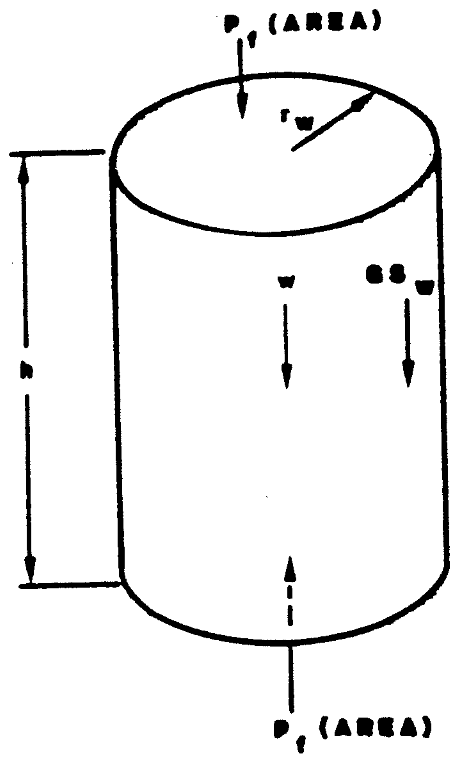
$$P_f = P_t + 0.052\rho h + 3.33 \times 10^{-3} GSh/D \tag{19}$$

where:

P_f = pressure at the contained formation in psi
P_t = pressure at the top of well
ρ = density of mud in lb/gal
h = height of mud column in feet
GS = gel strength in lb/100 ft^2
D = diameter of well bore in inches

FIGURE 8

STATIC MUD COLUMN
FORCE BALANCE DIAGRAM



P_t (AREA) = PRESSURE AT THE TOP OF WELL = $P_t \pi r_w^2$

W = WEIGHT OF FLUID COLUMN $\rho h \pi r_w^2$

GS_w = GEL STRENGTH OF MUD A ON CIRCUMFERENCE AREA OF WELL BORE = $GS_w (2 \pi r_w h)$

P_f (AREA) PRESSURE AT THE FORMATION BEING CONTAINED $P_f \pi r_w^2$

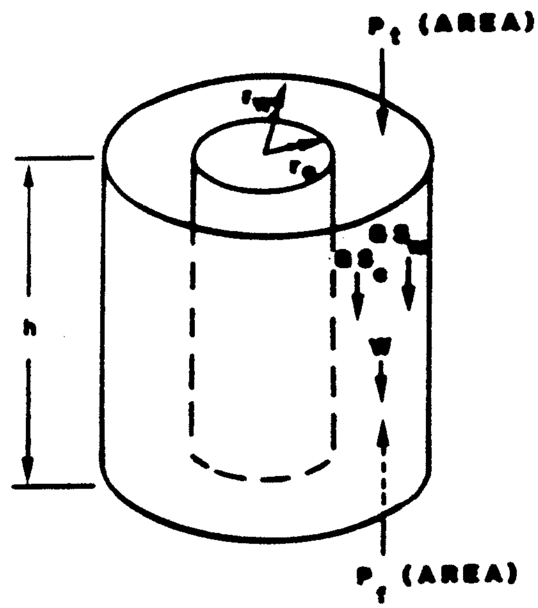
FORCES FROM MUD COLUMN SUM OF PRESSURE FORCES

$$W + GS_w (2\pi r_w h) = P_f (\pi r_w^2) - P_t (\pi r_w^2)$$

FIGURE 9

ANNULUS STATIC MUD COLUMN
FORCE BALANCE DIAGRAM

WELLBORE ANNULAR EFFECTS



FORCES FROM MUD COLUMN = SUM OF PRESSURE FORCE

$$W+GS_c(2\pi r_c h)+GS_w(2\pi r_w h) = P_f\pi(r_w^2-r_c^2)-P_t\pi(r_w^2-r_c^2)$$

The force balance equation for Figure 2 takes the form

$$w + GS_c(2\pi r_c h) + GS_w(2\pi r_w h) = P_f\pi(r^2_w - r^2_c) - P_t\pi(r^2_w - r^2_c) \qquad (20)$$

where

$$w = \rho h(r^2_w - r^2_c)$$

and

- w = weight of mud column in annulus
- GS = gel strength of mud acting on circumference area of both the well bore (GS_w) and casing wall (GS_c) and $GS_w = GS_c$
- P_t = pressure at top of well
- P_f = pressure at formation being contained
- r_w = radius of well bore
- r_c = outside radius of casing
- h = height of mud column in annulus
- ρ = density of mud

Simplifying the force balance and adjusting for standard units, we obtain the following pressure equation,

$$P_f = P_t + .\,\text{[illegible]}\rho h + \frac{3.33 \times 10_{-3} GSh}{D_w - D_c} \qquad (21)$$

where:

- P_f = pressure at the contained formation in psi
- P_t = pressure at the top of the well
- ρ = density of mud in lb/gal
- h = height mud column in feet
- GS = gel strength of mud in lb/100 ft^2
- D_w = diameter of well bore in inches
- D_c = outside diameter of casing in inches

Drilling Fluid Properties

It is generally recommended that the values required to calculate the flow resistance of a mud filled well bore or annular space be obtained from the well records. The physical configuration of the well can usually be obtained from many sources. These include but are not limited to state and federal permit records, the owner/operator files, commercial libraries, geological surveys and other public information sources. The density of the drilling fluid used to drill the well is normally recorded on the geophysical log heading as shown in Exhibit 1. The gel strength values may be more difficult to obtain. Mud properties are generally run while conditioning the mud to run casing and cement. These values are normally determined by the drilling fluid supplier or service company and are reported on standardized forms such as the one shown in Exhibit 2. These data are normally available from the owner/operator's well fi[illegible] o[illegible] the service company. Also, it is frequently not necessary to fin[illegible]

EXHIBIT 1

Schlumberger

BOREHOLE GEOMETRY LOG

COUNTY
FIELD or LOCATION
WELL
COMPANY

COMPANY ______________________________

WELL ______________________________

FIELD ______________________________

COUNTY ______________ STATE ______________

LOCATION

Sec. ________ Twp. ________ Rge. ________

Other Services:

Permanent Datum: ______________, Elev. ________

Log Measured From ________, ________ Ft. Above Perm. Datum

Drilling Measured From ______________

Elev.: K.B. ________

D.F. ________

G.L. ________

Date				
Run No.				
Depth—Driller				
Depth—Logger				
Btm. Log Interval				
Top Log Interval				
Casing—Driller	@	@	@	@
Casing—Logger				
Bit Size				
Type Fluid in Hole				
Fluid Level				
Dens. Visc.				
pH Fluid Loss	ml	ml	ml	ml
Source of Sample				
R_m @ Meas. Temp.	@ °F	@ °F	@ °F	@ °F
R_{mf} @ Meas. Temp.	@ °F	@ °F	@ °F	@ °F
R_{mc} @ Meas. Temp.	@ °F	@ °F	@ °F	@ °F
Source: R_{mf} R_{mc}				
R_m @ BHT	@ °F	@ °F	@ °F	@ °F
Time Since Circ.				
Max. Rec. Temp.	°F	°F	°F	°F
Equip. Location				
Recorded By				
Witnessed By				

EXHIBIT 2

Magcobar

Lea

New Mexico

Salt Gel - Brine[illegible]

7/29/80

8 5/8 | 1204 | 12¼ | 1

7 | 3750 | 8 3/4 | 3

1980													
3/1 DRILLING	1090	8.8	30	9			2000	Good	8	10	2 1	314.96	314.96
3/3 DRILLING	1877	10.3	30	0.1	.1	.8	50,000	Good	9	2	2 16	243.81	550.7[illegible]
3/4 DRILLING	2286	10.2	29	9	.2	1	60,000	Good	2			-0-	550.7[illegible]
3/5 DRILLING	3202	10.3	30	9	.2	1	160,000	Good	2			-0-	550.7[illegible]
3/6 DRILLING	3543	10.2	30	9	.2	1	160,000	Good	2		[illegible]	[illegible]	[illegible]
3/7 LOGGING	3750	10.2	30	6 3 2/3 9 15	.2	.8	160,000	Good	2		10 [illegible]	1737.27	2600.1[illegible]

FINAL [illegible] COST 3244.5[illegible] well records of each well since wells drilled adjacent to each other frequently use the same or similar mud systems. Historical records are also a good source of obtaining conservative values for gel strengths of specific types of drilling fluid systems.

Since the gel strength of different types of mud systems varies, it is difficult to determine the exact gel strength of the mud in a particular well bore. A review of the gel strength characteristics of various types of muds was made to evaluate the factors that effect the gel strength structure. The aim of this review was to provide sufficient information to determine the minimum gel strength structure that could be anticipated for any combination of formation, well bore and mud type. This value can then be used if insufficient data is available for a specific well bore.

Thixotropy is the property, exhibited by certain gels, of liquifying when stirred or shaken and then returning to their gelled state when allowed to stand quiescent. This property in drilling fluids is the result of various clay minerals being used as additives in drilling fluids. Generally, clay particles fall into the colloidal particle range. Colloidal systems used in drilling fluids include solids dispersed in liquids and liquid droplets dispersed in other liquids. These highly active colloidal particles comprise a small percentage of the total solids in drilling muds but act to form the dispersed gel forming phase of the mud that provides the desired viscosity, thixotropy and wall cake properties.

Clay particles and organic colloids comprise the two classes of colloids used when mixing drilling fluids. The common organic colloids include starch, carboxycelluloses and polyacrylomine derivatives.

Barker (1981) reported that, "The clay colloids utilized in common drilling fluids are characterized by a crystalline structure which influences the ability of the clay to retain water." Clays used in fresh water muds consist of hydrated alumnosilicates comprised of alternate plates of silica and aluminum to form layers of each mineral. The plate-like crystals have two distinct surfaces: a flat face surface and an edge surface. Slight surface polarities induce weak electrostatic forces along the faces and edges of the mineral plates. Garison (1939) noted that these electrostatic forces attract planer water to the colloidal particles forcing the clays to swell when wet and shrink when dry. The attraction of planer water to the faces of the plates is greater than the attraction of the sheets for each other therefore the structure tends to swell due to the absorbsion of the planer water from the drilling fluid. The bentonite clays demonstrate a strong ability to attract planer water as a result they experience extreme swelling. When in contact with fresh water, the face to face attraction of water by the mineral layers will continue until the swelling reduces the attraction of the plates to the point where they separate. This separation results in a higher number of particles and is referred to as dispersion. The dispersion causes the colloidal suspension to thicken. The degree of thickening depends on the electrolytic content, salt concentration of the water, time, temperature, pressure, pH, the exchangeable cations on the clay, and the clay concentration.

Gel Strength, The Measure of Thixotropy

Thixotropy is essentially a surface phenomenon which is characte by gel strength measurements. The gel strength indicates the attr forces between particles under static conditions. The strength of th structure which forms under static conditions is a function of the amou and type of clays in suspension, time, temperature, pressure, Ph, and th chemical treating agents used in the mud. Those factors which promot the edge-to-edge and face-to-edge association of the clay particl defined as flocculation increase the gelling tendency of the mud and tho factors which prevent the association decrease the gelling tendency.

Due to their size, colloidal particles remain indefinitely suspension. When suspended in pure water the clay particles will n flocculate. When flocculation occurs the particles form clumps or floc These loosely associated flocs contain large volumes of water. If t clay concentration in the mud is sufficiently high, flocculation wi cause formation of a continuous gel structure instead of individu flocs.

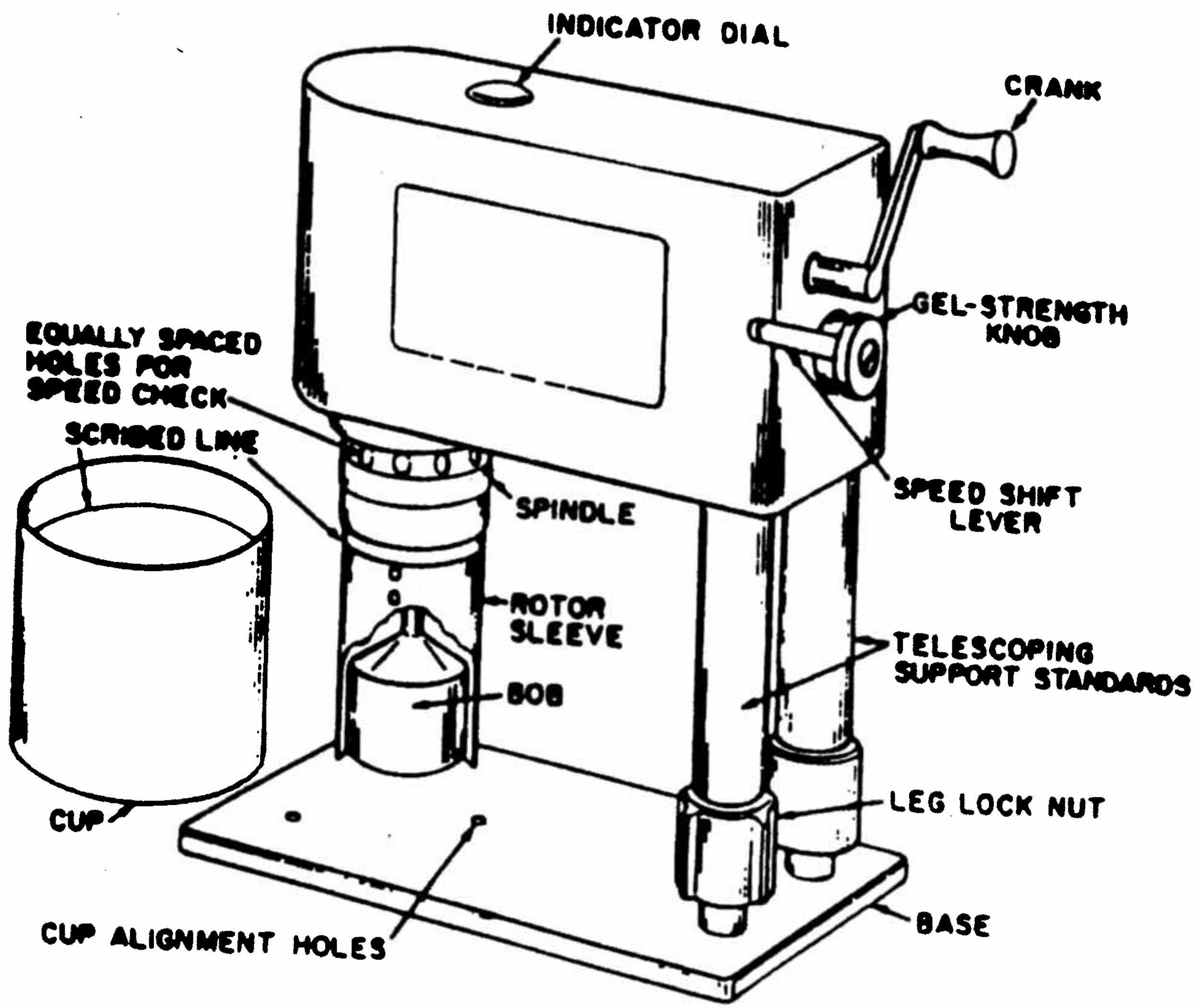
The gel structure commonly observed in aqueous drilling flui results from salt contamination. Soluable salts are usually present sufficient quantities to cause at least a mild flocculation. The ti required for the gel to attain an ultimate strength depends on t critical concentration of electrolyte required to initiate flocculatio the thinners present, and the concentration of the clay and of the sa present. During drilling the presence of salts and clay particles vari with each formation being drilled, therefore the drilling fl monitored and adjustments are made in order to maintain the desi strength.

Gel Strength of the Static Mud Column

Gel strength is measured by a multispeed direct indicating viscome (See Exhibit 3) by slowly turning the driving shaft by hand and observ the maximum deflections before the gel structure breaks. The gel stren is normally measured after quiescent periods of 10 seconds (initial strength) and 10 minutes. The measurements are taken at surf conditions of standard temperature and pressure. To determine the strength of the static mud column in an abandoned well it is necessary determine the gel strength of the mud under the influence of boreh conditions. The initial and 10 minute gel strengths bare to dir relation to the ultimate gel strength of the mud at borehole conditio To determine the ultimate gel strength of a mud it is necessary to disc the factors which act to influence the initial gel strength at boreh conditions.

Once the drilling operation is completed and the well is aband the mud is subjected to conditions vastly different from those encount at the surface. In the range of formation depths utilized for disposa industrial wastes the temperature would be expected to range from 8(300°F, the pressure from 1500 to 5000 psi and time from days to sev years. Several studies have been conducted to determine the i time, temperature and pressure on the gel strength of muds at

EXHIBIT 3
HAND VISCOMETER



conditions. The information obtained from this research should provid means of determining a reasonable minimum gel strength value for abandoned wells which exist in the range of formations described at

It is observed that common use water base muds develop high strengths after prolonged periods of quiescence. The relationship betw gel strength and time varies widely from mud to mud, depending on composition, degree of flocculation, temperature, pH, solids, pressure. Figure 10 (G.D. Gray, H.C. Darley and W.F. Rogers, 19 indicates the increase in gel strength with time for various mud types reveals that there is no well established means of predicting long t gel strengths with time. It is noted in all cases that the gel stren is observed to increase.

Garrison (1939) studied the gel strength in relation to time and r of reaction for California bentonites. He observed that both the sp and the final strength increased with the bentonite percentages. gelling was found to follow the equation:

$$S = \frac{S'kt}{1+kt} \qquad (22$$

where S is the gel strength at any time t, S' is the ultimate strength, and k is the gel rate constant. Figure 11 indicates that gel strength forms more rapidly at first then gradually approaches ultimate value as time elapsed. Equation 22 may be rewritten as:

$$\frac{t}{S} = \frac{t}{S'} + \frac{1}{S'k}$$

which indicates that a plot of t/S verses t should be a straight li Figure 11 represents the graph of t/S versus t, and indicates the slope the line is k and the y-intercept is 1/S'k. This approach provide means to evaluate the ultimate gel strength for each benton concentration. Table 2 represents the ultimate gel strengths and r constants for the five samples shown in Figures 11 and 12. Garrison a made measurements on similar suspensions at higher pH and determined t the ultimate strengths of the bentonite gels increased with e suspension as the pH increases. Table 3 reflects the pH - ultimate strength relationship observed.

Garrison also noted that the treating of muds with thinners had effect of decreasing the rate of gelling but not the ultimate strength. Thus it can be concluded that the reduced initial and 10 min gel strength will not be any less than that recorded for an untrea sample of the same mud. In fact, the ultimate gel strength may e increase as indicated in Table 2.

Garrison's work does not indicate that all muds comply with Equat 22, but it does point out that the initial and 10 minute gel strengths not provide a reliable means of predicting the ultimate gel st-ng Weintritt and Hughes (1965) conducted progressive gel strength

FIGURE 10

INCREASE IN GEL STRENGTH OF
VARIOUS MUD TYPES WITH TIME
(FROM GRAY, DARLEY, AND ROGERS)

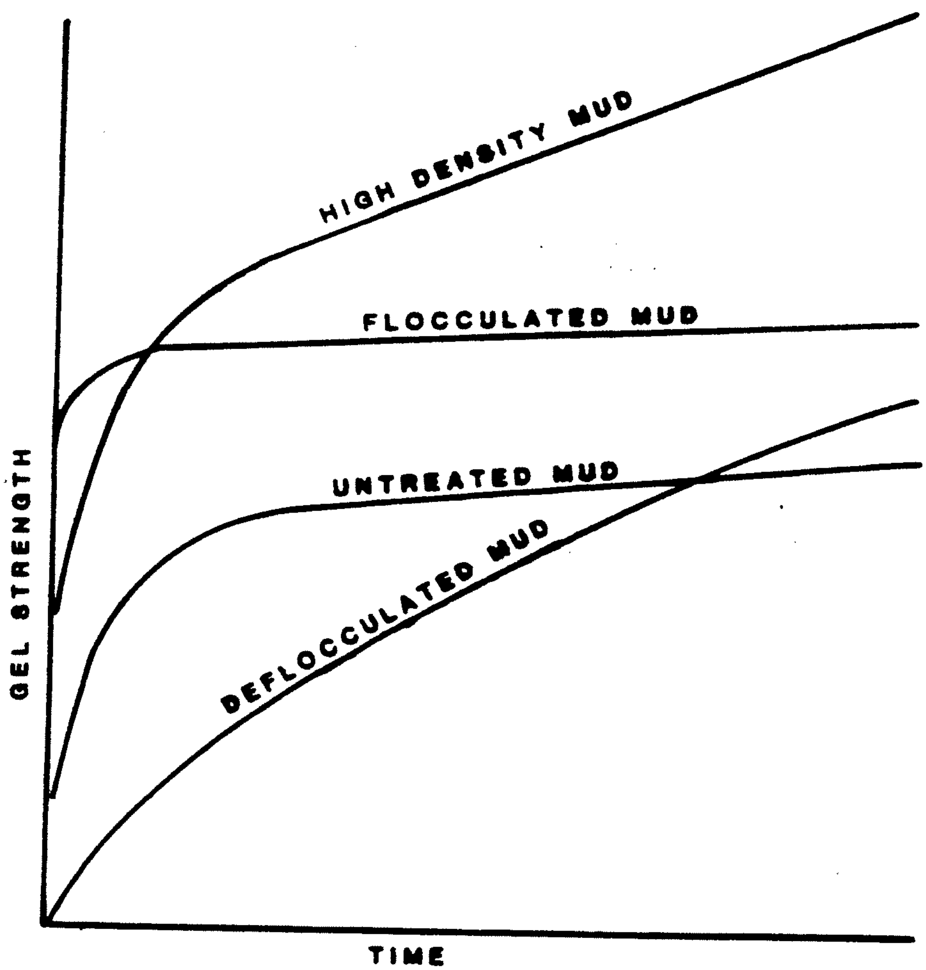


FIGURE 11
GEL STRENGTH IN RELATION TO TIME
AND RATE OF REACTION
(FROM GARRISON 1939)

SEE TABLE 2

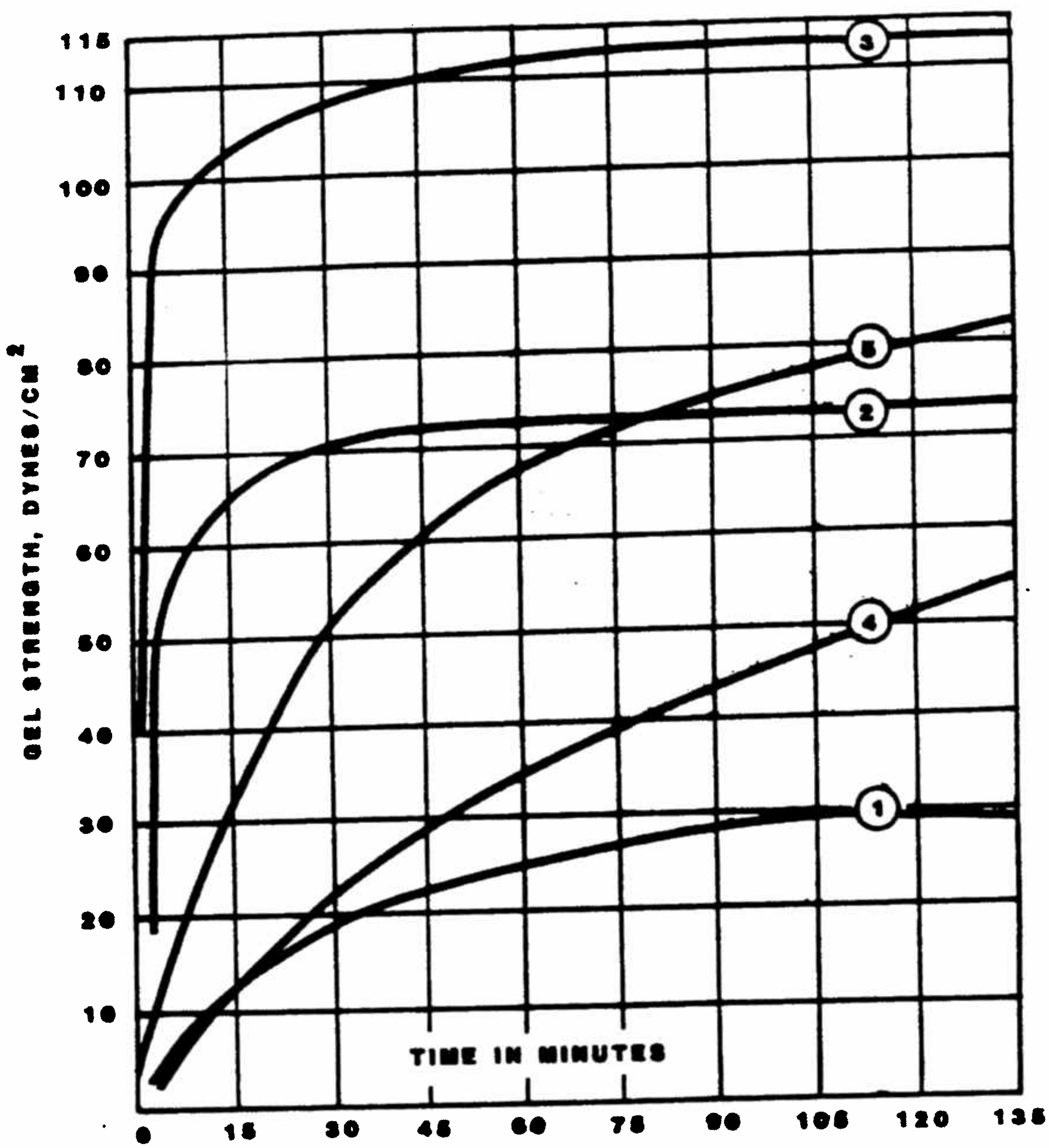


FIGURE 12

GEL STRENGTH AND RATE CONSTANTS
(FROM GARRISON 1939)
SEE TABLE 2

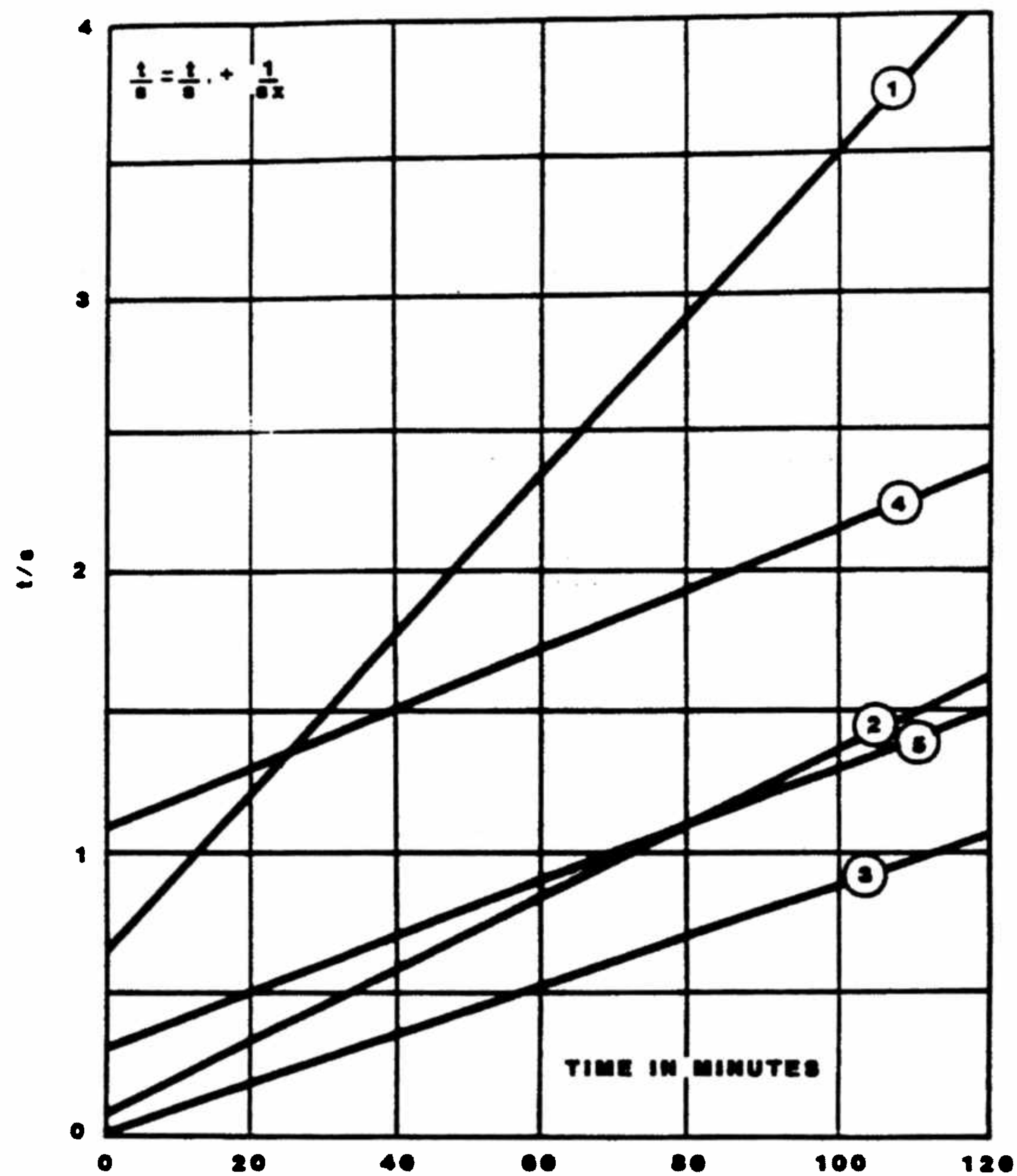


TABLE 2

GEL RATE CONSTANTS CALCULATED FROM FIGURES 11 AND 12

Bentonite Per Cent	Sample #	Additives	Gel Strength (Ultimate)	Rate Constant
4.5	1	---------	34.4	0.047
5.5	2	---------	74.4	0.75
6.5	3	---------	114.	0.79
5.5	4	0.1% Na Tannate	104.	0.0089
5.5	5	Sodium Hydroxide	99.7	0.033

(From Gray, Darley and Rogers)

TABLE 3

CONSTANTS IN GELLING EQUATIONS OF BENTONITE SUSPENSIONS

Bentonite Per Cent	Gel Strength and Rate Constant	pH+ 9.2	pH+ 9.3-9.5	pH+ 9.9-10	pH+ 10.8-11
4.5	S′	34.4	40.1	48.5	69.6
4.5	k	0.047	0.071	0.076	0.063
5.5	S′	74.4	32.2	129.9	152.7
5.5	k	0.75	0.22	0.13	0.18
6.5	S′	114.	141.	250.	268.
6.5	k	0.79	0.30	0.10	0.25

(From Garrison 1939)

ferrochrome lignosulfonate muds for periods up to 16 hours and obtained the results presented in Table 4. They noted that although Mud E and Mud F had similar properties, Mud F developed only a moderate gel strength while that of Mud E was much greater. Once again it is observed that the initial gel strength and 10 minute gel strength measurements are not always indicative of gel strength development which is observed at elevated temperatures and extended time. The three muds designated in Table 4 were obtained from wells within the same field just prior to cementing operations.

Annis (1976) noted that when a bentonite mud is quiescent, the gelling process depends on both temperature and time. Annis compared the effect of temperature on the initial and 30 minute gel strength of an 18 ppb bentonite suspension. Figure 13 indicates that the 30 minute gel strength of the 18 ppb suspension is at any temperature approximately six times the initial gel strength. The dependence of gel strength on time at different temperatures, as noted by Annis, is shown in Figure 14. Based on these and other tests of up to 18 hours Annis concluded that there is a strong indication that gel strength increases indefinitely with time.

Conclusion

In review, the above works indicate that the ultimate gel strength of water base muds is considerably higher than the values recorded for the initial and 10 minute gel strength. Although there is no direct relationship between gel strength and time, it is possible, based on available information, to conclude that the ultimate gel strength of a mud will be several times larger than the initial or 10 minute gel strength of the mud. In reference to the work by Garrison (1939), it is possible to consider the ultimate gel strength of a treated mud to be equivalent to that of a similar mud that was not treated, since the effect of the thinner is to decrease the rate of gelling and not the ultimate gel strength obtained.

In addition to time, temperature can have a major effect on the gel strength of water based drilling fluids. Srini-Vasan (1957) studied the effects of temperature on the gel strength of several water based drilling muds. Table 5 lists the muds which were tested and Figures 15 and 16 indicate the temperature versus gel strength relationships obtained. In most of the cases investigated by Srini-Vasan it was noted that the gel strength leveled off after 160°F. The emulsion and lime treated muds showed no change in gel strength with increase of temperature. It was found that each mud had its own characteristic curve and no quantitative interpretation was possible. The work of Weintritt and Hughes (1965) as noted in Table 4, indicates that emulsion Mud G experienced no change in gel strength in going from 75 to 180°F over a wide range of times. It is noted that although the gel strength did not vary with temperature, it went from an initial gel strength of 0 to a gel strength of 25 after 16 hours.

The equipment utilized by Srini-Vasan restricted his investigation to temperatures up to 220°F.

TABLE 4

COMPARISON OF MUD PROPERTIES WITH PROGRESSIVE GEL-STRENGTH TESTS GYP-FERROCHROME LIGNOSULFONATE EMULSION MUDS

	SAMPLE			
	Mud E	Mud F	Mud G	
			No Treatment	3 lb/bbl PCL
Weight, unstirred, lb/gal	11.0	10.7	10.6	
Weight, stirred, lb/gal	11.0	10.3	10.7	
Plastic Viscosity, cp	14	23	16	15
Yield Point, lb/100 sq ft	3	6	2	1
10-sec gel, lb/100 sq ft	1	2	1	0
10-min gel, lb/100 sq ft	8	8	7	3
API filtrate, sl	6.2	3.3	5.2	2.9
pH	10.9	10.6	10.5	10.4
Composition: Water, % by vol	76	63	75	
Oil, % by vol	5	11	9	
Solids, % by vol	19	16	16	
Solids, % by wt	39	36	37	
Solids, SG	2.7	2.9	3.0	
Filtrate Ion Analysis:				
Chlorides ppm	3500	400	3000	
Sulfate, epm	250	300	130	
Carbonate, epm	24	28	12	
Bicarbonate, epm	12	160	12	
Calcium, epm	44	52	44	

Progressive Gel Strengths lb/100 sq ft	**Temperature (°F)**							
Time	75°	180°	75°	180°	75°	180°	75°	180°
0 **minutes**	1	1	2	2	1	1	0	0
3 **minutes**	2	3	2	5	3	8	1	1
10 **minutes**	8	18	8	12	7	26	3	3
30 **minutes**	15	40	11	18	17	58	5	5
60 **minutes**	27	90	18	16	29	91	6	6
2 hours	31	145	22	22	29	104	7	7
4 hours	37	190	29	42	46	172	10	10
8 hours	46	190	33	42				
16 hours	80	320	40	57	95	320	25	2

(From Weintritt and Hughes 1965)

FIGURE 13

EFFECT OF TEMPERATURE ON INITIAL
AND 30-MINUTE GEL STRENGTH
(FROM ANNIS 1976)

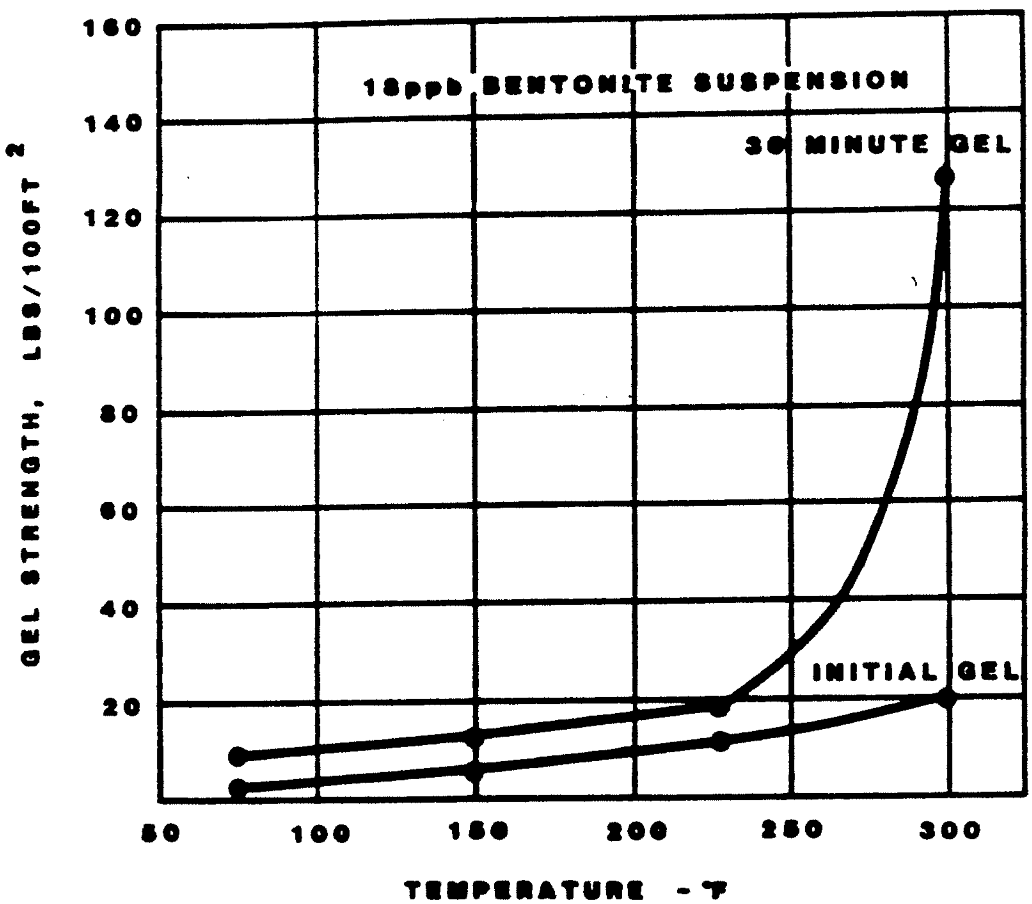


FIGURE 14
EFFECTS OF TIME AND TEMPERATURE
ON GEL STRENGTH
(FROM ANNIS 1976)

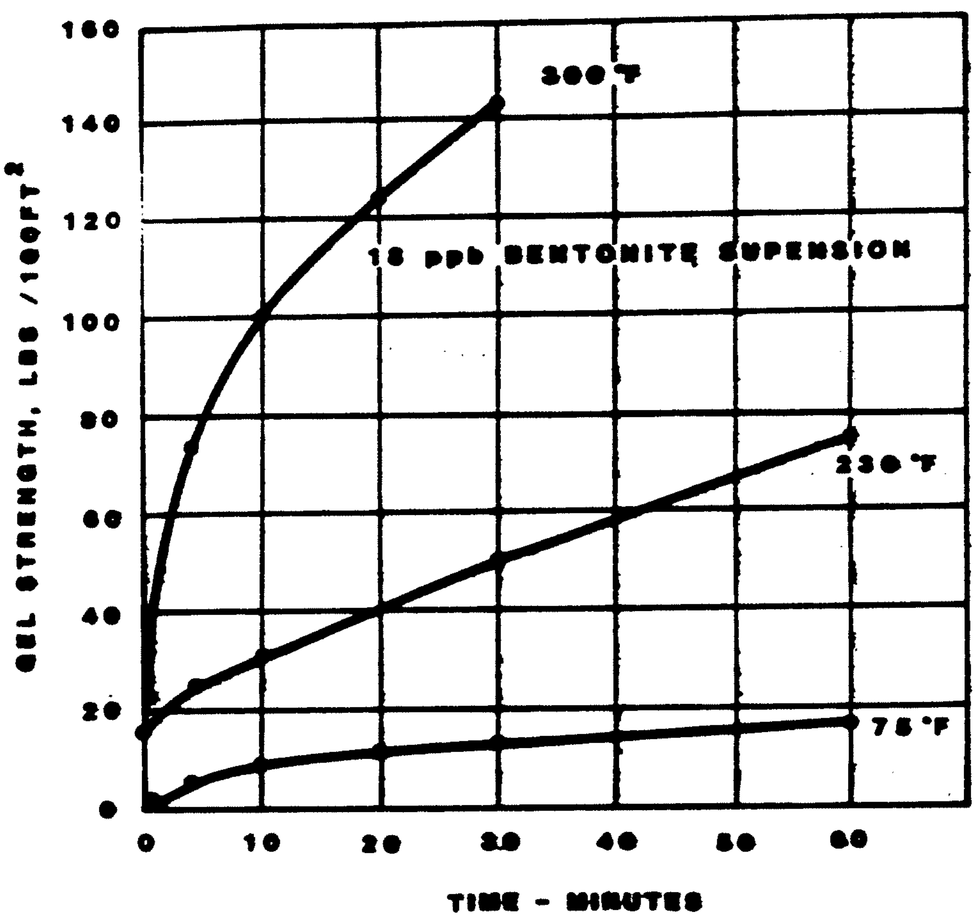


TABLE 5

COMPOSITION OF THE MUD SAMPLES TESTED FOR GEL STRENTGH

SAMPLE NUMBER	COMPOSITION OF THE MUD**
33	2 per cent bentonite mud
34	3 per cent bentonite mud
35	4 per cent bentonite mud
39	10 lb/gal, 4 per cent bentonite, barite mud
43	10 lb/gal, 10 per cent (by volume) Diesel oil, 4 percent bentonite, barite, emulsion mud
47	10 lb/gal, 4 per cent bentonite, barite, surfactant (DMS) mud
49	10 lb/gal, low lime (1 lb/bbl) treated, 4 per cent bentonite, barite mud

**All muds referred to are water base muds.
All per cent quantities mentioned denote weight per cents, unless otherwise designated.

(From Srini-Vasan)

TABLE 6

GEL STRENGTH OF A 4 PERCENT SUSPENSION OF PURE SODIUM MONTMORILLONITE TO WHICH AN EXCESS OF 50 MEQ/LITER OF NaOH HAS BEEN ADDED, MEASURED AT VARIOUS TEMPERATURES AND PRESSURES

		Gel Strength (lb/100 sq ft)		
t(°F)	P(psi)	1 min	10 min	30 min
78	300	2.2	—	35.0
	8000	2.2	—	7.0
212	300	18.0	26.0	40.0
	8000	9.0	9.0	15.0
302	300	240.0	290.0	265.0
	8000	88.0	100.0	100.0

(From Hiller 1963)

FIGURE 15
GEL STRENGTH VERSUS TEMPERATURE FOR
BENTONITE-WATER MUDS (FROM SRINI-VASAN 1957)

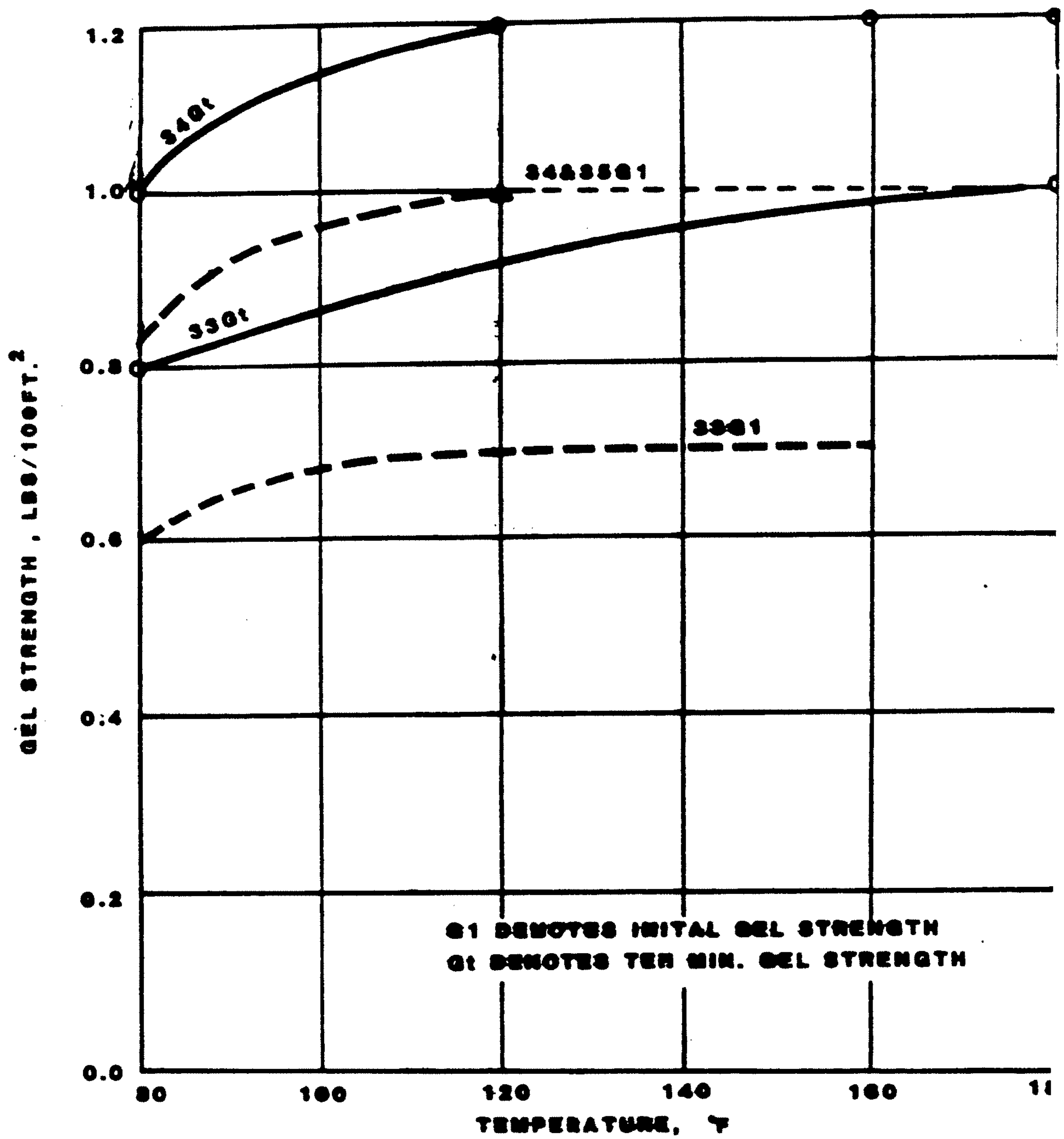
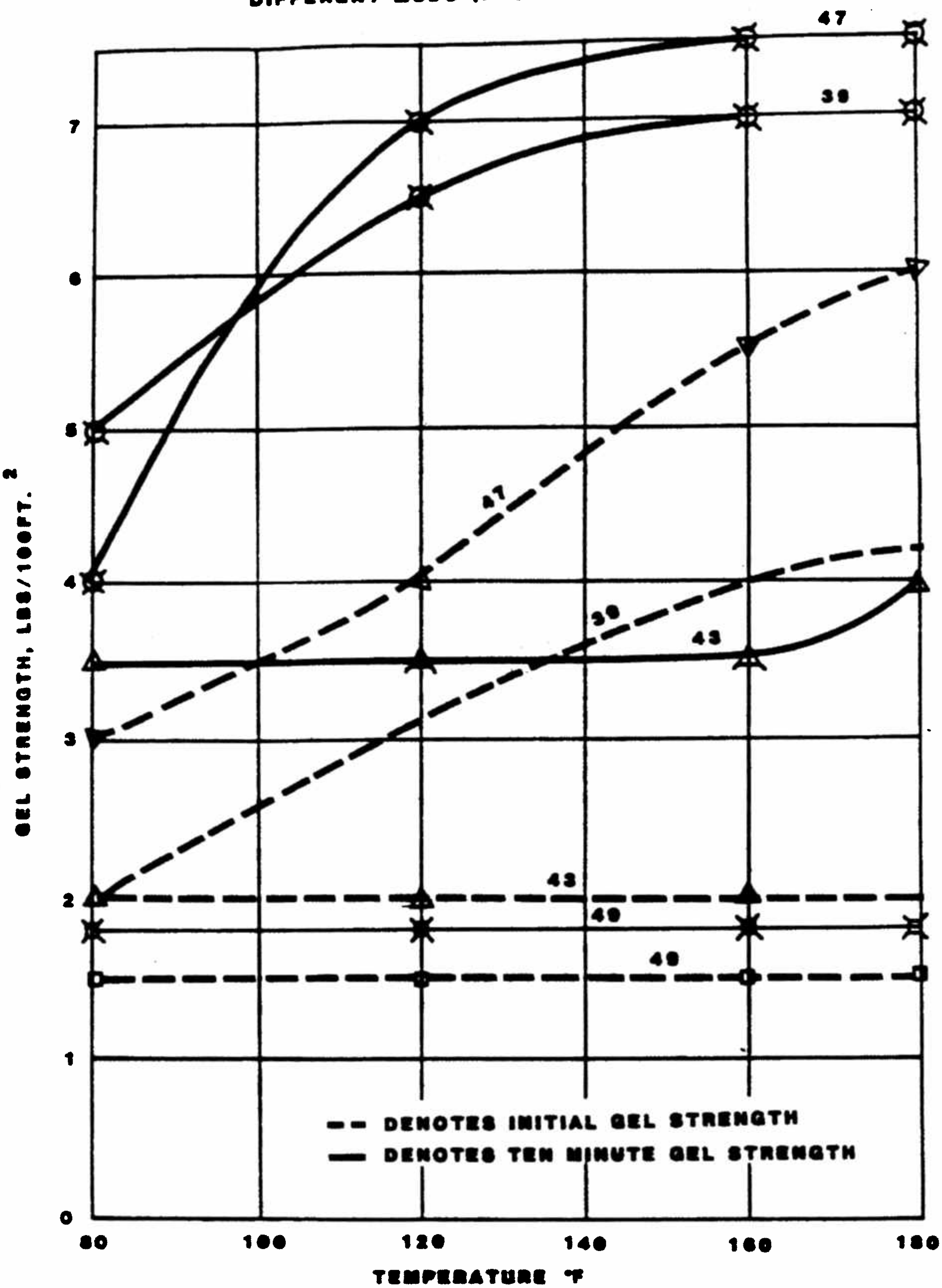


FIGURE 16

GEL STRENGTH VERSUS TEMPERATURE FOR DIFFERENT MUDS (FROM SRINI-VASAN 1957)



Annis (1976) was capable of investigating the gel strength up to temperatures of 350°F. Srini-Vasan observed that the gel strengths leveled off after 160°F but Annis noted that at higher temperature rapid increase in the gel strength was noted. Figure 17 reflects observation. Thus increased temperature, like increased bentonite concentration promotes flocculation. The temperature at which a rapid increase in gel strength occurs, represents the onset of flocculation. Therefore it is possible to expect the gel strength to increase significantly at some elevated temperature.

Annis studied the gel strength properties of about 40 water base field muds at temperatures ranging to 300°F. The muds covered a wide range of densities and mud types, although the majority were lignosulfonate muds. To draw conclusions on the effects of high temperature on gel strength, the gel strength properties were averaged and are presented in Figure 18.

Hiller (1963) noted that some clay suspensions display a decrease in gel strength with increased pressure, especially at high temperatures. It was noted that the gel strength was reduced to 1/4 of its original value for a pressure increase from 300 to 8000 psi at a temperature of 302°F. This reduction in the gel strength resulting from increased pressure is presented in Table 6.

Although no direct means exists to determine the ultimate gel strength of a drilling mud at borehole conditions, it is possible to safely say that the gel strength developed in the borehole is considerably greater than that indicated by the initial and 10 minute gel strengths recorded for a given mud. The effects of time, temperature and pressure on the gel strength of the static mud column have been discussed above. In the range of pressures and temperatures normally encountered in disposal formations, pressure should exert a negligible effect on the gel strength. Flocculation at high temperature should not occur except in the deepest of disposal formations. Certain muds do not display a temperature dependence, but the effect of time is ever present.

The research discussed above investigated muds with 0 initial gel strength to ultimate gel strengths of 100's lbs/100SF. In an attempt to select a minimum ultimate gel strength that could be expected for the worst of mud and borehole conditions, a value of 20 lbs/100 ft^2 should be utilized for the ultimate gel strength in all gel strength pressure calculations where actual numbers are not available. This value will provide a considerable safety factor in most cases.

The 20 lb/100 ft^2 ultimate gel strength was arbitrarily selected to insure that a sufficient safety factor is built into the proposed procedure. The selection is the result of individual judgment prejudiced by the above discussion."

FIGURE 17

EFFECTS OF TEMPERATURE AND BENTONITE
CONCENTRATION ON 30 MINUTE GEL STRENGTH
(FROM ANNIS 1976)

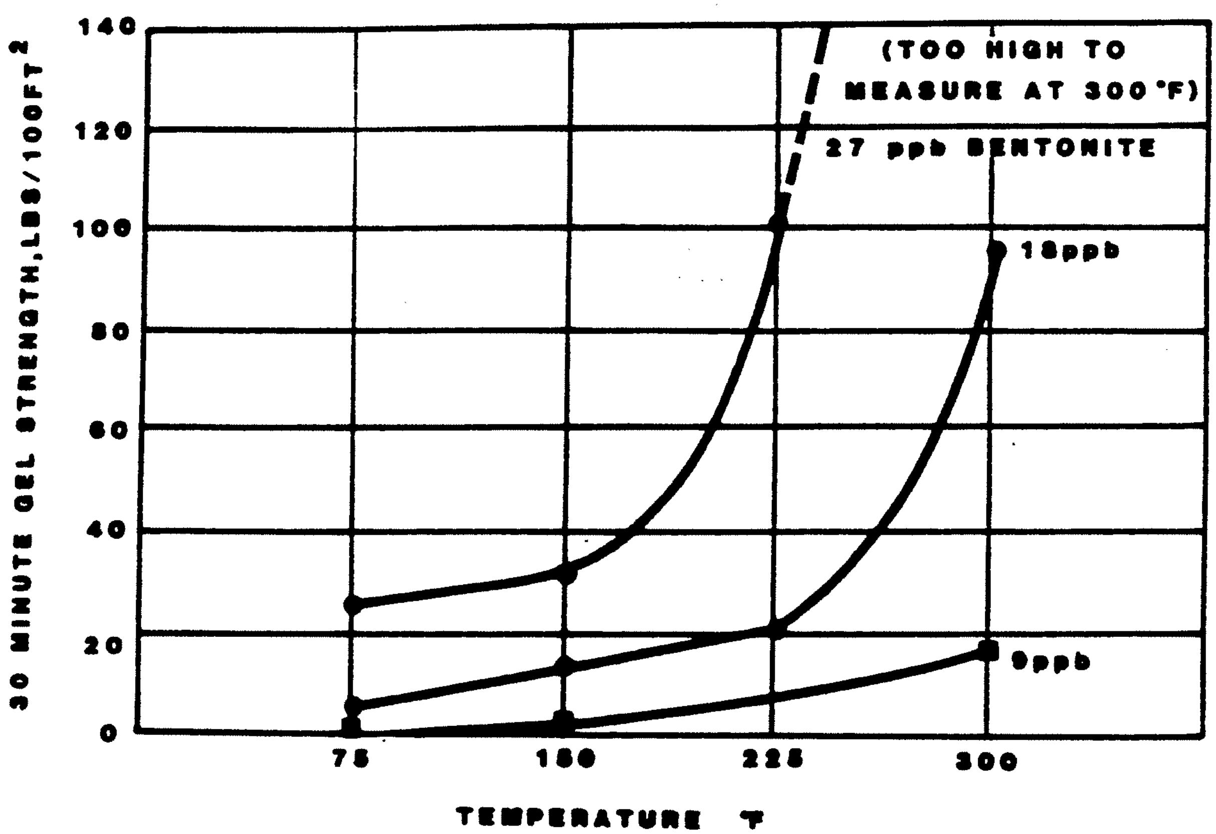
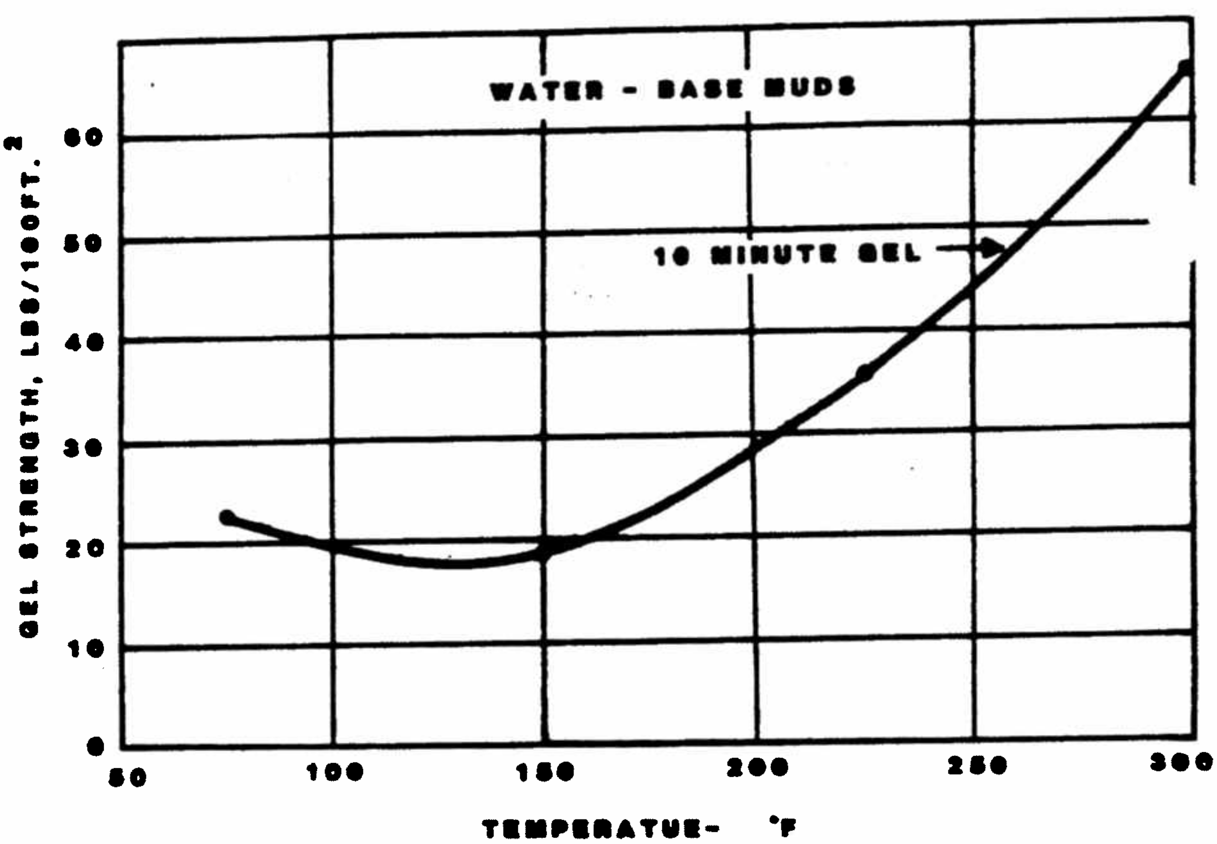


FIGURE 18

EFFECT OF TEMPERATURE ON 10 -MINUTE GEL STRENGTH (FROM ANNIS 1976)



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Ken E. Davis, President of Ken E. Davis Associates, 3121 San Jacinto, Suite 102, Houston, Texas 77004, has extensive experience in the field of injection well systems used for secondary recovery disposal and storage. He has either personally installed or been responsible for the installation of over fifty (50) Industrial Disposal Wells and over one hundred (100) Salt Water Disposal Wells in the continental United States, Europe and Mexico. He has also worked as technical advisor to the Environmental Protection Agency on their Underground Injection Control Program authorized by the Safe Drinking Water Act, The Department of Energy on their various Underground Storage Programs and The Bureau of Reclamation on their various salinity control projects.

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Composition and Properties of Oil Well Drilling Fluids

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Composition and Properties of Oil Well Drilling Fluids

Fourth Edition

George R. Gray H.C.H. Darley
Walter F. Rogers*

*Deceased

rates of shear. For this purpose a pressurized capillary viscometer, which permits viscosity to be determined over a wide range of shear rates, must be used. This instrument is particularly useful for determining power law parameters, as will be discussed later in this chapter.

The Effect of Thixotropy on Drilling Muds

If the gel strength of a mud is measured immediately after being sheared, and repeatedly after increasingly longer periods of rest, the values obtained will be generally found to increase at a decreasing rate until a maximum value is reached. This behavior is a manifestation of the phenomenon of *thixotropy*, originally defined by Freundlich[9] as a reversible isothermal transformation of a colloidal sol to a gel. In the case of drilling muds, the phenomenon is caused by the clay platelets slowly arranging themselves in positions of minimum free energy (see Chapter 4) in order to satisfy electrostatic surface charges. After a period of rest, a thixotropic mud will not flow unless the applied stress is greater than the strength of the gel structure. In other words, the gel strength becomes the yield point, τ_0. If subjected to a constant rate of shear, the clay platelet associations gradually adjust to the prevailing shear conditions, and the effective viscosity decreases with time until a constant value is reached, at which point the structure-building and structure-disrupting forces are in equilibrium. If the rate of shear is increased, there is a further decrease in viscosity with time until an equilibrium value typical of that rate of shear is reached. If the rate of shear is then decreased to the first rate, the viscosity slowly builds up until the equilibrium value for that rate of shear is again reached. Because of these phenomena, Freundlich's original definition of thixotropy has been extended to cover a reversible isothermal change in viscosity with time at constant rate of shear.[10]

Thixotropy must not be confused with plasticity. As we have already seen, the effective viscosity of a Bingham plastic depends on the rate of shear because its structural component forms a decreasing proportion of the total resistance to shear as the shear rate increases. The viscosity of a thixotropic fluid depends on time of shearing, as well as rate of shear, because the structural component changes with time according to the past shear history of the fluid. For this reason, thixotropic fluids are said to be "fluids with a memory." Bingham plastics may or may not be thixotropic, depending on composition and electrochemical conditions. A quick test for thixotropy may be made in a viscometer fitted with an *x-y* recorder, by increasing and then decreasing the rotor speed. If a hysteresis loop is obtained on the recorder, the fluid is thixotropic.

The opposite of thixotropy is *rheopexy*. The viscosity of a rheopectic fluid increases with time at constant shear rate. Rheopexy in drilling fluids has not been reported.

The effect of thixotropy on the evaluation of the rheological parameters of drilling muds was first investigated by Jones and Babson.[11] They observed the change in torque with the passage of time, when thixotropic muds were sheared at constant rate in a MacMichael viscometer. Curve 1 in Figure 5–10 shows the result when a gelled mud was sheared at a constant rate of 189 rpm. The torque decreased sharply during the first 15 minutes; then decreased gradually until equilibrium was reached after about one hour. Curve 2 shows the behavior of the mud after the shear rate was increased to 279 rpm, maintained there till equilibrium was reached, and then brought back to 189 rpm. Note that the torque gradually built back to the equilibrium value of Curve 1. Curves 4 and 5 show that approximately the same equilibrium value was obtained at 81 rpm, regardless of whether the mud was pre-sheared at 119 or 279 rpm. These results confirm that thixotropic muds have an equilibrium value which is typical of the shear rate at which it is measured, and which is independent of shear history.

The equilibrium viscosities of the mud at rates ranging from 189 rpm to 21 rpm are shown by Curve 1 in Figure 5–11. Jones and Babson emphasized that the concepts of plastic viscosity and yield point cannot be applied to this curve because each point represents a different degree of structural breakdown. In other words, the equilibrium curve relates stress to both rate of shear and to the effect of time, whereas flow equations relate stress only to rate of shear. Meaningful values of plastic viscosity and yield point can only be obtained by shearing to equilibrium at a specified speed, and then making torque readings as quickly as possible at lower rpm before any thixotropic change takes place. Curves 2 and 3 in Figure 5–11 show these instantaneous values after pre-shearing at 189 and 279 rpm, respectively. For each pre-shear rate, the area between the equilibrium and instantaneous curves defines the flow conditions at any lower shear rate at any point in time.

The effect of shear history on viscosity was also shown by Cheng et al.[12] They pre-sheared bentonite suspensions to equilibrium at rates varying from 700 to 20 reciprocal seconds. In each case the instantaneous curves were obtained at shear rates ranging downward from 700 reciprocal seconds. The results for a 4.8% bentonite suspension, shown in Figure 5–12, indicate that the instantaneous effective viscosity at 700 rpm varied from 11 to 63 centipoises depending on the rate of pre-shearing.

The principles and experimental results discussed above show that the effect of shear history must be taken into account when determining the flow parameters of thixotropic muds. For example, muds must be pre-sheared to equilibrium at a standard rate when comparing the flow properties of different muds. When the flow parameters are to be used for the purpose of calculating pressure drops in a well, the mud must be pre-sheared to a condition corresponding to that prevailing at the point of interest in the well.

Note that the time required for pre-shearing to equilibrium may be longer or shorter than the one hour reported by Jones and Babson. Figure 5–13

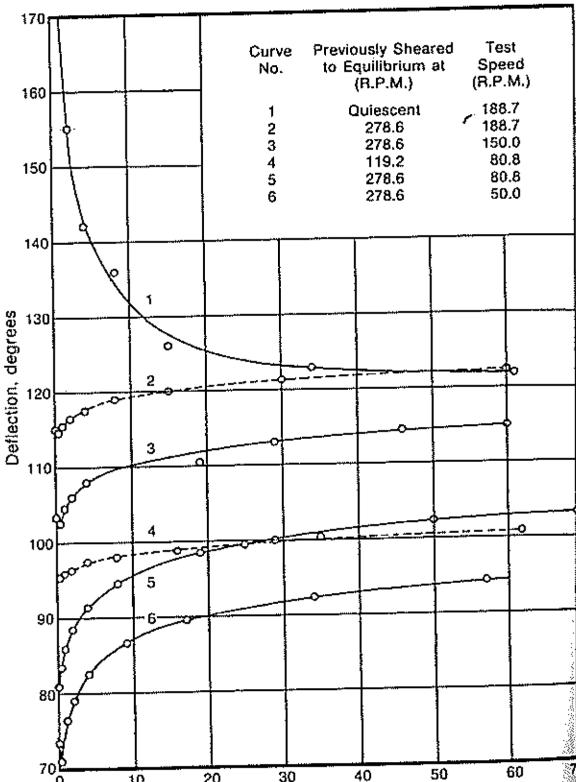


Figure 5-10. Flow behavior of a clay mud in a MacMichael viscometer. (*From Jones and Babson.*[11])

shows an extreme case where a very long time was required to pre-shear a flocculated monoionic montmorillonite suspension. Muds brought into the laboratory from a well may also require long pre-shearing times to reduce them to a state of shear similar to that in the well.

Slibar and Paslay[13] developed a set of constitutive equations containing five physical parameters which can be used to predict the effect of shear history on the flow of thixotropic materials. They obtained good correlation between their predictions and the experimental results of Jones and Babson.

The high gel strengths developed by thixotropic muds after prolonged periods of rest create another problem for the drilling engineer. The long-term

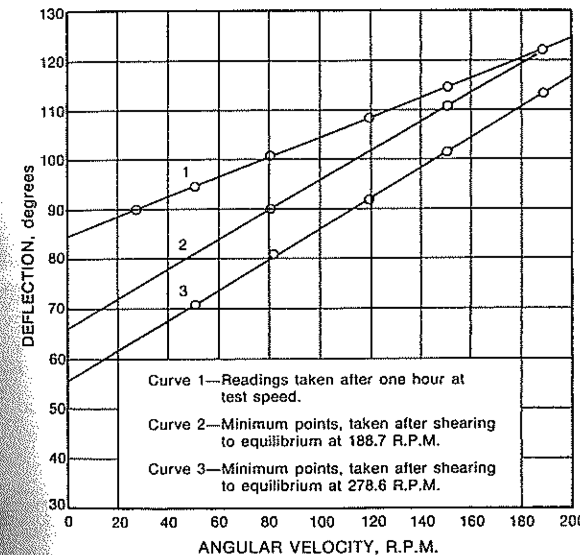
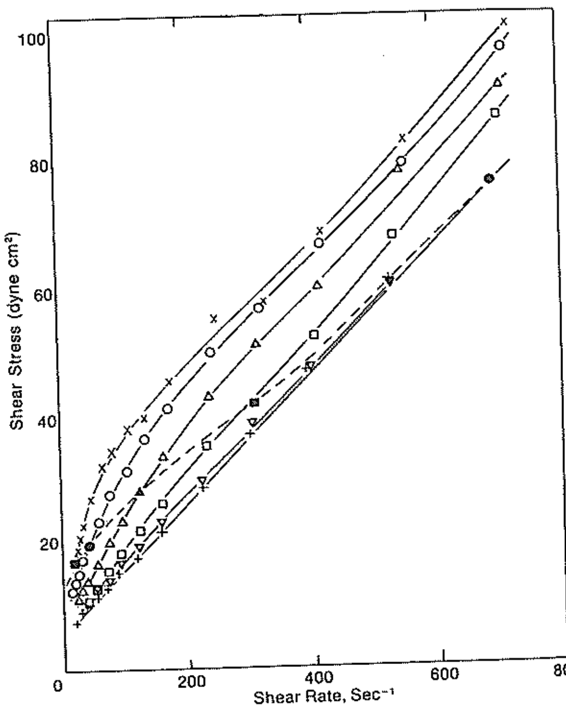


Figure 5-11. Equilibrium and instantaneous flow curves of the clay mud shown in Figure 5-10. Plastic viscosity and yield point are defined by instantaneous curves 2 and 3. (*From Jones and Babson.*[11])



—+— Instantaneous curves after pre-shearing to an equilibrium viscosity of 11.0 cp.
—▽— Instantaneous curves after pre-shearing to an equilibrium viscosity of 11.4 cp.
—□— Instantaneous curves after pre-shearing to an equilibrium viscosity of 13.6 cp.
—△— Instantaneous curves after pre-shearing to an equilibrium viscosity of 22.4 cp.
—○— Instantaneous curves after pre-shearing to an equilibrium viscosity of 47.2 cp.
—X— Instantaneous curves after pre-shearing to an equilibrium viscosity of 90.4 cp.
---- Equilibrium curve

Figure 5-12. Equilibrium and instantaneous curves for a 4.8% bentonite suspension. *(From Cheng, et al.*[12] *Courtesy of the Institute of Chemical Engineers.)*

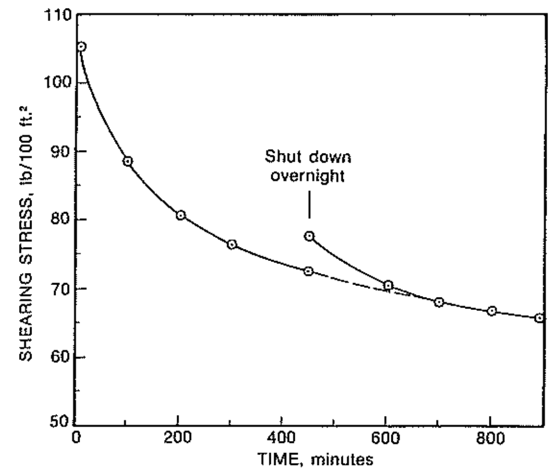


Figure 5-13. Slow breakdown of the gel structure caused by the shearing of a 4% slurry of pure sodium montmorillonite contaminated with 50 meq/liter of NaCl. Constant shear rate = 480 sec⁻¹. *(From Hiller.*[46] *Copyright 1963 by SPE-AIME.)*

gel strength is a major factor in the pressure required to break circulation after a round trip, and in the magnitude of swab and surge pressures. Unfortunately, the relation between gel strength and time varies widely from mud to mud, depending on composition, degree of flocculation, etc. (as shown in Figure 5–14), and there is no well-established means of predicting long-term gel strengths. The only important step in this direction was taken by Garrison,[14] who developed the following equation from the observed gelling rates of Californian bentonites:

$$S = \frac{S'kt}{1 + kt} \qquad (5\text{–}30)$$

where S is the gel strength at any time t, S^1 is the ultimate gel strength, and k is the gel rate constant. Equation 5–30 may be written as

$$\frac{t}{S} = \frac{t}{S'} + \frac{1}{S'k}$$

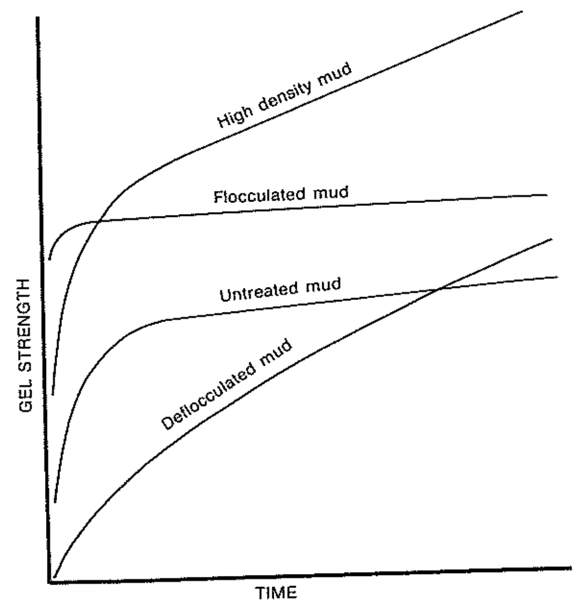


Figure 5-14. Increase in gel strength of various mud types with time (Schematic).

which shows that the plot of t/S versus t should be a straight line, the slope of which gives k and the intercept at zero time gives $1/S^{\prime}k$. Figure 5–15 shows plots of gel strength versus time for several bentonite suspensions, and Figure 5–16 shows t/S versus time for the same suspensions. Table 5–1 shows the ultimate gel strength and the gel rate calculated according to Equation 5–30.

There is little evidence in the literature to show whether or not Equation 5–30 applies to muds other than the bentonites tested by Garrison. Weintritt and Hughes[15] measured the gel strengths of some field muds containing

calcium sulfate and ferrochrome lignosulfonate in a rotary viscometer for rest periods up to one day. Application of their data to Equation 5–30 shows apparent compliance—although there was considerable scatter of the points—for rest periods up to two hours, but major deviations thereafter.

The work of these investigators showed the inadequacy of the current method of evaluating gel strength after 10-second and 10-minute rest periods. For example, Figure 5–15 shows that the gel strength may increase very rapidly immediately after the cessation of shearing, so that the initial gel strength (as commonly determined) is very sensitive to time, and meaningful values are therefore hard to obtain. Figure 5–15 also shows that the 10-minute gel strength is not a reliable indication of the ultimate gel strength. For instance, Curves 1 and 4 show approximately the same 10-minute gel strengths, but Table 5–1 shows that the ultimate gel strength of the Curve 1 mud was 34 and that of the Curve 4 mud was 104.

One obvious source of scatter in gel strength determinations is variation in the rate of application of load. The importance of this factor was demonstrated by Lord and Menzies,[16] who measured the gel strengths of a 10% bentonite suspension in a modified Fann rotary viscometer, at rates that varied from 0.5 to 100 rpm, and recorded the change in stress with time. Figures 5–17 shows the type of curves obtained. The maximum recorded stress was taken to be the gel strength, and the slope of the first part of the curve to be the rate of application of the load. Figure 5–18 shows that the observed gel strengths (designated Y) increased sharply with increase in stress load rate (designated τ). Similarly, in some tests using a pipe viscometer, Lord and Menzies observed that the breakdown pressure of a gelled mud increased with rate of application of pump pressure.

Table 5–1
Gel Rate Constants Calculated from Figure 5-15*

Curve	Suspension composition	S^{1}	k	pH
1	4·5% bentonite	34·4	0·047	9·2
2	5·5% bentonite	74·4	0·75	9·2
3	6·5% bentonite	114	0·79	9·2
4	5·5% bentonite 1% Na tannate	104	0·0089	9·2
5	5·5% monionic Na montmorillonite	99·7	0·033	9·9

*Data from Garrison (14).

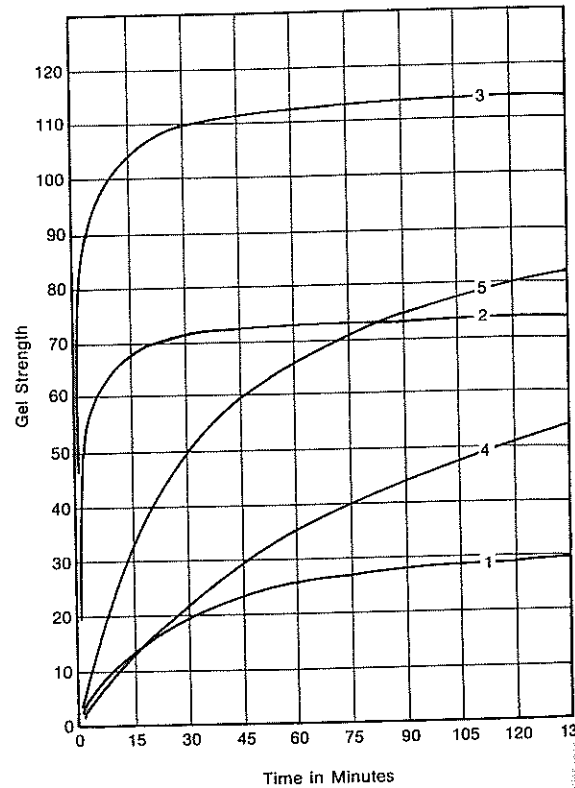


Figure 5-15. Relation between gel strength and time for Californian bentonites. *(From Garrison.[14] Copyright 1939 by SPE-AIME.)*

It appears, therefore, that there is a need for a method of predicting long-term gel strengths, so that circulation breakdown pressures can be estimated more accurately.

Pseudoplastic Fluids

Pseudoplastic fluids have no yield point; their consistency curves pass through the origin. The curves are nonlinear, but approach linearity at high shear rates. Thus, if stress readings taken at high shear rates are extrapolated back to the axis, there appears to be a yield point similar to that of a Bingham plastic; hence the name *pseudoplastic*. (See Figure 5–19.)

Suspensions of long-chain polymers are typical pseudoplastics. At rest, the chains are randomly entangled, but they do not set up a structure because the electrostatic forces are predominately repulsive. When the fluid is in motion, the chains tend to align themselves parallel to the direction of flow; this tendency increases with increase in shear rate, so that the effective viscosity decreases.

The consistency curve of the pseudoplastic flow model is described by an empirical equation, known as the *power law*,[17] viz:

$$\tau = K\left(\frac{dv}{dr}\right)^n \qquad (5\text{–}31)$$

where K and n are constants which characterize the flow behavior of the fluid. K is the *consistency index*, which corresponds to the viscosity of a Newtonian fluid, but is usually expressed in dynes/cm². n, the *flow behavior index*, indicates the degree of departure from Newtonian behavior.

Actually, the power law describes three flow models, depending on the value of n:

1. Pseudoplastic, $n < 1$, the effective viscosity decreases with shear rate.
2. Newtonian, $n = 1$, the viscosity does not change with shear rate.
3. Dilatant, $n > 1$, the effective viscosity increases with shear rate.

Since Equation 5–31 may be written

$$\log \tau = \log K + n(\log \gamma) \qquad (5\text{–}32)$$

(Text continued on page 210.)

JOHNSTON, O. C. AND GREENE, C. J., 1979
INVESTIGATION OF ARTIFICIAL PENETRATIONS IN THE VICINITY OF SUBSURFACE DISPOSAL WELLS

INVESTIGATION OF ARTIFICIAL PENETRATIONS IN THE VICINITY OF SUBSURFACE DISPOSAL WELLS

Technical Report

By

Orville Johnston, P.E. and

Charles J. Greene, Geologist

Texas Department of Water Resources

1979

ABSTRACT

The distance to which artificial penetrations should be reviewed in the vicinity of an injection well is dependent upon many variables including the hydrologic and geologic characteristics of the disposal zone, wastewater properties, injection rates and volumes, amount of separation between the base of fresh water and disposal zone, and other disposal operations utilizing the same interval. The Texas Department of Water Resources uses a 2½-mile radius of investigation as a rule of thumb for evaluating applications for waste disposal well permits; however, this distance can be adjusted if reservoir pressure resulting from well injection calculated using the nonequilibrium formula developed by Theis (1935) warrants. Recommendations to reenter and plug abandoned wells were made when pressure calculations indicated injection well operation might create a hazard in improperly plugged wells.

One method of establishing a uniform radius of investigation is the evaluation of disposal zone models. The models demonstrate the sensitivity of the radius of investigation to changes in different reservoir, fluid and injection variables. Since evaluations of artificial penetrations are made prior to drilling a disposal well, it is sometimes difficult to obtain accurate data for the variables affecting reservoir pressure. The investigation of a 2½-mile radius should be continued unless prior justification of a smaller radius is supported by reliable reservoir data. Injection operations should be reevaluated using the data obtained from reservoir testing after well completion.

INTRODUCTION

The Texas Department of Water Resources (TDWR) is the permitting agency for underground injection of industrial wastewater in Texas. One of the aspects of evaluating the suitability of a subsurface disposal project is the investigation of artificial penetrations in the vicinity of a proposed injection well. The distance to which abandoned or completed wells should be reviewed depends upon may variables, including the hydrologic and geologic characteristics of the disposal zone, wastewater properties, injection rate and volumes, amount of separation between base of fresh water and disposal zone, and other disposal operations utilizing the same interval.

The TDWR uses a 2½-mile radius of investigation as a rule of thumb. If reservoir pressure calculations indicate a significant pressure increase at 2½-miles, it may be determined that a greater area of review is necessary. Initially, all applicants must submit data on all known penetrations within a 2½-mile radius of investigation, unless prior justification for a smaller area of review is made. Additional data can be required if the reservoir pressure calculations warrant.

The determination of what constitutes an improperly completed plugged well is a difficult problem. Generally, a well that has been properly completed or abandoned is one where interformational transfer of fluids does not occur or will not occur as a result of changes in the reservoir pressure. Although our primary concern is protection of groundwater resources, oil and gas formations and other mineral bearing zones (i.e., magnesium produced from brines in the Yates Formation) should be protected.

The evaluation of a well must consider the regional geology, completion or plugging methods, and expected reservoir conditions. Most dry exploratory (oil wells) holes on the coastal plain were abandoned with surface casting set and cemented at the base of fresh water and long string casting was usually pulled. Cement plugs were set at the base of the surface casing and at the surface with drilling mud left in the hole in most wells. Due to the unconsolidated nature of the sediments and the plastic nature of most Tertiary shales, abandoned well bores probably do not remain open for long periods of time; however, for the technical evaluations of aquifer penetrations, the holes are assumed to remain open.

In the west and north-central part of the State injection zones, confining beds and most of the overburden strata are more competent, indurated rocks. Well bores will remain open for indefinite periods of time, and frequently drilling fluids and cement may not be in the well bore because of lost circulation zones.

Probably the greatest danger from artificial penetrations occurs in the West Texas area. Most reports of flowing abandoned wells or groundwater contamination from oil field brines are from this area. There are several possible causes for these problems including well bores that do not collapse around the casing or close after casing is removed, or lost circulation zones that force operators to unintentionally abandon or complete a well without adequate mud or cement.

Another problem common to all areas of the State is wells that are temporarily abandoned with casing in the hole and then forgotten. Often erroneous data is submitted on plugging or completion reports. For example, many tabulations indicate that a well is producing; however, the well may not have produced in may years and is temporarily abandoned.

METHOD OF EVALUATION

The staff evaluation of artificial penetrations primarily consists of review of the completion and/or plugging records in the subject area to identify improperly completed or abandoned wells. The pressure increase caused by the proposed injection program is calculated for each potential problem well using estimated values for transmissivity and storage in the nonequilibrium formula developed by Theis (1935). Multiple well and image well effects are considered where applicable. The nonequilibrium formula in United States Geological Survey units is expressed as:

$$\Delta h = \frac{114.6Q}{T} \int_{\frac{1.87r^2S}{Tt}}^{\infty} \frac{e^{-u}}{u} du$$

Where:

$$U = \frac{1.87r^2S}{Tt}$$

Δh = change in head at observation point (feet)
Q = discharge of well (gallons per minute)
T = transmissivity (gallons per day per foot)
r = distance to observation point (feet)
S = storage coefficient (dimensionless)
t = time (days)

The nonequilibrium formula is based on the following assumptions:

1) the aquifer is homogeneous and isotropic
2) the aquifer is of infinite areal extent and constant thickness
3) the discharging (injecting) well has a small diameter and completely penetrates the aquifer
4) water is released instantaneously from storage

Although no aquifer exists in nature that meets all of these assumptions, the nonequilibrium formula can be applied successfully to estimate pressure changes. The nonequilibrium formula was modified by Wenzel (1942) as follows:

$$\Delta h = \frac{114.6Q}{T} W(u)$$

Where W (u) represents the "well function of u" and other terms are as previously defined.

$$\int_{\frac{1.87r^2S}{Tt}}^{\infty} \frac{e^{-u}}{u} = W(u) = -0.577216 = \log_e u + u - \frac{u^2}{2.2!} + \frac{u^3}{3.3!} - \frac{u^4}{4.4!}$$

Values for W (u) for values of u from 10^{-15} to 9.9 were tabulated by Wenzel (1942).

The formula for obtaining u, as previously stated, is:

$$u = \frac{1.87r^2S}{Tt}$$

To solve the above equations and estimate pressure increases (Δh), the storage coefficient must be determined. The storage coefficient is the volume of water that is released or taken into storage per unit surface area of an aquifer per unit change in the component of head, normal to that surface. The formula for the coefficient of storage is:

$$S = f(w)\, Ø\, m \left(B + \frac{a}{Ø}\right)$$ (modified after Jacob (1950))

Where

- f(w) = weight of 1 cubic inch of formation water at stated temperature (pounds)
- Ø = porosity
- m = thickness of saturated aquifer (inches)
- a = 1/bulk modulus of compression of aquifer skeleton (square inches per pound)
- B = 1/bulk modulus of compression of aquifer water (square inches per pound)

REVIEW OF WASTE DISPOSAL WELL FILES

A review of TDWR Staff Technical Reports written during the evaluation of Industrial Waste Disposal Well Applications Nos. WDW-33 through WDW-151 was conducted to determine the distances from injection wells at which improperly abandoned or completed wells have previously posed a hazard to freshwater resources. The scope of this review is limited to those wells described in the Technical Reports as potential problems. An evaluation of the artificial penetrations in the vicinity of many of the earlier permitted wells should be made using real values for reservoir conditions and pressures resulting from many years of injection.

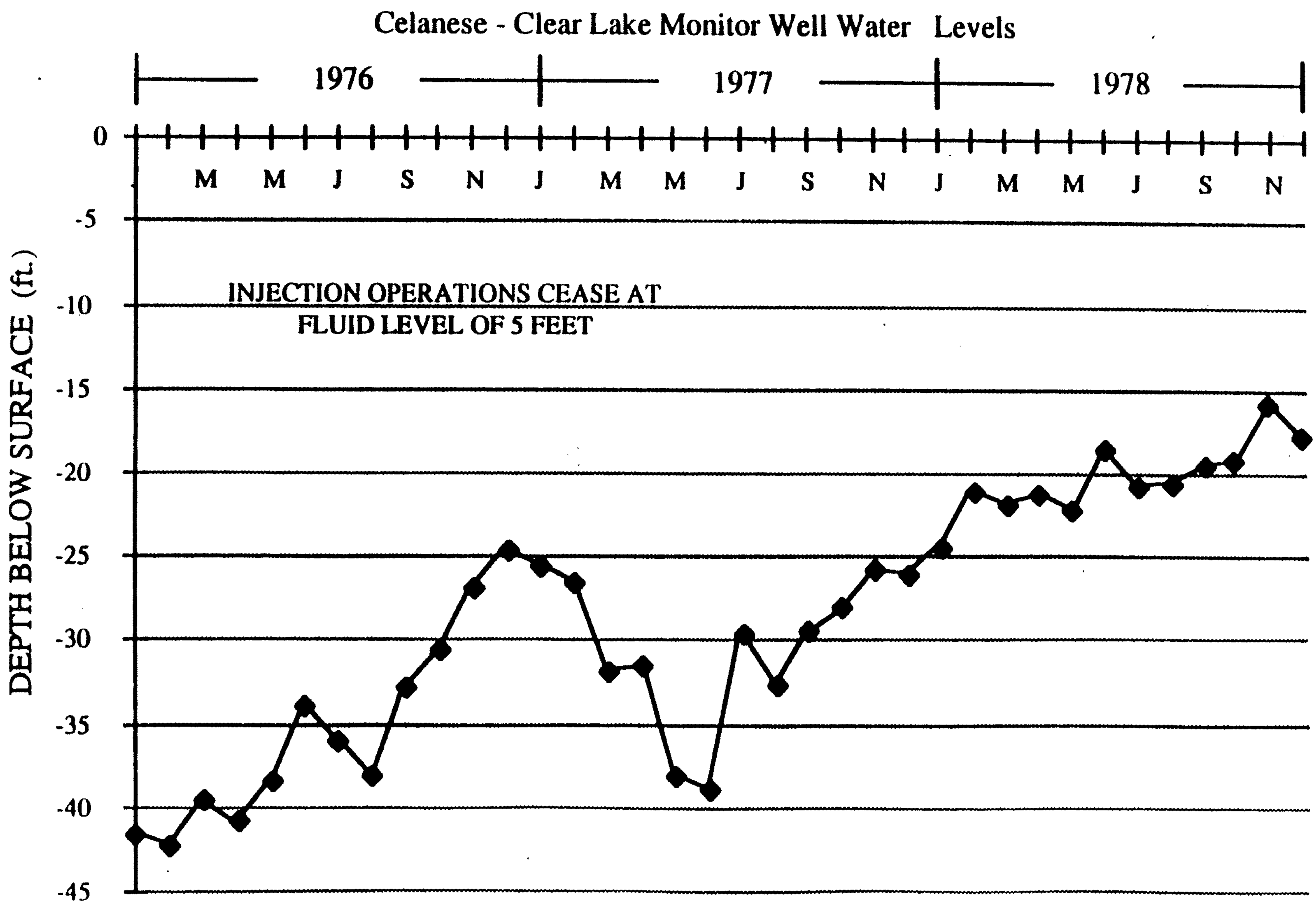
Recommendations to reenter and plug an improperly plugged well or to install a monitor well were made when the calculated increase in pressure at a potential problem well was predicted to be sufficient to cause fluids to migrate up the well bore of the problem well from the injection zone to the base of freshwater. If pressure calculations indicated that the injection well operation would not result in a significant increase in pressure at an improperly plugged well, plugging or monitoring was not recommended.

If pressure calculations indicated a potential hazard where plugging was not practicable, a pressure monitor well was installed and a provision in the permit required the permittee to cease injection operations and recomplete in another zone or plug and abandon the disposal well when reservoir pressures approached a critical level as indicated by the pressure in the monitor well. This approach was taken with Celanese Chemical Company's disposal wells which are located near the Clear Lake Oil Field where twenty producing wells were completed with insufficient surface casing. A graph of the pressure increase since 1976 is shown in Figure 1.

Of the files on 91 waste disposal wells reviewed, 39 Technical Reports described a total of 58 wells considered to be potential problems (not counting the 20 producing wells with insufficient surface casing near Celanese Chemical Company). Plugging or monitoring was recommended in the Technical Reports for 25 improperly completed or abandoned wells at distances ranging from 250 to 16,400 feet from the injection well. Calculations of pressure increase indicated that the injection operations would not create a hazard in 33 of the potential problem wells evaluated at distances ranging from 2,800 feet to 14,500 feet. These figures are listed in Table 1 and represented graphically in Figure 2.

This review suggests that no standard radius of investigation of artificial penetrations can be applicable to all proposed subsurface disposal projects. The distance from an artificial penetration to the injection well is only one of many variables controlling the pressure increase as a result of injection operations. For example, a recommendation to plug or monitor an unplugged well 16,400 feet from a proposed injection well in Harris County was made due to an injection rate of 1,650 gpm (WDW-89 and WDW-90) with nearby injection wells utilizing or permitted to utilize the same interval (Ethyl Corp. Permit No. WDW-86 @ 1000 gpm). Conversely, pressure calculations indicated no hazard for an unplugged well 2,800 feet from a proposed injection well in Nueces County (WDW-97 and WDW-98) based on an injection rate of 250 gpm with no other injection wells utilizing the same interval. Discussion of the relative significance of the variables affecting pressure increase is necessary to determine the distance from a proposed injection well at which artificial penetrations should be evaluated.

Figure 1



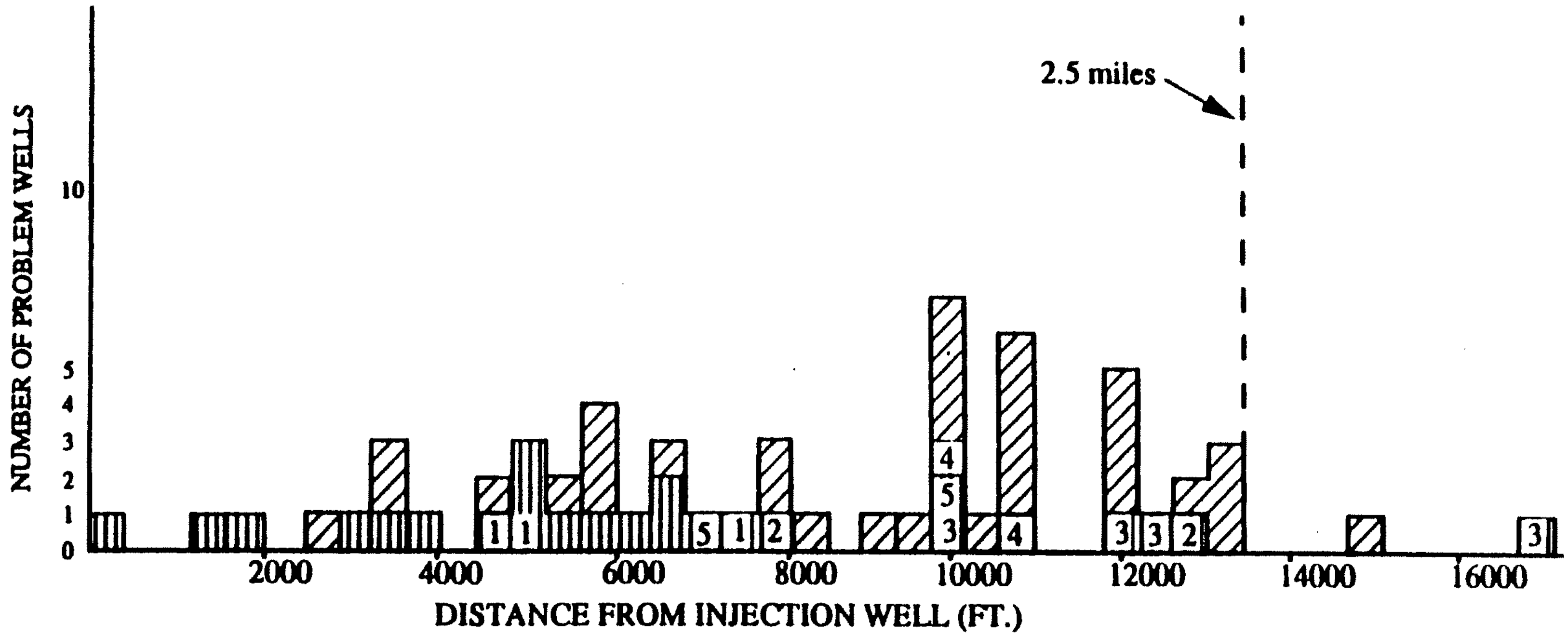
Celanese - Clear Lake Monitor Well Water Levels
1976
1977
1978
M M J S N J M M J S N J M M J S N
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
DEPTH BELOW SURFACE (ft.)
INJECTION OPERATIONS CEASE AT
FLUID LEVEL OF 5 FEET

Table 1. Evaluation of Petential Problem Well Recommendations
Waste Disposal Well Permit Nos. WDW-33 to WDW-151

WDW No.	No. of Wells	Distance (feet)	Recommendatio.
33, 45, 69*	20	7,920 to 13,200	monitor
34,113,114	4	10,200, 13,200 & 2 @ 12,000	Δρ calc no hazard
51	2	10,000, 10,560	Δρ calc no hazard
59, 71, 99		10,000, 10,560	plug or monitor
49	1	12,000	Δρ calc no hazard
70	2	11,800, 12,500	Δρ calc no hazard
73	2	5,400, 7,800	Δρ calc no hazard
78	2	3,000, 4,000	plug or monitor
78	3	5,900 to 6,000	Δρ calc no hazard
80, 127, 128	1	10,800	no hazard
80, 127, 128	1	12,700	plug
82, 83	1	8,000	Δρ calc no hazard
82, 83	1	4,900	plug or monitor
86**	4	1,900, 4,500, 5,000, 7,280	plug or monitor
89 & 90***		10,000, 12,000, 12,400, 16,400	plug or monitor
89 & 90	1	14,500	Δρ calc no hazard
91	1	7,920	plug or monitor
92	1	250	plug
97, 98	5	2,800, 6,700, 13,000 & 2 @ 13,200	Δρ calc no hazard
103	1	9,000	Δρ calc no hazard
105	1	9,500	Δρ calc no hazard
110	2	10,000	Δρ calc no hazard
111	2	3,300	Δρ calc no haz[illegible]
119	1	10,500	Δρ calc no h[illegible]
123, 124	1	3,600	plug or monitor
126	2	@ 10,500	Δρ calc no hazard
130	4	5,800, 6,500, 6,900 & 9,900	plug or monitor
133	1	1,320	plug or monitor
139	3	4,800, 2 @ 10,000	Δρ calc no hazard
140	1	5,000	plug or monitor
141	2	5,500, 6,500	plug or monitor

* Celanese Chemical Co. disposal wells are located near the Clear Lake Oil Field where some producing wells have short surface casing.
** 1,000 gpm
*** 1,650 gpm

Figure 2



Plug or Monitor Well Recommended

Δ_p Calculation No Hazard

Initial Review No Hazard
Plug or Monitor Well Recommended Later

1 - WDW 86 1000 gpm
2 - British - American UT B - 1 Plugged by Monsanto & Amoco
3 - WDW 89, 90 1650 gpm
4 - WDW 51 No Hazard; WDW 59, 71 99 - plug or monitor
5 - WDW 130 monitor

DISPOSAL ZONE MODELS

Establishing uniform regulations for a reasonable radius of investigation of artificial penetrations around injection wells is a complex problem due to the many variables that affect pressure. Models of disposal zones have been developed in an attempt to quantify the effects of some of these variables. The relative significance of the values assumed for these variables with respect to reservoir pressure can be assessed in this manner.

ASSUMPTIONS

A primary concern in the preliminary evaluation of a subsurface injection program is to insure that sufficient area around the disposal well is investigated; therefore, parameters required for the determination of the radius at investigation were selected which would result in a conservative analysis. The reservoir, fluid, and injection characteristics assumed for a general analysis are as follows:

1.	porosity	.10 to .30 (percent)
2.	permeability/viscosity ratios	10 to 400 milidarcies/ centipoise (md/cp)
3.	thickness	100 feet
4.	depth of injection zone	5.000 to 7.000 feet
5.	rock compressibility	4.8×10^{-6} to 3.2×10^{-6} psi^{-1}
6.	water compressibility	3.0×10^{-6} psi^{-1}
7.	fluid density (unplugged well bore)	9.0 lb/gal
8.	initial reservoir pressure gradient	.45 psi/ft.
9.	fracture gradient	.65 psi/ft.
10.	maximum injection rates	≤350 gpm (gallons per minute)
11.	project life	25 years

CALCULATION

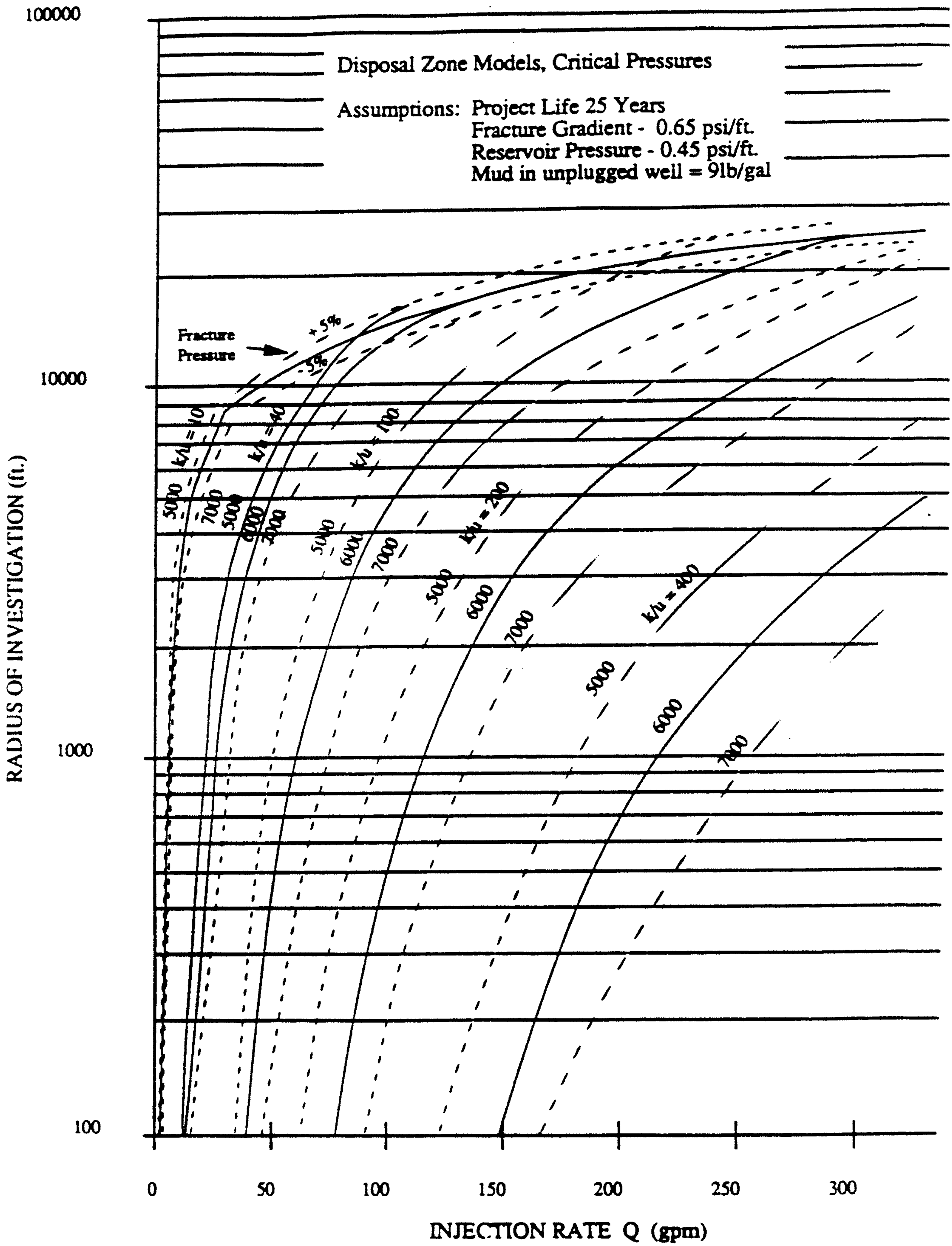
The increase in reservoir pressure resulting from 25 years of injection operations is estimated from the Theis non-equilibrium formula. The critical pressure shown on Figure 3 is the pressure required to displace 9 lb/gal mud in an unplugged well bore. These values are determined at various distances for three assumed depths (5,000, 6,000, and 7,000 feet) and five assumed permeability/viscosity ratios (10, 40, 100, 200, and 400 md/cp). Bottom hole pressure in the injection well is calculated assuming a fluid density of 30-40,000 ppm TDS (specific gravity of 1.04) and the bottom hole pressure in the unplugged well bore is calculated assuming a 9 lb/gal mud is left in the well (specific gravity of 1.085). The data is also plotted for porosity ranging from .10 to .30 and rock compressibility ranging from 4.8×10^{-6} psi/lb. A net sand thickness of 100 feet was assumed and various injection rates up to 350 gpm were used.

The maximum injection rate was determined that would not result in reservoir pressure exceeding the fracture pressure and is indicated on Figure 3. The fracture gradient was assumed to be .65 psi/ft and Figure 4 is a graph of the effect of $\pm 5\%$ error in the fracture gradient. Figure 5 is a graph of the effect of an error of $\pm 2\%$ in the initial reservoir pressure estimation.

LIMITATIONS

The limitations of a conservative nature of the disposal zone models presented include: no allowance for friction loss or skin effects, assuming constant injection rates and pressure for 25 years, constant (100 ft) thickness, assuming well bore of improperly plugged well remains open, and assuming hydrologic communication with improperly plugged well. Other limitations include the assumptions of: homogeneous isotropic media, compatibility.

Figure 3



Disposal Zone Models, Critical Pressures
Assumptions: Project Life 25 Years
Fracture Gradient - 0.65 psi/ft.
Reservoir Pressure - 0.45 psi/ft.
Mud in unplugged well = 9lb/gal
Fracture Pressure
+5%
-5%
k/u = 10
k/u = 40
k/u = 100
k/u = 200
k/u = 400
5000
6000
7000
RADIUS OF INVESTIGATION (ft.)
100000
10000
1000
100
0
50
100
150
200
250
300
INJECTION RATE Q (gpm)

Sensitivity of Calculated Radius of Investigation to Change of Fracture Gradient of ± 5%

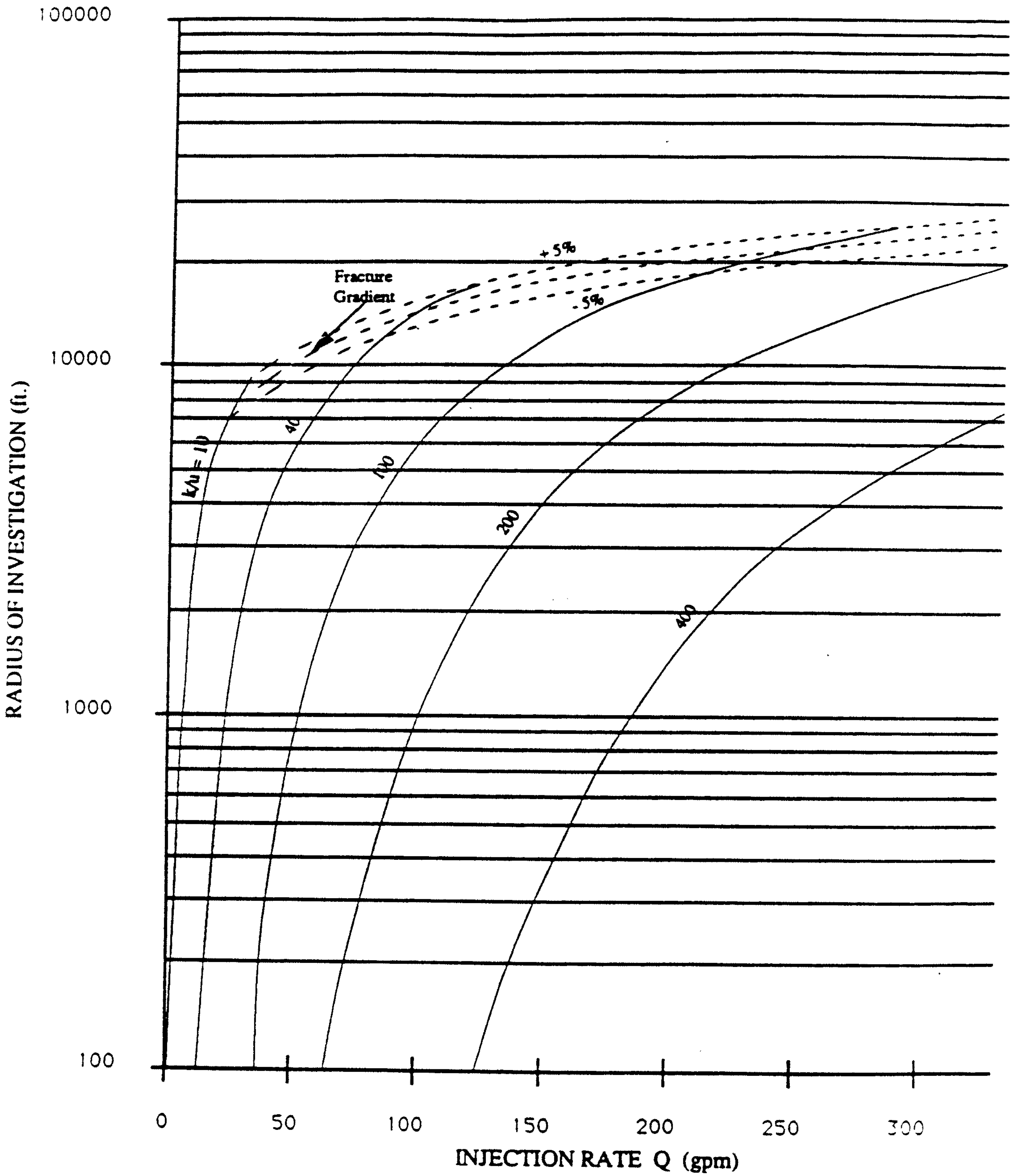
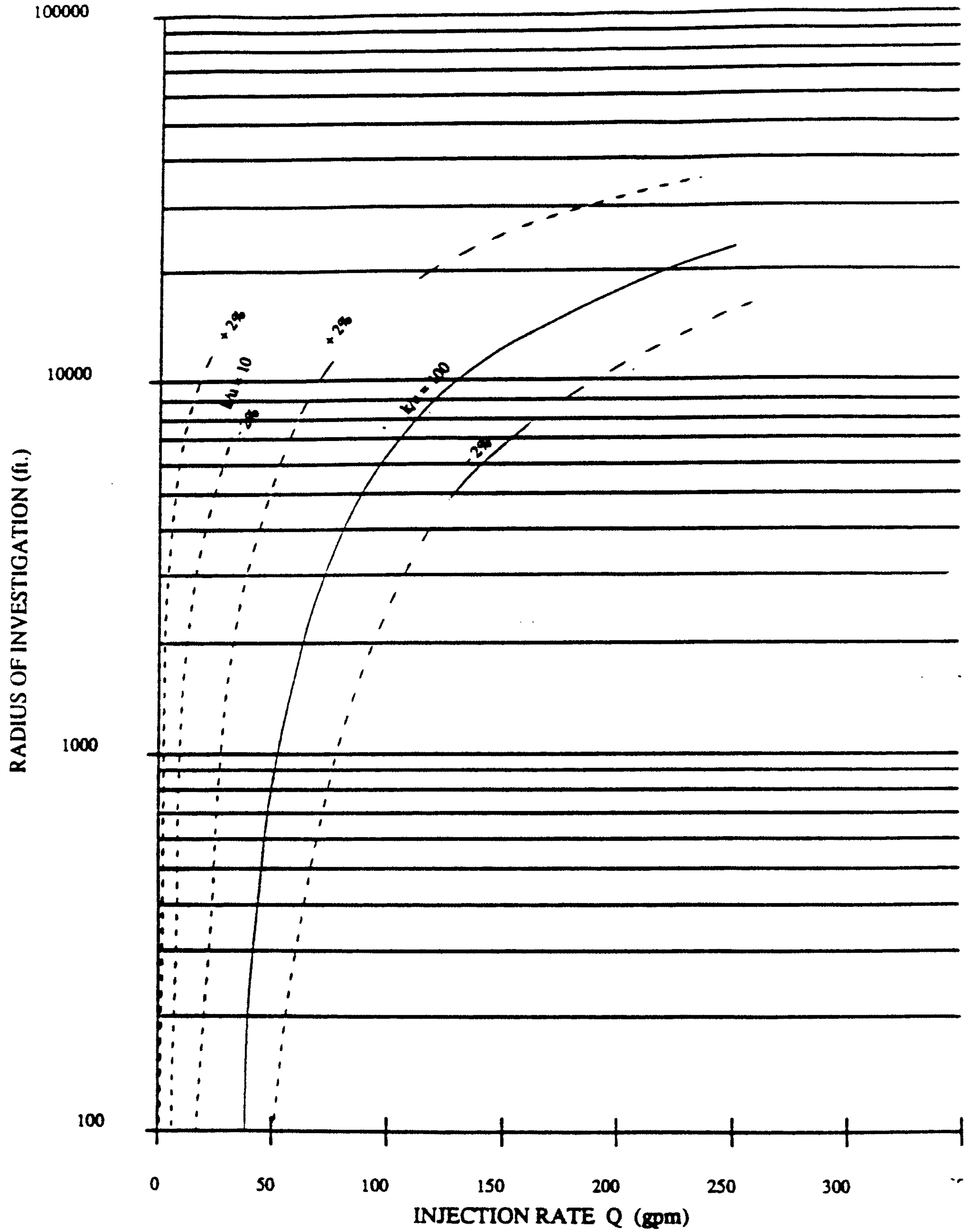


Figure 5

Sensitivity of Calculated Radius of Investigation
to Change of Fracture Gradient of ± 5%



CONCLUSIONS

The review of TDWR Staff Technical Reports prepared during the evaluation of waste disposal well applications indicated that the recommendations as to potential hazards of artificial penetrations were not strictly distance-related. Generally, more recommendations to plug abandoned wells were made for the closer wells evaluated, however, the exceptions show the significance of the assumed values for reservoir, fluid, and injection factors.

The disposal zones models demonstrated the relative significance of the reservoir, fluid and injection variables with respect to areal influence of well injection. The principal factors affecting reservoir pressure increase resulting from well injection appear to be: injection rate, thickness, initial reservoir pressure, permeability/viscosity ratios, method of plugging or completion of investigated wells, and depth of disposal zone. These models emphasize the necessity of obtaining accurate reservoir data for evaluation of pressure increases.

This report only scratches the surface of the possible applications of disposal zone models to predict pressure increases due to well injection. This approach should be very useful in evaluating salt water disposal projects associated with oil and gas production. The data developed from the disposal zone models indicates that the current practice of investigating artificial penetration within a 2½-mile radius around proposed industrial waste disposal wells should be continued, unless justification based on reliable reservoir data indicated otherwise. The modification of the disposal zone models to fit specific injection well sites should be considered, where applicable. Reevaluation of the radius of significant pressure increase should be examined when the reservoir data becomes available after well completion.

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Parameter Units	Time Days	Q gpm	Ø %	a psi/lb	B psi/lb	S	k/u md/cp	ρ ratio	Depth ft.	Radius ft.	Δp psi	Δp + BHP psi
									7000	10	321	3470
										1800	140	3290
		30								10	1040	2390
										9000	104	2350
		35							6000	10	1219	3919
										9000	122	2820
									7000	10	1393	4543
										9000	140	3290
		50	.30	$3.2X10^{-6}$	$3x10^{-6}$	.000185	100	1.04	5000	10	200	2450
										750	100	2350
									7000	10	200	3350
										130	141	3290
		250							5000	10	1005	3250
										25000	100	2350
		350							7000	10	1407	4556
										25000	141	3290
	9125	263	.10	$4.8X10^{-6}$	$3x10^{-6}$	.00023	100	1.04	5000	10	1045	
										16000	145	
		200								10700	145	
		100								2200	145	
		50								100	145	
		241								10	955	
		1100								35000	55	
		200								31000	55	
		100								16000	55	
		50								4800	55	
		25								450	55	
	9125	111.5	.10	$4.8X10^{-6}$	$3x10^{-6}$	.00023	40	1.04	5000	10	104[illegible]	
										10800	145	
		100								9400	145	
		50								2600	145	
		35								1400	145	
		25								225	145	
		102								10	955	
										23000	55	

Parameter Units	Time Days	Q gpm	Ø %	a psi/lb	B psi/lb	S	k/u md/cp	ρ ratio	Depth ft.	Radius ft.	Δp psi	Δp + BHP psi
		60								15000	55	
		30								6600	55	
	9125	50	.10	$4.8X10^{-6}$	$3x10^{-6}$	.00023	10	1.04	5000	10	1716	
		30.5								10	1046	
										6000	144	
		20								3400	145	
		10								700	145	
		27.8								10	955	
										12000	55	
										9800	55	
		10								5000	55	

APPENDIX

Parameter Units	Time Days	Q gpm	Ø %	a psi/lb	B psi/lb	S	k/u md/cp	ρ ratio	Depth ft.	Radius ft.	Δp psi	Δp + BHP psi
	9125	50	.10	$4.8x10^{-6}$	$3x10^{-6}$	.00023	10	1.04	5000	10	1716	3966
		30								10	1030	3280
										8000	105	2355
		50							6000	10	1716	4540
		35								10	1201	3900
										8000	123	2353
		50							7000	10	1716	4870
		40								10	1375	4525
										8000	141	3290
	9125	50	.10	$4.8x10^{-6}$	$3x10^{-6}$	.00023	40	1.04	5000	10	470	2820
										5500	103	2250
									6000	10	470	3170
										4000	121	2821
									7000	10	470	3620
										3000	137	3287
		100							5000	10	940	3190
										14000	102	2350
									6000	10	940	3640
										12000	118	3288
									7000	10	940	4090
										10000	138	3290
		105							5000	10	985	3235
										15000	100	2350
		130							6000	10	1200	3920
										15000	123	2920
		150							7000	10	1408	4560
										15000	142	3292
		50	.10	$4.8X10^{-6}$	$3x10^{-6}$	.00023	100	1.04	5000	10	198	2450
										750	98	2350
									6000	10	198	2900
										300	120	2820
									7000	10	198	3350
										100	140	3290

Parameter Units	Time Days	Q gpm	Ø %	a psi/lb	B psi/lb	S	k/u md/cp	ρ ratio	Depth ft.	Radius ft.	Δp psi	Δp + BHP psi
	9125	100	.10	$4.8X10^{-6}$	$3x10^{-6}$	.00023	100	1.04	5000	10	397	2650
										6000	99	2350
									6000	10	397	3100
										4000	120	2820
									7000	10	397	3550
										2500	140	3290
		200							5000	10	793	3050
										18000	100	2350
									6000	10	793	3500
										14000	121	2820
									7000	10	793	3950
										11000	140	3290
		252							5000	10	1000	3250
										23000	100	2350
		300							6000	10	1200	3900
										22500	120	2820
									7000	10	1400	4550
										22500	140	3290
	9125	200	.10	$4.8X10^{-6}$	$3x10^{-6}$	.00023	200	1.04	5000	10	410	2660
										8000	100	2350
									6000	10	410	3100
										5500	120	2820
									7000	10	410	3560
										3500	140	4550
		300							5000	10	619	2870
										17000	100	2350
									6000	10	619	3320
										13000	120	2820
									7000	10	619	3770
										10000	140	3290
	9125	300	.10	$4.8X10^{-6}$	$3x10^{-6}$	.00023	400	1.04	5000	10	321	2570
										5500	100	2350
									6000	10	321	3020
										3200	120	28

APPENDIX

CALCULATIONS

Fracture Pressures ±5%

Frac. press. = formation breakdown pr.
p = Frac press - bottom hole pressure

Depth (feet)	-5% Frac. Press.	p	Frac. Press.	+5% p	Frac. Press.	p
5000	3090	840	3250	1000	3410	116
6000	3705	1005	3900	1200	4100	140
7000	4325	1175	4550	1400	4780	160

Formation Fluid Density ±2%

Depth	-2%	
5000	2205	145
6000		
7000		

Depth	+2%	
2350	100	2295
2800	120	
3290	140	

ASSUMPTIONS

d = 100 ft.
t = 9125 days
Q = 350 gpm
Ø = 0.1 to 0.3
a = 4.8×10^{-6} to 3.2×10^{-6} psi^{-1}
B = 3×10^{-6} psi^{-1}
k/u = 10, 40, 100, 200, 400 md/cp
ρ = 1.04 (Formation Fluid)

depth = 5000, 6000, 7000 feet
frac. gradient = 0.65 psi/ft.
frac. pressure = 3250, 3900, 4550 psi
mud density = 9 lb/gal
specific gravity (mud) = 1.085
bottom hole pressure (unplugged well) 2350, 2820, 3290 psi
specific gravity (water) = 1.04
bottom hole pressure = 2250, 2700, 3000 (injector)

$$\Delta h = \frac{1146.Q}{T} W(u)$$

$$U = \frac{1.87\ r^2 S}{Tt}$$

Where:

Δh = change in head (feet)
Q = discharge (gpm)
T = Transmissivity (gpd/ft)
W(u) = well function of
r = radius from injection well (feet)
t = time since injection began (days)
S = storage coefficent

$$S = F(w)\ \varnothing\ m \left(B + \frac{a}{\varnothing}\right)$$

Where:

F(w) = formation factor
$\varnothing$ = porosity (percent)
m = thickness of aquifer (inches)
B = compressibility of water psi/lb
a = compressibility of aquifer skeleton psi/lb

JOHNSTON, O. C. AND KNAPE, B. K., 1986
PRESSURE EFFECTS OF THE STATIC MUD COLUMN IN ABANDONED WELLS

LP 86-06

Pressure Effects of the Static Mud Column in Abandoned Wells

Texas Water Commission

September 1986

PRESSURE EFFECTS OF THE STATIC MUD COLUMN IN ABANDONED WE

By

Orville C. Johnston and Ben K. Knape

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ABSTRACT

The objective of this research is to establish a reference framework (with respect to concepts, safety factors, etc.) concerning the status and condition of abandoned wells which may be located near an injection well operation. The validity of the assumption of a wellbore filled with mud of a minimum weight of 9 pounds per gallon for abandoned wells is confirmed through a survey of the literature and interviews of experts in the field. In addition to the resistance to vertical fluid flow in an abandoned well, which is conveyed by the hydrostatic head of 9 pounds per gallon mud, the gel properties of borehole mud alone in a 15-inch diameter wellbore at a 5,000 foot depth, will withstand at least 27.75 psi of reservoir pressure increase from injection. Other intangible safety factors include the following: (a) there is a high probability that wells abandoned after 1967 are properly plugged; and (b) wells abandoned during the period 1919-1967 may be properly plugged, even if documentation is lacking. Experience with well drilling has shown that uncased wells in the Gulf Coast region of Texas, and uncased wells which penetrate certain unstable rock formations of the Triassic System in West Texas, rapidly undergo borehole closure by the natural processes of borehole wall swelling, sloughing, and bridging. This report identifies 267 abandoned wells located near certain industrial waste disposal well sites which are assumed to be plugged with drilling mud only.

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PRESSURE EFFECTS OF THE STATIC MUD COLUMN IN ABANDONED WELLS

INTRODUCTION

The Texas Water Commission regulates Class I injection wells by permit. The permit process involves review of all artificial penetrations of the subsurface, within a 2.5 mile radius of a proposed injection well, to determine the maximum allowable reservoir pressure build-up without potential for causing fluid movement through abandoned wells. The review process must include consideration of problem wells which are abandoned with inadequate cement plugs or have inadequate or nonexistent plugging records. It has been assumed that such abandoned wells are filled with a 9 pound per gallon mud, unless otherwise documented.

The Commission has assumed in its permit review process, that the total reservoir pressure within the area of influence of an injection well should not exceed the hydrostatic head of the mud column at any unplugged abandoned well within the area. This criterion for safe limits on injection operations does not consider several factors which may add considerably to the safety of an injection operation.

Purpose

The purpose of this investigation is to evaluate the following with respect to artificial penetrations: (a) the history of drilling and plugging practices as they relate to the probability of interformational fluid transfer in abandoned wells; (b) gel strength of wellbore mud; and (c) effects of geologic and geographic differences as determinants of natural borehole closure.

Scope

This study includes the collection and compilation of all available data pertaining to the control of downhole pressure and potential for fluid movement in abandoned wells which are filled with drilling mud. In addition to the resistance to fluid flow conveyed by the weight of the mud column filling an abandoned well, the study will also consider the added pressure effects of the gel strength of drilling mud, the development of well drilling and plugging practices over the years, the probabilities of natural borehole closure, including the geologic determinants on the condition of the abandoned borehole, and the properties of drilling mud in the borehole after long periods of time. The scope of the study has been limited to literature and file research, interviews with persons experienced in well technology, and the preparation of a report which presents tabulated abandoned well data, location maps, and conclusions and recommendations.

Method of Investigation

Following the study proposal, formulated early in 1985, the investigation began in November, 1985, and involved two persons working full time. Persons experienced in the fields of well drilling, plugging procedures, and mud technology were interviewed concerning the ability of mud in abandoned wells to prevent fluid flow. Summaries of these interviews or "personal communications" are included in the Appendix to this report, along with summaries of literature of particular relevance to the study.

The literature review was accomplished by consulting references suggested by the persons interviewed, and by the assistance of the Commission's library staff and the U. S. Environmental Protection Agency (EPA) Region 6 staff in conducting computerized data base searches. The Commission's library staff used the Dialog Information Retrieval Services, Inc. system which has more than 220 available data bases. The four data bases of the Dialog system which contain engineering and geotechnical data were searched by inputting the key word groupings of "abandoned wells," "well plugging," mud-plugged wells," and "mud gel strength," and the various permutations of these groupings into the computer system. Also, a computer search of the National Ground Water Information Center (NGWIC) library files was provided by the EPA Region 6 office. The files or data bases searched are described under the heading of "Data Bases" following the Reference section of this report.

All literature relevant to the study is listed in this report under the heading of "References." Considering the extensive literature search undertaken, it was noted that there are remarkably few references in the literature to the specific topics of this study. Apparently, there have been very few opportunities to gather mud data from abandoned wells, since abandoned wells are seldom reentered. The relatively few known cases of reentering abandoned wells were either: (1) to recomplete the wells for injection operations for wastewater or brine disposal or water flood operations for enhanced recovery of petroleum, (2) excavations in mining operations which encountered abandoned mineral exploration holes, or (3) were ordered by the TWC or its predecessors, or the Railroad Commission of Texas, to properly plug the well to protect ground water or mineral resources.

Following the review of the literature and personal communications, criteria for identifying potentially problem abandoned wells within a 2-1/2 mile radius of an active permitted Class I waste disposal well were formulated. A potential problem well was defined, for the purpose of this study, as an abandoned well which lacked clear documentation of at least one cement plug between the disposal zone (injection formation) and the base of slightly-saline ground water (3,000 mg/l total dissolved solids). Using the criterion described above, potential problem abandoned wells were tabulated by the Commission's Underground Injection Control Section staff from the microfiche and hard copy files of permitted waste disposal wells.

The well tabulation portion of the study (Table 1) is presented alphabetically by waste disposal well permittee and/or site location. Figure 1 shows the sites in Texas of waste disposal well areas of review having one or more potential problem abandoned wells. Figures 2 through 28 show the locations of potential problem abandoned wells within each waste disposal well area of review.

In Table 1, each well is identified by well operator and well name (lease and well number within the lease). Drilling and abandonment dates are included in Table 1 to allow conclusions to be drawn concerning probable well depths, and well construction and plugging technology available at the time the well in question was drilled. Under the column heading of "Remarks," each of the wells compiled in Table 1 is characterized by documentation of wellbore mud, and long-string casing. When available, mud weights are also reported in this same column in pounds per gallon.

Acknowledgements

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HISTORICAL DEVELOPMENT OF DRILLING AND PLUGGING TECHNOLOGY

Drilling

Oil and gas wells that were drilled and abandoned prior to 1930 are probably not much deeper than 3,000 to 4,000 feet (Meers, 1985), (Hellinghausen, 1985), and (Smith, 1981). Data on these early wells is usually difficult to impossible to locate.

Prior to the early 1930's, much of the drilling for oil and gas production utilized cable tools and rotary rigs which were crude compared to today's equipment. The advent of World War II spurred efforts to improve drilling technology. Improvements in materials and computerization have contributed to the development of the sophisticated rotary rigs and drill bits which are available today. With the advances in drilling equipment, well depths have increased significantly so that depths exceeding 25,000 feet can be achieved today.

Coincidentally with rotary rig development, mud technology progressed from an art to a science. In contrast to cable tool drilling which did not employ drilling fluid systems (Davis, 1985 personal communication), rotary drilling requires drilling fluid to remove cuttings from the hole, to control pressure surges, to promote borehole stability, and to cool and lubricate the bit. In the early days of rotary drilling, drilling fluid was mostly water which when mixed with drill cuttings, resulted in "drilling mud" (Smith, 1985). Most early wells drilled by rotary techniques are therefore considered to have been drilled with "native muds" derived from the clay formations penetrated by the drill bit. Water had to be continually added to thin native muds, and the minimum weight for these drilling muds probably was not less than 9 pounds per gallon (Cox, 1986), (Davis, 1985), and (Marr, 1985). During the 1930's, bentonite and barite additives were first used to improve mud stability and increase mud weight for improved pressure control (Smith, 1985) and (Marr, 1985). Since that time, numerous service companies and research facilities have been established to provide personnel and technology necessary to control mud properties during a drilling operation. These properties include but are not limited to viscosity, gel strength, mud weight, and stability.

Plugging and Abandonment

Little thought was given to well abandonment in the early days of oil well drilling and production. Undoubtedly, many early wells which proved to be dry holes or which produced for a time before becoming inactive, were simply abandoned without any special closure procedures, either out of being unaware of any possible adverse environmental consequences of such actions, out of negligence, or out of being unwilling or unable to spend the necessary funds for plugging. Rotary drilled "dry holes" can be safely assumed to have been left full of mud as a minimum condition, because such wells are drilled, logged, and tested with mud in the wellbore, and there would be no economic reason to evacuate the hole of drilling mud prior to abandonment. Regarding abandonment of producing wells without filling the casing with mud, the Texas Water Commission and its predecessors have consistently not permitted waste disposal well completions in areas of a formation known to produce oil or gas. It is therefore unlikely that an inadequately plugged production well will lie within the area of influence of a permitted waste disposal well.

Some early attempts at plugging wells involved only driving a wooden plug into the well casing head. Over the years, abandoned wells have commonly had all sorts of unwanted debris thrown into the open well casings. The materials discarded into abandoned wells commonly included drilling site debris, scrap lumber, and metallic junk including broken tools. The modern practice of filling an abandoned well with mud and spotting cement plugs in the well has developed to meet the objective of confining all native fluids to the formations in which they were encountered. In leaving the wellbore full of mud, however, probably very little consideration has been given to possible circumstances such as (1) partial mud loss to "lost circulation" or "thief" zones in the subsurface, or (2) decrease in mud column height from removal of casing for salvage. Consequently, calculations of mud hydrostatic head in an abandoned well should take into account the possibility of incomplete filling of the hole from known lost circulation zones or other circumstances documented in records of the well.

The State of Texas has recognized the need for proper plugging of abandoned wells since 1899 (House Bill 542, 1899). The 1899 legislation calling for plugging of abandoned wells, however, did not designate to a particular branch of state government the regulatory and enforcement authority of this law.

In 1919, Senate Bill 350 gave the Railroad Commission of Texas (RRC) regulatory responsibility for proper well plugging. Current plugging regulations are detailed in Rule 14 of the Texas Railroad Commission, which was adopted on January 1, 1967. Rule 14 requires that abandoned wells be properly plugged with a specified combination of cement plugs and mud-laden fluid weighing at least 9.5 pounds per gallon, to confine oil, gas, or water to the strata in which they naturally occur. Rule 14 also requires that a well operator notify the Railroad Commission and all offset landowners and well operators of the intent to plug. Under Rule 14, the Railroad Commission reviews plugging plans for adequacy, requiring modifications to the plans as necessary to protect reserves of oil, gas, and water. According to Rule 14, plugging must commence in a well within one year of the end of drilling or production operations. Extensions of the maximum time period before commencing plugging operations may be granted by the Railroad Commission, provided that there is no pollution hazard, and provided there is adequate financial assurance in place to pay for well plugging without the expenditure of State funds. Noncompliance with Railroad Commission plugging rules subjects well operators to both civil and administrative fines. To remedy the problem of specific improperly abandoned wells in cases where the operator is unknown or financially insolvent, the Railroad Commission also administers a program which has plugged approximately 1400 such wells since 1965, using state funds.

MUD GEL STRENGTH

Most wells drilled for oil and gas use water-based drilling fluids which contain the native earth solids and rock cuttings acquired while drilling, and commercially available drilling mud additives. When a mud mix is allowed to remain quiescent for a period of time, a gel develops. Laboratory data acquired over relatively short intervals indicates that gel strength increases with time. Until the gel structure is broken, the mud will not be displaced. The pressure increase required to displace gelled mud can be significantly large and will often be a major factor in controlling fluid flow from a waste disposal formation.

The plastic flow of clay suspensions is well known. Gel strength data presented by (Garrison, 1938) indicates the strengths increase more rapidly at first, and then gradually approach a constant value as time passes. The reaction time follows a rather simple equation:

$$S = \frac{S'Kt}{1 + Kt}$$

where S' = gel strength after a long time
K = rate constant
t = time
S = gel strength at t

The equation may be rearranged so that a linear relationship exists between t/S and time.

The relationship can be expressed in the following equation:

$$\frac{t}{S} = \frac{1}{S'K} + \frac{t}{S'}$$

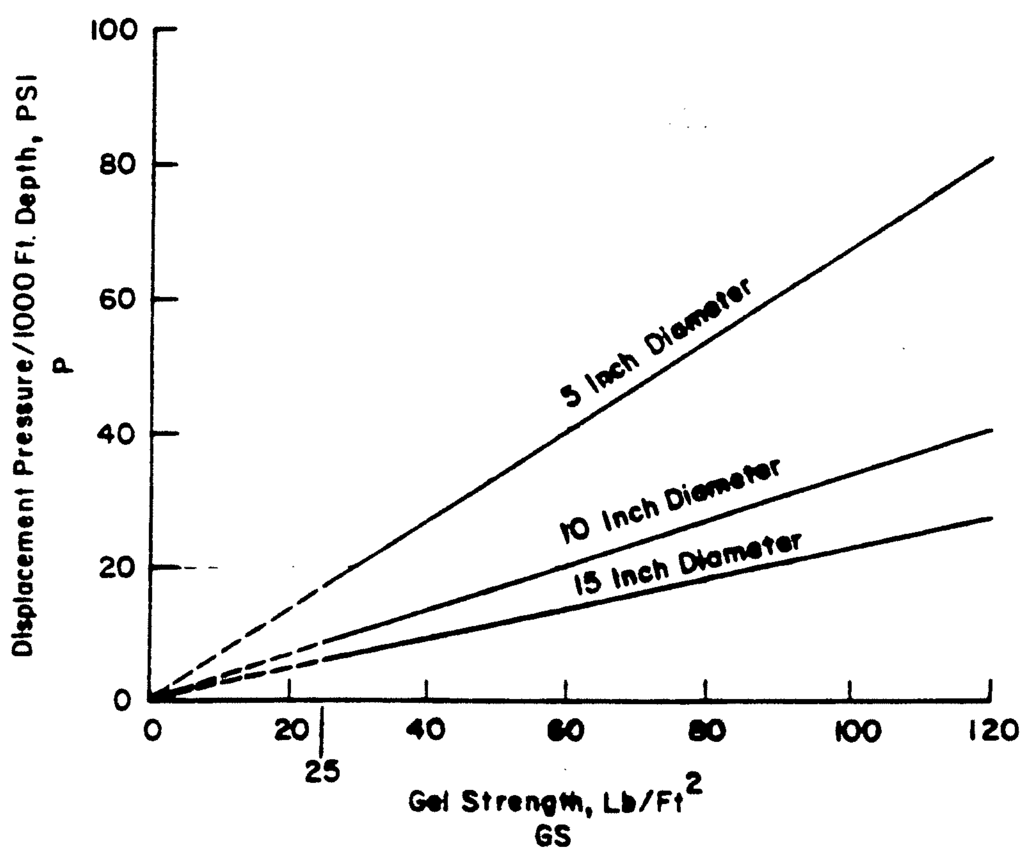
Based on limited data, drilling mud gel strengths ranging from 25 to 120 pounds per 100 square feet have been noted (Barker, 1981). When evaluating the effect of a mug plug on confining fluids in a reservoir, the most conservative value (or lowest gel strength) should be used to avoid an over optimistic estimate of the mud displacement pressure.

In addition to the pressure required to overcome the hydrostatic head of the borehold mud, the pressure necessary to displace the mud plug varies directly with the gel strength and well depth and inversely with borehole diameter (Barker, 1981) as follows:

$$P = \frac{0.00333\ (GS)(h)}{D}$$

where GS = gel strength, pounds/100 feet^2
h = height of mud column or depth of well, feet
D = hole diameter, inches
P = displacement pressure, psi

Displacement pressures based on gel strengths for hole diameters of 5, 10, and 15 inches are shown in graph form below:



Gel strengths of mud left in abandoned wells are generally unknown. The data cited above indicate that a mud plug with a gel strength of 25 pounds/100 feet^2, in a 5,000 foot deep well of 15-inch diameter should be capable of restricting a pressure difference of at least 27.75 psi. This is a relatively minor pressure restriction which should be regarded as a safety factor and not considered when developing operating parameters that would be acceptable for an injection well. It should be noted that drilling muds with high gel strengths (exceeding 100 pounds/100ft^2) would have a significant displacement pressure in abandoned wells 5000 feet or more in depth.

NATURAL BOREHOLE CLOSURE

Geologic factors such as sediment consolidation (cementation) and mineralogy are major determinants of the probability of natural borehole closure. These geologic factors are found to vary geographically throughout the State. Older sediments characteristic of West Texas are generally more consolidated, and uncased wellbores in that area are less prone to seal over by caving or sloughing of the wellbore walls (Marr, 1985), (Meers, 1985), (Johnson, 1985), (Davis, 1985), and (Kent and Bentley, 1985). Abandoned wells have been reentered and cleaned out for reuse after many years of dormancy in West Texas by merely washing out the wellbore mud with a drill bit (Marr, 1985).

In contast, the geologically young and unconsolidated sediments of the Gulf Coast tend to slough and swell, and an uncased well in that region commonly will squeeze shut within a matter of hours. Well bores have closed in while changing bits or running casing. Drillers sometimes have difficulty in finding and following the original wellbore when reentering and redrilling abandoned wells and attribute this problem to the natural healing of the sediments originally penetrated (Meers, 1985) and (Hellinghausen, 1985).

Most of the State's permitted industrial waste disposal wells are located on the Gulf Coast and in West Texas. Information gathered from literature and communications from experienced field personnel confirm the validity of characterizing these two regions of the State as one where natural closure of the boreholes probably occurs (Gulf Coast) versus one where boreholes may be stable and remain open for an extended time (West Texas).

A major exception to the normal stability of West Texas boreholes, however, is exhibited in uncased sections of wells penetrating certain shale formations of Triassic age. This phenomenon is typical below the base of the surface casing in a well with the long-string casing absent, because of never having been installed, or having been pulled from the well for salvage prior to abandonment. The Triassic formations which contribute to wellbore instability are generally referred to by drillers as "red beds." These beds consist largely of water-sensitive clays which swell and slough in a borehole, causing problems with the sticking of drill pipe and casing during well construction, and total hole closure during and after well abandonment.

ANALYSIS OF ARTIFICIAL PENETRATIONS

The 267 wells in Table 1 represent the results of the survey of Texas Water Commission files to locate all abandoned wells which (1) penetrate a disposal zone within 2-1/2 miles of an active waste disposal well, and (2) lack clear documentation of proper plugging with cement to isolate wastes injected into strata containing ground water of more than 10,000 mg/l total dissolved solids, from strata containing ground water of less than 3,000 mg/l total dissolved solids. This study has attempted to determine if these 267 abandoned wells (Table 1) pose a problem in being potential avenues of fluid movement between formations because of elevated reservoir pressures resulting from injection operations.

Sixteen (16) of the 267 abandoned wells in Table 1 were plugged after the 1967 adoption of Rule 14 by the Railroad Commission of Texas, and may therefore be assumed to be plugged in a manner which will prevent interformational transfer of fluids. Rule 14 standardized plugging procedures in all Railroad Commission districts in Texas, many of which procedures had long been required at the discretion of the various district supervisors. Implementation of Rule 14 also insured that abandoned wells are plugged within one year following the cessation of drilling or production operations, unless the Railroad Commission has granted an extension of this time period conditioned upon there being no pollution hazard and no risk of State funds for plugging the well.

Of the 251 wells in Table 1 which were abandoned prior to the adoption of Railroad Commission Rule 14, 238 are shown by available records to be Gulf Coast wells without long-string casing. Uncased wells in the Gulf Coast region are not considered to pose a problem to waste disposal well operations because of the high probability of natural borehole closure, which is a property of the unconsolidated sediments characteristic of that region of the State.

The remaining 13 wells in Table 1 which were abandoned prior to adoption of Rule 14 are assumed to have boreholes intact by reason of (1) full hole casing, or (2) consolidated host sediments. In regions such as West Texas, which are characterized by hard consolidated sediments, it has been determined that boreholes may remain open for several decades without casing. Each of these remaining 13 abandoned wells in Table 1 has been evaluated in the waste disposal well permitting process to confirm that the pressure build-up at the abandoned well, resulting from injection into the nearby waste disposal well, will be less than the hydrostatic head of 9 pound per gallon mud filling the abandoned well.

Additional factors which may add significantly to the safety of mud plugs in abandoned wells where documentation of the proper cement plugs is lacking include the following:

(1) Whereas Railroad Commission Rule 14 represented primarily a refinement and standardization of existing plugging practices, many wells which were abandoned before 1967 were properly plugged with cement, even if full documentation is lacking. The problem of inadequate documentation for abandoned wells includes circumstances ranging from failure to file the proper well records, to administrative problems in processing and storing records. Indeed, many instances of inadequate documentation are the result of well records having been rendered illegible by photocopying and microfilm reduction.

(2) Because of the limitation of early drilling technology, many wells drilled prior to 1930 will not penetrate to depths of modern waste disposal well injection zones.

(3) Mud gel strength increases the pressure required to displace the hydrostatic column of wellbore mud from an abandoned well.

(4) Triassic "red beds" in West Texas exhibit the property of natural borehole closure in uncased intervals of a well. It is therefore a possibility that an abandoned well with incomplete documentation in West Texas will be naturally sealed if the well was left with no casing through an interval of "red beds."

CONCLUSIONS

1. Wells that were abandoned during the period 1919-1967 may be properly plugged even if documentation is lacking, and there is a very high probability that all wells abandoned after 1967 are properly plugged.

2. Abandoned uncased wells in the Gulf Coast region of Texas and in Triassic "red beds" of West Texas rapidly undergo borehole closure by the natural processes of unstable formations.

3. Abandoned uncased wells in consolidated hard rocks may remain open and stable over time ranging from years to several decades.

4. In the absence of cement plugs in an abandoned well near injection operations, the wellbore mud will resist vertical fluid movement to the degree to which the sum of the mud hydrostatic head, mud gel strength, and borehole restrictions exceed the formation pressure of the injection zone.

5. Mud company lab data indicate that mud gel strength increases with time and temperature. In the general absence of mud gel strength data for abandoned wells, a minimum gel strength of 25 lb/100 ft^2 can be conservatively assumed.

6. Calculations of mud hydrostatic head in an abandoned well should take into account the possiblity of incomplete filling of the hole due to known lost circulation zones, or other circumstances documented in the operating records of the well.

7. A search of the Commission's waste disposal well files has identified 267 abandoned wells (Table 1) that were considered to be incompletely plugged or of uncertain plugging status, because cement plugs could not be documented between the injection zone (with groundwater of 10,000 mg/l or greater, total dissolved solids) and the base of fresh to slightly-saline ground water (3,000 mg/l or less, total dissolved solids). These 267 abandoned wells are distributed between 38 of the 53 active industrial or commercial waste disposal well operations (sites) in Texas. None of these abandoned wells are considered to pose a problem of interformational fluid flow.

RECOMMENDATIONS

Conditional upon available funding, a second phase of study should be carried out consisting of laboratory and field investigations to verify the conclusions of this initial phase of the study. The laboratory study should determine the effect of temperature, time, pressure, and composition on mud gel strength. The field investigations should consist of re-entering selected mud-filled abandoned wells in the Gulf Coast and West Texas regions to determine mud conditions and to look for evidence of fluid movement up the wellbore. Finally, this proposed second phase of work should include the drilling of test holes in the immediate vicinity of selected abandoned wells for the purpose of reservoir pressure monitoring.

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DATA BASES

COMPENDEX

1970-present, 1,415,000 records, monthly updates (Engineering Information, Inc., New York, NY).

The COMPENDEX data base is the machine readable version of the Engineering Index (Monthly/Annual), which provides abstracted information from the world's significant engineering and technological literature. The COMPENDEX data base provides worldwide coverage of approximately 3500 journals and selected government reports and books.

GEOREF

1919-present (North American material), 1967-present (worldwide material), 1,005,000 records, monthly updates (American Geological Institute, Falls Church, VA).

GEOREF provides comprehensive access to more than 4,500 international journals, plus books, conference papers, government publications, dissertations, theses, and maps concerned with all aspects of geology, geochemistry, geophysics, mineralogy, paleontology, petrology, and seismology. Approximately 40% of the indexed publications originate in the U.S. and the remainder from outside the U.S. Publications of international organizations make up about 7% of GEOREF.

NGWIC DATA BASE

Computerized bibliographic ground water data base featuring nearly 50,000 documents, indexed by more than 700 hydrogeologic descriptions and virtually any relevant aquifer geographic, chemical, biologic, and reference term. The National Ground Water Information Center (NGWIC) is funded in part by the U.S. EPA and is managed by the National Water Well Associaiton (NWWA). The NGWIC DATA BASE has recently changed its name and address to GROUND WATER ON-LINE, NGWIC, 6375 Riverside Drive, Dublin, Ohio 43017.

NTIS

1964-present, 1,122,000 records, biweekly updates (National Technical Information Service, NTIS, U.S. Department of Commerce, Springfield, VA).

The NTIS data base consists of government-sponsored research, development, and engineering, plus analyses prepared by federal agencies, their contractors or grantees. It is the means through which unclassified, publicly available, unlimited distribution reports are made available for sale from such agencies as NASA, DDC, DOE, HHS (formerly HEW), HUD, DOT, Department of Commerce, and some 240 other units. State and local government agencies are now beginning to contribute their reports to the file.

The NTIS data base includes material from both the hard and soft sciences, including substantial material on technological applications, business procedures, and regulatory matters. Many topics of immediate broad interest are included, such as environmental pollution and control, energy conversion, technology transfer, behavior/societal problems, urban and regional planning.

WATER RESOURCES ABSTRACTS

1968-present, 176,000 records, monthly updates (U.S. Dept. of the Interior, Washington, D.C.).

WATER RESOURCES ABSTRACTS is prepared from materials collected by over 50 water research centers and institutes in the United States. The file covers a wide range of water resource topics including water resource economics, ground and surface water hydrology, metropolitan water resources planning and management, and water-related aspects of nuclear radiation and safety. The collection is particularly strong in the literature on water planning (demand, economics, cost allocations), water cycle (precipitation, snow, ground water, lakes, erosion, etc.), and water quality (pollution, waste treatment).

WRA covers predominantly English-language materials and includes monographs, journal articles, reports, patents, and conference proceedings.

Table 1.—Wells Lacking Documentation of Cement Plugs to Protect Usable Water

Remarks: [1]Indicates inadequate documentation of proper construction and abandonment.
[2]Indicates abandoned with mud in hole but lacking documentation of proper cement plugs.
[3]Indicates long string casing in hole below surface casing.
Mud weights in pounds per gallon are indicated thusly, [9.5 lb/gal].
Disposal zone depths in feet below land surface are indicated thusly, DZD 4,900 Feet.

Permittee / Site, County / Disposal Zone Depth (DZD) / WDW No.	Well Number On Maps	Operator	Well Name	Date Drilled	Date Plugged	Remarks
Cecos International						
Odessa Plant, Ector Co.						
DZD 4,900 Feet						
WDW-146	1	Gulf Oil	CT-1	—	1956	1
Celanese Chemical Co.						
Bay City Plant, Matagorda Co.						
DZD 3,300 Feet						
WDW-14, 32, 49, 110	2	United N & S	Wendl, et al. No. 1	1942	1952	2, 3
	3	do	Dowdy No. 1	—	1944	1
	4	do	Lambert No. 1	—	1952	2, 3
	5	do	Stoddard No. 7	1942	1952	2, 3
	6	do	Pierce Est. No. 1	1954	—	2, 3
Bishop Plant, Nueces Co.						
DZD 4,200 Feet						
WDW-210, 212	7	Hooser	L. Davis No. 1	—	—	1
	8	Haynes & U. T. Drill	O. Janke No. 2	1963	—	1
	9	Humble Oil	King Ranch-Big Cesar No. 3	—	1966	1
Clear Lake Plant, Harris Co.						
DZD 4,600 Feet						
WDW-33, 45	10	Exxon	Humble-West Fee "C" 4	1939	1939	2
	11	do	Humble-West Fee "C" 45	1940	1948	2
	12	do	Humble-West Fee "C" 43	1940	1940	2
	13	do	Humble-West Fee "C" 3	1939	1963	2
	14	do	Humble-West Fee "C" 32	1940	1972	2
	15	do	Humble-West Fee "C" 58	1940	—	1
	16	do	Humble-West Fee "C" 2	1938	1939	2

Table 1.—Wells Lacking Documentation of Cement Plugs to Protect Usable Water—Continued

Permittee Site, County Disposal Zone Depth (DZD) WDW No.	Well Number On Maps	Operator	Well Name	Date Drilled	Date Plugged	Remarks
Celanese Chemical Co. Clear Lake Plant, Harris Co.	17	Exxon	Humble-West Fee "C" 12	1939	1970	2
	18	do	Humble-West Fee "C" 54	1940	1940	2
	19	do	Humble-West Fee "C" 50	1940	1940	2
	20	do	Humble-West Fee "C" 1	1964	—	2
	21	do	Humble-West Fee "C" 62	1957	1957	2
Chemical Waste Management Corpus Christi Plant, Nueces Co. DZD 3,470 Feet WDW-70	22	Ivan J. Allen	Agnes Jurica, et al. No. 1	—	1966	2
	23	Seaboard Oil	Ed Jurica, et al. No. 1	1937	1937	2
	24	Ben D. Marks	Lockett No. 1	1950	1950	2
	25	Texas Southern Oil & Gas	N. V. Rambo No. 1	—	1954	2
	26	Mariss, Weisman & Train	Joe Hroch No. 1	1950	1950	2
	27	Black & Steven	Jochete No. 1	—	1965	2
	28	Ed M. Jones	Lucy F. Cooke No. 1	—	—	1
	29	C. A. Black, Jr.	Petty No. 1	—	1964	2
	30	Sam Wilson	Herold No. 1	1937	1937	2
	31	Jack L. Hamon	W. T. Pulliman No. 1	1967	1968	2
	32	S. H. Powell & S. W. Corporation	Albeta Zolansky No. 1	—	1955	2
	33	Appel Petroleum	Lamar Folda No. 1	—	1958	2
	34	W. R. Lloyd	Jacob Nemce No. 1	—	1960	2
	35	W. E. Fox, Trust	R. N. O'Neil No. 1	1950	1950	2
	36	Graham & Waldron	Singer No. 1	1941	1941	1
	37	Arnold Well Service & Morgan	C. T. Richardson No. 1	—	1956	2
	38	Howell	Merriman No. 1	—	—	1
	39	C. C. Winn	Dane Lamar Smith No. 1	—	1960	2
	40	do	F. V. Arvin No. 1	—	1960	1
	41	Strike Resources	Sun Kosar No. 1	—	—	1
	42	Sun Oil	W. S. Kirkpatrick No. 1	1972	1972	2
	43	Knox Industries	Holly No. 1	—	—	1

Table 1.—Wells Lacking Documentation of Cement Plugs to Protect Usable Water—Continued

Permittee Site, County Disposal Zone Depth (DZD) WDW No.	Well Number On Maps	Operator	Well Name	Date Drilled	Date Plugged	Remarks
Chemical Waste Management Corpus Christi Plant, Nueces Co.	44	Coquina Oil	Valka No. 1	—	—	1
	45	Train-Wiseman	Ed Jurica Ent. No. 1	1950	1951	1
	46	Coastal States Gas	Pauline Kraft No. 1	1971	1971	2
	47	Canus Petroleum	F. Evans Gas Unit No. 1	1977	1981	2
	48	R. L. Siboal	Batek No. 1	—	—	1
	49	Aminol USA	Kureska No. 1	—	—	1
	50	McFarland	J. Houch No. 1	—	—	1
	51	Nor-Am Petroleum	Peterson Prop. No. 1	—	—	1
	52	W. B. Dansfield	Holly No. 1	—	—	1
	53	Winn	London No. 1	—	—	1
	54	Graham	Lear No. 1	—	—	1
	55	Cox	Fitzpatrick No. 1	—	—	1
	56	Kelly-Bell	Baldwin Farms "G" No. 1	—	—	1
	57	Canus Petroleum	Edwards No. 1	—	—	1
	58	McFarland	Jurica No. 1	—	—	1
	59	Marks	Houch No. 1	—	—	1
	60	Knox Industries	Peterson Properties No. 1	—	—	1
	61	Geodominion Petroleum	Irma R. Petty No. 1	1984	1984	2
	62	D. H. Geiser	L. P. Cook Est. No. 1	—	—	1
	63	R. C. Hagens	Behman Brothers Foundation No. 1	—	—	1
	64	Cenergy Exploration	Ennis Johnson No. 1	—	—	1
Corpus Christi Petrochemical Co. Robstown Plant, Nueces Co. DZD 7,130 Feet WDW-152, 153	65	Renwar Oil	C. Harrington No. 1	1938	—	1
	66	do	C. Harrington No. 2	1938	—	1

Table 1.—Wells Lacking Documentation of Cement Plugs to Protect Usable Water—Continued

Permittee Site, County Disposal Zone Depth (DZD) WDW No.	Well Number On Maps	Operator	Well Name	Date Drilled	Date Plugged	Remarks
DUMAS AREA						
Diamond Shamrock Corporation Dumas Plant, Moore Co. DZD 1,106 Feet WDW-102, 192, 225, 226						
Lundberg Industries, Ltd. Dumas Plant, Moore Co. DZD 1,125 Feet WDW-3	67	Diamond Shamrock	W. W. Burnett No. 1	1932	1932	2
	68	Shamrock Oil	Coffee No. 1	1931	1936	1
	69	do	M. Johnson No. 1	1941	—	1
	70	do	Luckhardt No. 1	1941	1965	1
	71	Gulf Oil & Phillips Petroleum	Fisher No. 2	—	—	2
	72	Shamrock Oil	Brumley No. 5	—	1966	2
E. I. DuPont De Nemours & Co. Corpus Christi Plant, San Patricio Co. DZD 4,050 Feet WDW-109, 121	73	A. L. Bob	J. Green Est. No. 2	1938	1938	1
	74	Eleanor Oil	J. Green Est. No. 1	1937	1937	1 [9.8 lb/gal]
	75	Hooper Rutherford	J. D. & Edith Willis No. 1	—	—	1
	76	Eleanor Oil	W. Kline No. 1	1936	1936	1
La Porte Plant, Harris Co. DZD 4,800 Feet WDW-82, 83, 149	77	Gulf Oil	Texas State (30413) No. 3	1963	1963	2
	78	do	Texas State (30413) No. 2	—	—	1
	79	do	Texas State (30413) No. 1	—	—	2

Table 1.—Wells Lacking Documentation of Cement Plugs to Protect Usable Water—Continued

Permittee Site, County Disposal Zone Depth (DZD) WDW No.	Well Number On Maps	Operator	Well Name	Date Drilled	Date Plugged	Remarks
E. I. DuPont De Nemours & Co. La Porte Plant, Harris Co.	80	Humble Oil & Refining Co.	Hog Island Fee (01796) No. 1	—	—	1
	81	Crown Central Petrochemical	Eugene Bray, et al. No. 1	1961	1961	1
	82	Copeland Oil	Robert Stateland No. 1	—	—	1
	83	Slater, Williamson, & Hughes	C. M. Morris No. 1	1966	1966	2
	84	Turnbull & Irwin	Helen Dunn No. 1	1934	1934	2
	85	Gidden & Shriver	W. D. Sutherland, et al. No. 1	—	—	1
	86	Humble Oil	S. A. Girard & C. A. Bryan No. 1	—	—	1
	87	Amerada Petroleum, or Humble Oil	Unknown	—	—	1
	88	Amerada Petroleum	Unknown	—	—	1
	89	W. D. Fitzgerald	E. K. Gray	—	—	1
	90	Melba Oil Co.	Humble Oil	—	—	1
	91	J. R. Copeland	Humble Oil, et al. No. 1	—	—	1
Sabine Riverworks, Orange Co. DZD 4,300 Feet WDW-54, 55, 56, 57, 132, 191, 207	92	J. R. Neal	L. Neal No. 1	—	1971	1
	93	Wells, Trustee	W. Stark No. 1	1927	1927	1
	94	do	H. W. Stark No. 1	1927	1927	1
	95	do	H. W. Stark No. 1	1927	1927	1
Victoria Plant, Victoria Co. DZD 3,000 Feet WDW-4, 28, 29, 30, 105, 106 142, 143 144, 145	96	Renwar Oil	J. Weaver No. 1	1939	—	2
	97	Bridwell Oil	T. Fromme No. 1	1948	—	2
	98	Guadalupe Valley Oil	Santa Claus No. 1	—	—	

Table 1.—Wells Lacking Documentation of Cement Plugs to Protect Usable Water—Continued

Permittee Site, County Disposal Zone Depth (DZD) WDW No.	Well Number On Maps	Operator	Well Name	Date Drilled	Date Plugged	Remarks
E. I. DuPont De Nemours & Co. Victoria Plant, Victoria Co.	100	Birdwell Oil	B. Spies No. 1	1944	—	1
	101	Renwar Oil	M. Stoner No. 1	1938	—	2
	102	Birdwell Oil	J. Whitney No. 1	1943	—	2
	103	C. Dunwoody, Jr.	H. Smith Est. No. 1	1953	—	2
	104	Pontail Refining	F. Bowman No. 1	1948	—	2
	105	Pontail Refining	F. Bowman No. 1A	1948	—	2
	106	Monday Oil	C. Stubblefield No. 1	1948	—	2
	107	Billy Birdwell et al.	R. Diebel No. 1	1949	—	2
	108	Randerson & Head	Rydolph & Smolik No. 1	1950	—	2
	109	Continental Oil	W. Maroney No. 1	1943	—	2
	110	R. S. Randerson	H. Stubblefield No. 1	1950	—	2
	111	W. G. Dorsey, Jr.	E. Rydolph No. 1	1949	—	1
	112	R. N. Ranger	W. Krahl No. 1	1952	—	1
	113	Union Production	Rydolph No. A-1	1950	—	2
	114	RBJ Company	Rydolph No. 1-M	1969	—	1
	115	Continental Oil	P. Rydolph No. ?	—	—	1
	116	E. I. DuPont	E. I. DuPont No. 1	—	—	1
Everest Minerals Corporation Hobson Mine, Karnes Co. DZD 5,610 Feet WDW-168	117	Standard	Pollok No. 1	—	—	1
	118	Bright & Schiff	Foegelle No. 1	—	—	1
	119	Mayo	Moczygamba No. 1	—	—	1
GAF Corporation Texas City Plant, Galveston Co. DZD 3,550 Feet WDW-34, 113, 114	120	Midstates	J. Braun No. 1	1950	—	1
	121	Pan American Oil	C. Martin No. 1	1954	—	1
	122	Humble Oil	D. S. Monen No. 3	1938	—	1
	123	Pan American Oil	J. N. Fream No. 5	—	—	1

Table 1.—Wells Lacking Documentation of Cement Plugs to Protect Usable Water—Continued

Permittee Site, County Disposal Zone Depth (DZD) WDW No.	Well Number On Maps	Operator	Well Name	Date Drilled	Date Plugged	Remarks
HEBBRONVILLE AREA						
Caithness Mining Corporation McBride Mine, Duval Co. DZD 4,100 Feet WDW-185						
Conoco, Incorporated Trevino Mine, Duval Co. DZD 3,800 Feet WDW-189						
Everest Minerals Corporation Las Palmas Mine, Duval Co. DZD 4,250 Feet WDW-187	124	Massingale & Rife	Benavides No. 1	1947	1947	2 [8.4 lb/gal]
	125	Hamon & Cox	Taylor No. 1	1950	1950	2 [10.1 lb/gal]
	126	Dan Auld	Taylor No. 2	—	—	2 [9.8 lb/gal]
	127	Hamon & Cox	Taylor No. 1-A	1952	1952	2 [10.3 lb/gal]
	128	Ben Marks	Gruy No. 1	1950	1950	2 [10.8 lb/gal]
	129	do	Gruy No. 2	1950	1950	2 [10.8 lb/gal]
	130	Killam & Hurd	Gruy No. 5	1958	1958	2 [9.9 lb/gal]
	131	Hewit & Dougherty	Gruy No. 1	1948	1948	2 [10.2 lb/gal]
	132	Morris Cannon	Gruy No. 4	1950	1950	2 [9.8 lb/gal]
	133	Southern Minerals	Silver Lake Ranch No. 1	1951	1951	2 [10.0 lb/gal]
	134	Ben Marks	Gruy No. 3	1951	1951	2
	135	Killam & Hurd	Gruy No. 6	1955	1955	2
	136	Rand Morgan	Gruy No. 1	—	—	2
	137	Valor Oil	Trevino No. 1	—	—	2
	138	Henshaw Brothers	Alonzo Taylor No. 1	1955	1955	2
	139	C. S. Sellars	do	1945	1945	2
	140	T. S. West	J. T. Rogers No. 1	—	—	2
	141	Chicago Company	Trevino No. 1	1951	1951	2
	142	John F. Camp	G. B. Buesher No. 1	1946	1946	2
	143	C. G. Classcock	J. Dunn No. 1	1952	1952	2

Table 1.—Wells Lacking Documentation of Cement Plugs to Protect Usable Water—Continued

Permittee Site, County Disposal Zone Depth (DZD) WDW No.	Well Number On Maps	Operator	Well Name	Date Drilled	Date Plugged	Remarks
HEBBRONVILLE AREA						
	144	Caroline Hunt Trust	E. Miller No. 1	1948	1948	2
	145	Trio Oil	E. S. Miller No. 1	1949	1949	2
	146	John F. Camp	Dunn Ranch B-1	1947	1947	2
	147	H. J. Porter	Sadie Hay No. 1	1943	1943	2
	148	La Gloria	T. B. Miller No. 1	1931	1931	2
	149	Southern Minerals	S. A. Loan & Trust	1951	1951	2
HOUSTON SHIP CHANNEL AREA						
Disposal Systems, Inc. Houston Plant, Harris Co. DZD 6,800 Feet WDW-169						
Empak, Inc. Houston Plant, Harris Co. DZD 6,800 Feet WDW-157						
W. R. Grace & Co. Houston Plant, Harris Co. DZD 6,600 Feet WDW-222, 223						
Merichem Co. Haden Road Plant, Harris Co. DZD 6,400 Feet WDW-147						
Shell Chemical Co. Deer Park Plant, Harris Co. DZD 6,800 Feet WDW-172, 173	150	J. W. Frazier	Houston Deepwater No. 1	—	1938	1
	151	McCormick	Greens Bayou Homesite No 1	—	—	1 (9.6 lb/gal)

Table 1.—Wells Lacking Documentation of Cement Plugs to Protect Usable Water—Continued

Permittee Site, County Disposal Zone Depth (DZD) WDW No.	Well Number On Maps	Operator	Well Name	Date Drilled	Date Plugged	Remarks
HOUSTON SHIP CHANNEL AREA						
	152	Turnbull & Irwin	R. Brooks Est. No. 1	—	—	1
	153	Housch & Thompson	Hine No. 1	—	—	1
	154	Frazier & Brunte	Houston Deepwater No. 2	—	1938	—
	155	Jack Frazier	Jones No. 1	—	1946	—
	156	Cockburn	Brooks Est. No. 1	—	—	—
	157	Amerada Petroleum	Esperson No. 1	1936	—	—
	158	Cockburn Oil	Hines No. 1	1935	—	—
	159	T. S. & F.	Hines No. 2	—	—	—
	160	Giddens & Shiver	Sutherland et al. No. 1	1952	—	—
	161	N. B. Hunt	L. H. Curtin No. 1	1952	—	—
	162	Irwin & Buck	J. B. Hine No. 1	1949	—	—
	163	Miller	Fee No. 1	1926	—	—
	164	do	Fee No. 2	—	—	—
	165	Olympia Oil & Gas	Miller No. 1	1954	—	1
	166	do	Miller No. 2	1954	—	1
	167	Cockburn et al.	White No. 1	1937	—	1
	168	Strang	Goode No. 1	—	—	1
	169	Turnbow	Miller No. 1	—	—	1
	170	West Production	A. Underwood No. 1	1937	—	1
	171	Wolfe	Trichelle No. 1	1952	—	2 (10.2 lb/gal)
	172	Inexco	Kelly-Brock No. 1	—	—	1
I. E. C. Corporation Lamprecht Mine, Liveoak Co. DZD 6,200 Feet WDW-156	173	Herman Brown	Wieding No. 1	1946	1946	1
	174	Kirkwood	W. W. Goebel No. 3	—	—	1
Zamzow Mine, Liveoak Co. DZD 3,050 Feet WDW-159	175	Coquat	W. W. Goebels No 1	1931	—	1
	176	Ohio Fuel	Goebels No. 1	1937	1937	1

Table 1.—Wells Lacking Documentation of Cement Plugs to Protect Usable Water—Continued

Permittee Site, County Disposal Zone Depth (DZD) WDW No.	Well Number On Maps	Operator	Well Name	Date Drilled	Date Plugged	Remarks
I. E. C. Corporation						
Zamzow Mine, Live Oak Co.	177	Phillips Petroleum	W. W. Goebels No. 1	—	—	1
	178	do	do	—	—	1
Lyondell Petrochemical Company Channelview Plant, Harris Co. DZD 4,900 Feet						
WDW-36, 148, 162	179	J. Frazier	Lang No. 1	—	1938	1
	180	do	Hornberger No. 1	—	1938	1
	181	W. Thompson	H. Johnson No. 1	—	—	1
	182	Circle W. Oil	Houston Realty No. 1	1936	—	1
	183	W. M. Hobson	Highland Farms No. 1	—	—	1
	184	O & G Corporation of America	R. Weiss No. 1	—	1959	2
Mobil Oil Corporation Holiday-El Mesquite Plant, Webb Co. DZD 3,550 Feet						
WDW-150, 151, 199	185	B. C. Graham	Benavides B-1	1948	1948	2 [10.2 lb/gal]
	186	Hamill & Smith	J. Benavides No. 1	1936	—	1
	187	Texon Royalty	S. Benavides No. 2	1947	1947	2 [10 lb/gal]
	188	do	S. Benavides No. 1	1947	1947	2 [10 lb/gal]
	189	Magnolia Petroleum	Benavides No. 1	1940	1940	2 [9.6 lb/gal]
	190	do	J. Benavides No. 8	1937	1937	2 [10.6 lb/gal]
	191	United Production	Benavides No. 5	—	—	1
	192	Otis Phillips	Martin No. 1-B	1936	1936	2
	193	Cole Petroleum	R. Benavides No. 69	1930	1930	2
	194	do	R. Benavides No. 75	—	1932	2
	195	E. L. Cox	Benavides No. C-1	1955	1955	2 [10.0 lb/gal]
	196	C. H. Lewis	R. Benavides No. 1	1943	1943	2 [9.9 lb/gal]
	197	Cole Petroleum	R. Benavides No. 68	—	1930	2

Table 1.—Wells Lacking Documentation of Cement Plugs to Protect Usable Water—Continued

Permittee Site, County Disposal Zone Depth (DZD) WDW No.	Well Number On Maps	Operator	Well Name	Date Drilled	Date Plugged	Remarks
Monsanto Chemical Company Chocolate Bayou Plant, Brazoria Co. DZD 4,987 Feet WDW-2, 13	198	Phillips Petroleum	Houston "S" No. 1-S	1952	1968	2
	199	Texas Company	Houston Farms Development Company No. 2	1955	1955	2
	200	Phillips Petroleum	Houston "X" No. 1	1954	1959	2
	201	do	Houston "AA" No. 1	1956	1957	2
Penwalt Corporation Crosby Plant, Harris Co. DZD 6,000 Feet WDW-122	202	Moody	E. Cook No. 1	1928	1928	1
	203	Brewster	Kratley No. 1	1954	1954	2 [10.2 lb/gal]
	204	General Crude	Garth No. 1	1952	1952	2 [11.2 lb/gal]
Tenneco Uranium W. Cole Mine, Webb Co. DZD 5,650 Feet WDW-195	205	Piney Point	Cuellar No. 1	1964	1964	2
	206	Flournoy	Benavides No. 1	1965	1965	2
	207	DDG	Benavides No. A-1	1960	1960	2
	208	DDG & Amerada	Benavides No. 1	1959	1959	2
	209	Killum & Hurd	Valdez No. 1-754	1973	1973	2
	210	Naring	Cuellar No. 1	1951	1951	2

Table 1.—Wells Lacking Documentation of Cement Plugs to Protect Usable Water—Continued

Permittee Site, County Disposal Zone Depth (DZD) WDW No.	Well Number On Maps	Operator	Well Name	Date Drilled	Date Plugged	Remarks
TEXAS CITY AREA						
Amoco						
Texas City Plant, Galveston Co.						
DZD 5,830 Feet						
WDW-80, 127, 128, 214						
Malone Service Company						
Malone Plant, Galveston Co.						
DZD 3,800 Feet						
WDW-73, 138						
Monsanto Company						
Texas City Plant, Galveston Co.						
DZD 5,000 Feet						
WDW-91, 196						
Textin, Inc.						
Texas City Plant, Galveston Co.						
DZD 5,600 Feet						
WDW-237						
	211	Stephens	Ruggles No. 1	1950	1950	2
	212	J. W. Mecom	Univ. of Texas No. 1	1951	1951	1
	213	Humble Oil	State Tract No. 1	—	—	1
	214	C. Y. Kosberg	Agnes Kirsten No. 1	—	—	1
	215	John W. Mecom	Univ. of Texas No. 1	—	1951	2
	216	Shell Petroleum	Maco Stewart & Son No. 2	1937	1937	2
	217	Stewart Petroleum	State Highland Bayou No. 3	1955	—	1
	218	M. Stewart & Company	Stewart Title Guaranty No. 1	1940	1940	1
	219	N. W. Hunter	Stewart Title Guaranty No. 2	1937	—	1
	220	do	Stewart Title Guaranty No. 1	1937	—	1
	221	Stewart Petroleum	State Highland Bayou No. 4	1955	—	1
	222	—	Thomas, et al.	—	—	1
	223	—	M. Stewart	—	—	1

Table 1.—Wells Lacking Documentation of Cement Plugs to Protect Usable Water—Continued

Permittee Site, County Disposal Zone Depth (DZD) WDW No.	Well Number On Maps	Operator	Well Name	Date Drilled	Date Plugged	Remarks
U. S. Steel George West Mine, Live Oak Co. DZD 3,200 Feet WDW-123, 124, 130, 140, 141, 174	224	Texas Oil & Gas	Mussman No. 1	1978	1978	2
	225	Penn-Devonian	Lyne No. 1	1935	—	1
	226	Holland Oil	do	—	—	1
	227	Calloway (Holland)	do	—	1936	1
	228	Lysey	Sein No. 1	—	1957	1
	229	O'Neal	—	—	1956	1
	230	Dugger	—	—	1967	2
	231	Calloway	Moczygemba No. 1	—	1936	1
	232	North Central Oil	Harlan-Nelson No. 1	—	1967	2
	233	Caribou	Lyne No. 1-69	—	1973	1
	234	McCarrick	Steinmeyer No. 1	—	1959	2
	235	do	Steinmeyer B-1	—	1959	2
	236	Midwest	Lyne No. 1	—	1962	2
	237	Smith & Stark	Lyne No. 2	—	—	1
	238	Continental Oil	Burns No. 2	—	1960	2
	239	Southland Drilling	Lynn No. 1	1976	1976	2
Vistron Corp. Port Lavaca Plant, Calhoun Co. DZD 6,750 Feet WDW-163, 164, 165	240	Mecom	Welder-Robinson No. 15	—	1952	2 [11.2 lb/gal]
	241	Humble Oil	P. H. Welder No. 29-A	—	—	2, 3
Wastewater, Inc. Guy Facility, Brazoria Co. DZD 6,150 Feet WDW-167	242	Harold Link	J. F. D. Moore W-2	1951	1951	2
	243	Mack Hack Petroleum	J. F. D. Moore W-3	1948	1948	2
	244	F. W. Zelden	Investment & Security W-7	1941	1941	1
	245	Harold Link	J. M. Moore W-10	1950	1950	2

Table 1.—Wells Lacking Documentation of Cement Plugs to Protect Usable Water—Continued

Permittee Site, County Disposal Zone Depth (DZD) WDW No.	Well Number On Maps	Operator	Well Name	Date Drilled	Date Plugged	Remarks
Westinghouse Electric Corp. Bruni Mine, Webb Co. DZD 2,900 Feet WDW-170						
	246	Harvey & Henderson	Benavides No. 1	—	1935	1
	247	Magnolia Petroleum	Volpe-Benavides No. 8	—	1939	2, 3
	248	do	R. Benavides No. 1	—	—	1
	249	do	S. Benavides No. 9	—	1940	2
	250	do	E. Benavides No. 1	—	1934	2
	251	Union Oil	Volpe-Benavides	—	—	1
	252	Magnolia Petroleum	O'Hearn-Benavides	—	—	1
	253	Killam & Anderson	Benavides No. 1	—	1949	2
	254	Schimmel	Volpe No. 1	—	1940	1
	255	National Refining	Benavides No. 1	1925	1925	1
	256	Magnolia Petroleum	S. Jones No. 1	—	1930	2
Witco Chemical Co. Almeda Road Plant, Harris & Fort Bend Co. DZD 5,450 Feet WDW-111, 139						
	257	W. H. Teel	M. Feld	1950	1950	2
	258	Thompson Drilling	S. Haynie No. 1	1939	1939	1
	259	Sunray DX	C. Arnold No. 1	1966	1966	1
	260	Pure Oil	A. Woods No. 1	1943	1943	2
	261	Maso Oil	W. McCrory No. 1	1956	1956	1
	262	Harrell Drilling	F. Weiser No. 1	1956	1956	2
	263	Cerro del Pasco	M. Feld No. 1	1957	—	1
	264	Jack W. Frazier	N. Waters No. 1	—	—	2
	265	R. A. Johnston	H. Cockburn No. 1	—	—	2
	266	Texoma Petroleum	A. Meyer, et al. No. 1	—	—	2
	267	Oil Production Maintenance	Stanolind No. 1	—	—	2

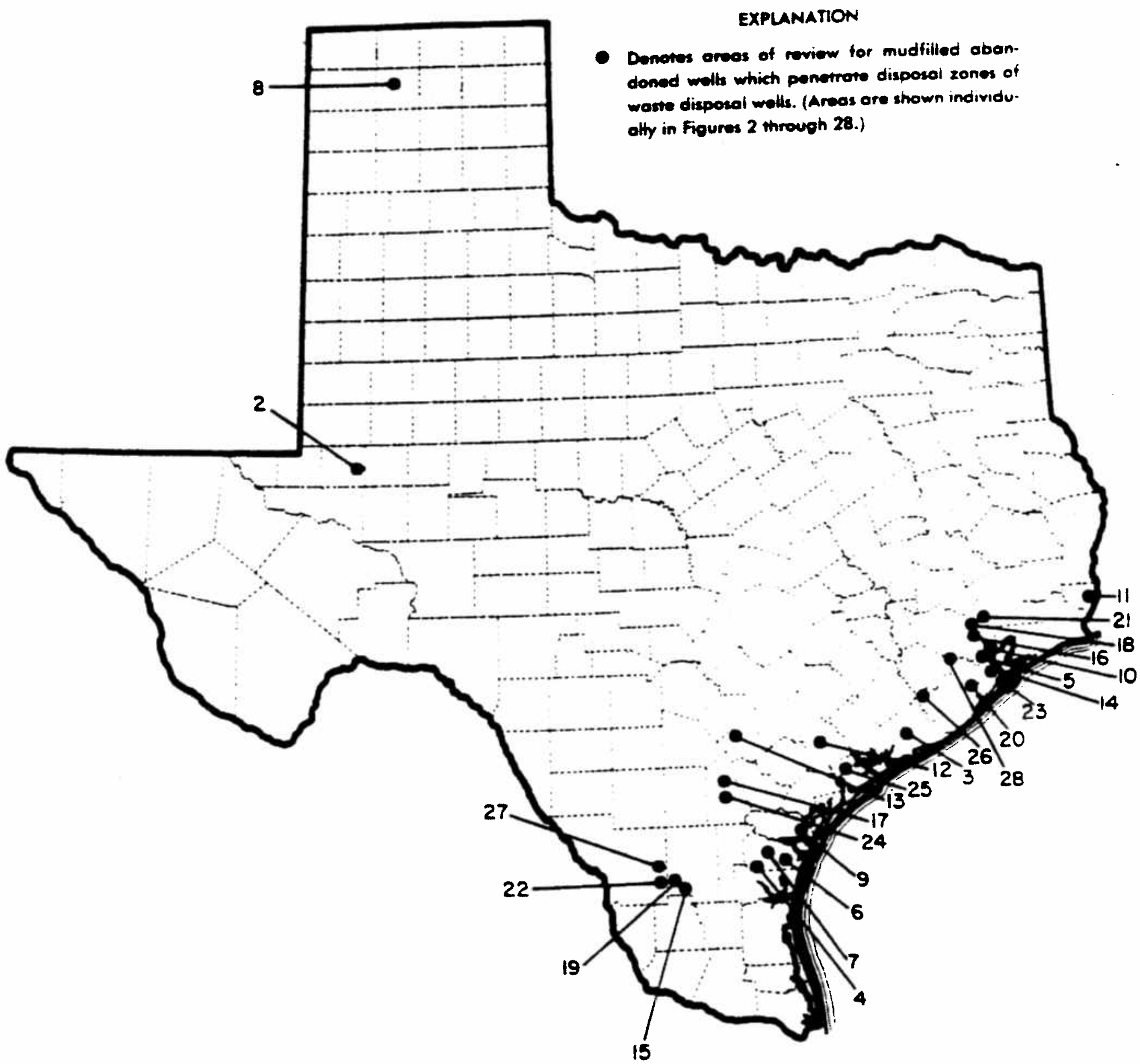

Figure 1--Index map to data in this report

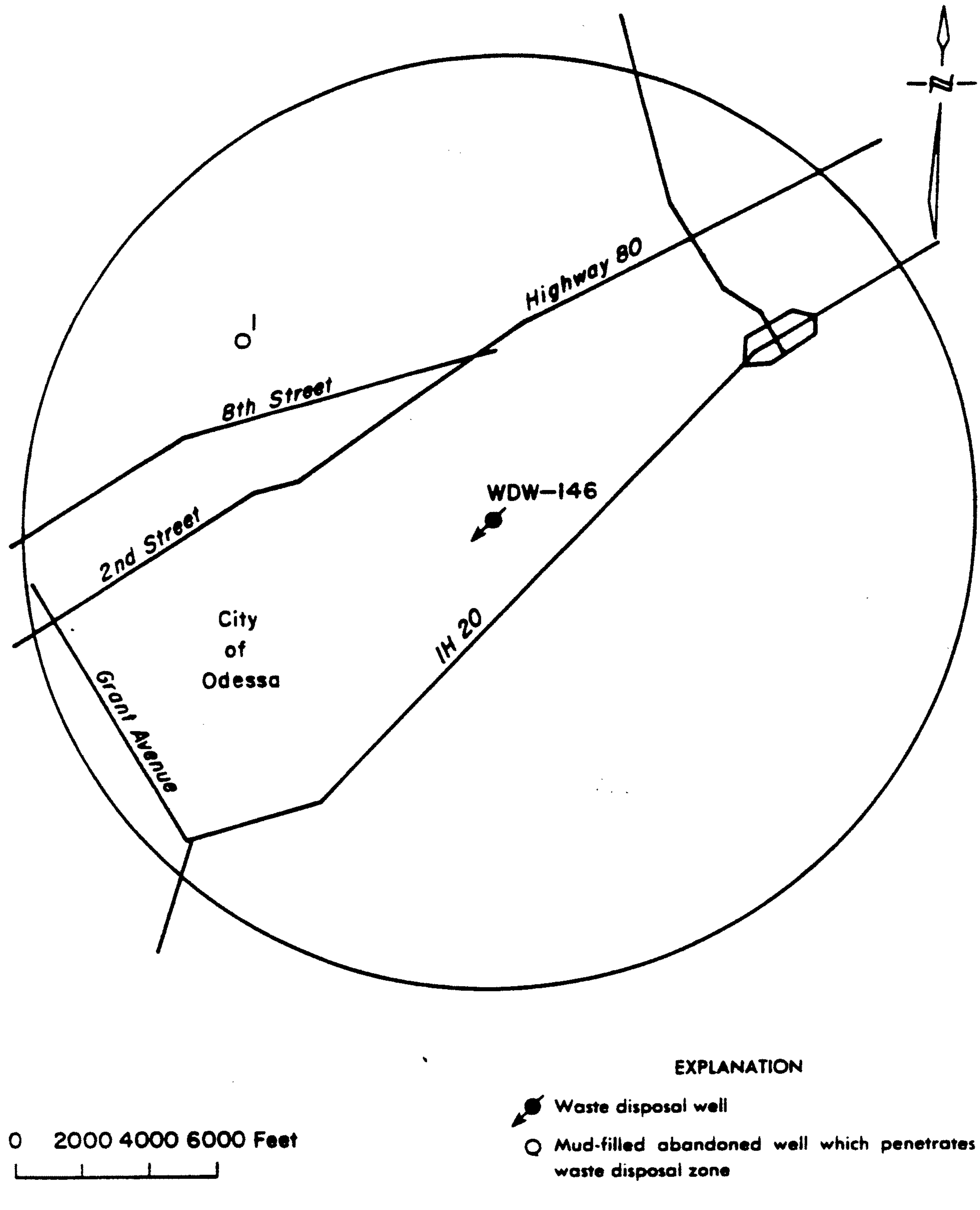

Figure 2--Area of review for CECOS International waste disposal well, Odessa Facility, Ector County

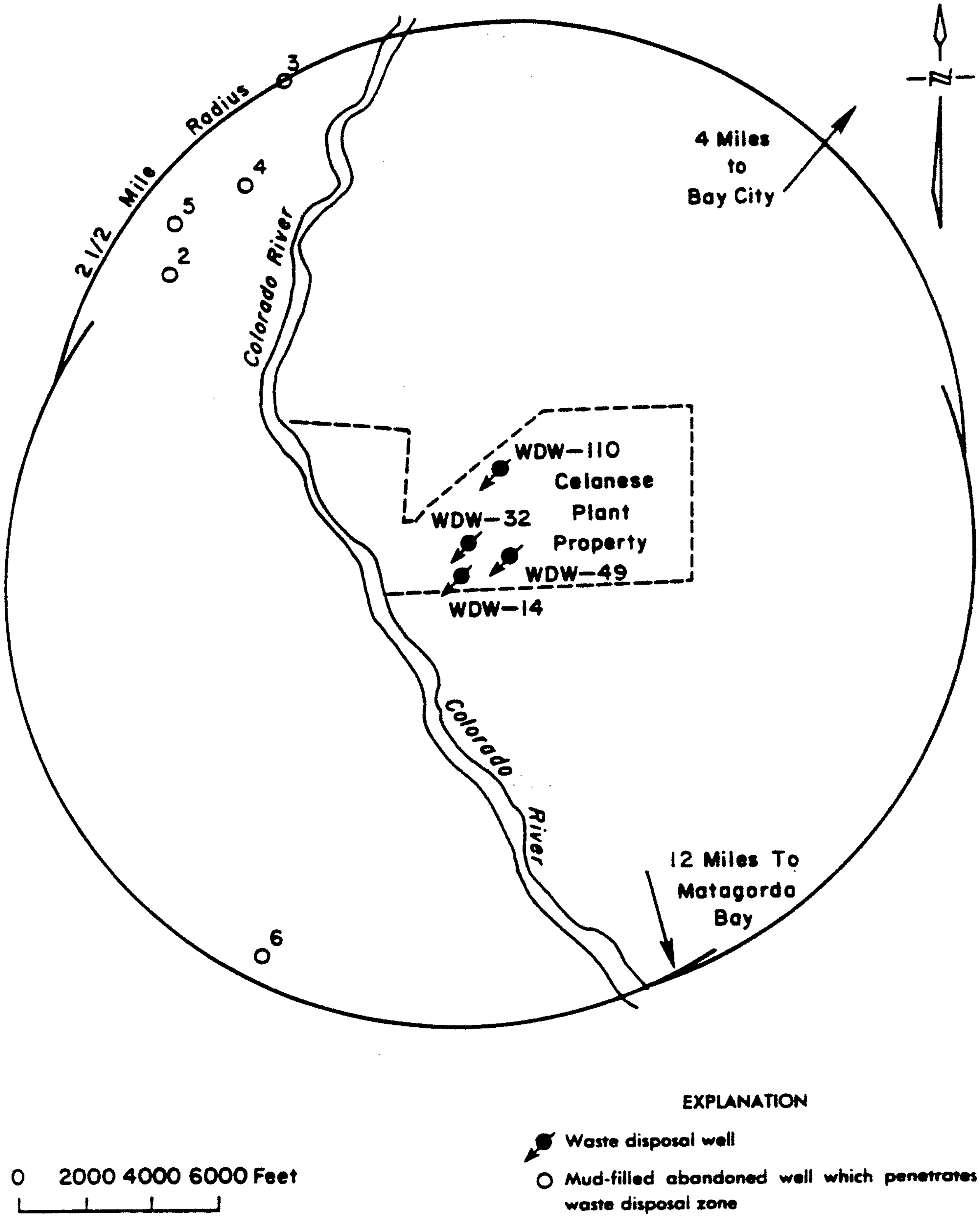

Figure 3--Area of review for Celanese Chemical Co. waste disposal wells, Bay City Plant, Matagorda County

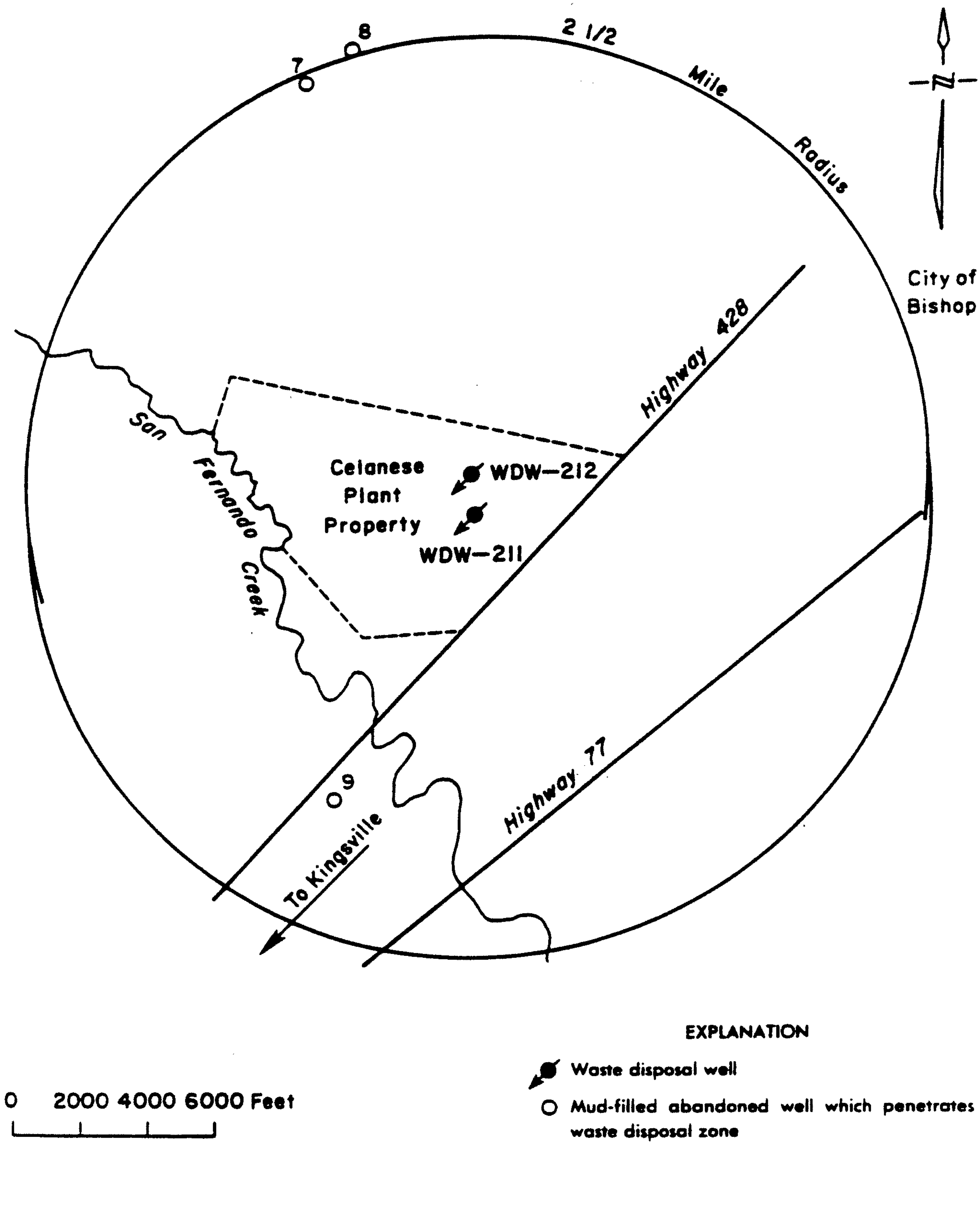

Figure 4--Area of review for Celanese Chemical Co. waste disposal wells, Bishop Plant, Nueces County

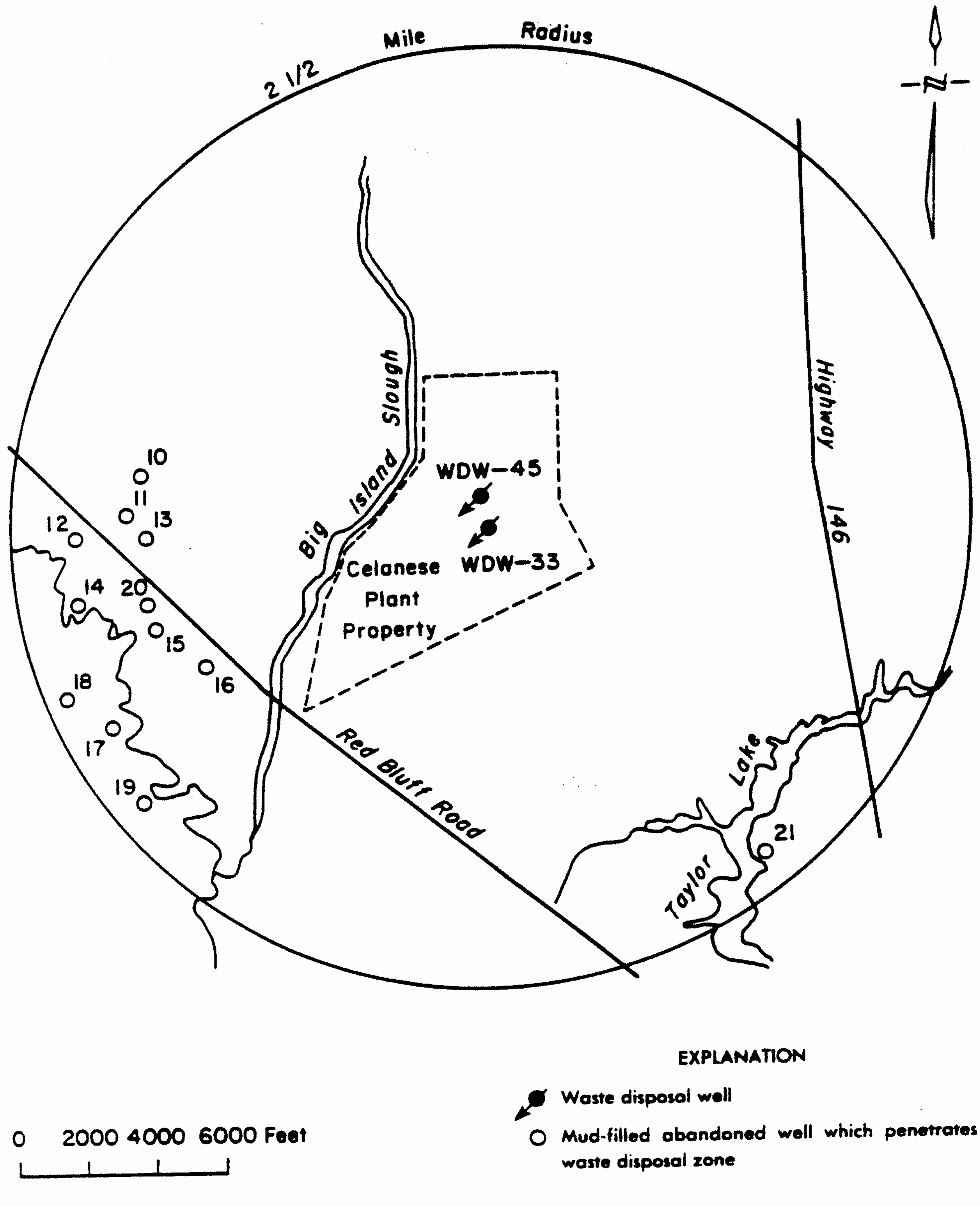

Figure 5--Area of review for Celanese Chemical Co. waste disposal wells, Clear Lake Plant, Harris County

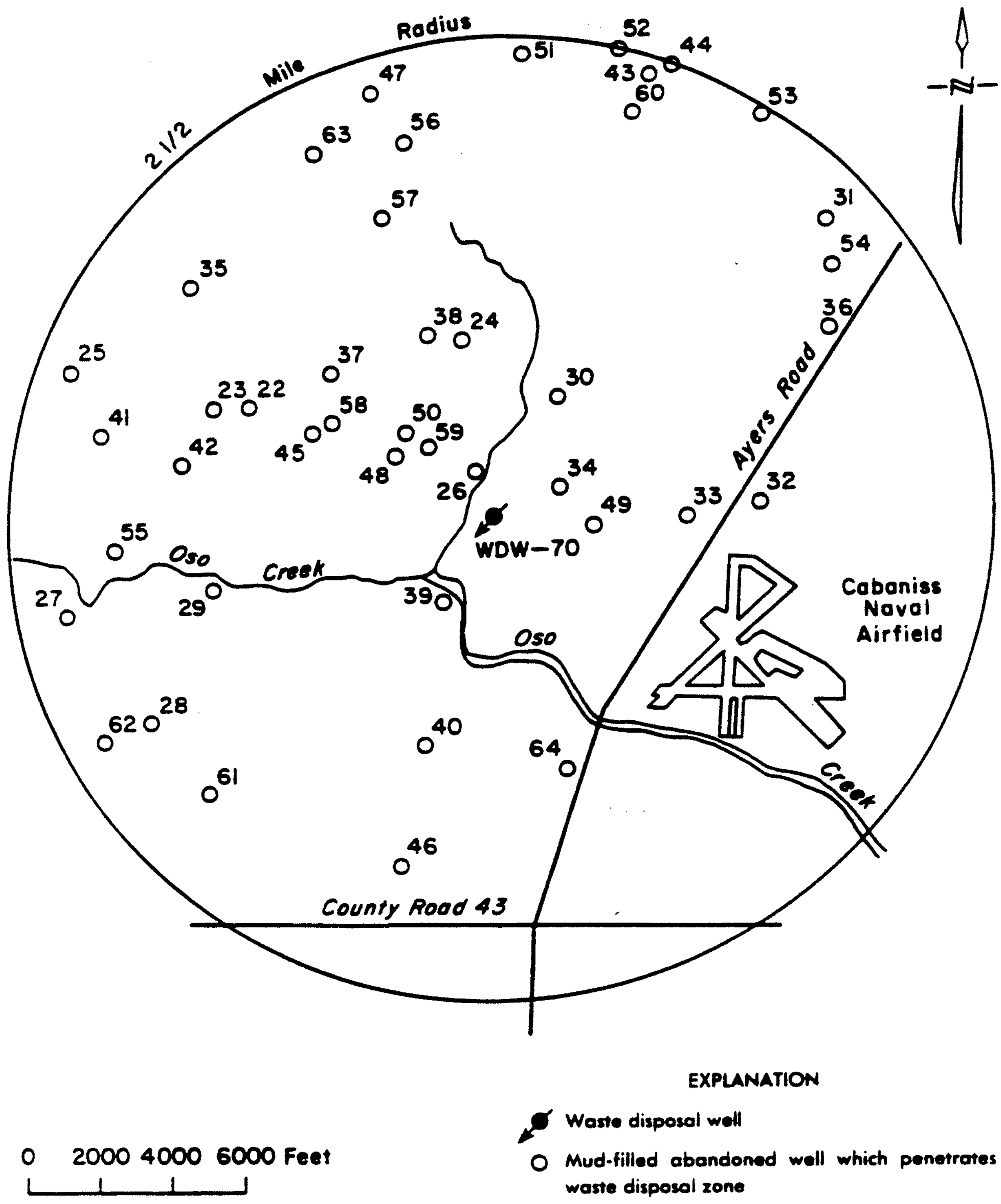

Figure 6--Area of review for Chemical Waste Management waste disposal well, Corpus Christi Plant, Nueces County

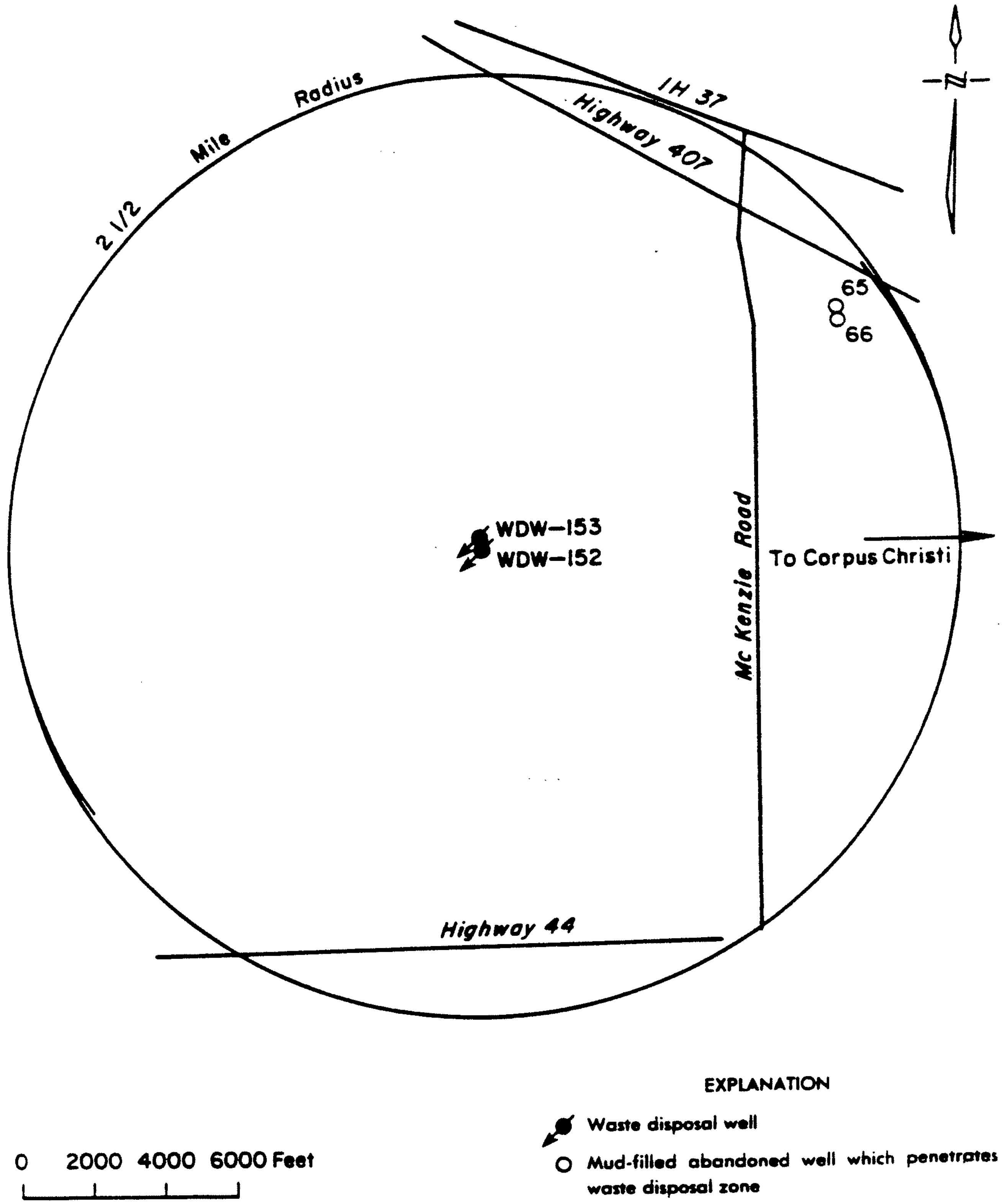

Figure 7--Area of review for Corpus Christi Petrochemical Co. waste disposal wells, Robstown Plant, Nueces County

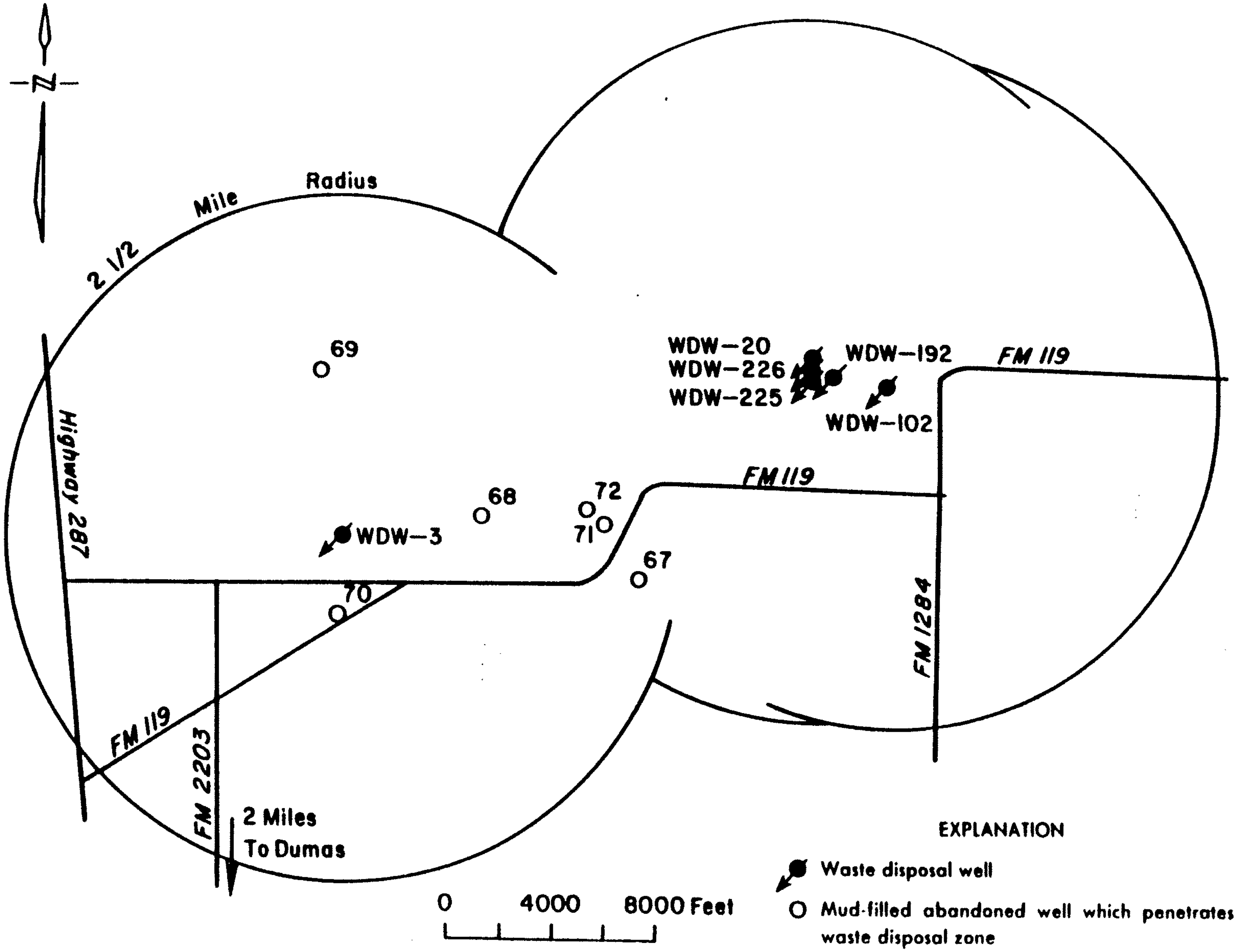

Figure 8--Area of review for waste disposal wells near Dumas, Moore County: Diamond Shamrock Corp. and Potash Co. of America

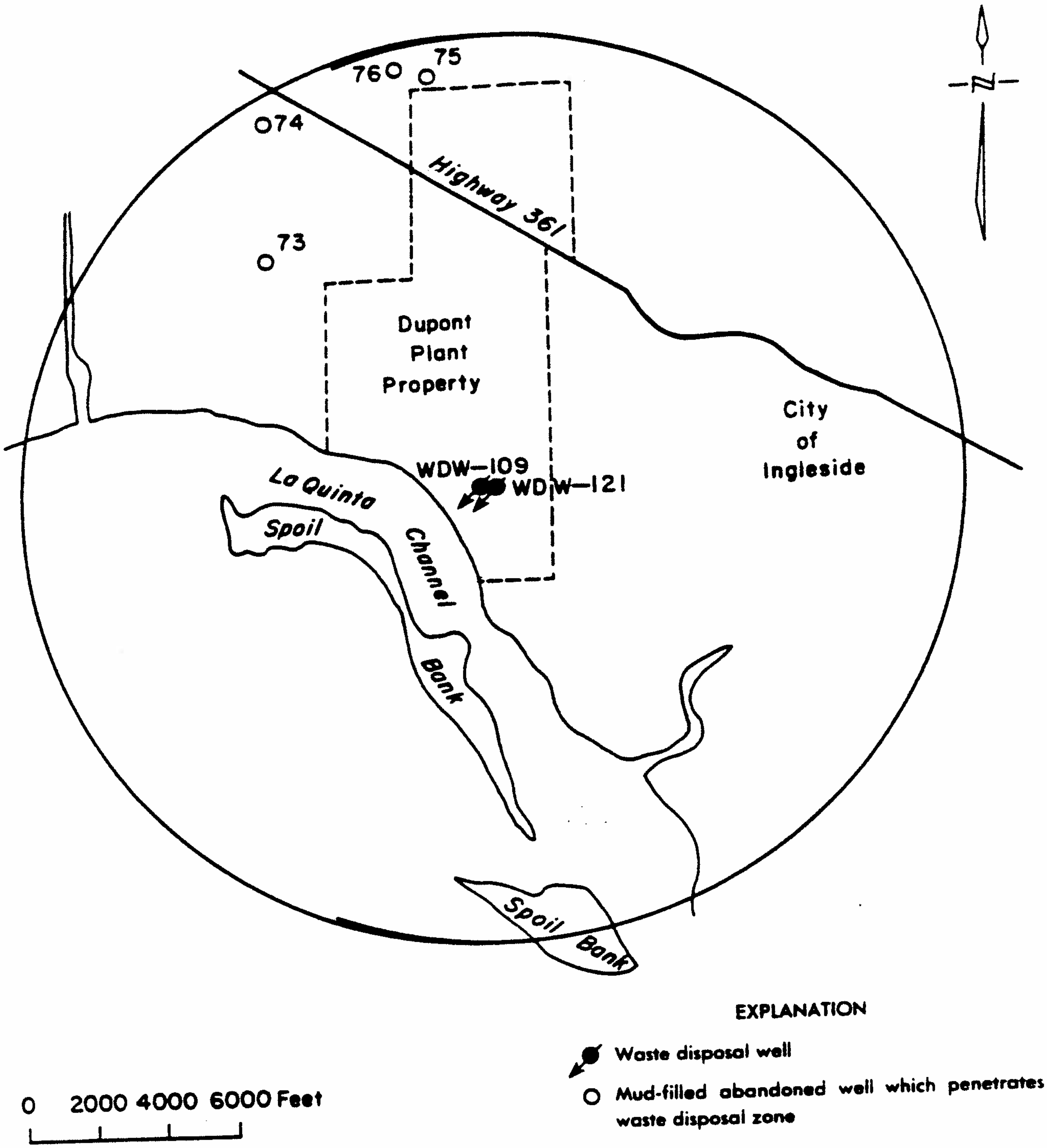

Figure 9--Area of review for E. I. Dupont de Nemours & Co. waste disposal wells, Corpus Christi Plant, San Patricio County

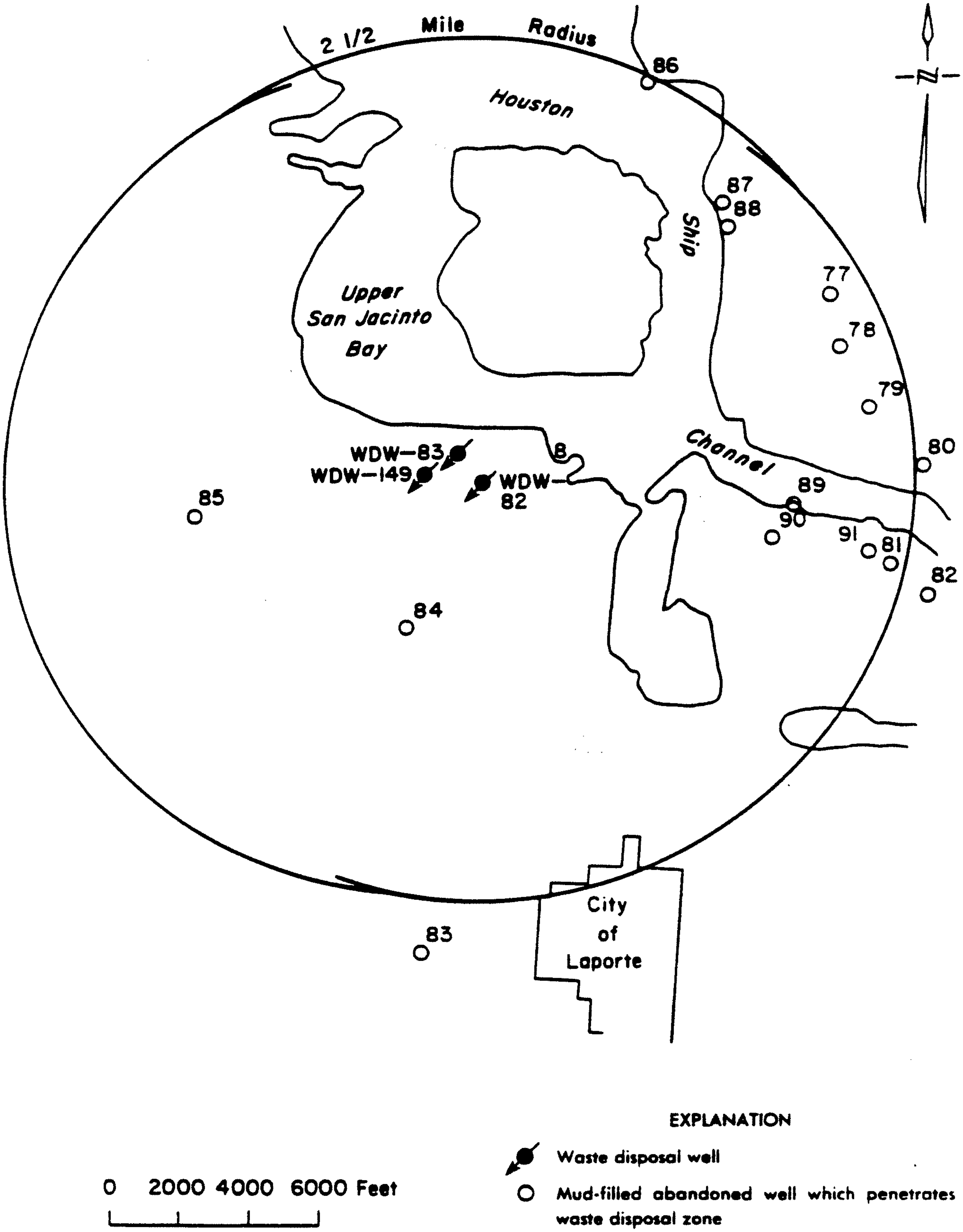

Figure 10--Area of review for E. I. Dupont de Nemours & Co. waste disposal wells, La Porte Plant, Harris County

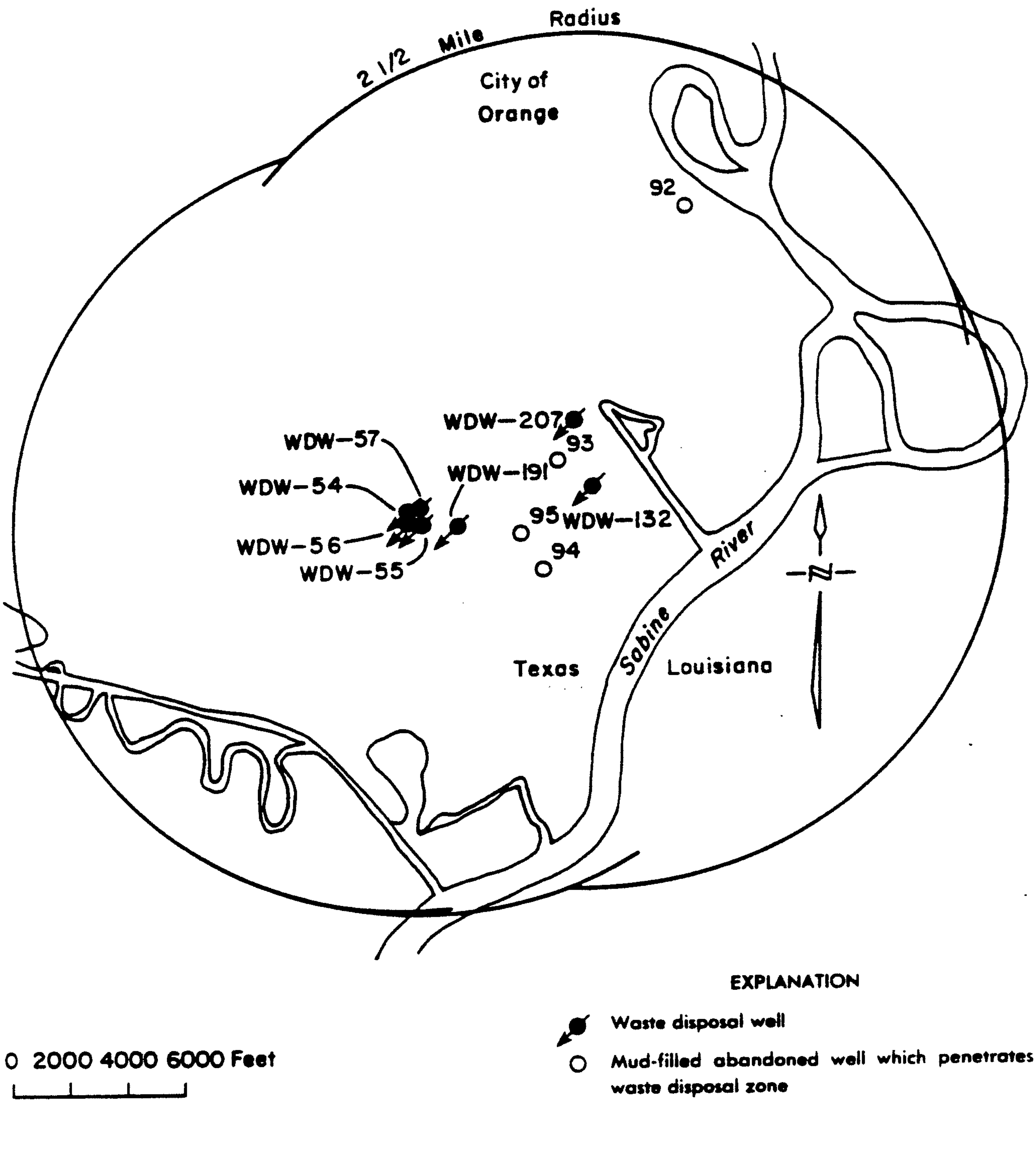

Figure 11--Area of review for E. I. Dupont de Nemours & Co. waste disposal wells, Sabine River Works, Orange County

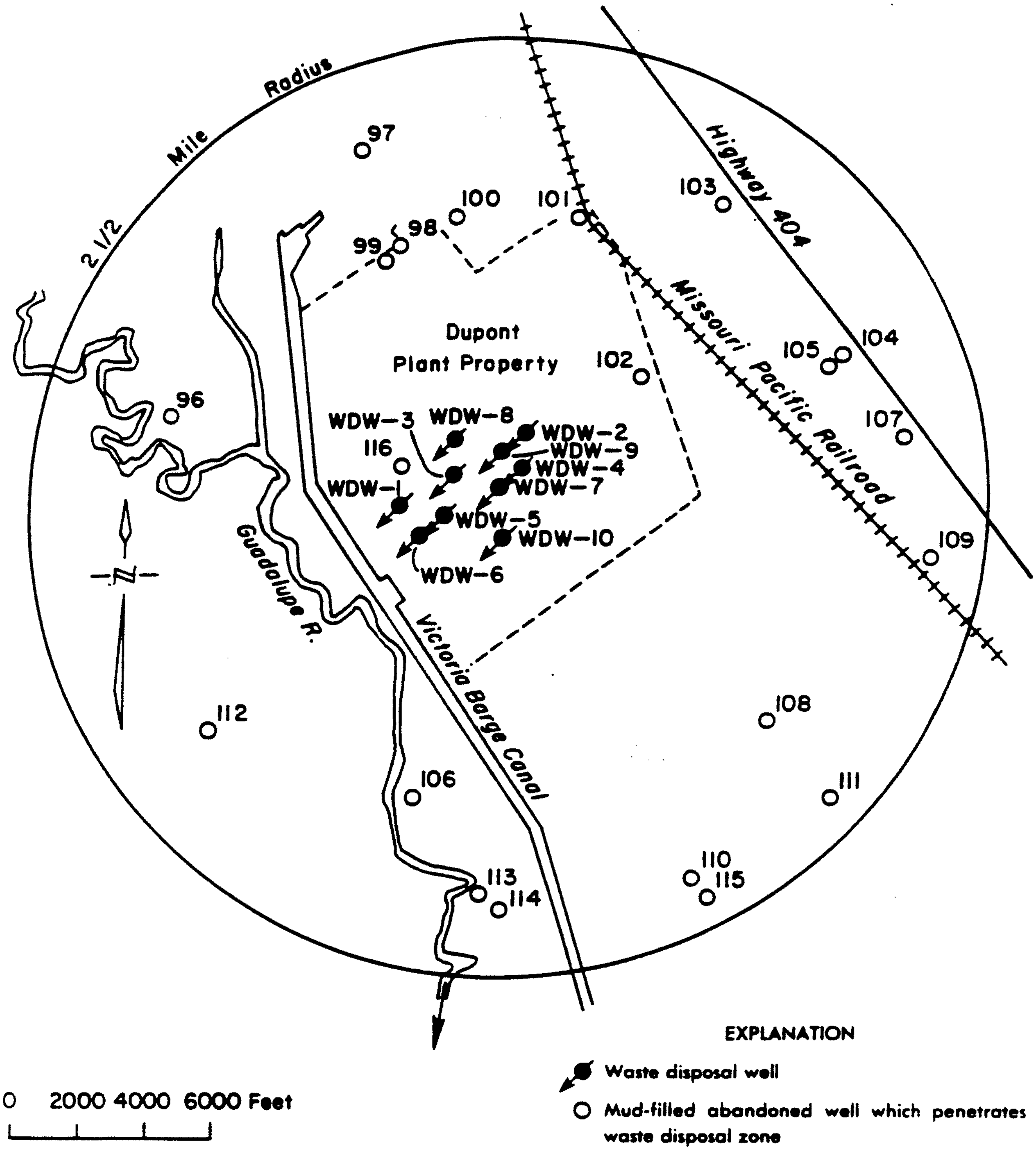

Figure 12--Area of review for E. I. Dupont de Nemours & Co. waste disposal wells, Victoria Plant, Victoria County

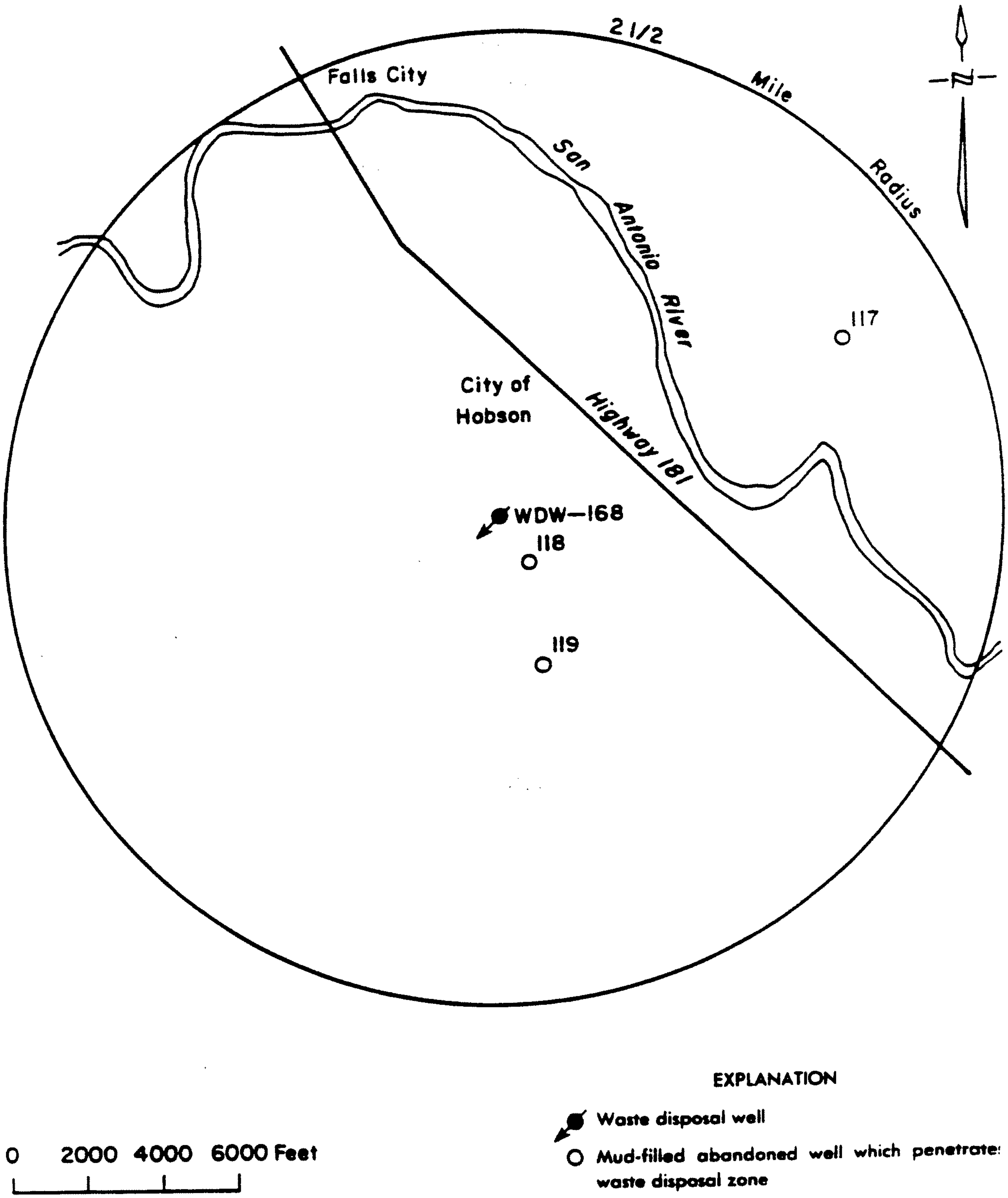

Figure 13--Area of review for Everest Minerals Corp. waste disposal well, Hobson Mine, Karnes County

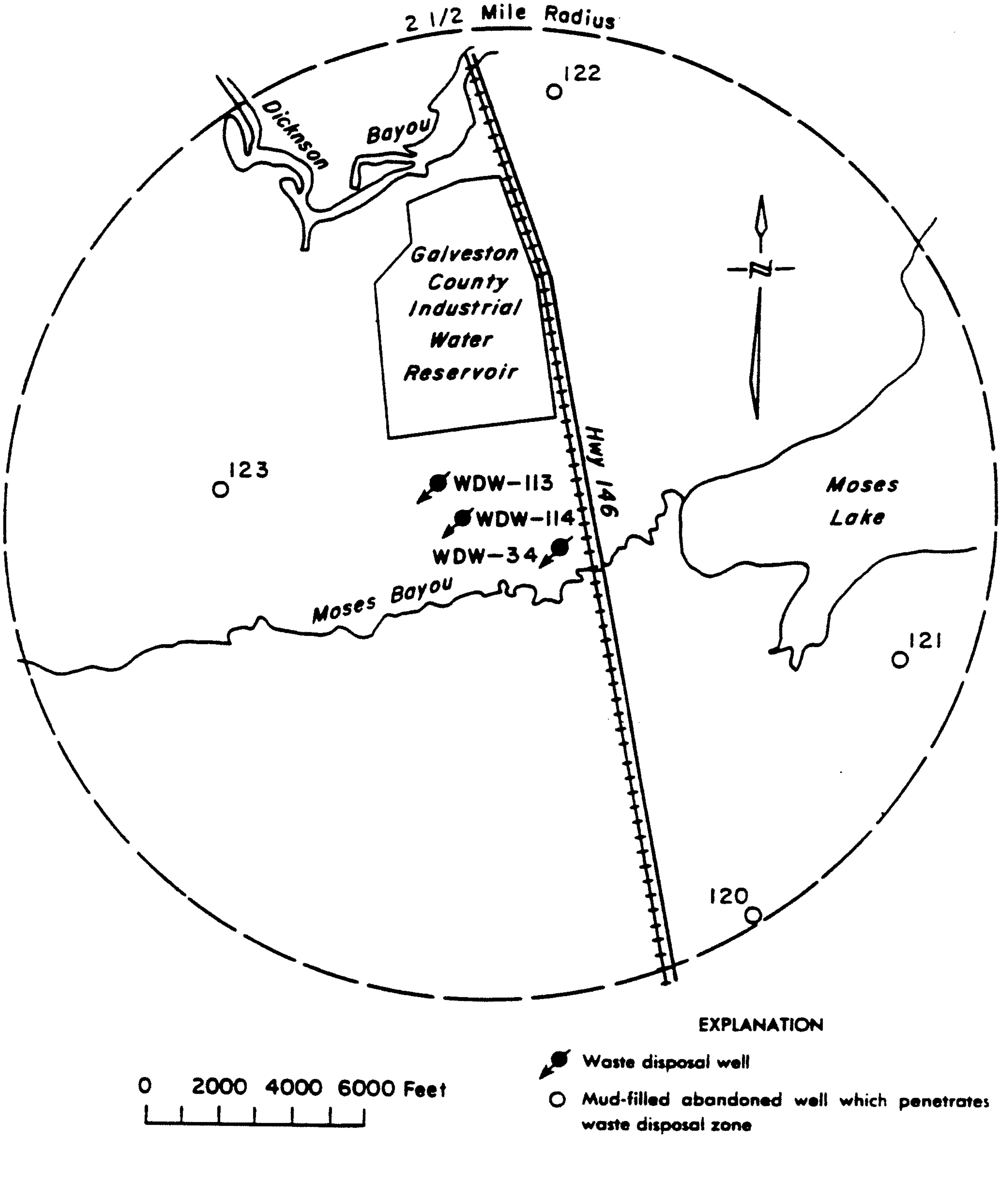

Figure 14--Area of review for GAF Corp. waste disposal wells, Texas City Plant, Galveston County

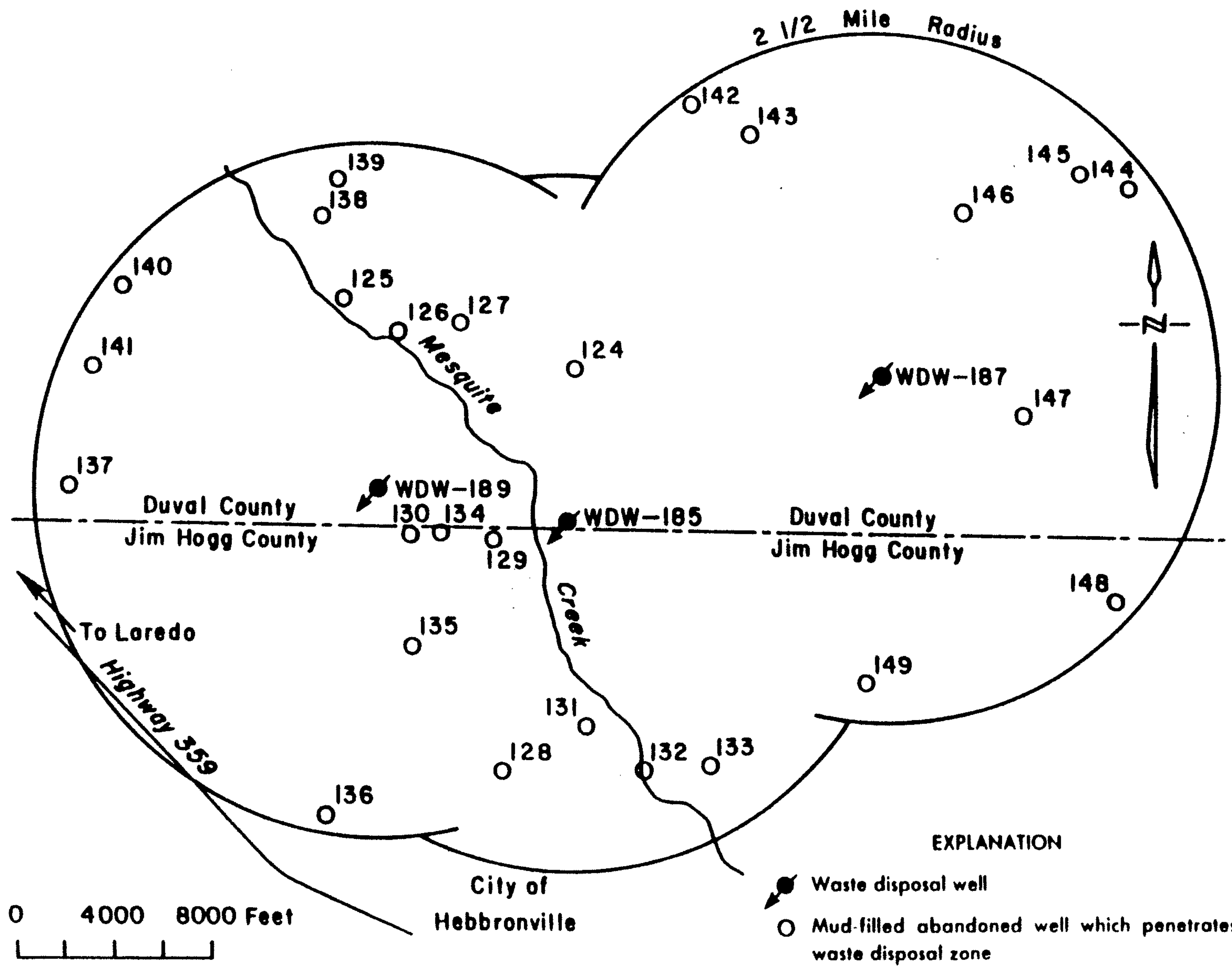

Figure 15--Area of review for waste disposal wells near Hebbronville, Duval and Jim Hogg Counties: Caithness Mining Corp., Conoco, Inc., and Everest Minerals Corp.

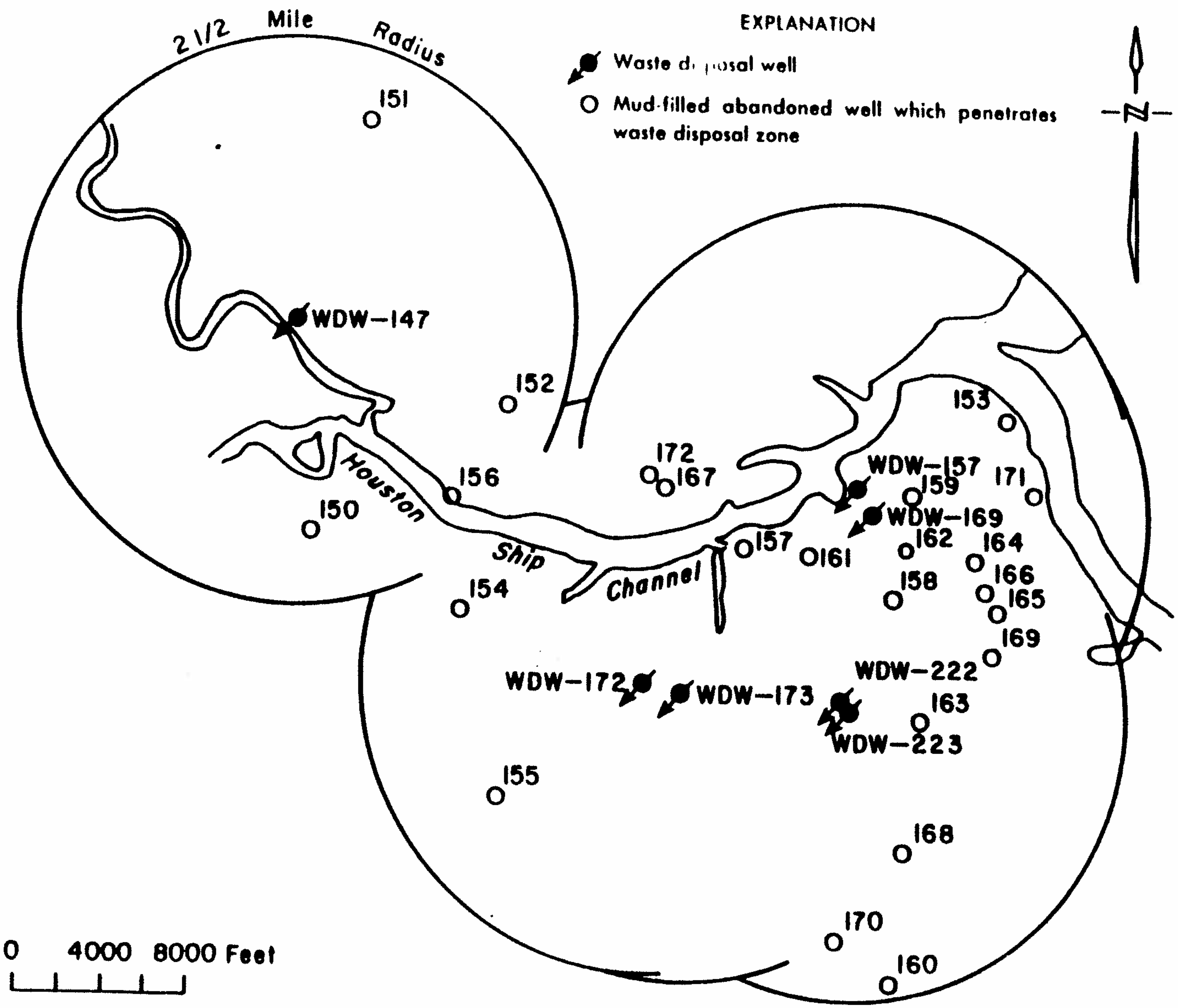

Figure 16--Area of review for waste disposal wells near Houston Ship Channel, Harris County: Empak, Inc., Disposal Systems, W. R. Grace & Co., Merichem Co., and Shell Chemical Co.

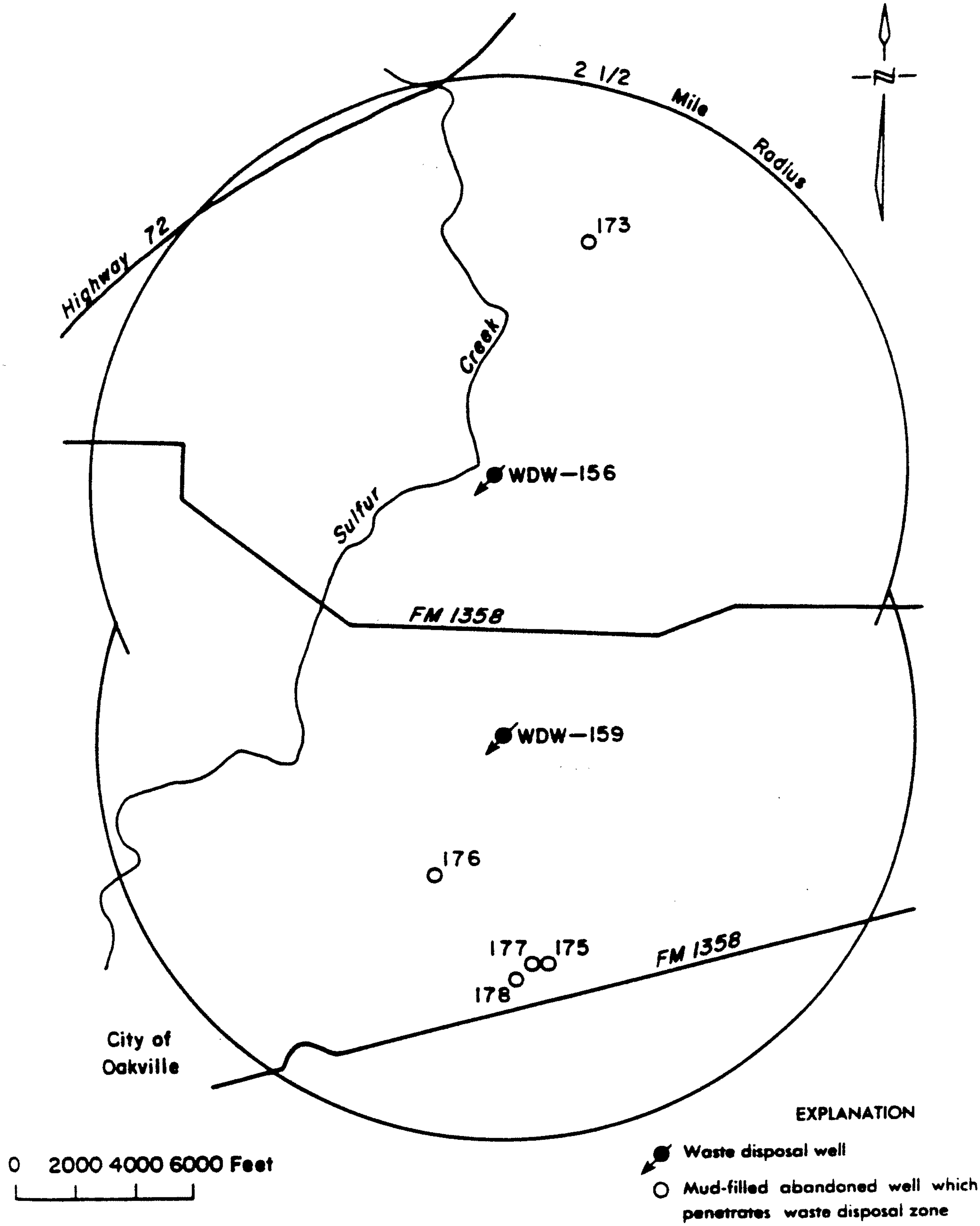

Figure 17--Area of review for IEC Corp. waste disposal wells, Lamprecht and Zamzow Mines, Live Oak County

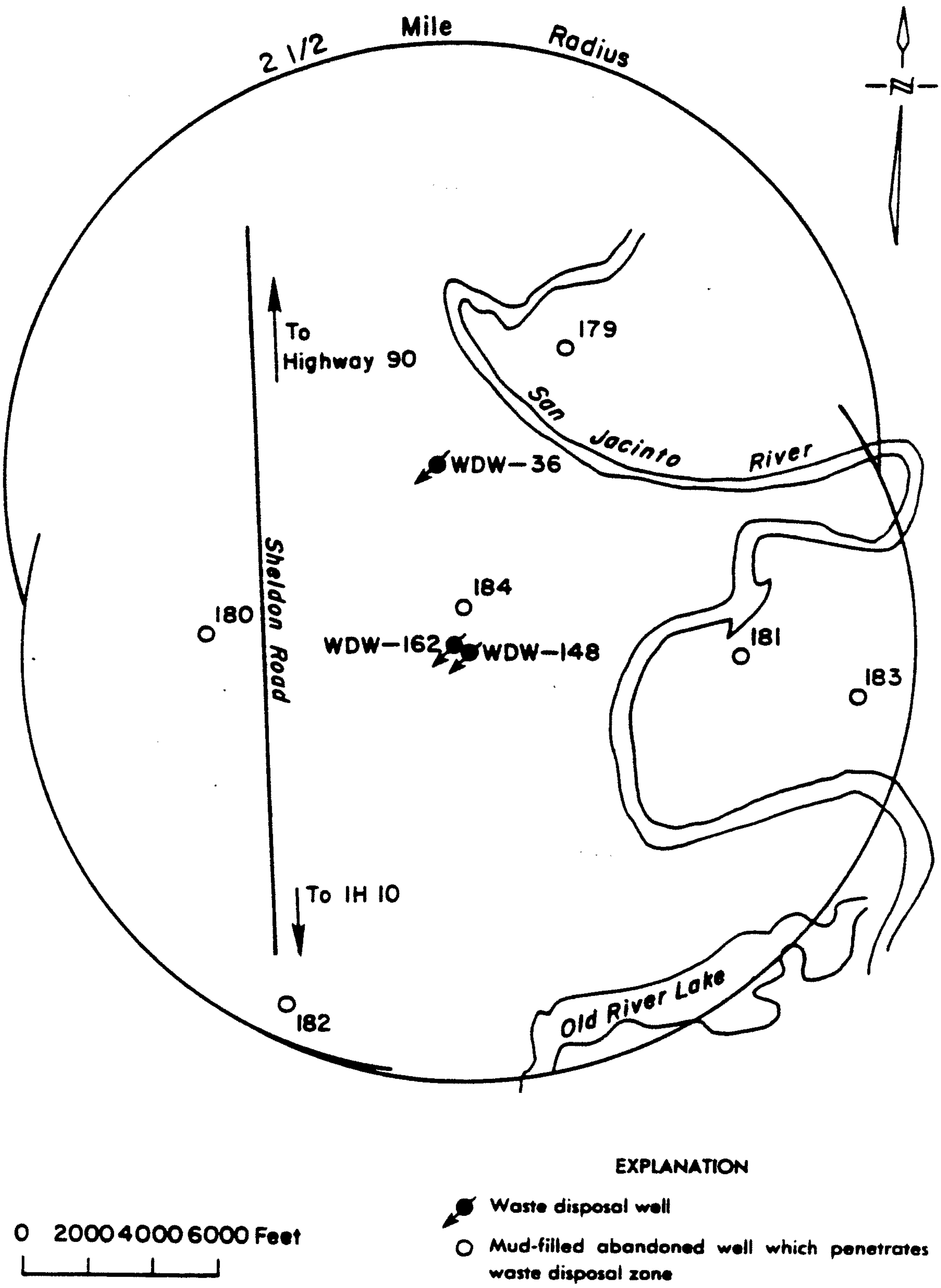

Figure 18--Area of review for Lyondell Petrochemical Co. waste disposal wells, Channelview Plant, Harris County

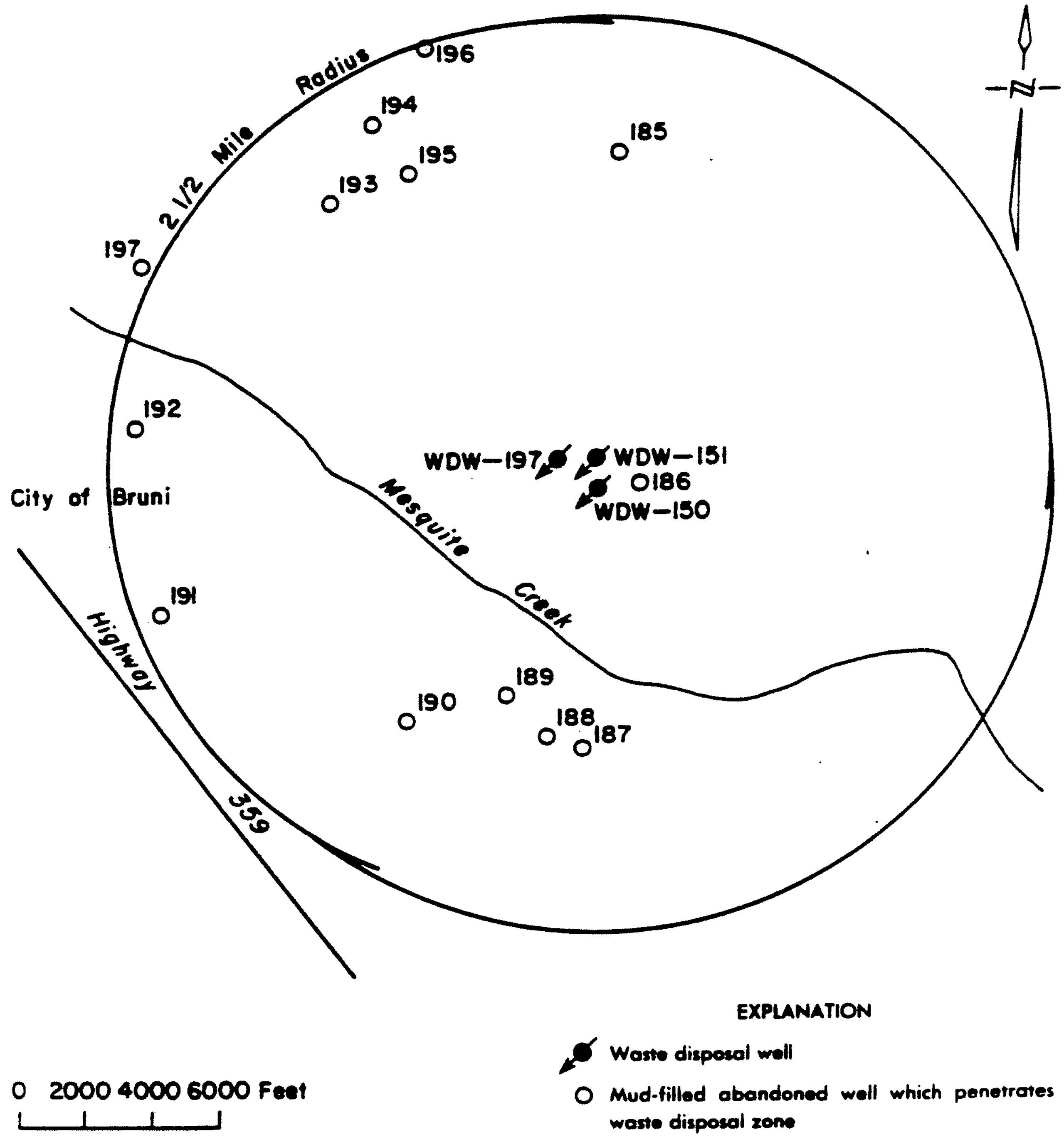

Figure 19--Area of review for Mobil Oil Corp. waste disposal wells, Holiday/El Mesquite Mine, Webb County

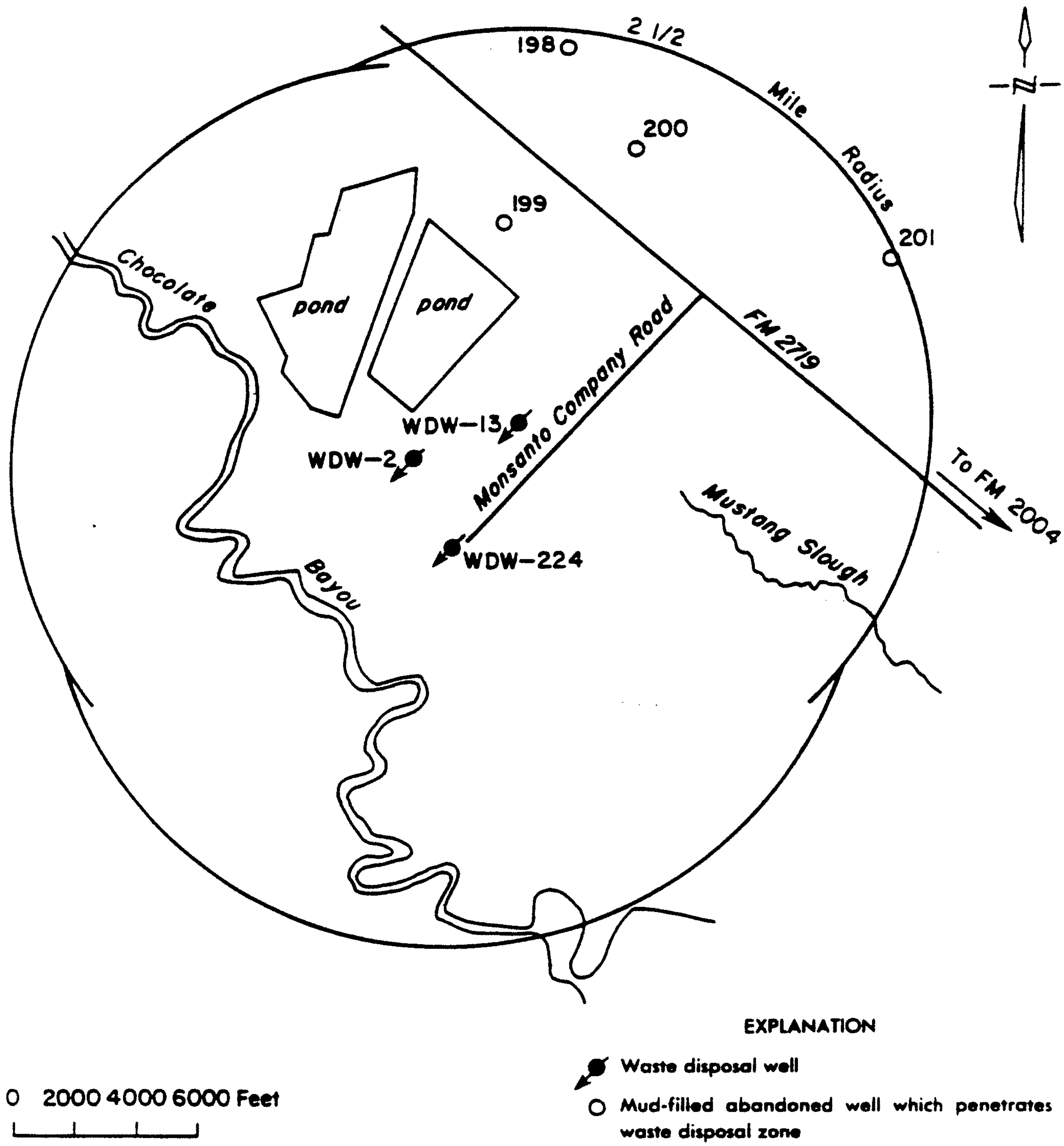

Figure 20--Area of review for Monsanto Chemical Co. waste disposal wells, Chocolate Bayou Plant, Brazoria County

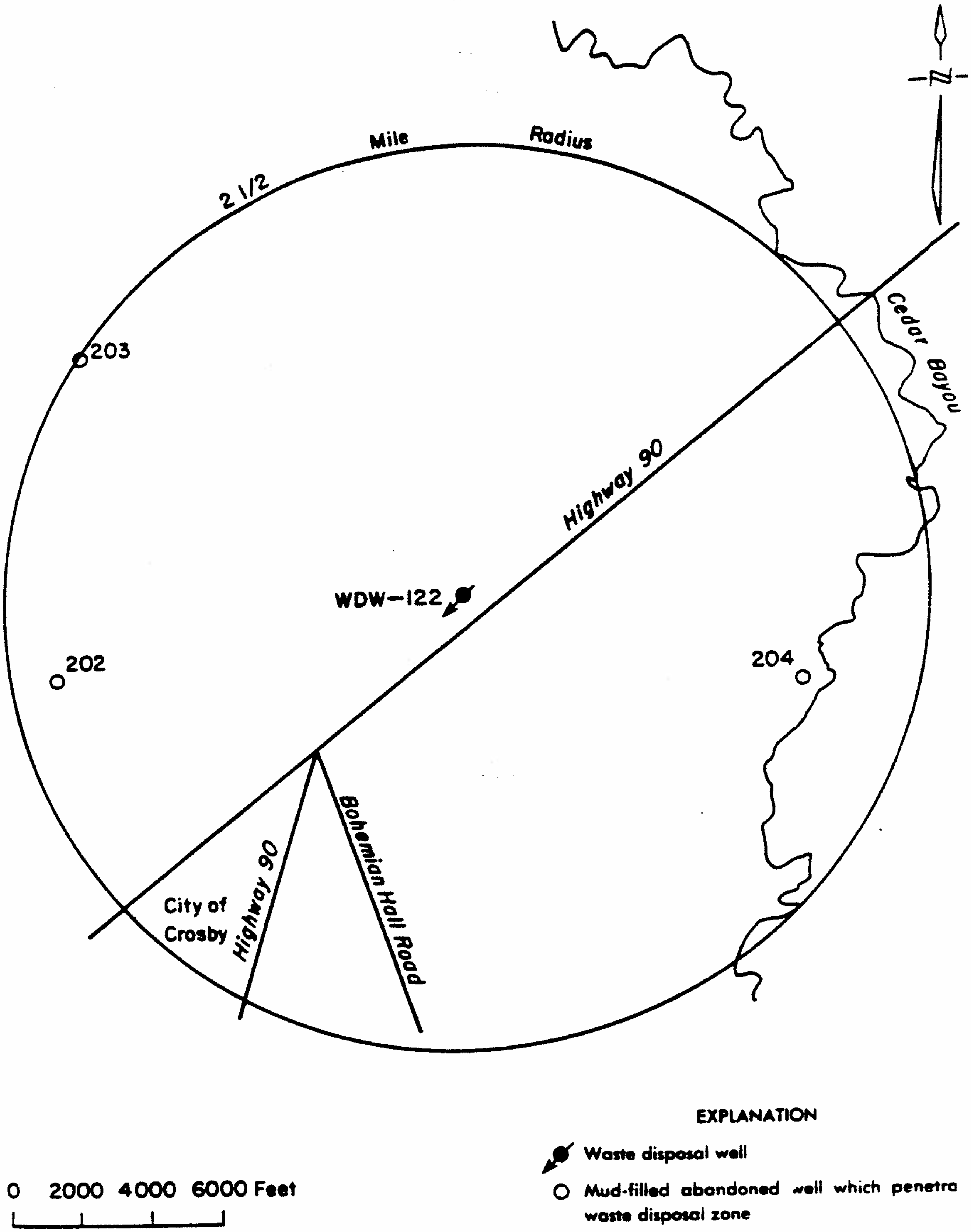

Figure 21--Area of review for Penwalt Corp. waste disposal well, Crosby Plant, Harris County

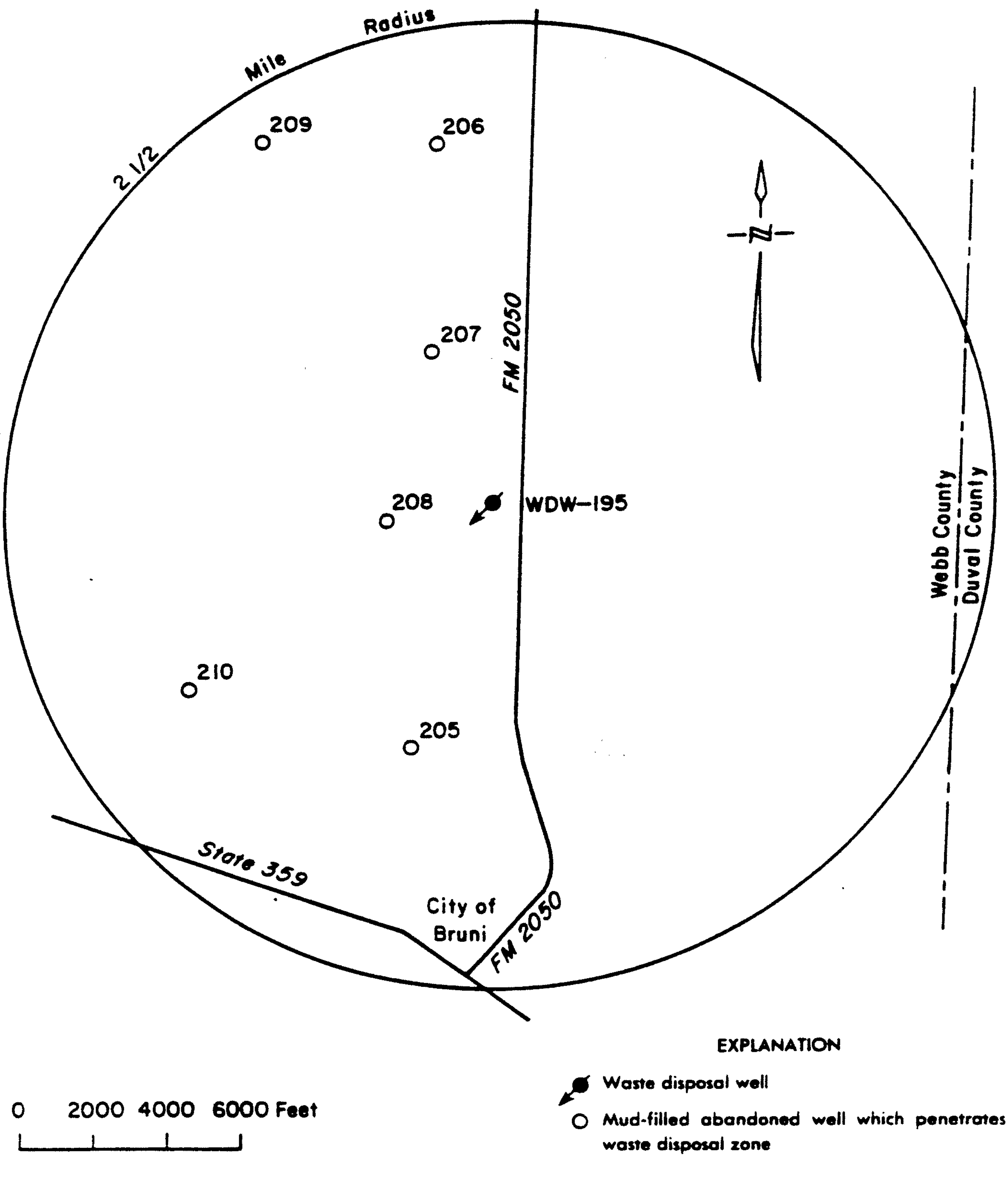

Figure 22--Area of Review for Tenneco Uranium, Inc. waste disposal well, West Cole Mine, Duval and Webb Counties

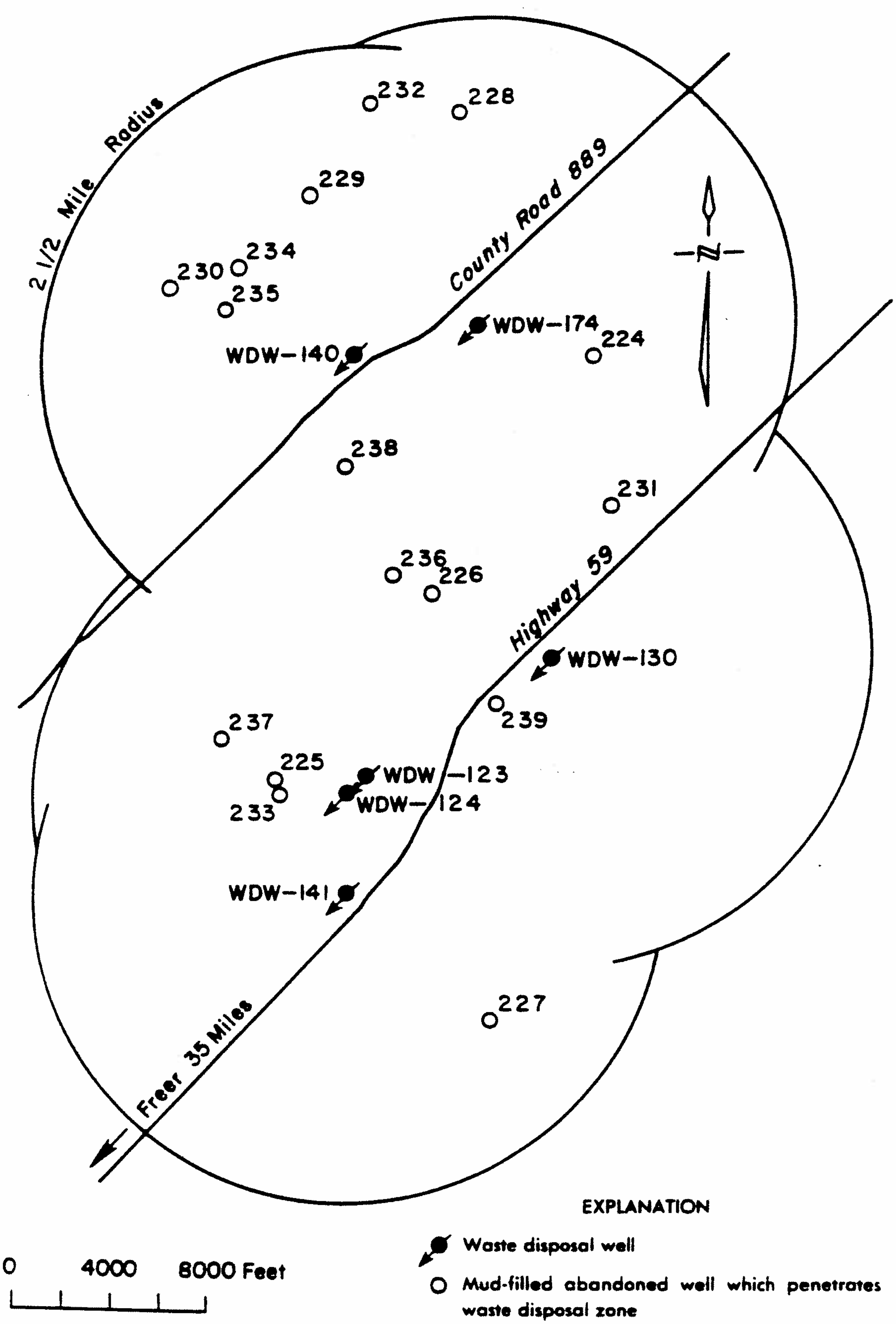

Figure 24--Area of review for U. S. Steel Corp. waste disposal wells, George West Sites, Live Oak County

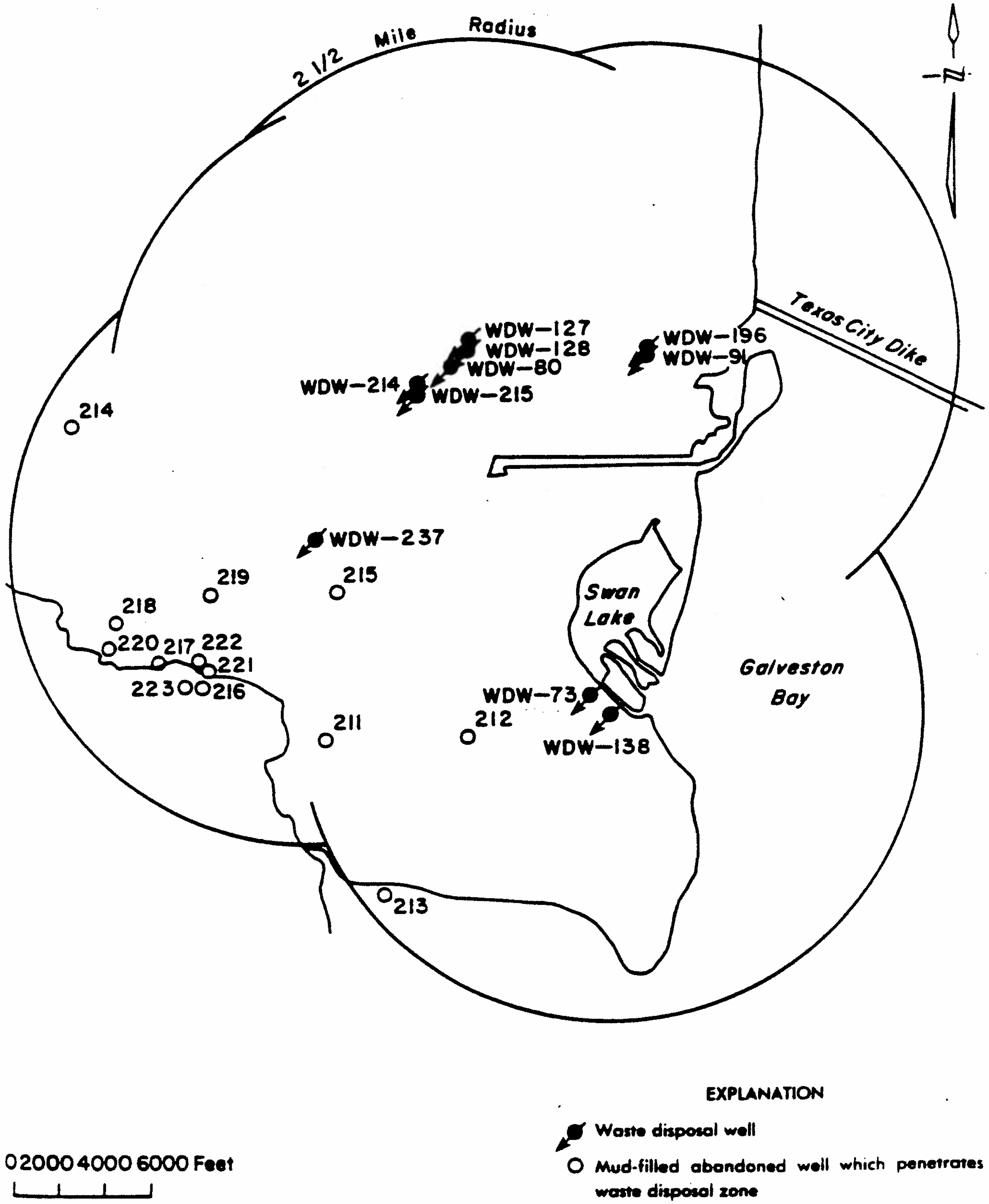

Figure 23--Area of review for waste disposal wells near Texas City, Galveston Coun' Amoco Oil Co., Malone Service Co., Monsanto Chemical Co., and Textin, Inc.

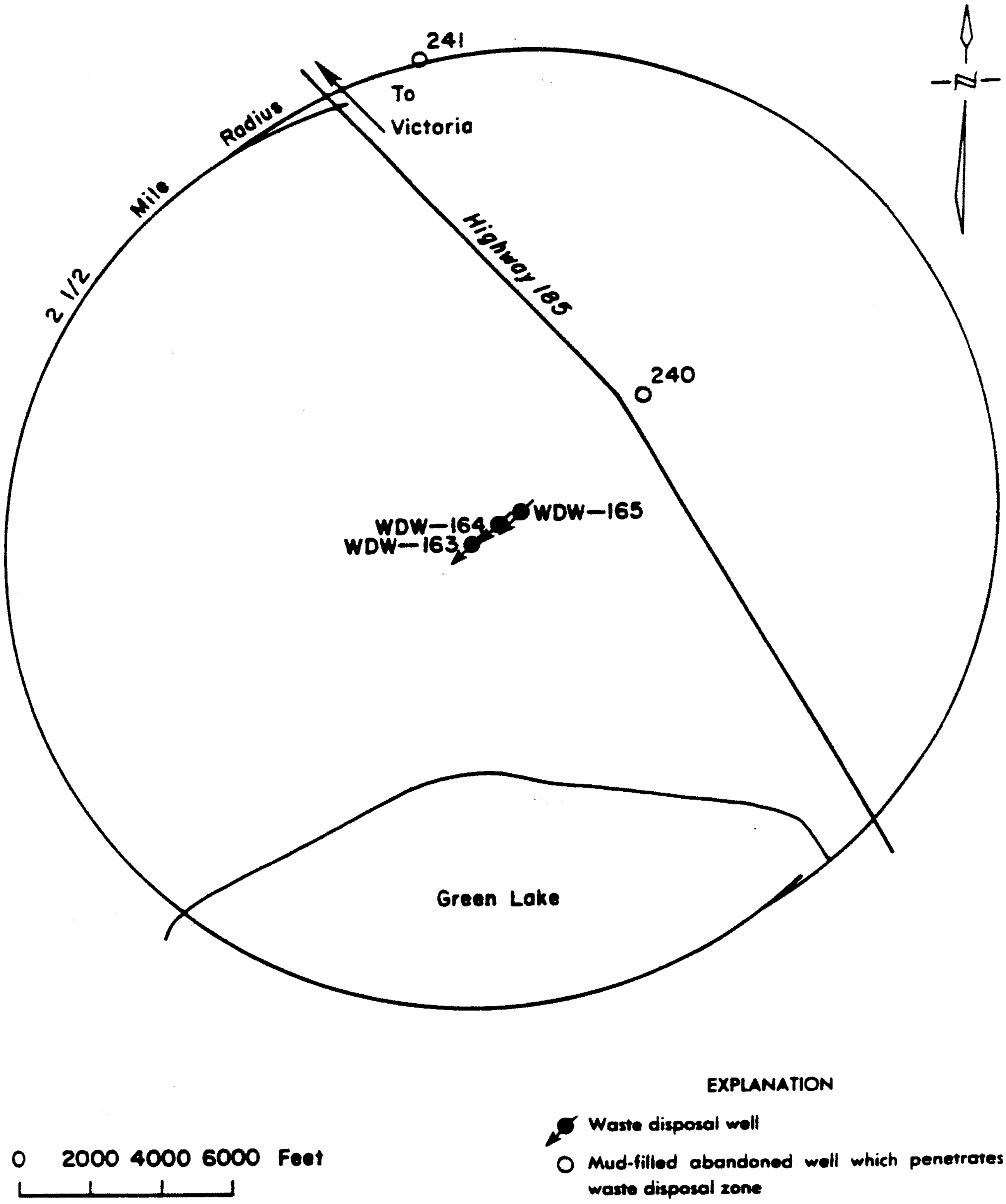

Figure 25--Area of review for Vistron Corp. waste disposal wells, Port Lavaca Plant, Calhoun County

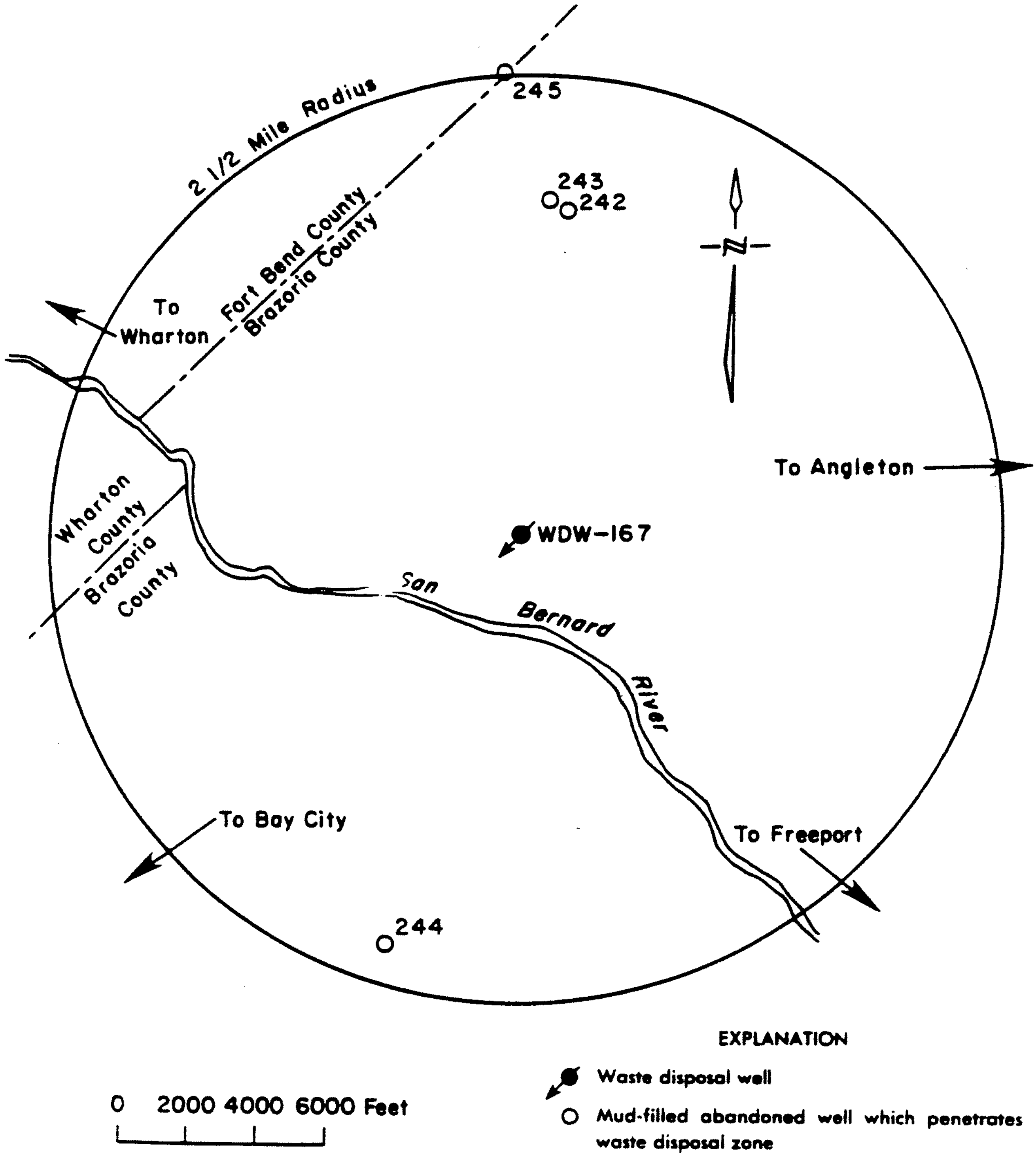

Figure 26--Area of review for Wastewater, Inc. waste disposal well, Guy Facility, Brazoria, Fort Bend, and Wharton Counties

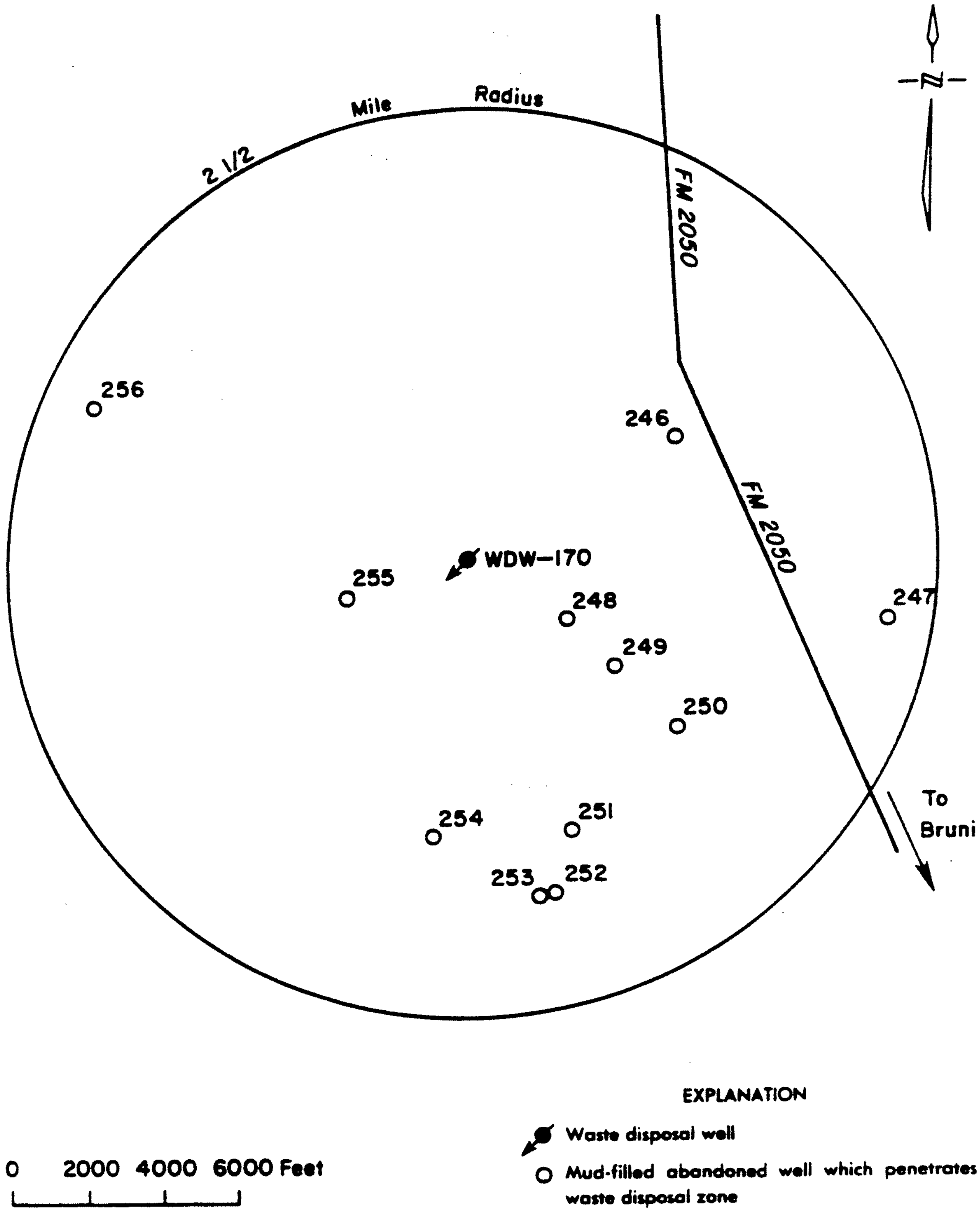

Figure 27--Area of review for Westinghouse Electric Corp. waste disposal well, Bruni Mine, Webb County

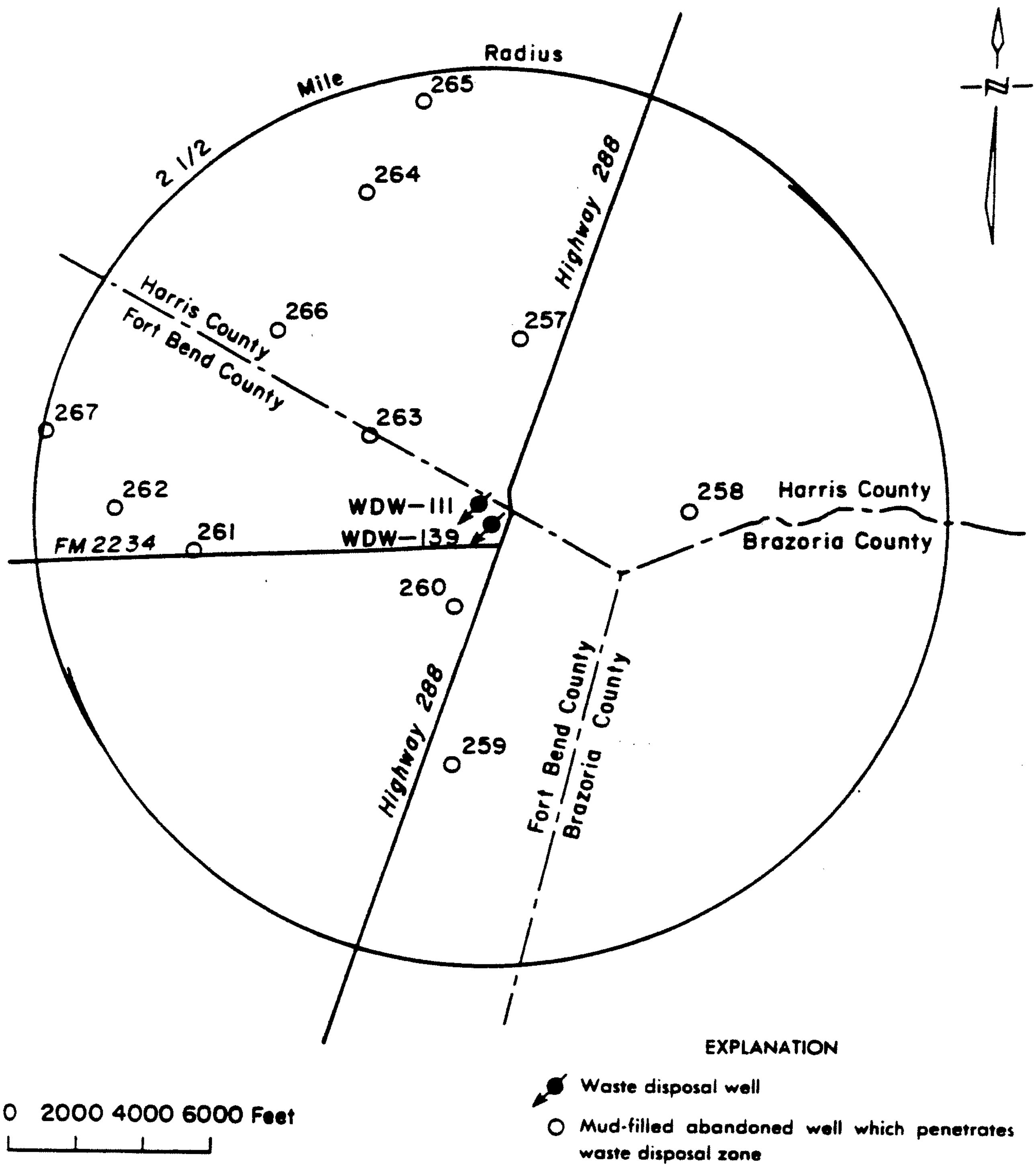

Figure 28--Area of review for Witco Chemical Co. waste disposal wells, Almeda Road Plant, Brazoria, Fort Bend, and Harris Counties

APPENDIX

Summaries of Literature and Personal Communications

Annis, Max R., August, 1967, High-Temperature Flow Properties of Water-Base Drilling Fluids: Journal of Petroleum Technology 1074-1080.

SUMMARY:

A study of mud rheology and gel properties was conducted in the laboratory to investigate the effects of time, temperature and mud composition. Included in the results was some data on gel strengths which should be applicable to a mud column in an abandoned well.

Investigation of a quiescent bentonite mud revealed that gel strength increased with time and temperature. On a given system the mud becomes more non-Newtonian with temperature. Gel strengths based on the breakdown of a gel increases indefinitely with time. As the bentonite concentrations are increased, gel strength and viscosity also increased. Gel strengths, and viscosity, are influenced in an unpredictable manner by the type of mud and electrolyte additives. Addition of sodium hydroxide, for instance, is a common deflocculant which lowers both gel strength and viscosity. Gel strengths of muds are controlled in part by electrical forces between particles and in part by mechanical interaction between particles (the more particles, the more interference between particles).

Under reservoir conditions much greater time is involved, and fluids from the mud are lost to the formation. Both of these factors would tend to increase the gel strength of the mud remaining in an abandoned well. Use of the more conservative gel strengths observed in the laboratory should insure that gel strengths assumed for reservoir conditions are overly conservative. It appears that a gel strength of 20 to 25 pounds per 100 square feet could be safely assumed.

CONCLUSIONS:

1. Mud gel strengths increase indefinitely with time
2. Mud gel strengths increase with temperature
3. Gel strengths are influenced in an unpredictable manner by the mud and electrolyte additives.
4. Addition of sodium hydroxide is a common deflocculant which lower both gel strength and viscosity
5. Mud gel strengths observed in the laboratory would probably increase under reservoir conditions due to the greater time involved and fluid loss to the formation.

Barker, Steven E., 1981, Determining the Area of Review for Hazardous Waste Disposal Wells: M.S. Thesis, University of Texas at Austin.

SUMMARY:

The ultimate gel strength of mud under bore hole conditions bears no direct relationship to the standard gel strength tests conducted on drilling fluids. Following abandonment of a well the mud in the bore hole is subjected to conditions that differ significantly from surface conditions. At formation depths encountered for disposal of hazardous wastes temperatures range fro 80 to 300°F, pressures range from 400 to 5,000 psig and residence times generally exceed 5 years.

Water based muds commonly used, develop high gel strengths after prolonged periods of quiescence. The gel strengths attained vary widely depending on chemical and physical properties. Information presented in this paper indicates that gel strengths do not follow any well established prediction of long term gel strengths with time. In all cases observed gel strengths increased with time. Garrison (Barker p. 95) in a study of California bentonites revealed that gel strengths follow a generalized mathematical relationship with constants that vary with the chem and physical characteristics of the drilling fluids.

The pressure necessary to break the gel strength of a static mu column varies directly with the gel strength and column heights and inversely with the hole diameter.

Oil base muds lack gel strength and wells drilled with this flu should be evaluated by an alternate procedure.

CONCLUSIONS:

The following conclusions were drawn from the portion of the pa dealing with the gel strength investigation:

1. Gel strengths of muds which remain undisturbed in wells do increase with time.

2. Information presented in this paper indicates gel strength in wells do not follow any well defined prediction over a long term.

3. A study of California bentonites revealed that gel strengths can be described by a generalized mathematic equation with constants that vary with chemical and physical properties.

4. A gel strength of 20 lb/100 ft^2 represents the minimum value that would be expected to be encountered when evaluating abandoned wells drilled with water base drilling fluids.

5. The pressure required to break the gel strength of a static mud column varies directly with the gel strength and column height and inversely with the hole diameter.

Cox, William, February 26, 1986, Personal Communication: Three
Oil Co., Houston, Texas.

SUMMARY:

William Cox described his years of experience in drilling w for Exxon as an independent oil operator. Much of Cox's work included drilling on the flanks of gulf coast salt domes and in shallow sands overlying the salt domes. Cox explained the comm problem of bit deflection toward the salt stock when drilling i the steeply upwarped strata on the flank of a salt dome. Use extra drill collars and very slow penetration rates are required obtain a straight hole in this situation. Cox indicated that m of the wells in his experience were dilled with "native mud" consisting of just water and drill cuttings. This native mud invariably exceeded 9 pounds per gallon, and frequently had to thinned by addition of more water to the hole.

CONCLUSION:

Native drilling muds in abandoned wellbores drilled by rot rigs, exceed 9 pounds per gallon.

Davis, Ken E., November 12, 1985, Address to U.S. Environmental Protection Agency Region IV, Mud-in-Annulus Workshop, Atlanta.

SUMMARY:

The maximum reservoir pressure that mud in a well will withstand before interformational fluid flow will occur, is equal to the combined resistive effects of the mud column hydrostatic weight, and the gel strength of the mud. The minimum gel strength of drilling mud in a well is a direct function of both the initial gel strength of the mud as determined by laboratory tests, and the length of the mud-filled interval, and an inverse function of the diameter of the well.

Most of the information needed to evaluate the ability of mud in a well to prevent interformational fluid flow, may be obtained from operator's well records, drilling and plugging reports, well log headings, and mud company records. In the absence of mud data specific for a well in question, a mud density of 9.5 pounds/gallon, and an initial mud gel strength of 25 pounds/100 feet^2 may be used for conservatively evaluations.

Once reservoir pressures attain a level sufficient to initiate interformational fluid flow through a mud-filled interval of a well, the channels created in the mud may not readily heal when the mud is returned to static conditions.

Besides considerations of mud column hydrostatic weight and mud gel strengths, other factors which may prevent interformational fluid flow in wells are, (a) the hydration swelling of water sensitive clay strata, (b) sloughing or caving of unconsolidated sand strata, and (c) low permeability plugs formed from the settling of native muds or barite-weighted muds, and from the hardening of lime or gypsum-based muds.

CONCLUSIONS:

1. A mud-filled interval of a well will prevent interformational fluid flow, provided that reservoir pressures do not exceed the combined resistive effects of the mud column hydrostatic weight, and the gel strength of the mud.

2. A mud density of 9.5 pounds/gallon and an initial mud gel strength of 25 pounds/100 feet^2 may be used for conservative evaluations of abandoned wells for which specific mud data is not available.

3. Mud gel strength generally increases with time and temperature.

4. Once gel strength of a mud has been exceeded by excessive reservoir pressures, the channels created in the mud may not readily heal when the mud is returned to static conditions.

5. Natural wellbore instability, and settling or hardening of some types of drilling muds may prevent interformational fluid flow within wells.

Deutsch, M., 1963, Ground-Water Contamination and Legal Controls in Michigan: U.S. Geological Survey Water Supply Paper 1691.

SUMMARY:

Concerning abandoned wells, Deutsch reported that vertical leakage of highly mineralized water through unplugged wells or test borings has caused extensive contamination of fresh water supplies over the last 100 years in Michigan. In instances where wells were not cased, as is common in hard bedrock formations, interformational flow of waters has occurred in response to the artesian pressures under which they were confined. In 1939, in Kent County, Michigan, it was concluded that a number of oil wells and test holes drilled between 1935 and 1937 at a location about 1/2 mile upgradient from water supply wells, had communicated high-chloride water from deep formations into the local fresh-water aquifer.

Contamination of drinking water by way of unplugged wells has also occurred in areas of the Saginaw Lowland in Michigan. Here, numerous cased wells were corroded by native formation brines, and the brines entered the aquifer used for drinking water supplies.

CONCLUSIONS:

1. Vertical leakage of highly mineralized waters through unplugged wells or test borings, in response to artesian pressures under which they have been confined, has caused extensive contamination of fresh-water supplies over the last 100 years in Michigan.

2. Brine contamination of fresh-water aquifers by way of unplugged wells and test borings has been documented for uncased holes and for wells with corroded casing.

Gray, George R., and Darley, H.C.H., 1981, Composition and Properties of Oil Well Drilling Fluids: Gulf Publishing Company, Houston, Texas

SUMMARY

The book on drilling fluids by Gray and Darley deals primarily with oil and gas well drilling. Some parts of the book might also be applicable to mud plugging of abandoned wells.

In their chapter on rheology of drilling fluids, data on quiescent muds are presented that indicate mud gel srengths increase with time. Empirical data has been fitted to an equation which increases linearly with time. Extrapolation of this data suggests that gel strength would increase indefinitely with time. However, the increase in gel strength noted after an extended time span would be insignificant.

Limited data presented by Gray and Darley also indicate that gel strength increases as the temperature is increased. Trends for the initial gel and 30 minute gel strengths demonstrate this property (Gray and Darley, p. 232). The explanation for this phenomenon is that high temperatures increase the interparticle attractive forces, so that the gel strength is increased accordingly.

The effects of temperature and time in increasing gel strength of muds are significant during drilling operations, when mud circulation is interrupted in the lower portions of the hole while making at trip out of the hole. The gel strength of this undisturbed (uncirculated) mud must be exceeded by the mud pump pressure in order to reestablish mud circulation and resume drilling. When lime-based muds have been used, semi-solid cement-like masses have been noted which are difficult to move. Extrapolating laboratory properties to wellbore conditions in abandoned wells would postulate that gelled or solidified muds aid in confining fluids in over-pressured reservoirs.

Humble Oil and Refining Company (now Exxon) experienced unexpected blowouts while drilling in the Conroe Field. The blowouts occurred while withdrawing drill pipe from the hole, although the mudweight was more than adequate to suppress the reservoir pressure. Investigation revealed the gel strength of the mud had increased in the well to the point that the gelled mud clung to the pipe and swabbed the well, allowing gas and oil to invade the wellbore.

Though conditions in abandoned wells were not specifically covered in Gray's and Darley's book, it is evident that muds in an abandoned well are subject to long time spans, high temperatures, and filtrate losses. Since all these factors tend to increase gel strength, the lab gel strengths reported should be conservative estimates of mud gel strength in an abandoned well. Therefore, use of a conservative gel strength of 20 to 25 pounds per 100 square feet, would ensure that the pressure-retaining capability of a mud gel is not overestimated.

CONCLUSIONS

1. Mud gel strength increase indefinitely with time.

2. Mud gel strength increase with temperature.

3. Mud gel strengths observed in the laboratory should be lower than those present in the reservoir. Therefore, assuming a gel strength of 20 to 25 pounds per 100 square feet, as observed in the laboratory, should be conservative for use in the field.

Hellinghausen, Jack, November 14, 1985, Personal Communication: Atlantic-Richfield Co., Dallas, Texas.

SUMMARY:

This discussion with Hellinghausen was primarily concerned with older wells drilled and abandoned in the 1920's and 1930's. Information concerning gel strength on native muds used in that era is practically nonexistent but he thought the gel strength was low.

Wells drilled during the 1920's generally ranged from 500 to 1000 feet. A 2500 foot depth was considered to be relatively deep. During the 1930's a well could readily be drilled from 3000 to 4000 feet with an occasional well as deep as 6000 feet. Plugging an abandoned well was usually accomplished by dumping about 25 sacks of cement down the annulus or pumping some cement down to the packer. Cement "plugs" placed in the well mixed with the mud and most probably were ineffective plugs. Wells drilled with the cable tool are dry open holes that could be sealed by dropping cement in the hole with a bailer.

Some of the old wells that were drilled and abandoned have mud plugs that have set up and become more dense than the surrounding formations. Drill bits have been sidetracked when drilling out the old holes. Also holes that were drilled at that time were crooked, as only short drill collars were available which allowed the hole to drift. It was also mentioned that during abandonment of some of these old wells all the junk from the drill site was dumped in the well bores which would make drilling out of these holes more difficult.

CONCLUSIONS

1. Gel strengths of native muds left in wells of the 1920's and 1930's were unknown

2. Wells drilled in the 1920's averaged about 1000 feet in depth with a maximum of about 2500 feet. Wells drilled in the 1930's generally ranged from 3000 to 4000 feet in depth with a maximum depth of about 6000 feet.

3. Plugging of wells during that time generally consisted of a 25 sack cement plug dropped in the annulus or pumped to the packer. As a result these plugs were probably mixed with the mud rendering them ineffective.

4. Mud plugs that have setup and become more dense than the surrounding formation have been encountered when drilling out old well bores.

5. During abandonment of many old wells junk from the surrounding drill site was dumped in the well bores.

Jeffery, David, and Istvan, John, January 9, 1986, Personal Communication: PB-KBB Inc., Houston, Texas.

SUMMARY:

David Jeffery and John Istvan were interviewed during a visit to the agency on other business. During a discussion of mud properties both individuals agreed the most important property of a mud to control pressure in an abandoned well is the weight, or density, of the mud. Gel strength makes a small contribution towards controlling pressure in the borehole and should be regarded only as safety factor in their opinion. Muds containing bentonite are relatively stable gels when quiescent and do not setup or solidify. As a consequence they would be expected to be displaced from an unplugged open well if the hydraulic head and the gel strength were exceeded by the reservoir pressure. Lime base muds used prior to bentonite additives tend to solidify blocking the wel bore against fluid flow.

In a discussion concerning abandoned wells located on theGulf Coast it is believed that abandoned open hole wellbores heal over due to the relatively unconsolidated formations. However, if casin is left in the hole a channel is provided for fluids to migrate between permeable zones or to the surface In West Texas hard country the boreholes of abandoned wells tend to remain unchan for sometime. In some areas the Red Bed clays tend to close our wellbores within a few days and some cases in a few hours.

Wells drilled before the mid-thirties most probably do not exceed 3000 to 3500 feet depth due to the limitations of the drilling equipment. These wells were generally too shallow to penetrate permeable zones that might be considered for a waste injection zone. While discussing this issue it was suggested that depth of at least 2500 feet (3500 feet would be preferable) should be required for a waste disposal zone. Any reservoir considered should be evaluated on its own merits.

Reentry of abandoned wells in the Gulf Coast area has disclose that open wellbores have healed over sufficiently to prevent migration of fluids between formations. In one case the old wellbore could not be followed. In another case mud appeared on th shaker screen indicating the hole was being followed, however, the hole had healed over so that fluid migration would be prevented.

CONCLUSIONS:

1. Mud weight, or density, is the most important property of mud to control migration of fluid in wellbore.

2. Gel strength makes a small contribution to control fl migration and should be regarded as a small safety factor.

3. Abandoned wells in unconsolidated formations of the Gulf Coast will probably heal over thereby preventing fluid migration.

4. Abandoned well bores in West Texas are more likely to remain intact where Red Bed clays are known to exist, these wellbores may be closed.

5. Any casing left in an abandoned well can provide a channel for migration of fluids to ground water zone or to the surface.

Johnson, R.L., November 19, 1985, Personal Communication: Amoco Production Company (USA), Houston, Texas.

SUMMARY:

Johnson described his experience in reentering wells for a waterflood project near Wichita Falls. In general, the mud in the reentered holes was found to have thickened to a gel strength greater than that of the original mud conditions. However, no evidence was found that such thickened muds ever solidified completely.

Johnson also supervised the 1983 reentering and plugging of an abandoned well located near the Amoco industrial waste disposal well site in Texas City. This well had originally been drilled and abandoned in 1944. Amoco was able to follow the original borehole, using a bit to wash the old mud from the hole to total depth. The old mud appeared to have thickened over 40 years, and there was no evidence of fluid flow through the borehole during this period of time.

Bridging of the unconsolidated or water-sensitive sediments in the borehole wall may completely seal a well. Johnson cited the commonplace difficulty of getting tools and casing strings downho in the Gulf Coast region due to natural borehole sealing.

Johnson further indicated that even when reservoir pressures are sufficient to displace the hydrostatic weight of borehole mud, the buildup of impermeable mud filter cake on the borehole wall may retard or prevent interformational flow of fluids.

Johnson stressed that no plugging and abandonment technique is absolutely failsafe. Even cement plugs may be ineffective in plugging a well if they are not set properly and confirmed by tagging.

CONCLUSIONS:

1. Experiences in reentering abandoned wells have found the borehole mud to have thickened over time, but not to have solidified.

2. Difficulty in running tools and casing strings into newly drilled wells indicates a tendency for natural borehole sealing in Gulf Coast-type unconsolidated sediments.

3. The build-up of impermeable mud filter cake on borehole walls may retard or prevent interformational flow of fluids.

4. No plugging and abandonment technique is absolutely failsafe. Care should be taken to confirm that mud and cement have been properly placed in an abandoned well.

Johnston, O.C. and Greene, C.J., 1979, Investigation of Artificial Penetrations in the Vicinity of Subsurface Disposal Wells - Technical Report: Texas Department of Water Resources.

SUMMARY:

In considering permit applications for waste disposal wells, artificial penetrations should be evaluated by reviewing completio and plugging records in the subject area, to identify improperly plugged wells. The pressure increase caused by the proposed injection program should be calculated for each potential problem well, using estimated values for transmissibity and storage in th nonequilibrium formula developed by Theis (1935). Generally, a we that has been properly completed or abandoned is one where interformational fluid transfer does not occur, or will not occur a result of changes in reservoir pressure.

Due to the plastic nature of most Tertiary shales, abandoned well bores probably do not remain open for long periods of time. However, for technical evaluations in conjunction with waste disposal well permitting, uncased boreholes are assumed to remain open and full of drilling mud. In the west and north-central par of Texas, a wellbore or an uncemented annulus may remain open indefinite periods of time, and often drilling fluids and ceme... not be in the wellbore or annulus because of lost circulation zone:

Where calculated reservoir pressures resulting from injectio are sufficient to overcome the resistive effect of the hydrostati pressure of mud in an improperly completed or abandoned well, the well should be reentered and properly plugged, or a reservoir pressure monitor well should be completed. Operation of a pressur monitor well will enable the pressures within a reservoir to be limited to prevent the possibility of fluid flow through improperl plugged wells.

CONCLUSIONS:

1. Completion and plugging records of artificial penetrations ne proposed waste disposal wells should be reviewed to determin which abandoned wells require remedial plugging or reservoir pressure monitoring to prevent interformational transfer of fluids.

2. Abandoned wellbores filled with mud, and wellbore closure by natural formation wall instability are reasonable conditions for the Gulf Coast area.

3. In many wells in west and north-central Texas, an uncased borehole or uncemented borehole-casing annulus will stay open indefinitely, and may not be safely assumed to contain the full amount of mud or cement indicated by well records.

Kent, Robert T., November 20, 1985, Personal Communication: Underground Resource Management, Inc., Austin, Texas .

SUMMARY:

This discussion with Kent dealt primarily with geologic variations between geographic regions. Kent was mostly concerned with whether or not the drilling fluid in the well at closure was retained in place.

In Gulf Coast wells with no longstring casing the well bores slough and the shales swell trapping the mud. In this case, assuming the mud column hydrostatic head based on a mud filled hole, should be valid. When the hole is cased, a mud filled hole cannot be safely assumed, unless a record is available indicating the presence of mud at closure. Some operators abandoned depleted or dry wells without bothering to fill the well with mud. Formation water from the zone of interest could then enter the open hole and corrode the casing, to create a channel for fluids to escape to the surface from a formation outside the casing.

Though west Texas formations are usually competent, thief zones are common within the production reservoirs in the northern Caprock areas around Lubbock and Amarillo. Where thief zones occur, drilling fluids remaining in an open hole below surface casing, r drain to a level that the hydraulic pressure of the thief zone w support.

Kent indicated that, when documentation exists that an abandoned wellbore was filled with mud, and lost circulation problems were not present, assuming the hydraulic head for the full mud column is justified. Coastal wells and wells in the Odessa area fall in this category. He warned, however, that in cased holes and areas where low pressure zones exist, the wellbore may be empty or partially filled with mud. In these cases injection should be limited to maintain the injection zone pressure below that of the low pressure lost circulation zones. In spite of these problems, Kent indicated that injection of liquid wastes into deep wells is a preferred method of disposal under the proper geohydrologic conditions.

CONCLUSIONS:

1. Assuming a mud hydrostatic head based on a mud-filled column should be valid in uncased Gulf Coast abandoned wells where unstable formations can bridge over a hole.

2. In cased abandoned wells, a mud column may be absent or reduced significantly if mud has been removed for production or testing, and was not replaced. Unless records indicate otherwise, it should be assumed that the mud does not completely fill the casing in these wells.

3. In the northern Cap Rock area of west Texas, where low pressure zones exist, the drilling fluid and cement may drop to the levels of thief zones. Injection should be limited so that reservoir pressures do not exceed the mud column hydrostatic head calculated from the depth of the thief zone.

Kent, Robert T., and Bentley, Michael E., 1985, Risk Assessment of Deep Well Injection Systems: Second Annual Canadian-American Conference on Hydrogeology, Banff.

SUMMARY:

Concerning injection well failures by upward fluid migration through artificial penetrations, it should be noted that standard cementing practice for the long-string or production casing of oil or gas wells is to cement only the lower 600 to 1,000 feet of casing, leaving the borehole-casing annulus full of drilling mud.

Numerous wells around the perimeter of the Barbers Hill Salt Dome at Mont Belview, Texas have uncemented sections of long-string casing, due to lost circulation problems experienced in the cavernous cap rock penetrated by these wells. This cap rock comprises an injection reservoir for salt water injection wells at the Barbers Hill dome. In 1975, several abandoned oil wells at the dome began to flow salt water to the ground surface during periods of injection operations taking place nearby. It is believed that waste brine encountering uncemented portions of the long-string casing in the abandoned wells, may have caused corrosion of the casing and a consequent flow of brine through the open casing to ground surface.

In 1970, an oil well one mile away from a brine injection well in Scurry County in west Texas, developed a wellhead pressure adequate to flow salt water to the ground surface. Analyses of the brine collected from the uncemented oil well annulus indicated a strong similarity to brine from the nearby injection well. From records showing the long-string casing of the oil well to be uncemented through the injection zone, it was hypothesized that casing corrosion by injected or native brines had allowed the injected brine to be produced from the oil well.

Cases of abandoned wells beginning to flow near injection well sites have also been reported in the 1930's in Michigan, and in southwest Ontario in the late 1960's. In these hard rock areas, a large number of wells had been drilled and abandoned by cable tool methods. Since cable tool drilling does not use drilling fluid, most of these wells were probably abandoned without mud in the wellbore.

Whereas the noted examples including cap rocks of salt domes, and hard rocks in west Texas, Michigan, and Ontario, point out the potential danger of upward flow in regions where wellbores stay open, it is believed that in areas of unconsolidated strata, drilling mud and natural sealing of wellbores provide some protection against fluid flow.

CONCLUSIONS:

1. For oil and gas wells constructed by rotary drilling techniques, standard practice for cementing long-string casing is to cement only the lower 600 to 1,000 feet of casing, leaving the borehole casing annulus full of drilling mud.

2. Documented cases from areas of consolidated rocks have shown that abandoned or producing wells without casing cemented through an injection zone may produce fluids as a direct result of nearby injection well operations.

3. In areas of unconsolidated strata, drilling mud and natural sealing of wellbores may provide some protection against fluid flow.

Marr, J.J., November 6, 1985, Personal Communication: Resource Enginering, Houston, Texas.

SUMMARY:

Marr indicated that mud gel strengths increase with time and temperature under abandoned well conditions. In fact, some gypsum and lime base muds solidify so that difficulty is experienced durinc drilling out of abandoned wells. Both bentonite and gyp additives tend to exhibit high gel strengths. In areas where formation materials are swelled by water, sloughing and caving in of the hole results. The bore hole heals over and the formation approaches original predrilled conditions. In areas where formations are consolidated the drilled hole remains unchanged.

Formations used for waste disposal along the Gulf Coast are mos unconsolidated and subject to caving and sloughing discussed above. Abandoned wells located in West Texas maintain the original diamete with time so that a hole may be recovered by merely washing out wit a drill bit. In an inadequately plugged well in this area pressure control depends on the mud head and gel strength. Abandoned wells in these areas are more likely to lose fluids when the zone is overpressured.

Wells drilled prior to World War II used natural mud with no control of density or viscosity. Many times the natural mud remaining in the well bore had high densities (up to 15 lb/gal). The minimum density of wellbore muds (natural and modern drilling muds) is considered to be 9 lb/gal. Additives to drilling muds have resulted in high gel strengths which under well bore conditions could require a substantial pressure to displace the mud. In some cases the mud has solidified.

CONCLUSIONS:

1. Mud gel strengths increase with time and temperature. Som gypsum and lime base muds solidify to a stage that hinders drilling out abandoned wells.

2. Formations generally used for waste disposal zones along the Gulf Coast tend to be unconsolidated and subject to sloughing and caving in of the well bore. As a result the bor hole may heal over so the formation may approach original conditions.

3. Formations in West Texas are well consolidated so that the bore hole remains intact. Inadequately abandoned well completed in a waste disposal zone could lose fluids when the zone is overpressured.

4. Wells abandoned before World War II were drilled with natural mud which could result in high density mud (as much as 15 lb/gal).

5. The minimum density of wellbore muds is considered to be 9 lb/gal.

Meers, R.J., November 7, 1985, Personal Communication: Pollution Control & Waste Disposal, Inc., Metairie, Louisiana.

SUMMARY:

Meers stated that mud density is a major factor in controlling pressures in abandoned wells, and the gel strength would be an added benefit. Gel strengths can be significant in wells as illustrated during the reentry of old wells in Maryland to complete cementing of the annulus outside the casing. After perforating the casing above the original cement, the original mud outside the casing was circulated to the surface. The pressure required to break the gel was great enough to require a packer above the perforations to protect the casing. Also in old wells in the Orange Du Pont Plant in 1977 plugs of gelled mud in the open well bore have been observed to be more resistant to drilling than the original formation.

Abandoned wells along the Gulf Coast probably are sealed off due to sloughing of the formation and briding of the hole. For this reason the Gulf Coast is a good location for a waste disposal well.

In the West Texas area, the formations usually used for waste disposal are well consolidated and well bore holes remain intact. As a result abandoned wells drilled into these zones would be more susceptible to losing fluid when overpressured.

Wells drilled prior to 1940 were generally abandoned with little thought given to proper plugging procedures. These wells rarely exceeded 4000 feet depth and should not endanger most injection operations as the waste disposal zones generally exceed this depth.

CONCLUSIONS:

1. Mud density is a major factor in controlling pressures in abandoned wells, however, gel strength is an added benefit.

2. Mud gel in the annulus outside the casing of a well required considerable pressure to break down and circulate out of the well.

3. Drillers have encountered plugs of gelled mud in a well bore that were more resistant to drilling than the original formation.

4. Abandoned wells along the Gulf are probably sealed off due to sloughing of the formation and bridging of the bore hole, consequently, reservoirs in this area are excellent for injection of wastes.

5. West Texas formations are generally consolidated and well bore holes do not heal over. Consequently, abandoned wells penetrating waste disposal holes could lose formation fluids if inadequately plugged.

Price, William Henry, 1971, The Determination of Maximum Injection Pressure for Effluent Disposal Wells - Houston, Texas Area, M.S. Thesis, University of Texas at Austin.

SUMMARY:

Regarding abandoned wells, Price indicated that dry holes in the Houston-Galveston area which were improperly plugged, must be a primary consideration in setting maximum injection rates and volumes for injection wells. In contrast with modern well-plugging standards involving combinations of properly set cement plugs within a mud-filled wellbore, many dry holes in this area of the Gulf Coast were improperly plugged with only mud in the wellbore. Price further indicated that .01 psi per foot of depth was the maximum advisable pressure build-up at an improperly plugged well which lacked mud density data. This suggested limit is based on the pressure gradient difference between a 9.2 lb/gal mud (@ .477 psi/ft) and a normally-pressured formation piezometric head (@ .467 psi/ft). The probabilities that a mud of unknown density actually exceeds 9.2 lb/gal, and that many Gulf Coast wellbores will be sealed by wall sloughing and clay swelling, combine to make .01 psi/ft a conservative amount of pressure build-up for an improperly plugged or inadequately documented well.

CONCLUSIONS:

1. Judged by modern plugging standards, many Gulf Coast area wells were improperly plugged by filling with heavy mud without setting down-hole cement plugs.

2. Improperly plugged or inadequately documented wells in the Gulf Coast area will safely withstand downhole pressure build-ups to the degree to which the well-bore mud hydrostatic pressure exceeds the reservoir pressure.

Schuh, Frank J., November 19, 1985, Personal Communication: Atlantic Richfield Company, Dallas, Texas.

SUMMARY:

This discussion with Schuh dealt largely with drilling fluids and cement plugs, and their capacity to contain fluids in wells. He also cited cases in which drilling mud was used above packers and found to be unsatisfactory because of difficulty in unseating the packers after the mud gelled. Schuh indicated that untreated mud columns tend to set up as the pH decreases from breakdown of organic constituents in the mud. Muds also thicken due to filtration, as fluids bleed from the mud to surrounding pays. In shale zones where filtration is extremely low, the fluid column remains intact and is effective in the control of pressure. It is desirable, therefore, that the injection zone be separated by a thick shale zone to maintain a mud column of sufficient height to control the waste zone pressure.

In old wells drilled in the 1930's and earlier, the clay muds used at that time have thickened and solidified to the point that considerable pressure can be contained. When using these muds as drilling fluids, mud thinners had to be added to decrease viscosity and gel strength.

As a side issue, Schuh mentioned that failure of cement plugs had been experienced when located next to a gas zone. In these cases it was concluded that during the setting process, the interna pressure in the cement plug dropped to that of the surrounding formation, allowing gas to penetrate the plug and render it useless

CONCLUSIONS:

1. Untreated mud columns tend to set up as pH is reduced.

2. Mud columns become thicker and more dense due to filtratio losses to the surrounding pays.

3. Mud columns remain intact and effectively control pressur in shale and other impermeable zones where filtration is nil. It is desirable, therefore, to have thick impermeabl zones between the waste zone and ground water to prevent loss of the fluid column.

4. Clay muds used in old wells in the 1930's and earlier, hav thickened and solidified sufficiently to contain considerable reservoir pressure build-ups.

5. Failure of cement plugs has occurred when set opposite ga zones. During setting of the plug, pressure in the cemen

plug dropped to that of the surrounding formation, allowing gas to penetrate and destroy the plug.

Smith, Dwight, November 8, 1985, Personal Communication: Halliburton Services, Duncan, Oklahoma,

SUMMARY:

Smith indicated that it was impossible to predict the gel strength of mud in an abandoned well, or the probability of a mud retaining fluids in an overpressured reservoir. The somewhat pessimistic opinion on the benefits of mud gel in abandoned wells is based on the lack of data to substantiate mud gel strengths in a well after an extended time. Smith stated that over long periods of time at elevated temperatures, mud gels will break down into pockets of filtercake and fluid. Also, hydrochloric acid can shrink mud gel so that mud-filled intervals may be breached by channels.

Smith cited a case in Pennsylvania where casing in an overpressured zone was ejected from an abandoned well which was adjacent to the injection well. Also in Kankakee, Illinois, an overpressured gas storage reservoir resulted in gas intrusion into the surrounding farmer's water wells rendering them unfit for use.

Bentonite muds were first introduced to improve mud gel strength in the 1930's. Prior to that time, native drilling muds comprised of drill cuttings and water, had poor gel strengths. Wells drilled before 1930 generally did not exceed 4,000 feet in depth. Because most waste disposal zones for industrial wells are below this depth, these pre-1930 wells should exert little or no influence on waste disposal well projects. Plugging records of wells abandoned prior to 1960 are usually not well documented, and are not generally reliable as a result.

Boreholes in abandoned wells in the Gulf Coast region probably close over time, due to sloughing, or caving, of the borehole walls, and healing of the pay. In west Texas and the Panhandle, zones used for waste disposal are relatively consolidated, and will maintain boreholes in an open condition for an extended time. "Red beds" in some areas of west Texas, are the principal zones of instability that would be likely to slough and seal a well bore.

CONCLUSIONS:

1. It is not possible to predict gel strength in an abandoned well.

2. Mud gel in contact with hydrochloric acid may shrink sufficiently to cause channels to breach the mud-filled intervals.

3. Wells drilled prior to the mid 1930's used native muds which had poor gel strengths.

4. Wells drilled before 1930 generally were less than 4,000 feet in depth and consequently do not penetrate most disposal zones for industrial waste disposal wells.

5. Abandoned wells on the Gulf Coast area have a higher probability of borehole closure by sloughing of the borehole than wells in west Texas and the Panhandle. Red bed clays in west Texas and Panhandle are the principal zones of borehole instability in these areas.

Williams, C.C., 1948, Contamination of Deep Water Wells in Southeastern Kansas: State Geological Survey of Kansas, Bulletin 76

SUMMARY

Williams documented some of the modes of ground-water contamination which have occurred through producing or abandoned wells, in which care has not been taken to prevent interformatinal fluid flow. In southeastern Kansas, highly mineralized water from the Cherokee Shale has entered numerous deep water wells. The practice of setting well casing without completely cementing (grouting) the borehole-casing annulus, has allowed mineralized formation waters to enter the well by corroding through the casing, and by traveling down the unsealed annulus to the well completion zone. It was therefore recommended by the State Geological Survey, and the Kansas State Board of Health, that the borehole-casing annulus of all wells be sealed by grout through all zones of inferior water quality, to protect steel casing from corrosion, and to maintain the quality of local aquifers which supply fresh water for domestic uses.

CONCLUSIONS:

Cases documented in the southeastern part of Kansas indicate that failure to seal the borehole-casing annulus of a well during construction, may subject a well to casing failure by corrosion, and/or to vertical flow of fluids between formation.

Permeability, porosity and surface characteristics of filter cakes from water bentonite suspensions

Permeability, porosity and surface characteristics of filter cakes from water–bentonite suspensions

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Abstract

Water – bentonite suspensions behave as non-Newtonian fluids with exceptional rheological and filtration characteristics at low temperatures which deteriorate at temperatures higher than 120^0C. Additives restore these characteristics but many of them are thermally unstable at the temperatures encountered, for example in oil-well and geothermal drilling. Greek lignite has been proven to be an excellent additive for water–bentonite suspensions at temperatures up to 177^0C.

In this work we attempt to assess the reason for such good performance by studying the surface characteristics and the permeabilities of filter cakes of water – bentonite suspensions with and without the additive (various lignite types) after exposing the samples to thermal static aging at 177^0C for 16 hours.

The filter cakes are produced with an American Petroleum Institute filter press allowing filtration for sufficient time to produce a filter cake with adequate thickness. The surface morphology of the filter cakes has been assessed with a scanning electron microscope. The permeabilities of the filter cakes were determined with an in-house technique which creates a 'wet core' of the filter cake of sufficient thickness and the water permeability is measured in a Hassler type meter. The differences between the reference samples (cakes from bentonite suspensions at room temperature) with cake samples from thermally aged water–bentonite suspensions and water–bentonite–lignite suspensions both in surface characteristics and in cake permeability are noted and discussed.
Keywords: filter-cake, permeability, lignite, bentonite, high-temperature.

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1 Introduction

The creation of low permeability filter cakes is one of the desirable properties of water–bentonite suspensions used as drilling fluids in order to minimize fluid loss into permeable formations which could be detrimental to hydrocarbon identification and production.

The filtration properties of bentonite-water suspensions are greatly affected by the way bentonite particles associate and the state of the suspension, being flocculated or deflocculated, aggregated or dispersed. The best filtration performance is when a clay suspension is deflocculated and dispersed since the very small clay particles give low porosities and permeabilities of the filter cake that is formed. When bentonite particles are flocculated, they are larger, giving higher porosities and permeabilities. Soluble salts in muds increase cake permeability but thinners usually restore these permeabilities because they disperse clay aggregates into smaller particles. Filter cake permeabilities are of the order of 10^{-2} mD for flocculated suspensions, of the order of 10^{-3} mD for untreated fresh water muds and of the order of 10^{-4} mD for muds treated with thinners [1].

Fluid loss through such filter cakes is generally measured in the laboratory in a single pressure drop, usually 6.9 bar (100 psi), with an American Petroleum Institute standardized procedure [2, 3]. In reality, however, the filter cakes are exposed to different differential pressures and different drilling fluid formulations requiring thus a general understanding of the properties of filter cakes [4] which will help predict not only fluid loss in conditions different from the lab but also the behavior under extreme conditions like high temperatures which are encountered now more often in oil-well exploration.

Filter cakes of bentonite-water suspensions are low in permeability, compressible and compactable [5]. To obtain the permeability of the filter cake, k, a permeating fluid of known pressure gradient should be applied to the sample and the permeable flux should be measured. If the applied pressure is large in order to give a measurable flux, the sample may deform. In addition, sealing of the boundaries of a wet and deformable sample may be difficult. Thus, measuring the permeability of the filter cakes in a direct way over a large porosity range is very difficult. It is for this reason that specific values of the permeabilities of filter cakes are not usually reported in the literature. Indirect techniques for measuring cake permeability have been reported by Meeten and Sherwood [5] using an inversion technique, which requires data obtained from filtration measurements at a series of pressure gradient values.

The good properties of bentonite-water suspensions deteriorate at temperatures above about 120°C [1, 6]. When drilling stops, the drilling fluid may stay static for a long time while it is exposed to high temperatures and strong gels may develop which cause excessive pressure drop when flowing and do not form good filter cakes. Therefore, water–bentonite suspensions are treated with various materials, to enable them to withstand these high temperatures [7]. The stability of bentonite suspensions at high temperatures may be improved either by modifying the surface charge of bentonite particles or by introducing a steric barrier against agglomeration using various additives which may be either modified, or non-modified, natural products like lignosulfonate complexes with various metals, tannins, humic acid, lignite and modified lignite, synthetic polymer products, mono- or poly-acrylic acid [8, 9]. Lignite has been used together with many other substances like sodium chromate as alkali solubilized lignite to improve filtration and thermal stability of chrome-lignosulfonate drilling fluids [1, 7, 10].

Results have been reported [11, 12] which show that several Greek lignite types can be used as additives, at optimum concentration of 3% in water–bentonite suspensions giving exceptional filtration control properties even after the bentonite-lignite-water suspension has been exposed to 177 ^{0}C for 16 hrs. The performance has been equal or sometimes even better to suspensions with a commercial lignite additive. However, the mechanism of action of the lignite additives for improving the performance of water–bentonite suspensions at high temperatures has not been understood. It is the intention of this ongoing research work to attempt to understand some of the mechanisms involved and processes that take place in such systems. This is accomplished by examining the surface characteristics of filter cakes using scanning electron microscopy and by directly measuring filter cake permeabilities, of filter cakes created with different water–bentonite suspensions, using two different bentonites and various lignite types as additives. In the present work the methodology that was developed will be presented together with preliminary experimental results.

2 Experimental procedure

Two sodium bentonites were used, a Greek bentonite (Zenith, kindly provided by S & B Industrial Minerals S.A.) and a Wyoming bentonite (kindly provided by Baroid – Cebo Holland). Various lignite types from different places in Greece, which were provided by the Greek Institute of Geological and Minerealogical Exploration [11] as well as a commercial lignite (Caustilig) kindly provided by M-I Drilling Fluids were used as additives. The particle size of both bentonites is finer than 70 μm, thus meeting the API 13A specifications [2], while lignite samples were ground, when needed, to less than 70 μm.

The suspension preparation procedure followed the specifications of the American Petroleum Institute for drilling fluids [2, 3]. The water–bentonite suspension constitutes of deionized water and bentonite clay in the proportion of 6.42 gr of bentonite in 100 gr of deionized water, while in case of additive addition the proportion is 3 gr of lignite in 100 gr of deionized water. After mixing, the suspensions were either stored in sealed containers for full hydration for about 16 hours at room temperature (hydrated samples) or placed in a high temperature aging cell, pressurized at 100 psig to avoid the evaporation of water and statically aged at 177°C for 16 hours in a portable oven (thermally aged samples) [11]. The static aging procedure simulates the behaviour of the static muds in high temperature wells. The pH of the suspensions was 9.82 for Zenith and 9.00 for Wyoming bentonite. At pH range of 9.0 to 10.0 the rheological and filtration properties of water–bentonite suspensions are insensitive to changes in pH [13].

After aging, the filtration properties of the suspensions were measured in a Low Pressure – Low Temperature (LPLT) filter press (Fann 30201). The Whatman filter paper used in the API filter press has a retention size of 2.7 μm, an area of 4560 cm^2 and offers no hydraulic resistance to the flow of water which flowed 100 to 1000 times faster compared to case when there was drilling fluid in the filter press [14]. Moreover, different filter paper retention size has also no effect on the filtration properties.

The API filtration procedure allows for 30 min filtration time and the filtrate is measured over this period and reported as fluid loss per thirty minutes. The filter cake that is produced over this period is fairly thin with a thickness of one to three millimetres [1, 11]. Investigation of surface morphology of the cake can be performed on a cake of such thickness as the material required is extremely small. However, for the permeability measurements, a cake of sufficient thickness is required for use on the permeability apparatus. This was created by allowing filtration in the filter press for about 16 hrs and at that time only a very low volume of filtrate was flowing from the press. This procedure gave a fairly thick filter cake of approximately 10-15 mm thickness while at the same time it resulted in an almost uniform cake concentration allowing full compaction of the filter cake. Similar procedures have been followed by Meeten and Sherwood [4] and Sherwood et al. [15] who have confirmed experimentally the uniform cake thickness.

Drying of the filter cake for use in SEM was accomplished under room temperature conditions (~25°C), without placing the filter cake in an oven or other drying equipment. It was observed that few days were needed (~3-4 days) for the filter cake to become completely dry. The cake was then prepared for SEM observations. Analysis of morphology of filter cakes created by water–bentonite suspensions have been performed in particular for drilling fluid characterization by Porter [16], Hartmann et al. [17], Plank and Gossen [18] and Chenevert [19]. In this work the microstructure of the fillter cakes was studied by scanning electron microscope (SEM) JEOL JSM 5400, working at 15 kV of electron accelerating voltage. The dried filter cakes were mounted and gold coated with a layer about 10 nm thick by using a vacuum of 10^{-3} Torr metal-coating process. Microchemical qualitative analyses of clay and lignite particles were carried out using an EDS energy dispersive X-ray analyzer INCA Energy 300. Each sample was studied at several magnifications. The x3500 and x7500 magnifications were taken as optimal for study of the microstructure details and the results presented are at the x7500 magnification.

The permeability of the mud cake was measured using an in-house developed experimental setup based on a Hassler type core holder. The mud cake as it was produced from the API filter press was loaded in a ring with 2.54 cm external diameter, 0.1cm thickness and 0.5 cm length. The ring was subsequently placed between two Berea core samples, 2.54 cm diameter and 2 cm long each, of known permeability. The specimen, consisting of the two cores and the ring containing the mud cake was encased in a thermo-shrinkage plastic (Figure 1) and placed in the sample holder of a Hasser type core holder. Water was injected in the sample using an Isco positive displacement pump at a constant pressure of

105 psi. After equilibration, the flow though the core was measured and the permeability of the filter cake was determined assuming flow though porous media in series.

Figure 1: In-house developed specimen used for permeability experiments.

3 Experimental results

SEM and permeability results are presented for filter cakes created using two bentonites and two lignites, a commercial product (Γ) and a Greek lignite (TH7).

In Figure 2 the SEM pictures of the tested filter cakes are shown. All the pictures were taken in a plane perpendicular to the flow plane of the filter cakes. Evident differences in the character of the formed microstructure of the different filter cakes can be observed. The microstructure of the hydrated Wyoming filter cakes (Fig. 2(a)) are characterized by large amounts of leafs placed very closely to each other and thus creating compact orientated layers of smectite particles (EDS analysis). The hydrated Zenith filter cakes (Fig. 2(b)) create very similar microstructure to the Wyoming ones, with comparable particle sizes, densities and compactness of individual grains. The filter cakes from the thermally aged Wyoming and Zenith suspensions (Fig. 2(c), 2(d)) present a more permeable microstructure, which is characterized by a large amount of leafs with open-air voids having small interfacial zones and mutual bonds. The SEM micrographs of the filter cakes treated with commercial lignite Γ (Fig. 2(e) and 2(f)) and with Greek lignite TH7 (Fig. 2(g) and 2(h)) show that the cakes have undergone a reduction in porosity compared to the corresponding thermally aged ones. The smectite particles draw closer and their interaction increases, so they give a less permeable microstructure.

In Figure 3 the measured permeabilities of the tested filter cakes are shown. The results reveal first of all that on the two identical tests that have been performed with Wyoming-bentonite filter cakes, the measured permeabilities are within 5% of each other, indicating the measurement capabilities and the repeatability of the system set-up. Secondly, the values of the permeabilities of all samples are very small, of the order between 10^{-4} and 10^{-3} mD, close to the permeability values of filter cakes observed from fresh-water muds and muds treated with thinners [1]. Evaluation of the Wyoming-bentonite results shows the significant reduction in permeability values on the samples treated with

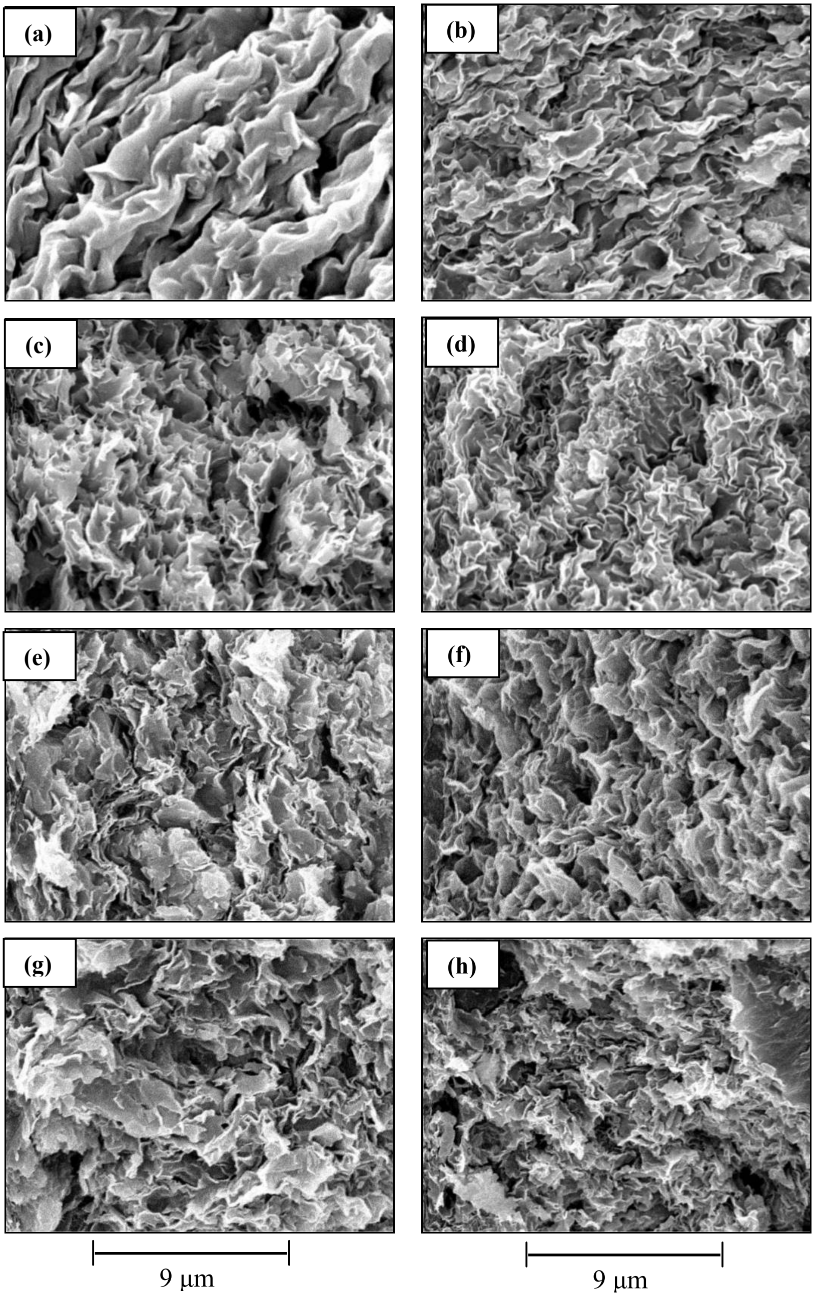

Figure 2: Scanning electron micrographs (SEM) of tested filter cakes. Magnification x7500: (a) H-W, (b) H-Z, (c) TA-W, (d) TA-Z, (e) TA-W+Γ, (f) TA-Z+Γ, (g) TA-W+TH7, (h) TA-Z+TH7 (H: hydrated, TA: thermally aged, W: Wyoming, Z: Zenith).

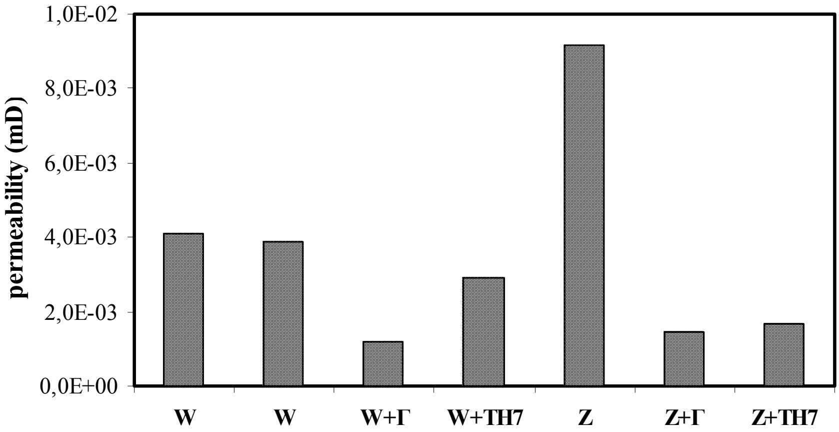

Figure 3: Measured permeabilities of filter cakes of the tested bentonite-water suspensions. All suspensions have been thermally aged.

lignite. The effect of the different lignite types is different, with the commercial lignite (W+Γ) giving a permeability ratio to the permeability with only bentonite of 4.1/1.21=3.4, better than the TH7 lignite, which gives a ratio of 4.1/2.89=1.4. Evaluation of the Zenith bentonite suspension results shows the higher permeability values of the filter cake of the Zenith suspension, compared to the Wyoming counterpart, with a ratio of the two permeabilities of 9.17/4.1=2.2. Lignite addition lowers again the permeability of the filter cakes, with the different lignites having different effect. Better performance is observed with the commercial lignite (Z+Γ) with a ratio of permeabilities of 9.17/1.45=6.3, while lignite TH7 exhibits a very good performance as well, giving a ratio of 9.17/1.69=5.4. Furthermore, the values of the permeability of the filter cakes obtained with the Zenith-suspensions and with the two lignite types are comparable to the Wyoming counterparts.

4 Discussion

Based on the analysis of the SEM micrographs of the filter cakes created with water–bentonite suspensions, it appears that the structure of the filter cake changes according to the additive in the suspension and to the treatment it has undergone. When no additive is present and the suspensions has been only hydrated for 16 hrs, the bentonite platelets, Zenith or Wyoming, are aligned in a direction almost normal to the flow direction, creating a network structure that results in a very low permeability of the filter cake, thus giving low fluid loss value and hence making the suspension excellent for use in drilling applications. When the same suspensions are thermally aged to 177°C, the filter cakes created afterwards offer a more permeable structure, which results both from the association of several clay platelets and the opening up of the platelets thus leaving more open space. This is observed for both bentonite types. The addition of the two lignites studied, Γ and TH7, presents a different filter cake structure from the previous two. The micrographs show that the clay platelets are smoothly associated, although not in the same way as when the bentonite is only hydrated, thus leaving probably similar open space to the hydration case resulting in similar permeability values among each other and with the hydrated case and much smaller than the case when the suspension is thermally aged. No identifiable differences can be reported from these SEM micrographs from the filter cakes derived with the different lignite types.

The permeability measurements are similar to the SEM micrograph observations and show the decrease in permeability values for the filter cakes derived with the suspensions treated with lignite. However, the permeability measurements indicate differences also among the lignite types. However, it should be noticed that the values of the permeability of the filter cakes are extremely small when compared, for example with permeabilities of the permeable formations, which are of the order of 0.1 to 1000 mD. Thus, the developed technique allows for the identification of differences among the lignite types, but one should look at the essential differences which are the ones between bentonite suspensions and bentonite-lignite suspensions.

5 Conclusions

A methodology has been established for the evaluation of the permeability and the surface characteristics of filter cakes created by using different water–bentonite suspensions. The methodology involves the creation of adequate thickness filter cake in an API filter press, the evaluation of surface morphology of the filter cake by scanning electron microscopy and the measurement of the permeability of the filter cake.

The permeability measurement presented significant challenges which have been resolved. The thick filter cake is placed between two cores of known permeability and thickness, all held together in a thermo-shrinkage plastic and put in a Hassler type holder for the permeability measurement with water. The technique has been tested and gives repeatable results. It should be stressed that permeability measurements of filter cakes rarely appear in the literature.

The technique has been applied to study the characteristics of filter cakes from Wyoming and Zenith bentonite-water suspensions at 6.42% wt. which were hydrated, thermally aged and thermally aged after adding different lignites at 3% wt.

SEM micrographs reveal that hydrated bentonite suspension filter cakes form a network of platelets almost normal to the flow direction. This structure opens up when the suspension is thermally aged and multiparticle association is observed increasing the permeability of the filter cake. The addition of the two lignite types studied gives a structure which is closed again and not leaving much open space for the flow of the filtrate. There were not many differences observed among the filter cakes of the two different lignites that were analyzed with SEM.

The permeability measurements give permeability values for the thermally aged suspensions for both bentonites used which are typical of flocculated suspensions, with a variation among the two bentonite types. Additions of lignite at 3% wt. results in drastic reduction of the permeability of filter cakes derived after thermal aging of the suspension. Variations in permeability values have been observed between the different lignites tested.

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Groundwater Flow in Low-Permeability Environments

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Groundwater Flow in Low-Permeability Environments

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Certain geologic media are known to have small permeability; subsurface environments composed of these media and lacking well developed secondary permeability have groundwater flow sytems with many distinctive characteristics. Moreover, groundwater flow in these environments appears to influence the evolution of certain hydrologic, geologic, and geochemical systems, may affect the accumulation of pertroleum and ores, and probably has a role in the structural evolution of parts of the crust. Such environments are also important in the context of waste disposal. This review attempts to synthesize the diverse contributions of various disciplines to the problem of flow in low-permeability environments. Problems hindering analysis are enumerated together with suggested approaches to overcoming them. A common thread running through the discussion is the significance of size- and time-scale limitations of the ability to directly observe flow behavior and make measurements of parameters. These limitations have resulted in rather distinct small- and large-scale approaches to the problem. The first part of the review considers experimental investigations of low-permeability flow, including in situ testing; these are generally conducted on temporal and spatial scales which are relatively small compared with those of interest. Results from this work have provided increasingly detailed information about many aspects of the flow but leave certain questions unanswered. Recent advances in laboratory and in situ testing techniques have permitted measurements of permeability and storage properties in progressively "tighter" media and investigation of transient flow under these conditions. However, very large hydraulic gradients are still required for the tests; an observational gap exists for typical in situ gradients. The applicability of Darcy's law in this range is therefore untested, although claims of observed non-Darcian behavior appear flawed. Two important nonhydraulic flow phenomena, osmosis and ultrafiltration, are experimentally well established in prepared clays but have been incompletely investigated, particularly in undisturbed geologic media. Small-scale experimental results form much of the basis for analyses of flow in low-permeability environments which occurs on scales of time and size too large to permit direct observation. Such large-scale flow behavior is the focus of the second part of the review. Extrapolation of small-scale experimental experience becomes an important and sometimes controversial problem in this context. In large flow systems under steady state conditions the regional permeability can sometimes be determined, but systems with transient flow are more difficult to analyze. The complexity of the problem is enhanced by the sensitivity of large-scale flow to the effects of slow geologic processes. One-dimensional studies have begun to elucidate how simple burial or exhumation can generate transient flow conditions by changing the state of stress and temperature and by burial metamorphism. Investigation of the more complex problem of the interaction of geologic processes and flow in two and three dimensions is just beginning. Because these transient flow analyses have largely been based on flow in experimental scale systems or in relatively permeable systems, deformation in response to effective stress changes is generally treated as linearly elastic; however, this treatment creates difficulties for the long periods of interest because viscoelastic deformation is probably significant. Also, large-scale flow simulations in argillaceous environments generally have neglected osmosis and ultrafiltration, in part because extrapolation of laboratory experience with coupled flow to large scales under in situ conditions is controversial. Nevertheless, the effects are potentially quite important because the coupled flow might cause ultra long lived transient conditions. The difficulties associated with analysis are matched by those of characterizing hydrologic conditions in tight environments; measurements of hydraulic head and sampling of pore fluids have been done only rarely because of the practical difficulties involved. These problems are also discussed in the second part of this paper.

CONTENTS

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INTRODUCTION

Improved laboratory and in situ testing techniques have demonstrated that the permeability of many geologic materials is very small. At the same time, no properly tested geologic media have proved to be entirely impermeable. Large regions composed of low-permeability lithologies are often significantly more permeable than small volumes of the same rock, owing to the presence of joints, fractures, and faults. Nevertheless, there is ample evidence that many sizable regions possess low permeability, presumably because fractures either fail to develop, are not connected or transmissive, or tend to be sparse. For example, artesian systems often have extensive confining beds of quite low regional permeability. In certain other settings, one finds fluid pressures indicative of transient hydrodynamic conditions which, because they are unrelated to human activity, are presumably long lived. Such conditions are explicable in the presence of large volumes of low-permeability media but are otherwise difficult to explain. Examples include some of the "anomalous" pressures known from drilling in many parts of the world. In still other settings, distributions of ions in groundwater suggest the presence of extensive low-permeability bodies which act as semipermeable membranes.

Low-permeability environments are most commonly associated with fine-grained sedimentary deposits such as shales and clays. These occur in active and ancient sedimentary basins and in accretionary wedges at plate boundaries. Crystalline rocks generally prove to be relatively permeable at large scale because of extensive fracturing. However, at depth they may have regionally low permeability because of healing or filling of fractures [*Walder and Nur*, 1984]. Even in shallow crystalline rocks, fractures may be sparse, leaving relatively large unfractured areas [*Balk*, 1937], or they may be numerous but unconnected as *Marsily* [1985] suggested is the case in the French Massif Central. Certain other terranes may have small permeability, including parts of the oceanic crust at depth [*Anderson et al.*, 1985] and salt and other evaporite deposits [*Kreitler et al.*, 1985]. Groundwater flow in such environments, which are low in permeability at the scale of interest, is the subject of this review. Flow under partially saturated conditions, occurring near the surface and in soils, will not be considered. The term "low permeability" is here applied to media with hydraulic conductivity to water of approximately 10^{-8} m/s and smaller.

Fluid flow in permeable rocks has been extensively studied and analyzed in several contexts, notably in the development of groundwater resources and the recovery of petroleum. By comparison, less effort has been spent to analyze the flow behavior in tight, or poorly permeable, rocks. However, the past several years have seen this begin to change. There are several reasons. It has, for example, become clear that aquifer behavior prior to development and the response to development is often mediated by adjoining tight formations [*Walton*, 1965; *Gill*, 1969; *Neumann and Witherspoon*, 1972; *Bredehoeft et al.*, 1983]. It has also been recognized that the flow in tight formations has an important role in the evolution of groundwater flow systems over geologic time. Attention has turned recently to the flow in evolving sedimentary basins [*Sharp*, 1978; *Tóth*, 1978; *Cathles and Smith*, 1983; *Smith et al.*, 1983; *Garven and Freeze*, 1984*a*, *b*; *Bethke*, 1985], which affects the migration of hydrocarbons and the formation of ore bodies. The role of fluids in mechanical processes [*Pincus et al.*, 1982] dictates the importance of groundwater flow in low-permeability portions of the crust for understanding the mechanical behavior of these regions. This has recently been emphasized by *Westbrook and Smith* [1983] for sedimentary accumulations and *Walder and Nur* [1984] for crystalline rocks. Knowledge of the flow in tight media is also necessary for understanding the geochemical evolution of their pore fluids and solids. Such regions are a unique environment where fluid and solid phases have been in contact for long periods while little chemical mass has been exchanged with the surroundings. A recent and highly significant motivation for the study of low-permeability environments is geologic disposal of toxic materials so as to minimize their exposure to moving groundwater [*Bredehoeft et al.*, 1978].

The study of flow in low-permeability environments has been possible at widely disparate size and time scales. Performance and analysis of controlled experiments in the laboratory and in situ permit the investigation of various flow phenomena and direct measurement of their parameters on relatively small scales of distance and time. At the other extreme are quantitative, theoretically based analyses of large-scale and long-term flow behavior which cannot be observed. This raises the important point that where the permeability is small, flow experiments encompassing significant volumes are not practical. Even areally extensive in situ tests, such as aquifer-confining layer tests, sample the tight confining layer but a short distance in from its boundary. Usually a small fraction of the confining layer is involved. Tests using boreholes in tight rocks likewise involve relatively small volumes of the rock. Thus, compared with the volumes of interest, practicable laboratory and in situ tests are small in scale. Yet, these are often the only source of information on which to base analyses. Only in systems which are at steady state is it sometimes possible to directly measure the hydraulic conductivity of large volumes of tight media. The problem is much more complex if the flow is in a transient state because the changes occur extremely slowly. One is, therefore, unable to observe the large-scale transient response to a known stress which often helps characterize more permeable formations [e.g., *Randolf et al.*, 1985].

Extrapolation of flow behavior in tight rock from small to large scale is fraught with difficulties. As indicated, the size scale dependence of permeability is a problem; similar and less well understood difficulties are associated with the nonhydraulic conductivities governing various types of osmotic flow. A less well recognized but highly significant problem concerns the time scale dependence of storage properties. This results from descriptions developed for relatively short lived transient flow being applied to long-term behavior in low-permeability environments.

The slow transient response of the flow and long periods of time involved add another challenging dimension to the problem. Slow geologic processes acting on the system, which are normally ignored in studies of groundwater development, can be the dominant control of the flow. Hydrologic conditions may reflect cumulative geologic changes extending well back into the past. Indeed, it is often difficult to determine whether present conditions represent steady flow in equilibrium with stable boundary conditions, whether they are slowly transient in response to natural geologic changes, or whether they are due to other effects entirely, such as osmosis.

To the various difficulties mentioned should be added those encountered in practice which are related to determining existing hydraulic conditions in the field. Normally routine procedures such as measuring hydraulic head and sampling pore fluids are much more difficult in tight materials.

The history of hydrogeology-related disciplines appears to have influenced how low-permeability environments have been studied and analyzed. Because relatively permeable environments were studied earlier and more extensively, the study of tight environments has been influenced by experience with more permeable ones. Phenomena associated only with tight media have therefore received less emphasis than they perhaps should. Osmotic flow and related coupled flow phenomena are probably the best example.

Because of the significance of flow in low-permeability environments, the increasing interest in it, and the number of disciplines making contributions toward understanding it, an overview of this emerging field of study seems warranted. The purpose of this review is to provide such a perspective. Specifically, there are four primary aims: (1) to synthesize and place in perspective the diverse research carried out in various disciplines which is important for understanding groundwater flow in saturated low-permeability environments, (2) to consider whether historical bias has influenced the approach to the problem, (3) to enumerate questions and issues which, at present, hinder analysis and to discuss appropriate approaches for overcoming them, and (4) to set forth observations on important uncertainties related to the problem.

In practical terms, the problem of flow in low-permeability environments may be summarized as follows: How can knowledge of behavior at small scales be extrapolated to large dimensions and long periods of time? Uncertainties related to small-scale behavior strongly affect the ability to understand and analyze large-scale behavior. Consequently, the first part of the paper considers the basis of our understanding of flow in low-permeability media, namely small-scale experiments and tests. The second part of the paper examines the problem of analyzing low-permeability systems in which flow is occurring at scales that make direct observation of the flow dynamics impractical. It considers how experimental experience has influenced analysis of large-scale flow and when extrapolation of experimental behavior to large scale may be misleading. To conclude, the final part of the paper offers a general, philosophical overview of the problem with observations on inherent difficulties.

THE SMALL SCALE: EXPERIMENTAL CHARACTERIZATION OF FLOW IN TIGHT ROCKS

In the present context a useful definition of "small scale" is one at which flow experiments in tight media can be completed in a practical period of time. Thus both laboratory and in situ tests are included.

Experiments have addressed questions related to two rather different perceptions of low-permeability flow. One perception, an outgrowth of traditional groundwater studies, emphasizes the hydraulic character of the flow. From this viewpoint, the primary task is to devise techniques to reliably measure the parameters governing hydraulic flow, namely, the permeability and storage properties. The latter include, in addition to specific storage, the loading efficiency, which describes the response to changes in external mechanical stress. Recent advances have been made which facilitate measurement of hydraulic parameters in the laboratory and in the field.

The other viewpoint emphasizes nonhydraulic flow phenomena which are linked specifically with tight media. Here the primary task is generally viewed as gaining a better understanding of the flow laws. This includes assessing the applicability of Darcy's law in very tight media and investigating osmotic phenomena related to coupled flow. The problems involved in these investigations are generally quite complex, and few, if any, field techniques have been developed for them.

Hydraulic Flow: Measurement of Parameters

Laboratory approaches. Laboratory strategies for measuring hydraulic conductivity of tight geologic materials can be arranged in three classes. These are (1) application of Darcy's law to flow or pressure data from steady or quasi-steady flow, (2) application of a transient groundwater flow description (which implicitly assumes Darcy's law) to transient flow or pressure data, and (3) application of a transient flow description to a mechanical surrogate for flow and pressure data, such as time dependent sample deformation. The last two classes of tests analyze the same phenomenon, namely, transient flow of a fluid in a deformable medium. However, in the second class of tests, which was developed for indurated media, stress change and deformation of the medium are considered only insofar as they affect fluid storage. The third class of tests, which was developed for relatively deformable media, considers strains and stress changes in the medium explicitly.

The prolonged flow transients which occur in low-permeability rocks provide an interesting benefit for laboratory scale testing; the time dependent behavior can be analyzed to compute the specific storage. This usually is not practical for samples of permeable rock in which transient changes in small samples occur too rapidly to be studied. The second and third classes of tests, which analyze time dependent behavior, generally permit determination of both hydraulic conductivity and specific storage.

Steady and quasi-steady tests: When the hydraulic conductivity K $[L/T]$ is very small, two problems make its measurement in simple steady flow tests difficult. First, the time required to attain steady flow through the sample may be inconveniently long [*Olsen et al.*, 1985]. Second, measuring or generating sufficiently small rates of flow may be difficult [*Remy*, 1973; *Olsen et al.*, 1985]. The first can be mitigated somewhat by decreasing the sample length in the flow direction. The second problem can be overcome by using large hydraulic gradients. Very small values of K have been measured this way, using hydraulic gradients as large as 10^6 and more, much greater than those found in nature.

Large-gradient steady flow tests have been described by *Ohle* [1951*a*, *b*], *von Englehardt and Tunn* [1955], *Lutz and Kemper* [1959], *Gloyna and Reynolds* [1961], *Young et al.* [1964], *Pearson and Lister* [1973], *Coplen and Hanshaw* [1973], *Kharaka and Berry* [1973], *Kharaka and Smalley* [1976] and *Morrow et al.* [1981, 1984], among others. Values of K of the order of 10^{-15} m/s were obtained in some instances, but large hydraulic gradients were required to obtain them.

An alternative approach is to pump small, predetermined rates of flow through the sample because it can be easier to pump small flow rates than to measure them. *Olsen* [1966] and *Olsen et al.* [1985] used a small-bore syringe to pump at rates as small as 10^{-6} cm^3/s. It permitted measurements of K in the range 10^{-7} to 10^{-10} m/s with gradients of 0.2 to 40. *Olsen et al.* [1985] recently have suggested that pumping rates as small as 10^{-7} cm^3/s are feasible with a differential diameter piston. *Summers et al.* [1978] used input pumping rates to compute the permeability of Westerly Granite, but with relatively large pumping rates and correspondingly high gradients.

Some advantage is gained by using gas permeants because of their much lower viscosity. However, corrections are necessary [*Scheidegger*, 1974, p. 172] because of gas slippage. More importantly, the physicochemical iteractions between permeant and solids, which may be significant in small pores, will be quite different for gases and water; this makes the relation between gas and liquid permeabilities in many tight media uncertain. However, in certain instances these objectives may not be important. For example, gas and liquid permeability of Westerly Granite measured by *Brace et al.* [1968] and of Grand Saline salt measured by *Gloyna and Reynolds* [1961] were in close agreement.

A variant of the steady flow test, the falling head test, has also been used to test tight media. Described by *Darcy* [1856], the test is conducted by permitting an elevated water level in a standpipe to cause flow through the sample; as the level falls, the gradient across the sample and the flow rate decline. As long as the storage in the standpipe is large compared with that in the sample, the flow remains quasi-steady, that is, the hydraulic gradient within the sample remains approximately linear. *Terzaghi* [1925] claimed to have measured K smaller than 10^{-11} m/s using falling head tests, and *Lambe* [1951] formalized the experimental stategy for measuring small K with the technique. More recently, falling head tests were used extensively by *Tavenas et al.* [1983] for testing tight clays.

The falling head test per se is not particularly advantageous for measuring small K. However, a distinct technique specifically suited for tight media is, consciously or not, a variation of it. In this version of the test, a closed reservoir instead of an open standpipe is connected to one end of the sample. At the beginning of the test, the reservoir is abruptly pressurized. The pressure declines with time as water flows through the sample. The great advantage of the closed system lies in the fact that the storage in the reservoir, owing to the equipment and water compressibility, is much smaller than in an open standpipe. An equivalent head decline requires the flow of a much smaller quantity of water into the sample. When K is small, this can sufficiently reduce the time required for the test to make it feasible. This test methodology and analysis was first developed by *Bianchi and Haskell* [1963], who used a deformable diaphragm with strain gauges to determine flow from the closed reservoir; *Nightingale and Bianchi* [1970] later used the technique to test clays. Somewhat after Bianchi and Haskell published their paper, *Overman et al.* [1968] described a similar test in which flow was related to reservoir pressure measured with a pressure transducer. At nearly the same time, *Brace et al.* [1968] independently developed a similar but somewhat more complex test design and analysis; they used closed reservoirs of arbitrary volume placed at both ends of the sample. After the upstream reservoir is abruptly pressured, its head declines and the head in the downstream reservoir rises. The analysis permits extraction of K from the pressure changes. Using this method, *Brace et al.* [1968] measured the conductivity of Westerly Granite for a range of effective pressures, using both gas and water. They obtained values as small as 10^{-14} m/s. The mean gradient across the sample ranged between approximately 10^4 and 10^3 during the tests.

Shortly after the methodology was presented by *Brace et al.* [1968], *Sanyal et al.* [1971, 1972] and *Remy* [1973] reported using a test and analysis, apparently developed independently, which was essentially the same. In the tests by Sanyal et al. on Precambrian chert, hydraulic oil was used as a permeant, and the upstream reservoir was pressurized thermally rather than mechanically. Conductivities as small as 10^{-10} m/s were computed with hydraulic gradients ranging up to 10^4. *Zoback and Byerlee* [1975] also tested Westerly Granite, *Kranz et al.* [1979] tested Barre Granite, and *Reda and Hadley* [1985] tested welded tuff, using essentially the same technique outlined by *Brace et al.* [1968].

The advantage of closed reservoir tests, i.e., the smallness of the storage in the reservoirs, renders the assumption of quasi-steady flow inappropriate in many instances. When shut in, the reservoir storage is not always much greater than that of the sample, and fully transient flow in the sample is possible. While the quasi-steady assumption is probably justified for rocks such as granite, which have small storage, *Overman et al.* [1968], *Miller et al.* [1969], and *Nightingale and Bianchi* [1970] used the quasi-steady analysis for clays, which have significant compressive storage. Indeed, it appears that storage effects led *Miller et al.* [1969] to incorrectly conclude that their sample exhibited non-Darcian flow behavior. *Neuzil et al.* [1981] analyzed the error associated with the assumption of quasi-steady flow and showed that it could produce the behavior *Miller et al.* [1969] observed, resulting in underestimates of K.

Hydraulic transient flow tests: The effect of storage in the sample can be accounted for if the test is analyzed with the transient groundwater flow equation in one dimension, which may be stated as

$$K \frac{\partial^2 h}{\partial z^2} = S_s \frac{\partial h}{\partial t} \quad (1)$$

Compressive storage, which permits transient flow, is accounted for by the one-dimensional specific storage S_s $[L^{-1}]$. As discussed later in this paper, (1) is strictly valid when no lateral strain occurs in the specimen. With the appropriate boundary conditions to describe the two-reservoir test methodology of *Brace et al.* [1968], the solution of (1) can be used to analyze fully transient flow. *Lin* [1978] and *Trimmer et al.* [1980] adopted this approach, using numerical solutions of (1). Lin tested argillite of the Eleana Formation and measured conductivities between 10^{-13} and 10^{-16} m/s with initial gradients across the sample ranging from 5×10^2 to 5×10^3. Trimmer et al. tested crystalline rocks, obtaining conductivities as small as 5×10^{-17} m/s.

The procedure used by Lin and Trimmer et al. requires additional information about the storage properties of the sample. In essence, S_s must be independently determined from more fundamental properties. Both Lin and Trimmer et al. determined these properties separately to analyze their tests. *Hsieh et al.* [1981] and *Neuzil et al.* [1981] developed an analysis and test methodology utilizing an analytical solution of the equation for the test boundary conditions. Their method permits both K and S_s of the sample to be determined from the test data. In a sample of the Pierre Shale, *Neuzil et al.* [1981] measured K as 2×10^{-12} m/s and S_s as 8×10^{-7} m^{-1} with an initial gradient of 2×10^3.

Variations of the test procedure for fully transient flow have been used. *Al-Dhahir and Tan* [1968] obtained a solution for a somewhat different test procedure. Their procedure requires measurements of flow, negating much of the advantage of shut-in transient tests. *Gondouin and Scala* [1958] used a similar analysis for testing shales but apparently based it on an incorrect analogy with diffusion. R. H. Morin and A. W. Olsen (unpublished manuscript, 1986) have described a technique wherein a predetermined flowrate from a pump is abruptly applied at the sample boundary. Analysis of the time dependent pressure change at the boundary permits computation of K and S_s. Either positive or negative flowrate (injection or withdrawal) may be applied, allowing determination of both rebound and compression values of S_s.

Most if not all experimenters who have used the fully transient techniques discussed have used a constant lateral and longitudinal load on the specimen. Some error, probably small, may be expected as a result because of the no lateral strain condition implicit in (1). A more appropriate experimental design would fully constrain the specimen laterally while applying a constant stress longitudinally.

Mechanical transient flow tests: The tests described so far require one to measure (or pump) small rates of flow or to measure reservoir pressure changes, which are a surrogate for flowrate measurements. One can also perform tests which permit determination of K and S_s from the transient mechanical behavior of the sample. Such tests have been mainly the demesne of soil mechanics and have been developed for relatively compressible media which can be described with standard consolidation theory. Thus the available methodologies are appropriate for media with high loading efficiencies (see next section), although they could, with modification, be applied to less efficient media.

The study by *Terzaghi* [1923] of consolidation of low-permeability media beneath foundations provided the derivation of (1) well before it was developed independently by *Theis* [1935] and *Jacob* [1940] for water supply applications. Terzaghi's derivation recognized that expulsion of pore fluid, at a rate governed by the hydraulic conductivity, was required for consolidation to proceed.

In a step load consolidation test [*Terzaghi*, 1927; *Lambe*, 1951; *Scott*, 1963], the specimen is laterally constrained and subjected to an abrupt loading which remains constant. Pore water is permitted to drain at one or both ends. Solution of (1) for the time dependent strain under appropriate boundary conditions [*Šuklje*, 1969] permits computation of the ratio K/S_s by comparing observed and computed strain. Specific storage is computed from the porosity and observed compressibility of the specimen. *Hamilton* [1964] and *Bryant et al.* [1975] obtained hydraulic conductivities for deep sea sediments, and *Wolff* [1970] obtained conductivities for a clay confining bed by analyzing consolidation data. *Bredehoeft et al.* [1983] used consolidation tests to compute hydraulic conductivity of the Pierre Shale. They obtained conductivities between 10^{-11} and 10^{-14} m/s with hydraulic gradients [see *Mitchell*, 1976, Figure 15.7] ranging as high as 10^4 to 10^5.

Variations in testing methodology and analyses based on less restrictive assumptions have been advanced as a variety of mechanical test techniques. For example, the case of large strain consolidation was analyzed by *Gibson et al.* [1967] as a generalization of *Terzahi*'s [1923] theory. The application of a varying load to maintain a constant strain rate was analyzed by *Smith and Wahls* [1969]. *Lowe et al.* [1969] suggested a test in which the applied stress is controlled to maintain a constant hydraulic gradient, and *Aboshi et al.* [1970] describe a test in which loading is changed at a constant rate. *Znidarčić* [1982] provides a summary of the various analyses and tests which have been proposed.

Comparability: There is growing confirmation of the ability of nonsteady flow techniques to reliably measure the permeability of many types of tight media. *Mitchell and Younger* [1967], *Wolff* [1970], *Mesri and Olson* [1971], and *Silva et al.* [1981] found reasonably good agreement between results of steady state tests and values computed from step load consolidation tests. Some systematic discrepancies have been reported by others, but many are relatively minor or appear to be attributable to special circumstances. *Seaber and Vecchioli* [1966] called attention to permeabilities computed from step load consolidation tests which were substantially smaller than those from quasi-steady tests, but the differences may have been due to the lack of any confining load during the latter. *Olson and Daniel* [1981] also reported underestimates of K obtained from step load tests. Using theoretical arguments, *Znidarčić* [1982] suggested that inherent error of a few tens of percent is likely in K determined in constant rate of strain tests. In a rather thorough study of tight clays, *Tavenas et al.* [1983] compared K computed from step load, constant strain rate, and constant hydraulic gradient consolidation tests with values form steady and open standpipe quasi-steady flow tests. Constant strain rate and constant gradient tests gave values which agreed, within a few tens of percent, with directly measured values. Values computed from step load tests were usually too small by as much as a factor of 10.

Most instances where discrepancies arise between consolidation tests and direct determinations of K involve highly deformable media such as clays. It is likely that because of the high deformability, assumptions in standard consolidation analysis are violated sufficiently to cause errors. Precise measurement of K in highly deformable media is difficult with any technique. As discussed by *Smiles and Rosenthal* [1968], *Smiles* [1968], and *Kharaka and Smalley* [1976], large hydraulic gradients can result in varying degrees of consolidation in the sample; during transient flow the hydraulic properties being measured vary in time and space. Also, the larger deformations during consolidation of soft materials may need to be accounted for [e.g., *Gibson et al.* 1967]. Despite these potential problems, consolidation techniques seem to be quite useful. At stresses of interest in most hydrogeologic problems, media are sufficiently stiff that these difficulties are not serious.

Few instances have arisen where it is possible to compare K obtained from both hydraulic and mechanical transient tests with steady flow measurements. Moreover, little attention has been given to the comparability of specific storage, and therefore hydraulic diffusivity, derived from the two types of transient tests. One reason is that many tight media cannot be tested with both types of transient techniques. Mechanical tests are inappropriate for stiff media, such as argillites and crystalline rocks, because only a small fraction of the measured strain is caused by fluid flow and resulting pore volume change. Deformable media present the problems mentioned above when tested with hydraulic transient techniques.

Comparative data are, however, available from tests on the Pierre Shale. Because of its high loading efficiency but moderate compressibility, it is amenable to testing by both consolidation and transient hydraulic techniques. *Bredehoeft et al.* [1983] presented preliminary data on the Pierre Shale. More extensive data are now available and are presented in Figure 1. The hydraulic and mechanical transient flow tests (Figure 1*a*) are in reasonable agreement. Despite a spread in the data, they characterize K of the shale sufficiently well to be useful in analysis of the flow system. Mechanical test data points at the same stress level each represent a different sample. The spread in Figure 1*a* may largely reflect a subtle lithologic diversity; the variation in K with effective stress in a single sample is generally quite regular. The hydraulic transient test data also represent tests on several samples, some at multiple stress levels. In these the variation in K with effective stress in a sample was less regular.

The ability of the two different transient test techniques to characterize S_s and, by extension, hydraulic diffusivity of the Pierre Shale (Figure 1*b*), is less satisfactory. In Figure 1*b*, diffusivities computed from hydraulic transient tests tend to be larger than those from mechanical transient tests (and thus S_s tends to be smaller) by as much as 2 to 3 orders of magnitude. It has been recognized [e.g., *Cooper et al.*, 1967] that the response during a transient test is generally more weakly dependent on S_s than K; relatively large errors in S_s are therefore possible. Many of the assumptions implicit in the description of transient flow provided by (1) are only approximately satisfied, among them the assumptions of no lateral strain and a perfectly elastic porous skeleton. While insufficient to strongly affect computed K, the associated errors may strongly affect computed S_s.

Another shortcoming of currently available techniques is their inability to measure small values of S_s. Small S_s is found in stiff rocks which cannot be tested mechanically. Hydraulic transient tests are also unable to measure small S_s because the response curves become so similarly shaped that they cannot

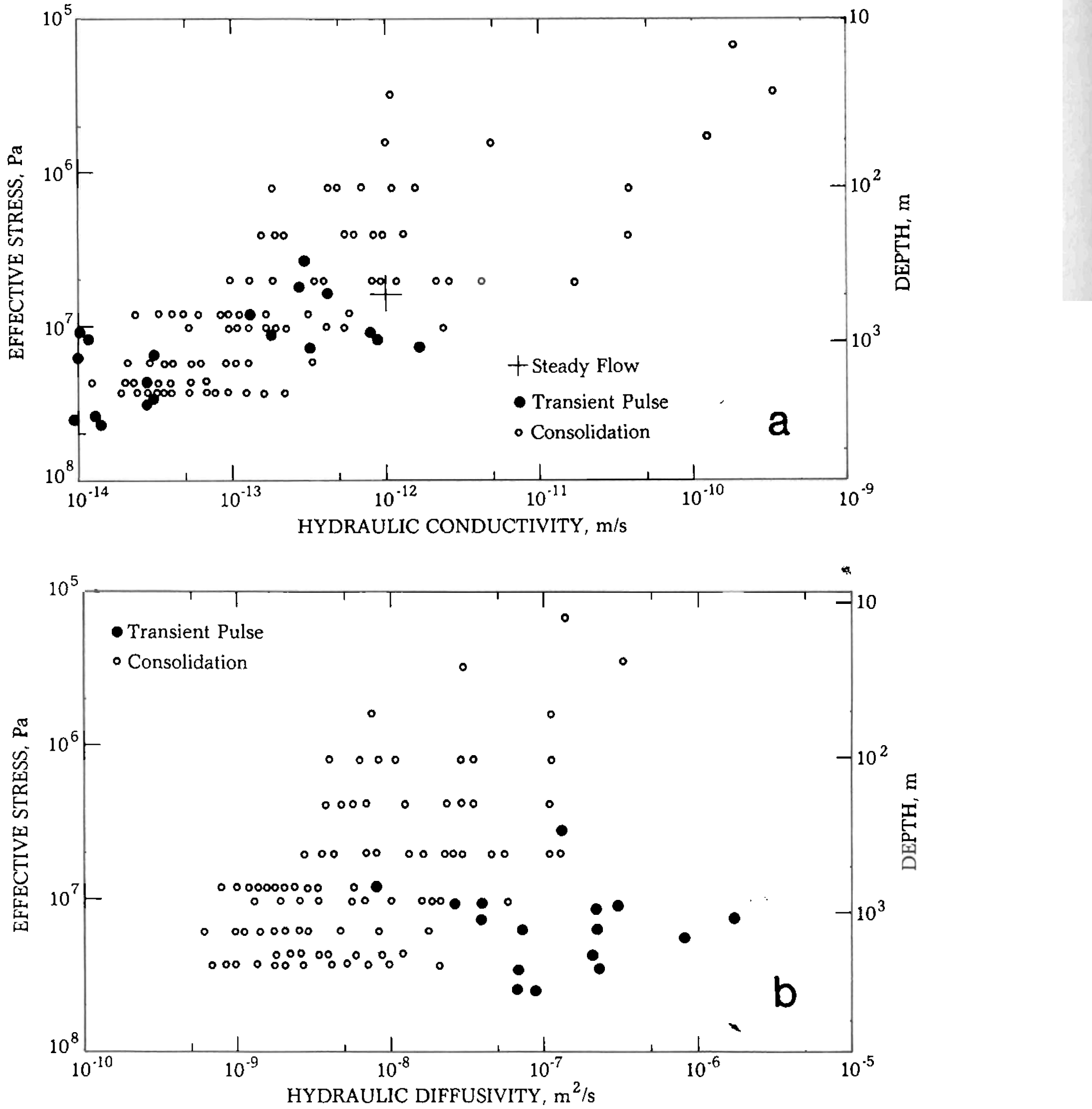

Fig. 1. Hydraulic properties of the Pierre Shale derived from a steady flow test and transient hydraulic and mechanical tests. The transient hydraulic test methodology used was that described by *Hsieh et al.* [1981] and *Neuzil et al.* [1981]; the transient mechanical tests were step load consolidation [e.g., *Scott*, 1963]. The data are plotted against effective stress and an equivalent depth in meters using the convention that effective stress increases at approximately 1.3 × 10^4 Pa/m: (*a*) hydraulic conductivity and (*b*) hydraulic diffusivity.

be distinguished and only K can be computed [*Neuzil et al.*, 1981]. Computation of hydraulic diffusivity under these conditions is possible at present only with independent determinations of rock and grain compressibility and porosity.

A distinction between hydraulic transient and mechanical transient tests can be made on purely practical grounds. Of the two, mechanical transient tests, and step load consolidation tests in particular, are performed more routinely and use more readily available equipment. Equipment requirements for the relatively newer hydraulic transient techniques can be severe [e.g., *Neuzil et al.*, 1981; *Trimmer*, 1982] and relatively few sets of test equipment have been built.

Indirect estimates of permeability: It is sometimes possible to estimate the permeability of tight materials using the relation between permeability and other properties. *Brace et al.* [1968] and *Brace* [1977] investigated the relation between electrical resistivity of saturated granite, its pore sizes, and permeability. *Brace et al.* [1968] found a consistent relation between resistivity and permeability in the Westerly granite which they extrapolated to estimate the permeability at large confining loads. *Brace* [1977] examined the theoretical relation between the formation factor, pore hydraulic radius, and permeability and showed that it held for a variety of porous media, including tight crystalline rocks. *Heard and Page* [1982] estimated permeability of the Westerly granite and Stripa granite at elevated temperatures and pressures by relating it to changes in porosity. Because microcracks transmitted the water, they related permeability to the cube of porosity.

The drawback of these techniques is that the information needed to make the estimates is often difficult to obtain. For example, establishing the relation between resistivity and permeability for the Westerly granite required *Brace et al.* [1968] to make several permeability measurements. The relation discussed by *Brace* [1977] is more general but requires the pore hydraulic radius, which is difficult to measure. The measurements of porosity change used by *Heard and Page* [1982] are also inconvenient to make. These techniques seem to be of greatest value when the required data are already available or when estimating permeabilities over a wider range of conditions than that for which measurements are available.

Measurement of loading efficiency: One- and three-dimensional loading efficiencies represent the ratio of pore fluid pressure change to external stress change for conditions of one- and three-dimensional strain, respectively. In principle, the one-dimensional efficiency, ζ, can be measured in a step load consolidation test by measuring the internal pore pressure increase at the moment of load application. In practice, however, the measuring system disturbs the sample response by acting as a fluid sink because of its own compressive storage. The result is a somewhat muted pressure response with a time lag. *Gibson* [1963] has discussed these effects, and *Whitman et al.* [1961] and *Perloff et al.* [1965] have presented transient flow analyses which account for them. Measuring systems constructed to minimize storage have been used by *Hansbo* [1960] and *Mitchell and Younger* [1967]. *Mesri et al.* [1976] described tests to measure three-dimensional efficiency, β. They derived an expression for β for use in undrained tests which accounts for the apparatus storage.

In situ measurement of hydraulic parameters. In situ testing has a different significance in low-permeability environments than in permeable ones. The volumes of tight rock tested using in situ methods are larger than in laboratory tests but are still relatively small, particularly compared with those involved in tests in permeable media. Perhaps more importantly, they are restricted to the region close to a borehole or the boundary with a permeable formation; for practical test periods a hydrodynamic disturbance penetrates only a small distance into tight rock. The tests described in this section involve the rock essentially at a point or along a line (borehole tests), or over a surface at the boundary between a low-permeability formation and one of significantly higher permeability (aquifer-confining layer tests). The primary advantage of in situ procedures is thus the ability to test large one- or two-dimensional samples of tight formations. Tests of large three-dimensional volumes cannot be made except, to a small degree, by relatively indirect methods which are also described in this section.

As in the case of laboratory testing, standard testing techniques are applicable, in principle, even when the permeability is small. In practice, however, the problems of implementing such tests can be severe. For example, the use of observation wells is generally impractical because of the long time required for the effects of injection or withdrawal to reach them. Similarly, long periods are required for water levels in a well to recover from pumping.

Single borehole and periodic tests: The difficulty of using observation wells in tight media dictates an important role for single-borehole tests. Significant contributions to the theory of single-borehole tests have come from both the geotechnical and groundwater disciplines. Such tests may be categorized as either slug (or recovery) tests or injection/withdrawal tests.

Slug tests are single-borehole tests carried out by abruptly increasing or decreasing the fluid head in the well and observing the transient response as it returns to equilibrium. The test was introduced by *Ferris and Knowles* [1954] using a line source or sink to represent the borehole. *Gibson* [1963] was the first to analyze the recovery from an abrupt head change in a piezometer with storage; he obtained a solution for spherically symmetric flow about a spherical piezometer tip. However, the usefulness of the solution is limited because tests are often carried out through the walls of a cylindrical borehole and because anisotropy may be expected to prevent the flow from being spherically symmetrical in many instances. An important advance was made when *Cooper et al.* [1967] generalized the earlier solution of Ferris and Knowles to account for borehole or standpipe storage.

The slug test procedure of *Cooper et al.* [1967] is not itself particularly suited to measuring small permeability. The rate of response to a slug depends on the rate at which water flows between borehole and formation and the storage in the borehole or standpipe. When the transmissivity is small, the response time can be inordinately long. This can be overcome to some degree by decreasing the standpipe diameter. However, practical limitations to the smallness of the standpipe render the test impractically long if the transmissivity is very small.

To overcome this problem, *Bredehoeft and Papadopulos* [1980] modified the analysis of *Cooper et al.* [1967] to accommodate a shut-in test procedure specifically designed for low-permeability formations. This innovation closely parallels the development of laboratory hydraulic transient techniques which were discussed earlier. Interestingly, an analysis for a shut-in slug test using a spherical piezometer tip had been outlined earlier by *Gibson* [1963], but its significance seems to have been overlooked. In a shut-in test, the storage in the well is due to water and system compressibility, which is much smaller than that due to water level changes in a standpipe. The response time is proportionally reduced.

Shut-in slug tests of the type described by *Bredehoeft and Papadopulos* [1980] were compared with conventional slug tests and recovery techniques in moderately low permeability rocks in New Mexico by *Dennehy and Davis* [1981]. In this case the shut-in test gave a value for transmissivity approximately 10 times larger than the value from the open slug test. This error may have resulted from the potentially erroneous methodology outlined by Bredehoeft and Papadopulos; *Neuzil* [1982] showed that the test procedure they described did not ensured the necessary equilibrium condition at the beginning of the test. *Bredehoeft et al.* [1983] used shut-in slug tests in the Pierre Shale to measure hydraulic conductivities between 4×10^{-12} and 10^{-11} m/s. The smallest transmissivity they measured was 3×10^{-10} m^2/s in a 70 m test section.

Injection/withdrawal tests were first discussed by *Gibson* [1963] in a paper describing a constant head test. At the initiation of such a test, fluid is injected or withdrawn, changing the hydraulic head in the borehole or piezometer by an arbitrary amount. Thereafter the flow is controlled to maintain the arbitrary head constant. Analysis of the flow with time permits computation of K and S_s. As in the case of his slug test analysis, *Gibson*'s [1963] solution applies to the case of spherically symmetrical flow. *Wilkinson* [1968] later considered three dimensional and purely radial flow to a cylindrical borehole. He analyzed constant head tests in clays to obtain in situ values of K ranging from 10^{-7} to 10^{-9} m/s. *Mieussens and Ducasse* [1977] used a similar test procedure to measure in situ K ranging from 2×10^{-9} to 4×10^{-9} m/s with corresponding hydraulic diffusivity between 10^{-6} and 8×10^{-8} m^2/s. Mieussens and Ducasse also presented an analysis for determining the anisotropy of K when a short test section is located at the bottom of the borehole.

Periodic and related tests involve repeated stressing of the well and observation of the outwardly propagating head changes in one or more observation wells. An immediately apparent disadvantage is the necessity of an observation well; if the hydraulic diffusivity of the rock is small, the observation well may have to be impractically close to the excitation well in order to obtain a measurable response.

One approach which is amenable to analysis is sinusoidal pressure variations in the excitation well. The fluctuations produced in the obervation well are damped in amplitude and shifted in phase, both of which are characteristics of the formation diffusivity. An analysis of the problem was presented by *Black and Kipp* [1981] wherein they demonstrated the practicability of the method in rocks with diffusivities as small as 10^{-4} m^2/s. Although rocks of reasonably small permeability may have diffusivity this large if the specific storage is quite small, much smaller diffusivities characterize many tight rocks. The technique therefore does not appear generally applicable in low-permeability environments.

A similar procedure is the repeated application of pulses or slugs in the excitation well. *Walter and Thompson* [1982] investigated this technique with the intention of applying it to tight formations. In spite of the limitation of utilizing an observation well they were able to measure transmissivities as small as 3×10^{-7} m^2/s. It appears that the method would not be useable for significantly smaller transmissivities.

Aquifer-confining layer tests: Among the earliest motivations for hydrologists to study the behavior of tight confining layers was their influence on adjoining aquifers. The standard (Theis) analysis of aquifer drawdown during pumping was often seen to be inaccurate as a result of leakage from confining layers. This problem was first addressed by incorporating quasi-steady state [*Jacob*, 1946; *Hantush and Jacob*, 1955; *Hantush*, 1956] and then a more realistic transient [*Hantush*, 1960] confining layer leakage into the analytical solution for drawdown in the aquifer. Although not intended for identifying confining layer properties, *Hantush*'s [1960] analysis permits computation of the product KS_s for the confining bed when sufficient data are obtained to distinguish among his family of type curves. *Bredehoeft et al.* [1983] took advantage of this ability to estimate properties of Cretaceous shales adjoining the Dakota aquifer in South Dakota.

A similar tack was taken by *Witherspoon et al.* [1962], with the difference that their techniques was motivated specifically by the desire to characterize the confining layers. Witherspoon et al. argued that the measurement of aquifer drawdown by itself was insufficient to provide good indications of confining bed properties in many instances, an argument supported by *Bredehoeft et al.* [1983, p. 42]. Instead, they suggested that head measurements in the confining layer itself are desirable and presented a technique for analyzing such a test. Over the next several years this method was refined by *Witherspoon and Neuman* [1967] and *Neuman and Witherspoon* [1968, 1969*a*, 1969*b*, 1972]. *Neuman and Witherspoon* [1972] applied the technique to an aquifer-confining layer system in California; they determined diffusivities for the confining layers there to be of the order of 10^{-5} m^2/s.

Wolff [1970] presented a slightly different approach to the analysis of head data in a confining layer. He approximated aquifer drawdown by a step function. Head changes in the confining layer were matched to analytical type curves to obtain the hydraulic diffusivity. Wolff obtained a value of 10^{-6} m^2/s for confining beds in Maryland. *Wolff and Papadopulos* [1972] presented a similar analysis for the case where the confining bed is vertically inhomogeneous.

Indirect in situ determinations: As noted, the slow rate of propagation of pressure disturbances in low-diffusivity rocks means that only relatively small volumes of rock can be tested in reasonable periods of time. This limitation can be bypassed to some extent where a well-documented disturbance has occurred in the past.

Old excavations are analogous to load decrements in consolidation tests with the advantage that large volumes of rock and periods of years or decades are involved. *Bromwell and Lambe* [1968] instrumented a clay layer beneath a building excavation in order to measure the fluid heads. Comparing their head data with solutions of (1) from consolidation theory, they estimated the hydraulic diffusivity of the clay as 3.5×10^{-6} m^2/s, a value 6 times larger than that obtained using laboratory consolidation tests. *Lutton and Banks* [1970] found subnormal heads in the clay shales near the Panama Canal. The heads were apparently still responding to excavation and resulting unloading which occurred 70 years before the measurements. Like Bromwell and Lambe, they compared theoretical behavior with observed to estimated in situ diffusivities of a clay shale unit a few tens of feet thick. They obtained values between 10^{-9} and 10^{-8} m^2/s. Interestingly, these values compared well with laboratory-determined values, even though well-developed joints and slickensides were present in the shales. *Vaughan and Walbancke* [1973] used the same approach to compute the diffusivity of the London clay beneath a 7-year-old highway cut. They computed a diffusivity of the order of 10^{-8} m^2/s for the uppermost few meters of the clay.

Riley [1970] estimated the hydraulic properties of low-permeability lenses in an aquifer by analyzing their strain under changes in effective stress. Vertical strain in a 123-m section of well bore was measured using an extensometer. Effective stress changes resulted from cyclically varied fluid head in the aquifer, caused by agricultural pumping, and the subsequent groundwater flow between the lenses and the aquifer. Riley's analysis recognized the analogy between the field behavior and that in laboratory mechanical transient tests; in essence, the observations were analyzed as large-scale consolidation test data. The actual analysis was considerably complicated by the complex nature of the stress changes and the variability of the lens thickness. Riley estimated K of the lenses as being 2.9×10^{-11} m/s. He distinguished between S_s under conditions of virgin consolidation, which he estimated at 7.5×10^{-4} m^{-1} and S_s in the elastic range of deformation, which he estimated at 9.3×10^{-6} m^{-1}. Numerical simulations by *Helm* [1975] indicated that Riley's estimates were quite reasonable. *Helm* [1976] also found that somewhat improved agreement between computed and observed strain could be gotten if stress dependent properties were used. Specifically, his results suggested that K of the lenses could vary between 3.3×10^{-11} m/s and 2.9×10^{-12} m/s with the observed changes in stress.

Analysis of purely hydrodynamic stress and response is also possible in aquifer-confining layer systems. In instances where well documented hydraulic stresses on an aquifer have occurred for an extended period, numerical simulation of the system will permit estimation of the confining layer properties. If a relatively long period of aquifer-confining layer interaction is simulated, the estimated properties will reflect a proportionally thick zone of the confining layer. Efficient numerical algorithms for simulating transient leakage from confining layers are now becoming available [*Herrera and Yates*, 1977; *Premchitt*, 1981; L. Torak and R. L. Cooley, unpublished manuscript, 1986] and should permit wider application of this technique.

In situ testing: *Discussion*: The small volume of rock involved in most in situ tests in low diffusivity rocks is a stronger disadvantage than may be first be realized [*Faust and Mercer*, 1984; *Moench and Hsieh*, 1985]. The rock influencing borehole tests, for example, is a narrow annulus surrounding the borehole. This is the same region most subject to disturbance by drilling the hole; in tight media, permeability enhancement by mechanical disturbance is perhaps the most likely effect of drilling, although permeability decreases caused by clogging or by "smearing" soft formations is also possible. This problem was first considered by *Wilkinson* [1967, 1968], who suggested using an analytical solution by *Gibson* [1966] to account for the effects of "smear" around a piezometer during constant head injection tests. *Faust and Mercer* [1984] and *Moench and Hsieh* [1985] have shown that slug tests will be strongly influenced by the properties of such borehole "skins" when the shut-in technique for tight formations is used.

Tests involving confining layers and aquifers are subject to a similar disadvantage. To reduce the time for the test, the piezometer in the confining layer must be placed close to the aquifer. However, the zone near the aquifer may not be representative of the bulk of the confining bed, particularly if the contact is gradational. There are also practical problems associated with these tests. It is difficult to precisely locate and effectively isolate piezometers in a confining layer at depth.

Finally, it is worth noting that like laboratory tests in tight media, and for analogous reasons, in situ tests have utilized unrealistically large hydraulic gradients. In spite of these problems, the tests do offer the advantage of sampling large vertical sections in the case of borehole tests and large areas in the case of aquifer-confining layer tests. Inhomogeneities such as those due to fractures, and which otherwise would be missed, may be found with these tests.

Transient flow under experimental conditions. Published results of transient tests are remarkably consistent in one aspect; in all instances, including media with some of the smallest permeabilities yet measured, solutions of (1) appear to provide good descriptions of test behavior. Results of consolidation tests (except in very deformable media) have long indicated this was the case in soillike media. The results of more recently developed hydraulic tests, which depend more directly on the flow, now provide stronger evidence that this is true, and for a wide variety of lithologies. Laboratory tests in crystalline rocks [*Trimmer et al.*, 1980; *Trimmer*, 1982] and argillite [*Lin*, 1978] and both laboratory and in situ tests in shale [*Neuzil et al.*, 1981; *Bredehoeft et al.*, 1983] all were well described by the appropriate solutions of (1). Thus, under experimental conditions, (1) appears to be an adequate model of transient flow even in the tightest rocks.

Nonhydraulic Flow Phenomena

A distinguishing feature of all tight media is the smallness of the pores through which flow occurs. With a large fraction of the pore fluid in close proximity to the solid surfaces, the physicochemical phenomena which occur at the surfaces may produce significant flow effects. These are not accounted for in the Navier-Stokes flow model (on which the theoretical basis of Darcy's law rests [*Hubbert*, 1956]) and are called nonhydraulic flow phenomena in this paper. Reported nonhydraulic effects in tight media include those which indicate other than direct proportionality between the hydraulic gradient and flow (non-Darcian behavior) and those which indicate pore fluid flow in response to driving forces other than the hydraulic gradient (osmotic or coupled flow). Geologic media in which significant coupled flow occurs are called geologic membranes in this paper.

Applicability of Darcy's law. Over the past several decades many experimentalists, including *Deryagin and Krylov* [1944], *von Engelhardt and Tunn* [1955], *Lutz and Kemper* [1959], *Hansbo* [1960], *Miller and Low* [1963], *Mitchell and Younger* [1967], and others (see compilations by *Kutílek* [1972] and *Elnagger et al.* [1974]) have reported apparently non-Darcian behavior in low-permeability media. The effects reported include changes in apparent conductivity with hydraulic gradient and so-called "threshold gradients," below which little or no flow occurs.

Mechanisms suggested to explain non-Darcian behavior are generally changes in the properties of water, such as viscosity, near solid surfaces. Study of the physics of water lends some support for this view. Several discussions of water properties [e.g., *Low*, 1961; *Mitchell*, 1976, chap. 6; *Forslind and Jacobsson*, 1975; *Clifford*, 1975] note the large volume of evidence for altered water properties near interfaces. However, the nature of the changes and the distance they extend from the interface are disputed. As *Clifford* [1975] notes, the nature and behavior of water near boundaries "is one of the most controversial aspects of the study of water."

While reported deviations from Darcy's law are numerous, it is difficult to defend them from the suspicion that they are due to subtle experimental errors. Many measurements were made at or near the limit of resolution of the technique used. Some investigators, most notably *Olsen* [1965], have been able to demonstrate that some anomalies are almost certainly erroneous. Possible sources of error are numerous and include error in measuring gradients [*Olsen*, 1965], small leaks [*Neuzil et al.*, 1981], bacterial and particulate clogging [e.g., *Gupta and Swartzendruber*, 1962], transient flow during a steady flow test [*Olsen*, 1962; *Smiles and Rosenthal*, 1968; *Smiles*, 1969; *Pane et al.*, 1983], changes in the solid matrix [*e.g., Miller and Low*, 1963; *Olsen*, 1966; *Hansbo*, 1960], and gas generation and dissolution [*Fettke and Copeland*, 1931; *Olsen*, 1962]. Discussions of many of the various possible errors are presented by *Mitchell and Younger* [1967] and *Olson and Daniel* [1981]. Interestingly, another type of nonhydraulic flow phenomenon, osmosis, is often credited with producing effects mistaken for non-Darcian behavior [*Wentworth*, 1944; *Kemper*, 1960; *Low*, 1961; *Bolt and Groenevelt*, 1969; *Jackson*, 1967; *Miller et al.*, 1969]. In particular, *Olsen* [1969, 1985] presents persuasive evidence that chemical or electrical potential gradients are generated internally in argillacous specimens during hydraulic flow tests, causing osmotic in addition to hydraulic flow. His experiments in kaolinite display a linear relation between flow and hydraulic gradient which remains consistent when the gradient and flow are reversed. However, under a hydraulic gradient only, the trend of the data does not pass through the origin. By applying external chemical or electrical potential differences, the trend could be adjusted to intersect the origin. *Olsen* [1985] concluded that the applied external osmotic forces cancelled those generated internally, eliminating the osmotic flow. This seems to offer a rational explanation for many reports of a threshold gradient without appealing to non-Darcian flow.

Other negative evidence for the existence of true non-Darcian flow in experiments to date include (1) carefully conducted experiments, such as those of *Olsen* [1965] and *Smiles and Rosenthal* [1968] which exhibited Darcian behavior and (2) the fact that there is little consistency in the types and magnitudes of reported anomalies [see *Kutílek*, 1972]. A rea-

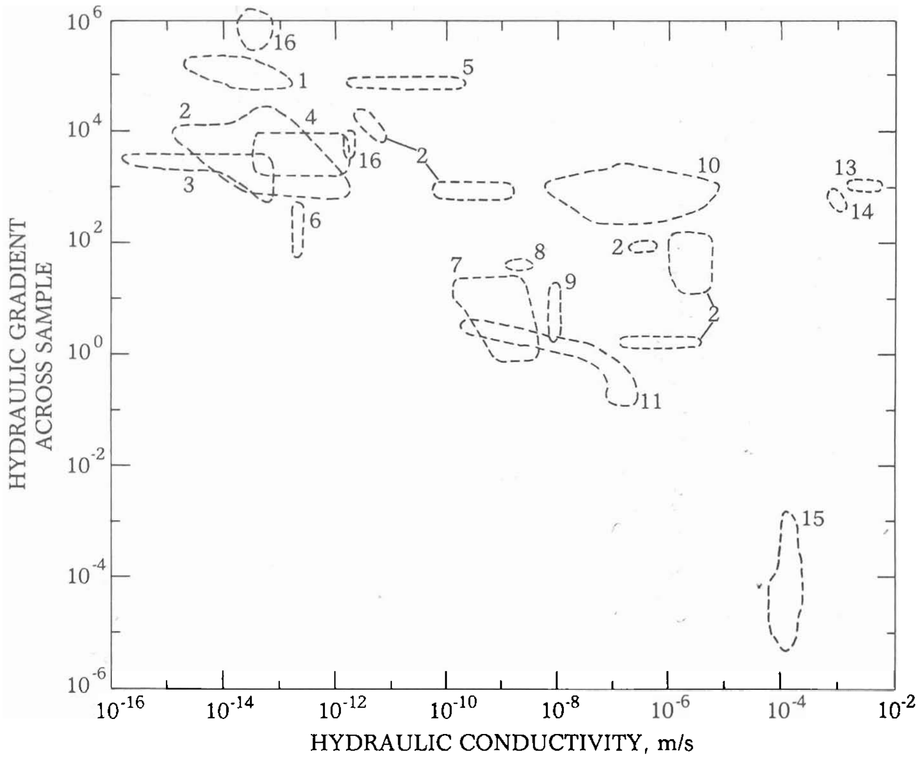

Fig. 2. Plot of measured hydraulic conductivity versus the hydraulic gradient or range of gradients used to obtain the measurement. Tests were steady flow unless noted. Data are from (1) *Morrow et al.* [1981]; (2) *Young et al.* [1964]; (3) *Lin* [1978] (hydraulic transient test); (4) *Brace et al.* [1968] (quasi-steady test); (5) *Ohle* [1951*a*]; (6) *Trimmer et al.* [1980] (hydraulic transient test); (7) *Silva et al.* [1981]; (8) *Pearson and Lister* [1973]; (9) *Overman et al.* [1968] (quasi-steady test); (10) *Piwinskii and Netherton* [1977]; (11) *Olsen* [1966]; (12) *von Engelhart and Tunn* [1955]; (13) *Fettke and Copeland* [1931]; (14) *Fancher et al.* [1933]; (15) *Meinzer and Fishel* [1934] and *Fishel* [1935]; (16) *Kharaka and Smalley* [1976].

sonable conclusion at present is that the case for observed non-Darcian behavior in experimental data is weak, an opinion also voiced by *Mitchell* [1976, p. 350]. Some deviations are always likely in any difficult measurements. It is probable that the bias of the experimenter influences whether deviations from predicted behavior are viewed as anomalies or as experimental error and noise.

Nonetheless, it would be premature to dismiss the possibility of unanticipated flow behavior in low-permeability media. This is simply because we lack experimental data for flow in tight media under realistically small hydraulic gradients. As we have seen, extremely large hydraulic gradients (up to the order of 10^6) have been utilized in order to produce measurable flow rates. Various refinements such as shut-in transient flow methods have been introduced, but with the object, it seems, of reducing the time necessary for testing [*Hsieh et al.*, 1981] and permitting computation of specific storage rather than reducing the applied head gradient. As useful as these advancements have proved to be, the hydraulic gradients they require are still large.

Several workers [*Olsen*, 1966; *Mitchell and Younger*, 1967; *Smiles and Rosenthal*, 1968; *Gairon and Swartzendruber*, 1975; *Olson and Daniel*, 1981; *Pane et al.*, 1983] have recognized that the artifical conditions created by high gradients may affect flow behavior. Without experimental observations, the applicability of Darcy's law at small gradients can only be inferred. The gap in observational data is clearly illustrated by Figure 2, which is a plot of measured K versus the hydraulic gradient, or range of gradients, used in tests described in the literature. Referring to Figure 2, we see that by taking 1 as an upper limit for representative in situ hydraulic gradients, our observation of flow behavior under these conditions extends to K no smaller than approximately 10^{-9} m/s. Flow over nearly the entire range of low permeability, as defined in this paper, has not been observed under realistic gradients. At the lowest permeabilities, flow has been measured only with gradients several orders of magnitude larger than any in nature.

Because of this observational gap, the use of Darcy's law to describe flow under these conditions represents a hypothesis; to be on firm analytical ground, it should be tested. It is therefore desirable to extend experimental observation of flow behavior to gradients representative of in situ conditions. There are two possible approaches: (1) devising methods for measuring smaller flow rates between reservoir and sample, and (2) developing techniques for monitoring transient fluid pressures within a sample during transient flow testing. At present, the smallest flow rate measurements have apparently been achieved using a hydraulic transient flow test (Figure 2, data set 3), while steady flow tests have measured flow rates approximately 10 times larger. However, steady flow tests may offer the best chance for significant improvement, particularly with small flow rate pumps, as suggested by *Olsen et al.* [1985]. Steady flow tests also have the advantage of greatest simplicity and generality. Accurate measurement of transient pore pressures within a sample has been limited by storage in the measuring systems and the technical difficulty of the measurements [*Ortiz*, 1986].

Coupled flow in geologic membranes. The problem of applicability of Darcy's law, as addressed in the previous section, is distinct from that posed by flow in geologic membranes or media in which coupled flow is significant. In the theoretical framework of coupled flow, developed through irreversible thermodynamics [e.g., *Katchalsky and Curran*, 1967] Darcy's law is generally held to apply as a special case to describe the flow in response to a hydraulic gradient only.

Experimental experience indicates that certain tight geologic materials, notably argillaceous media, behave as membranes; they exhibit coupled flow. This refers to the fact that flows of one kind are caused by driving gradients of another kind. For example, fluid flow in these media is found to be driven not only by hydraulic head gradients (hydraulic flow) but also, through coupling, by gradients of chemical and electrical potential and of temperature [*Mitchell*, 1976]. This nonhydraulic fluid flow as a result of coupling is called osmosis. Coupling also exists between all of the driving gradients mentioned and flows of solute, electrical charge, and heat. The flows, J_i, are usually assumed to be linearly related to the gradients X_k, as expressed by [*Katchalsky and Curran*, 1967, *Bear*, 1972]

$$J_i = \sum_{k=1}^{n} L_{ik} X_k \qquad i = 1, 2, \cdots n \tag{2}$$

where the subscripts i and k indicate the various types of flows and driving gradients, respectively, and their coupling coefficients. The driving gradients X_k and flows J_i which are important in geologic media are vector quantities, while the coupling coefficients L_{ik} may be scalar or tensor quantities (one such quantity is hydraulic conductivity). Onsager's relations [*Katchalsky and Curran*, 1967; *Bear*, 1972] suggest that the coefficients L_{ik} are related as

$$L_{ik} = L_{ki} \tag{3}$$

By analogy with hydraulic conductivity, the coefficients for osmotic flow may be thought of as conductivity coefficients of a special sort. Thus, for example, the coefficient linking fluid flow to the gradient in chemical potential may be considered a chemical osmotic conductivity.

Of most direct concern in this paper is the flow of groundwater described by (2) (hydraulic flow and osmosis). However, the other flows described by (2) are also central to the problem. For example, flows of solute and electrical charge alter the chemical and electrical potential fields, in turn affecting chemical osmosis and electroosmosis.

Flow of chemical solute is of particular interest in geologic membranes. The appropriate form of (2) will show that the flow of solute relative to the pore fluid is caused by several driving forces, including the hydraulic gradient. The latter coupling with the hydraulic gradient is manifested as the relative retardation of solutes when solutions flow through a membrane, a phenomenon known as ultrafiltration, hyperfiltration, or reverse osmosis. The coefficients governing osmosis and ultrafiltration are related by (3) (see the discussion by *Katchalsky and Curran* [1967, pp. 119–126]).

The ratio of chemical osmotic conductivity and hydraulic conductivity can be shown to be a measure of the membrane's ability to exclude, or filter, solute [*Katchalsky and Curran*, 1967]. Called the reflection coefficient or osmotic efficiency, this ratio is one for perfect membranes (complete exclusion of solute) and less than one for "leaky" membranes. A heuristic explanation of ultrafiltration can also be given in terms of the exclusion of ions from small pores by electrical properties of the clay [e.g., *Kemper and Evans*, 1963; *White*, 1965; *Greenberg*, 1971; *Mitchell*, 1976].

Laboratory experiments by many workers have shown that many clays and argillaceous rocks exhibit the properties described above. As early as 1948, *Wyllie* [1948] showed that shale samples exhibited the electrical properties of membranes. Ultrafiltration was demonstrated in bentonite by *Kemper* [1960] and in bentonite and other clays by *McKelvey and Milne* [1962]. *Hanshaw* [1962] demonstrated the ultrafiltration and electrode properties of montmorillonite and illite. Electroosmotic and thermoosmotic flow of the pore fluid were observed in a saturated soil by *Taylor and Cary* [1960]. Osmotically developed pressures were observed in bentonite and reconstituted shale by *Kemper* [1961], in bentonite by *Kemper and Rollins* [1966], and in undisturbed argillaceous rocks by *Young and Low* [1965]. The latter experiments are important because they used natural rather than prepared or reconstituted samples. These and other of the earlier experimental investigations are discussed by *Berry* [1969].

More recently, ultrafiltration properties of various argillaceous materials were demonstrated by *Kharaka and Berry* [1973], *Kharaka* [1973], *Hanshaw and Coplen* [1973] and *Fritz and Marine* [1983]. Osmosis and related coupled-flow behavior were reported by *Olsen* [1969, 1972] *Letey and Kemper* [1969], *Dirksen* [1969], *Kemper and Quirk* [1972], *Srivastava and Avasthi* [1973] and *Elrick et al.* [1976]. *Coplen and Hanshaw* [1973] demonstrated the fractionation of certain isotopes by clay cakes. *Benzel and Graf* [1984] showed that clay fabric affects the osmotic efficiency, and *Haydon and Graf* [1986] observed an increase in osmotic efficiency of clay cakes with tempertaure.

The general applicability of (2) and (3) in geologic media is not established, but some studies have shown them to hold for the specific conditions and media tested. In kaolinite cakes subjected to varying chemical, electrical, and hydraulic gradients *Olsen* [1969, 1972] found that (3) was valid as well as the linearity expressed by (2). *Letey and Kemper* [1969] likewise found (3) to be valid in the bentonite cakes that they subjected to chemical and hydraulic gradients.

There are also indications of deviations from (2) and (3). *Milne et al.* [1964], *Kharaka* [1973], and *Kharaka and Smalley* [1976] found that osmotic efficiency varied with applied hydraulic head in their tests of bentonite cakes. Because osmotic efficiency is the ratio of the chemical osmotic and hydraulic conductivities, these data indicate that one or both can vary under the conditions of the tests. While (2) and (3) may be useful descriptions, it appears that this variability must be considered.

The most important coupled flow phenomena in geologic environments appear to be those involving chemical and electrical gradients and flows. *Dirksen*'s [1969] experiments indicated that thermoosmosis is significant in clays only when thermal gradients are of the order of 1°C/m, a condition attained only in a few geothermal areas. Hydraulic, chemical, and electrical phenomena appear to be intimately and intricately related in argillaceous materials [*Kemper et al.*, 1972; *Elrick et al.*, 1976; *Olsen*, 1985]. For example, *Elrick et al.* [1976] showed that concentration differences across a montmorillonite cake induced not only a pressure difference but also an electrical potential difference across the cake. The electroosmotic effects associated with chemical osmosis are sometimes sufficient to cause flow of water toward smaller solute concentrations, an effect known as negative osmosis. Negative osmosis in clay cakes was observed by *Kemper and Quirk* [1972].

While these phenomena are demonstrable in the laboratory, their mechanisms are complex; various theoretical explanations of observed behavior have been suggested by *Kemper* [1960, 1961], *Kemper and Evans* [1963], *Hanshaw* [1962], *Kemper and Rollins* [1966], *Kemper et al.* [1972], *Kemper and Quirk* [1972], *Kharaka and Berry* [1973], *Groenevelt and Elrick* [1976], *Groenevelt et al.* [1978], and *Marine and Fritz* [1981], among others. Although this work is important for understanding the mechanisms of coupled flow phenomena, it has limited predictive applicability in groundwater systems because of its complexity. A phenomenological approach, as used by *Letey and Kemper* [1969] and *Olsen* [1969, 1972] seems to offer more promise. Instead of attempting to elucidate the chemicophysical phenomena involved, the latter experimentalists sought to test the applicability of (2) and (3) and to measure the coupling coefficients in specific systems. If the phenomenologic laws described by (2) and (3) apply in geologic membranes, then, in principle, the associated groundwater flow can be understood if the appropriate values of the coupling coefficients can be measured, their variability determined, and the driving gradients mapped.

Measurement of coupling coefficients: Like hydraulic conductivity, measurements of coupling coefficients can be made using a variety of techniques, including direct measurement with (2). Tests using (2) analyze steady state flow and are analogous to steady state hydraulic tests to determine K. This approach has been used almost exclusively; little development of transient testing techniques has been done. The equation for water flow may be written in the form of (2) for hydraulic, chemical, and electrical driving forces as [*Olsen*, 1972; *Greenberg*, 1971]

$$q = -K\nabla h - \frac{K_c}{C_s}\nabla C_s - K_e\nabla E \qquad (4)$$

where C_s is the concentration of dissolved solids $[M/L^3]$, E is electrical potential $[L^2M/QT^2]$, and $K_c[L^2/T]$ and $K_e[QT/M]$ are coupling coefficients (Q denotes units of electrical charge). If dissolved concentrations are high, it may be necessary to cast (4) in terms of activities rather than concentrations. Equation (4) describes fluid flow within the the membrane. Experimentally, however, it is difficult to measure the quantities of interest within a tight sample. As in permeability determinations, the conditions external to the sample are most readily monitored. For this purpose (4) may be rendered in difference form as

$$q = -\frac{K}{L}\Delta h - \frac{K_c}{L}\ln\left(\frac{C_A}{C_B}\right) - \frac{K_e}{L}\Delta E \qquad (5)$$

where C_A and C_B are the solute concentrations on either side of a membrane of thickness L. Linear (steady state) gradients in solute concentration generally are not attained during testing if the sample is of appreciable thickness. However, the relation between fluid flow and external concentration differences implied by (5) applies even for nonlinear concentration gradients within the membrane when the net fluid flux is zero, which is the usual experimental condition.

Equation (5) and similar equations may be used in a variety of experimental configurations to measure the coefficients. This approach was used by *Olsen* [1969, 1972] to measure K, K_c and K_e in kaolinite cakes. *Olsen* [1972] found that under increasing effective stress, K, K_c, and K_e all decreased, but the decrease in K was greatest. At 0.1-MPa load, K was 1.3×10^{-8} m/s, K_e was 7.0×10^{-9} m^2/V s, and K_c was 9.8×10^{-11} m^2/s; at 70 MPa, K was 1.6×10^{-11} m/s, K_e was 2.5×10^{-10} m^2/V s, and K_c was 4.3×10^{-12} m^2/s. *Letey and Kemper* [1969] made similar determinations in a bentonite-water-salt system. Their results at unspecified load suggest that K_c was 1.1×10^{-11} m^2/s for their system. *Mitchell* [1976, p. 355] has tabulated several values of K_e for geologic media, nearly all of which fall in the range 10^{-9} to 10^{-8} m^2/V s.

Equation (4) and the analogous equation for solute flow may be combined with statements of mass conservation for solution and solute to obtain descriptions of transient behavior associated with coupled flow (see the discussion of large-scale membrane effects). One such transient phenomenon is osmotic consolidation of a membrane, which occurs when osmosis causes water to flow out, producing a mechanical strain. Both chemical and electrical osmosis have been observed to produce this effect [*Greenberg*, 1971; *Mitchell*, 1976]. *Greenberg* [1971] analyzed chemicoosmotic consolidation to compute coupling coefficients. Results of tests using bentonite cakes at 0.1-MPa loading suggest a K_c of 6.5×10^{-11} m^2/s with a K of 2.2×10^{-11} m/s.

The results cited, particularly *Olsen*'s [1972], are intriguing because they indicate that coupling is significant at moderate depths in clays with only moderately low K and that its relative importance may be even greater in tighter materials and at greater depths. However, despite this extensive body of experimental evidence, the significance of coupled flow in situ remains controversial (see the discussion of large-scale membrane effects). A question arises as to whether further experimental work is likely to play a significant role in resolving the issue of large-scale behavior in situ. This may be related to waning activity in this line of investigation during the last decade.

While further experimental work alone is not likely to resolve questions surrounding larger-scale problems, certain extensions of the experimental groundwork appear to be not only desirable, but necessary. The lack of data for coupled flow in undisturbed geologic media under in situ conditions is particularly conspicuous. Other important questions requiring experimental investigation include (1) under what conditions the phenomenologic relations (2) and (3) are adequate, (2) how coupling coefficients vary on what they depend, (3) how the clay mineralogy (e.g., kaolinite versus montmorillonite) affects the values of the coupling coefficients, (4) whether coupling coefficients exhibit significant anisotropy, and (5) in systems with several different ions, the nature of their interaction.

Important questions also surround coupled flow behavior within the membrane medium itself, particularly when this behavior is transient. Experimental techniques utilized so far for the study of geologic membranes have been limited in this respect. Specifically, they have utilized only observations of conditions external to the membrane, and, with the exception of osmotic consolidation studies by *Greenberg* [1971], they have considered only steady flow. Thus there is a dearth of direct information on transient behavior within the membrane with which to compare theoretical predictions.

If coupled flow proves to be a significant component of certain flow systems, an understanding of these systems will require answers to the questions posed above. Problem specific testing, like that routinely done for hydraulic properties, will also be required to determine the values of the coupling coefficients. This is because of the multiplicity of factors affecting the coefficients, which include effective stress, absolute dissolved concentrations, the paticular ions involved, both absorbed and in solution, the lithology of the membrane, and, presumably, spatial changes in the type as well as the concentration of ions.

LARGE LOW-PERMEABILITY FLOW SYSTEMS

... and man, who finds himself constrained by the want of time, or of space in almost all of his undertakings, forgets, that in these, if in any thing, the riches of nature reject all limitation.

Playfair [1802, p. 137]

As suggested in the introduction, large-scale groundwater movement in regions known to have low permeability on a small scale is problematical. This is particularly true when the flow is transient, because the flow dynamics are difficult, if not impossible, to observe. Indeed, it may be difficult to determine whether or not the groundwater flow is transient and which are the relevant driving processes. "Large scale" is applied here to size and time scales significantly larger than those involved in direct testing, and ranging upward to encompass regional flow and geologically significant periods of time.

The motivation for attempting to analyze large-scale flow in low-permeability environments can be conveniently considered within the framework of prediction problems, inverse problems, and detection problems. Prediction has obvious significance for certain purposes, such as isolation of toxic wastes. The inverse problem is highly significant in low-permeability environments because it may be the only way of estimating parameter values appropriate at large scale. Few analyses have been posed as detection problems, in which one attempts to understand past stresses on the system from its current condition. However, it may be a useful approach in some instances; an example is detection of cumulating mechanical strains as evidenced by fluid pressures.

Despite such a classification, the problems, in reality, are closely interrelated. One may attempt to sort out the flow processes which are responsible for current conditions in a low-permeability system. This will lead to a better understanding of the flow history, the chemical evolution of the groundwaters, and the relation of the groundwaters to the geologic evolution of the system. As a corollary, if the history can be understood, it may also be possible to improve predictions of behavior for significant periods of time in the future.

Having considered experimental investigations of low-permeability flow in the first part of this paper, we are in a position to examine their results in relation with efforts to analyze large flow systems. We earlier recognized experimentation and testing which addressed two types of questions. One line of inquiry concerns the nature of flow laws and constitutive relations controlling groundwater movement in tight media, while the other accepts the premises of standard mathematical models of groundwater flow and seeks to evaluate the parameters in these models. The extension of small-scale observations to large-scale analysis may be considered in a parallel fashion.

Let us first examine our understanding of the nature of low-permeability flow, as derived from experimentation, in relation with large-scale theoretical analyses to date. The following broad generalization can be drawn:

1. Hydraulic gradients appear to cause flow in accordance with Darcy's law at all observed gradients, but realistically small gradients have not been tested. In the absence of direct observations of flow behavior at reasonable in situ gradients, most investigators, whether conscious of the problem or not, have assumed that Darcy's law forms an adequate basis for analysis. In view of the evidence at present, this is the more conservative approach. However, the readiness with which this premise is accepted undoubtedly stems from the demonstrable success of Darcy's law in more permeable media over the range of in situ gradients. A few analyses have been made, which will be mentioned, using relations other than Darcy's law.

2. Transient flow under experimental conditions is well described by the same mathematical descriptions widely used for more permeable media, one form of which is expressed by (1). The underlying model assumes linear elastic deformation of the solid skeleton in response to changes in effective stress. This is a poor assumption over the long periods of interest in large-scale systems. It has, nonetheless, formed the basis for most analyses. This can be laid to its successful application in conventional groundwater studies, familiarity of descriptions such as (1), and the suite of solutions available. There has also been a lack of consensus on the need for a more complex model and the form it should take.

3. Nonhydraulic coupled flow is often experimentally significant in argillaceous media. With few exceptions, however, quantitative analyses of flow in argillaceous environments have ignored osmosis and other coupled flow phenomena. There are at least three possible reasons for this. First, there is a great deal of uncertainty related to extrapolating laboratory experience to field scales and subsurface environments, leaving unanswered the question of its significance in situ. Second, ignoring coupled flow has often been a matter of expedience; it significantly complicates the analysis, is imperfectly understood, and has data requirements which are difficult to meet. Third, abundant experience with more permeable media, in which coupled flow is demonstrably unimportant, may have increased acceptance of the assumption of insignificant coupling.

Next, consider the relation between experimentally measured parameters and their large-scale counterparts. There is a need for estimates of parameters which describe large volumes of rock over long periods of time if large-scale flow is posed as a prediction or detection problem. Aside from estimates of regional K which can be made in certain steady flow systems and indirect techniques such as geochemical studies, data from short-term tests involving relatively small volumes of rock provide the only information about these properties. For lithologic types or for specific formations these data suggest ranges of values for the large-scale parameters.

Experimental data are helpful in suggesting minimum permeability values for large volumes of rock because fractures and other discontinua tend to increase the aggregate value. Extrapolation to field scale thus involves an uncertain size scale dependency for K. *Brace* [1980, 1984] has compiled laboratory and in situ permeability measurements for argillaceous media and crystalline rocks. His compilation suggests that in argillaceous media, K can range as small as 10^{-15} m/s and in crystalline rocks as small as 10^{-16} m/s. He notes that while K may not increase drastically with scale in argillaceous media, it often does in crystalline rocks because they can maintain transmissive fractures. *Walder and Nur* [1984] have argued, however, that large volumes of low-permeability crystalline rock can exist at depth because fractures fill or heal.

For transient flow, the quantity K/S_s, known as hydraulic diffusivity and here denoted $\kappa[L^2/T]$, is more significant. Few comparisons of measured κ in tight media are available. Therefore I have compiled from various sources measured values of κ for a variety of tight lithologies; these are shown in Figure 3 plotted against depth or equivalent effective stress. The bulk of these data are from transient laboratory tests discussed earlier. A few were determined using in situ techniques. The difficulty of reliably determining S_s and therefore κ by experimental techniques should be borne in mind when

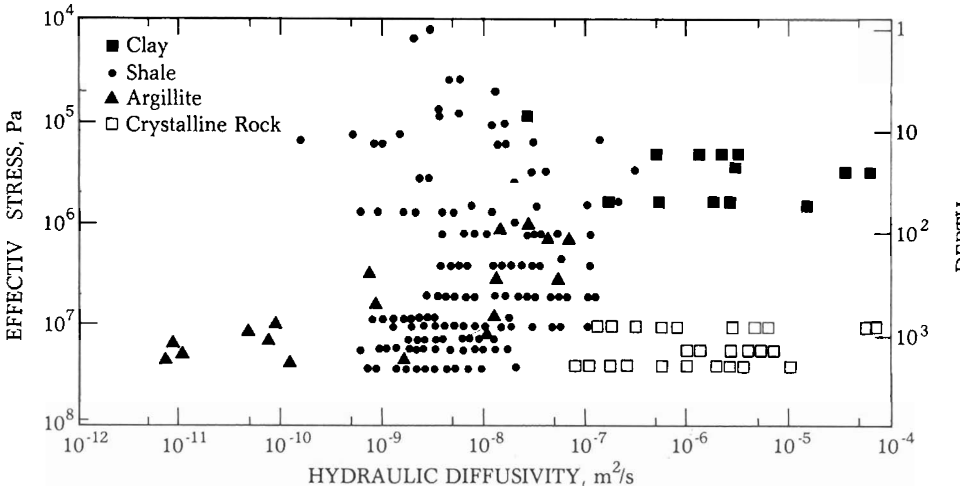

Fig. 3. Measured hydraulic diffusivity (κ) for a variety of low-permeability media plotted against effective stress during the measurement and the equivalent depth. Most data were obtained from laboratory tests. Data are presented for London clay [*Vaughan and Walbancke*, 1973], Tertiary clay [*Wolff*, 1970], clay aquitards in California [*Neuman and Witherspoon*, 1972], Bearpaw Shale and Morden Shale [*Balasubramonian*, 1972], Fort Union Shale [*Smith and Redlinger*, 1953], Cucaracha Formation and Culebra Formation [*Lutton and Banks*, 1970], Pierre Shale [*Bredehoeft et al.*, 1983; C. E. Neuzil, unpublished data, 1986], Eleana argillite [*Lin*, 1978], and Westerly Granite and Creighton Gabbro [*Trimmer et al.*, 1980]. D. Trimmer kindly supplied additional data necessary for computing the diffusivity of the granite and gabbro.

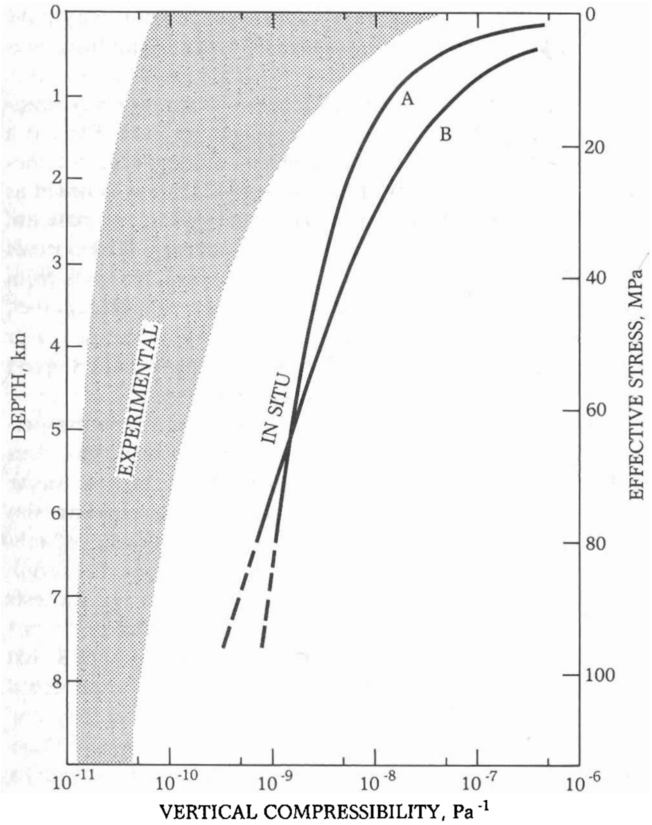

Fig. 4. Plot comparing experimental values of vertical compressibility of sedimentary media with in situ values derived from observed porosity-depth relations in sedimentary sequences. The shaded region encloses all experimental data from sources cited by *Neuzil* [1985]. Curve A was computed from porosity data for the Gulf Coast presented by *Dickinson* [1953]; curve B is from a representative porosity-depth relation suggested by *Cathles and Smith* [1983]. The convention that effective stress increases at approximately 1.3×10^4 Pa/m was used to compute curves A and B and to plot the experimental data on an equivalent depth scale.

interpreting these data. Figure 3 suggests that experimental κ for argillaceous media often lies in the range of 10^{-9} to 10^{-7} m^2/s, while that of intact crystalline rocks tends to be somewhat larger because of their small specific storage and lies in the range of 10^{-7} to 10^{-5} m^2/s.

The relation between these data and the appropriate large-scale values is more equivocal than in the case of hydraulic conductivity; unlike K, these data may not indicate minimum values for large volumes. While the size scale dependence of K is important, the uncertainty associated with laboratory values of S_s is mainly its time scale dependence. This is an artifact of the choice of transient flow model, as elaborated below.

The parameter S_s is defined using elastic constants. However, it appears that (1) geologic media deform viscoelastically over long periods, and (2) the equivalent, or effective, elastic compressibility needed to account for the long-term viscoelastic deformation can be significantly larger than the experimental compressibility. Viscoelastic deformation is known experimentally [e.g., *Šuklje*, 1969] and from settlement of structures, [*Bjerrum*, 1967] but extrapolation of this observed behavior much beyond a human time scale is uncertain. A better indication of the potential significance of viscoelastic effects is provided by geological evidence. Porosity-depth profiles permit computation of effective long-term compressibility if one assumes that porosity decrease with depth is due solely to one-dimensional mechanical compression. Figure 4 is a plot comparing vertical compressibility computed from representative porosity profiles in sedimentary sequences with experimental values for sedimentary media obtained from published sources. Figure 4 suggests that effective compressibility over geologic time may exceed experimental values by 1 to 3 orders of magnitude. The effective long-term compressibilities computed in this fashion may be too large because the porosity changes in situ can also reflect extraneous effects such as diagenesis and horizontal strain. Nonetheless, the data strongly suggest that there is significant viscoelastic deformation over geologic time in sedimentary media; if we choose to apply models based on elastic behavior, the corresponding effective values of S_s can therefore be substantially larger than experimental values. Thus the data in Figure 3 should be viewed with the understanding that the effective values of κ may be either larger or smaller. Loading efficiencies, which are also defined with elastic constants for the solid skeleton, are probably also significantly greater over long periods of time than laboratory data suggest.

Analyses of large-scale low-permeability systems are limited to varying degrees by the problems discussed above. The following sections consider analysis of large-scale systems with steady state, transient, and nonhydraulic flow, respectively. These are followed by a discussion of the problems of site specific studies.

Steady Flow in Low-Permeability Environments

Attainment of steady flow in a low-permeability flow system is favored by a stable geologic setting, small S_s, and small dimensions. An important instance where steady flow is often assumed to be occurring is in strata confining undeveloped aquifers. Indeed, the earliest recognition of low-permeability formations seems to have been in their role in steady state flow systems as confining layers. *Chamberlin* [1885] and *Darton* [1909] were among the first to recognize the significance of steady state leakage through confining layers.

Walton [1960, 1965] was probably the first to attempt to quantify steady state leakage through confining layers. To do this, he analyzed transient pumping test data to characterize the vertical permeability of the confining layers. His results can be questioned because he used an analysis [*Hantush and Jacob*, 1955] which did not allow for confining layer storage. However, his work provided an early indication of the large fraction of the flow which can leak through confining layers.

Steady state flow presents the possibility of determining the regional K of the tight units. The flow in the system is determined by the geometry of the aquifer and confining layer, the boundary conditions, aquifer conductivity, and leakage through the confining layer. Thus, if one knows the head in the aquifer, leakage through the confining layer (and thus K) may be estimated if the other properties are known.

This approach has recently been used in a number of studies of tight confining layers. *Bredehoeft et al.* [1983] studied the Cretaceous shales confining the Dakota aquifer in South Dakota. Quasi-three-dimensional numerical simulations of the flow in the aquifer-confining layer system over an area of 3×10^5 km^2 indicated that most of the flow through the aquifer system occurred as leakage through the confining layers. Further, the hydraulic head in the aquifer was strongly controlled by this leakage. *Bredehoeft et al.* [1983] found that the regional K of the composite confining layer was 6×10^{-11} m/s and that for the individual shales it ranged from a low of 5×10^{-12} m/s at depth to 2×10^{-9} m/s near the surface. Interestingly, these regional values were as much as a factor of 10^3 larger than laboratory and in situ determinations of K of the shale. *Bredehoeft et al.* [1983] and *Neuzil et al.* [1984] interpreted this result as indicating fracture enhancement of the regional K. *Wirojanagud et al.* [1984] and *Senger and Fogg* [1984] analyzed the flow system in the Palo Duro basin, Texas, using quasi-three-dimensional and vertical two-dimensional simulations, respectively. Like *Bredehoeft et al.* [1983], they concluded that leakage through an extensive confining layer, in this case composed of evaporites, constituted a large fraction of the flow in the system. The simulations provided an estimate of 10^{-12} m/s for the regional K of the evaporites. This is close to the value suggested by small-scale testing. *Belitz* [1985] analyzed flow in the Denver Basin which contains a thick, low-permeability sequence of Cretaceous shales. Because of the nature of the flow system there it was possible only to determine a maximum regional K of approximately 3×10^{-13} m/s for the sequence. *Butler* [1984] simulated flow in the Williston Basin and obtained estimates of confining layer K. However, his estimates may be inaccurate because of an assumption of steady state conditions soon after development of the aquifers.

As valuable as these regional determinations are, they represent such large volumes of rock that behavior at intermediate scales is problematical. While *Bredehoeft et al.* [1983] show the probable presence of fractures which enhance the shale permeability, *Neuzil et al.* [1984] suggest that large blocks of lower-permeability shale may exist between the fractures. They hypothesize that fractures may dominate the regional leakage across the shales at near–steady state conditions while much more slowly responding transient conditions exist in the blocks.

The determination that steady state flow indeed exists in a large volume of tight rock is not easy to make. *Bredehoeft et al.* [1983] argued the likelihood of steady state flow conditions in the Dakota aquifer confining layers on the basis of their geologically stable setting. The Denver Basin, simulated by *Belitz* [1985] as being at steady state, has in fact often been interpreted as being transient [e.g., *Ottman*, 1984]. In these instances, as in most, knowledge of hydraulic head within the low-permeability units is insufficient to make firm interpretations. One can only demonstrate, as *Belitz* [1985] did, that observed conditions are consistent with a steady state system.

Persistence of Transient Flow

One of the more interesting and challenging aspects of low-permeability environments is transient flow on a large scale. Many of the "anomalous" pressures which occur worldwide in a variety of geologic settings appear to be manifestations of very old transient conditions in low-permeability environments.

As noted earlier, analyses of large-scale transient flow in tight environments have usually been based on well-established descriptions applied in permeable media. In order to understand the various analyses using this approach, their relations to one another, and their limitations, it is necessary to consider a fairly general description of transient flow in an elastic porous medium. *Biot* [1941] first presented such equations accounting for the complete coupling between stress and strain in the porous skeleton and fluid pressure in the pores. *Rice and Cleary* [1976], using the results of *Nur and Byerlee* [1971], generalized Biot's equations for the case of compressible grains. In more familiar notation [see *van der Kamp and Gale*, 1983], their equations may be written as

$$\nabla \cdot K\nabla h = \hat{S}_s \frac{\partial h}{\partial t} - (\alpha - \alpha_s) \frac{\partial \sigma_t}{\partial t} - \frac{1}{v} \frac{\partial v}{\partial t} \qquad (6)$$

and

$$\nabla^2 \sigma_t = \gamma_f \lambda \, \nabla^2 h \qquad (7)$$

The quantity $\hat{S}_s$ is a three-dimensional specific storage [L^{-1}] [*van der Kamp and Gale*, 1983]. It and other notations are defined at the end of the paper.

The term $(\partial v/\partial t)/v$ accounts for a variety of processes which result in an actual or apparent change in fluid volume. These include temperature changes, fluid release or uptake during diagenetic reactions, and porosity changes due to strain of the porous skeleton, pressure solution, and other causes. The inclusion of this term is intended merely as a reminder of the multiplicity of processes which are not usually considered in permeable environments but which may play a role in causing transient flow when the permeability is small. The stress change term, $\partial\sigma_t/\partial t$, which affects flow through porosity change, could have been lumped under this term. Equations (6) and (7) assume that the solid grains and matrix are perfectly elastic and the strains are small. For nonhomogeneous fluids they can be formulated in terms of pressure rather than hydraulic head.

Examination of the relation expressed by (6) affords a qualitative understanding of one of the most significant aspects of low-permeability environments, namely the great longevity of transient flow and the consequent ability of slow geologic processes to profoundly affect flow. This is best seen when (6) is nondimensionalized; in this way, systems with differing values of K, $\hat{S}_s$ and different dimensions can be reasonably compared. It is helpful at this point to note that the quantity $K/\hat{S}_s$ is a three-dimensional hydraulic diffusivity, here denoted $\hat{\kappa}[L^2/T]$.

As an example, consider the effect of stress changes, $\partial\sigma_t/\partial t$, caused by geologic processes. The nondimensional version of the stress term in (6) may be approximated as $(l/\hat{\kappa}\gamma_f)\ \partial\sigma_t/\partial t$. In this form it is clear that even when rates of stress change are small, the term can be numerically significant if $\hat{\kappa}$ is sufficiently small and l is sufficiently large. Studies of one-dimensional systems [*Gibson*, 1958; *Neuzil and Pollock*, 1983; *Walder and Nur*, 1984] indicate that the effect of stress changes on flow becomes significant when this term is of the order of 0.1. Suggested rates of stress change caused by erosion [*Neuzil and Pollock*, 1983], deposition [*Bredehoeft and Hanshaw*, 1968], or tectonic activity (M. D. Zoback, personal communication, 1984), together with values of $\hat{\kappa}$ suggested by the one-dimensional values in Figure 3, indicate that the term can significantly exceed 0.1 in reasonably large regions ($l \approx 100$ m).

If a geologic process maintaining transient flow ceases, the flow evolves to a steady state. The response time or time to attain steady state may be referenced to dimensionless time, t^*, another quantity appearing in the nondimensional form of (6); it is defined by $t^* = \hat{\kappa}t/l^2$. Although exact behavior in any instance depends on the domain geometry and boundary conditions, some generalization is possible. Analytical solutions to the transient flow equation (see, for example, the transient flow solutions of *Bredehoeft and Hanshaw* [1968], *Hanshaw and Bredehoeft* [1968], and *Hsieh et al.* [1981] and consolidation theory in the work by *Šuklje* [1969, p. 140]) indicate that transient behavior persists until t^* is of the order of 1. We can thus compute the approximate time involved as $t = t^*l^2/\hat{\kappa} = l^2/\hat{\kappa}$. Again using $\hat{\kappa}$ values suggested by Figure 3 and assuming reasonable dimensions ($l \approx 100$ m), we arrive at values of t ranging up to 10^6 yr and greater. This illustrates that transient flow response times may be comparable with geologic time scales.

As the square of l appears in t^*, the dimensions of the low-permeability region are particularly important. If l is 1000 m rather than 100 m, the computed times are 100 times greater. Conversely, if transmissive fractures are present, and l is smaller, the response time is drastically reduced. The significance of size is particularly well illustrated on a large scale by shale units in the South Caspian basin described by J. D. Bredehoeft and R. D. Djevanshir (unpublished manuscript, 1986). They presented data from a region which has been subjected to relatively homogeneous depositional loading which shows that the transient excess pressures in the shales become more pronounced as the average thickness of the shales increases.

These simple computations illustrate the necessity of considering the effects of slow geologic processes on groundwater flow in low-permeability environments. Of course, flow in relatively permeable regions must also change as the geologic framework evolves in time; however, in these the flow adjusts so readily that it remains quasi-steady (or fully steady from a human viewpoint) through all but the most rapid disturbances. Only in low-diffusivity regions does fully transient flow develop. The significance of low permeability in this context was stated by *Dickinson* [1953] and was discussed by *Hubbert and Rubey* [1959] in their classic paper on thrust faulting. However, the quantitative relation between rates of geologic change, hydraulic diffusivity, and transient flow seems to have been first appreciated and explored in a pair of papers by Bredehoeft and Hanshaw [*Bredehoeft and Hanshaw*, 1968; *Hanshaw and Bredehoeft*, 1968]. In these papers a variety of geologic processes potentially capable of inducing long-lived transient flow were analyzed.

The interaction of geologic processes and transient flow can be broadly generalized. Some geologic processes affect the flow by altering conditions at the boundaries of the low-permeability region. For example, uplift or erosional exposure of outcrops can alter hydraulic head at a boundary. Other processes, such as stress and temperature changes and related diagenetic effects, act to produce, in effect, distributed fluid sources or sinks as expressed in the last two terms of (6). Excess or deficient heads are generated which either slowly dissipate or are maintained if the generating process continues. Flow into or out of the low-permeability region over long periods of time can occur as a result, a point of interest for the confinement of waste. This is illustrated diagrammatically in Figure 5 for the case of vertical flow.

It appears that in nature, processes causing changes which act as effective fluid sources are most common. As an example, burial metamorphism may cause porosity reduction and fluid generation but has no counterpart during erosional exhumation. Thus one would expect excess transient pressures to be more common than deficient transient pressures, which indeed seems to be the case [*Fertl*, 1976].

The interaction between geologic processes and flows is centrally important to the consideration of transient flow phenomena. Large-scale quantitative analyses which incorporate it have usually addressed problems involving depositional burial or erosional exhumation and associated physical and chemical phenomena. Therefore the following discussion will be centered on these processes and the approaches devised to analyze them.

Effects of geologic processes: Simple burial and denudation. Burial and denudation are perhaps the most ubiquitous and significant geologic processes affecting flow in low-permeability environments; few areas escape their effects over geologically significant periods. They are relatively amenable to analysis because the stress and temperature history can be directly related to overburden history. Also, erosion and sedimentation are often laterally extensive, enabling simplification of the analysis to one dimension vertically. A great deal of insight has been gained through analysis of these processes because nearly all the significant types of geologic effects capable of affecting flow, such as stress and temperature changes, and diagenesis, can be involved. In particular, sedimentary

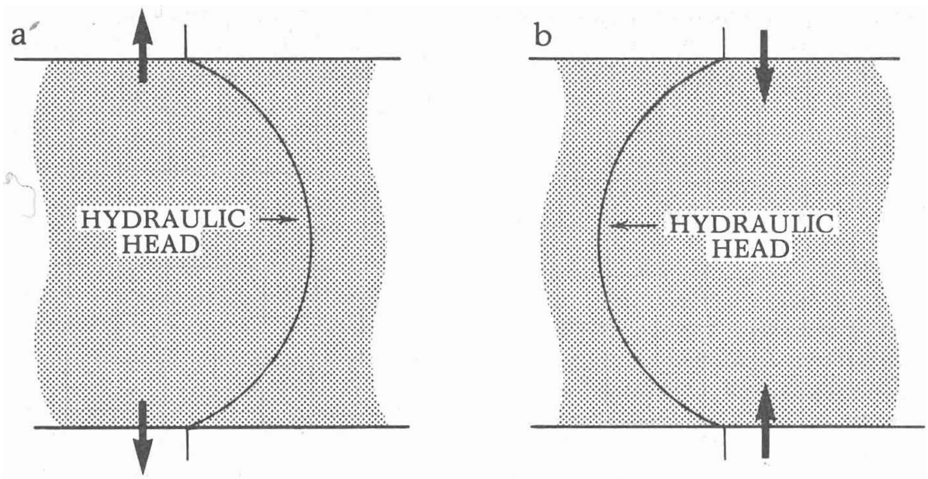

Fig. 5. Schematic illustration of hydraulic head in a low-permeability region (shaded) and the flow between it and adjacent, more permeable regions. The vertical groundwater flow is indicated by the arrows; head increases to the right. (*a*) Effective distributed fluid source such as compressive strain, fluid thermal expansion, or diagenetic collapse of the pores and (*b*) Effective distributed fluid sink and such as extensional strain or fluid thermal contraction. In both instances, hydraulic heads and fluid fluxes would be superimposed on those caused by hydraulic boundary conditions.

burial has been studied because it occurs in areas such as the Gulf Coast, where significant excess transient pressures have been encountered during petroleum exploration.

Stress effects: If the processes considered are laterally extensive, and lateral strains can be ignored, (6) and (7) may be simplified to a single equation. Using *Biot*'s [1941] constitutive relation between stress, strain, and fluid head, this can be shown to be

$$\kappa \frac{\partial^2 h}{\partial z^2} = \frac{\partial h}{\partial t} - \frac{\zeta}{\gamma_f} \frac{\partial \sigma_v}{\partial t} \tag{8}$$

A similar equation was first presented by *van der Kamp and Gale* [1983]. One-dimensional hydraulic diffusivity, κ, is defined as K/S_s, where S_s is one-dimensional specific storage and ζ is the one dimensional loading efficiency. Equation (8) completely describes the coupling between stress and fluid flow in one dimension. The expression used in many transient laboratory test techniques, (1), is a form of (8); as used here, the storage parameters S_s and ζ correspond exactly, in definition, to those obtained in one dimensional tests.

For problems involving change of overburden it has also been found helpful to cast stress in terms of overburden thickness and to use excess pressure in place of pressure [*Gibson*, 1958] or, in this instance, excess head in place of head. Following *Neuzil* [1985], (8) may thus be written as

$$\kappa \frac{\partial^2 h'}{\partial z^2} = \frac{\partial h'}{\partial t} - C \frac{\partial L}{\partial t} \tag{9}$$

where C is a dimensionless coefficient incorporating the loading efficiency and defined by

$$C = [\gamma\zeta - \gamma_f]/\gamma_f \tag{10}$$

and $\partial L/\partial t$ is the erosion or deposition rate, L being the land surface elevation. This form of the equation simplifies the problem by ignoring variations in sediment specific weight, γ, with depth. For most geologic problems this is held to be a reasonable simplification because most of the variation in γ occurs close to the surface.

The resulting formulation, (9), describes the transient groundwater flow in response to depositional loading ($\partial L/\partial t > 0$) or erosional unloading ($\partial L/\partial t < 0$) in a convenient fashion. If C is positive, (9) predicts that deposition ($\partial L/\partial t > 0$) will produce excess heads and erosion ($\partial L/\partial T < 0$) will produce subnormal heads. The opposite is true when C is negative. The creation of "fossil" pressures or "paleopressures," which has sometimes been discussed [e.g., *Bradley*, 1975; *Fertl*, 1976; *Tóth and Millar*, 1983], is conceived as resulting from a process which is described by (9) when C is negative. Whether "fossil" pressures, in the sense discussed here, actually exist is questionable; data presented by *Neuzil* [1985] indicate that C is rarely negative. In general, the larger the absolute value of C, the more pronounced the effects of stress change associated with deposition or erosion on the fluid pressures.

The preceding discussion implicitly assumes that the process being considered acts on a sequence which is "normally" pressured initially. This need not be the case; for example, it is entirely possible for excess fluid pressures to exist, as a result of earlier depositional or tectonic processes, when an episode of erosion begins. The tendency for erosion to reduce fluid pressures would then be superimposed on the existing high pressures. If the erosion were not sufficiently vigorous, it could fail to reduce the pressures to hydrostatic or lower values; excess pressures would persist. Likewise, deposition could occur above a "subnormally" pressured sequence and fail to raise pressures above hydrostatic. In any event, the effects of processes are superimposed on the preexisting fluid pressures.

The process described by (9) has been qualitatively appreciated for some time, particularly among some petroleum geologists. Faced with many examples of "anomalously" high pressures encountered during drilling, they cited the effect of increasing overburden weight as a possible cause. *Dickinson* [1953] was perhaps the first to suggest sedimentary loading of a low-permeability sequence as a cause of overpressures found in the Gulf Coast. *Hubbert and Rubey* [1959] also suggested that it may sometimes cause the high pore pressures they implicated in thrust faulting.

If the grains are assumed to be incompressible ($\alpha_s = 0$) and one further assumes $\alpha_v \gg n\alpha_f$, (9) can be written as

$$\kappa \frac{\partial^2 h'}{\partial z^2} = \frac{\partial h'}{\partial t} - \frac{\gamma'}{\gamma_w} \frac{\partial L}{\partial t} \tag{11}$$

Gibson [1958] first derived (11) and solved it analytically for the case of a layer which thickens at a constant rate. *Bredehoeft and Hanshaw* [1968] recognized that the solution could be applied to the geologic problem of continuous sedimentation in a basin and used it to evaluate loading as a cause of abnormally high pressures in the Gulf of Mexico. Their results can be viewed as a solution to the inverse problem; they concluded that if the sediments had a κ of 10^{-8} m^2/s or smaller, sedimentary loading by itself could cause the excess pressures often encountered in the Gulf Coast. Somewhat later, and apparently independently, *Smith* [1971, 1973] examined the problem of sedimentary loading using an equation equivalent to (11) but derived in terms of porosity. *Bishop* [1979] used (11) to analyze pressure generation in tight sediments being buried beneath permeable strata. *Keith and Rimstidt* [1985] followed an approach similar to Smith's and also derived their equation in terms of porosity. Smith, Bishop, and Keith and Rimstidt all concluded that sedimentary loading alone is capable of generating and maintaining the excess pressures in the Gulf Coast environment.

Both *Smith*'s [1971, 1973] development and that of *Keith and Rimstidt* [1985] accounted for dimension changes due to vertical strain of the porous matrix as well as changes in matrix compressibility with effective stress. Finite strain in vertically loaded media has also been analyzed in the context of soil mechanics, most notably by *Gibson et al.* [1967]. A comprehensive discussion of finite strain analyses is given by *Pane* [1981]. For the geologic problems considered here, neglect of dimension changes due to porous matrix strain does not introduce singificant error.

Erosional unloading may also explain subnormal pressures in some instances as speculated by *Russell* [1972] and *Dickey and Cox* [1977]. *Neuzil and Pollock* [1983] solved (11) numerically for the case of erosion at a constant rate and concluded that subnormal transient pressures could be generated. They also suggested that unloading presents the possibility that pressures will drop into the negative range or that desaturation may occur. Considering the problem in the context of soil mechanics, *Koppula and Morgenstern* [1984] obtained analytical solutions for (11) which described erosion.

Thermal effects: Temperature changes may be expected as deposition or denudation displaces rocks through the geothermal gradient and heat is convected with flowing groundwater. Rocks undergoing burial are heated and then, if denudation of the overburden occurs, are cooled. *Barker* [1972] used a very simplifed analysis, which allowed for no solid strain or fluid flow, as a basis for suggesting that thermal expansion of water may cause anomalous pressures. Controversy over the relative importance of thermal and loading effects ensued, and several qualitative arguments for various views were presented [*Bradley*, 1975, 1976; *Dickey*, 1976; *Chapman*, 1980; *Plumley*, 1980].

Thermal changes cause thermoelastic responses in the solid matrix which act to change the pore volume and thus the fluid pressures, as well as the state of stress. Concurrently, thermal expansion of the fluid alters the fluid pressure, which affects the state of stress in the solid. As *Palciauskas and Domenico* [1982] point out, the resulting problem is quite complex; however, they suggested that thermomechanical effects in the solid can be ignored. Considering the magnitude of thermal expansivity of water, minerals, and rocks, *Delaney* [1982] also argued that the thermal effect on the solid could be ignored for porosities exceeding 0.01. That is, the expansion of water will dominate the thermal effects. For nonisothermal conditions under these assumptions the flow and deformation in the rock are decribed by (6) and (7). In this case, (6) is written as

$$\nabla \cdot K \nabla h = \hat{S}_s \frac{\partial h}{\partial t} - (\alpha - \alpha_s) \frac{\partial \sigma_t}{\partial t} - \alpha_{Tf} n \frac{\partial T}{\partial t} \tag{12}$$

where α_{Tf} is the thermal expansivity of the pore water [°C^{-1}]. The last term in (12) is a specific version, for nonisothermal conditions, of the term $(\partial v/\partial t)/v$ found in (6).

It will be noted that (12) and equations which follow are written in terms of head; buoyancy effects are thus ignored. Although investigators such as *Domenico and Palciauskas* [1979] wrote their equations in terms of pressure, they too ignored buoyancy effects. Indeed, in one-dimensional analyses in which free convection cannot occur, buoyancy has little effect on the flow. The one-dimensional simplification is not particularly restrictive in this regard because free convection is likely only in relatively permeable settings. However, *Blanchard and Sharp* [1985] have argued that free convection can occur in thick sequences with permeability as small as that corresponding to a K of 10^{-9} m/s. This suggests that free convection may be possible in the most permeable settings with which we are concerned in this review.

The movement of heat and groundwater in porous media are coupled phenomena. Heat is transported by moving groundwater as well as by conduction, and temperature changes affect the flow through the last term in (12) and through buoyancy changes. Coupled flow of heat and groundwater have been analyzed by *Bredehoeft and Papadopulos* [1965], *Domenico and Palciauskas* [1973], *Sharp and Domenico* [1976], *Sharp* [1976], *Garven and Freeze*, [1984*a*, *b*], and *Bethke* [1985], among others. Studies by these investigators have served to demonstrate that while groundwater flow may noticeably affect temperature distributions in low-permeability systems, conductive heat transport is dominant over convective heat transport. That is, in low-permeability systems, groundwater flow does not significantly alter the temperature distribution from that produced by conduction alone. This can be seen by the approximately linear thermal profiles computed by *Sharp and Domenico* [1976] and the approximately linear thermal profiles present in the Gulf Coast [*Bodner et al.*, 1985].

While *Bodner et al.* [1985] correctly argue that convective perturbations of temperature may be valuable indicators of flow, the preceding observations have led to the use of justifiable simplifications of the coupled system. Thus *Domenico and Palciauskas* [1979] and *Palciauskas and Domenico* [1980] assumed that, during burial or exhumation, slow displacement along the geothermal gradient occurs without significantly disturbing it. The change in temperature at a point in the sediment column can therefore be directly related to the erosion or deposition rate by the geothermal gradient. Under this assumption and in one dimension, (12) and (7) become, in terms of excess head h',

$$\kappa \frac{\partial^2 h'}{\partial z^2} = \frac{\partial h'}{\partial t} - C \frac{\partial L}{\partial t}$$

where C is now given by

$$C = \frac{\zeta\gamma - \gamma_f}{\gamma_f} + \frac{\alpha_{Tf} nG}{\hat{S}_s}$$

A similar equation, for the more restrictive assumptions that $\alpha_s = 0$ and $\zeta = 1$, was first obtained by *Domenico and Palciauskas* [1979]. A comparable equation was also presented by *Walder* [1984]. Equation (13) becomes identical with (9) in the absence of thermal effects (when α_{Tf} or G is zero). *Domenico and Palciauskas* [1979] and *Palciauskas and Domenico* [1980] discussed the solution of (13) with a simpler form of C which they assumed had a constant, representative value. Their results indicated that the thermal contribution to pressuring was significant and, in fact, might permit pressures tending to exceed lithostatic. They surmised that this would lead to inelastic dilation of the rock.

Treatments of the problem of burial and exhumation are distinguished largely by differences in the assumed relative importance of water (α_f) and grain compressibility (α_s) and water thermal expansivity (α_{Tf}) as compared with rock compressibility (α_v). The assumptions employed by various investigators can be expressed as different forms of the dimensionless coefficient C multiplying $\partial L/\partial t$; this provides a convenient method of summarizing and comparing approaches. Several of the analyses cited are compared in this manner in Figure 6, which plots C versus depth.

Also plotted in Figure 6 and shown as dashed lines are computed values of C using the more general form given by (14). One of the dashed lines (curve 5) represents values computed using "in situ" α_v derived from a representative porosity depth relation presented by *Dickinson* [1953] for the Gulf Coast (see Figure 4, curve A). The other (curve 6) represents C values computed using laboratory-measured α_v for a variety of sedimentary lithologies. The dashed lines and line 4 are largely distinguished from the other treatments by the fact that the variation of α_v with effective stress is accounted for.

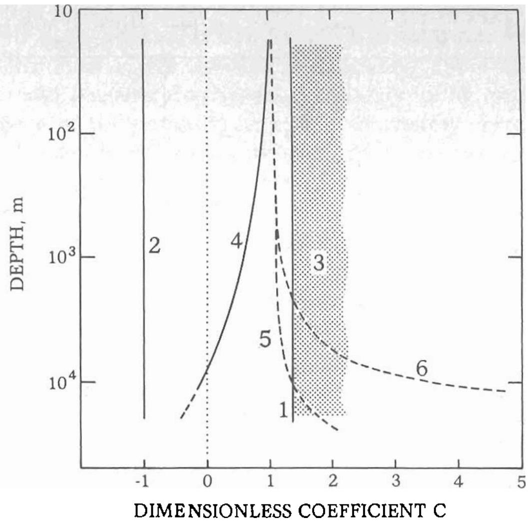

Fig. 6. Graphical summary of various treatments of effects of burial and exhumation as expressed by C, the coefficient of $\partial L/\partial t$ in (9) and (13): (curve 1) constant coefficient, isothermal ($G = 0$), $\zeta = 1$ [*Bredehoeft and Hanshaw*, 1968; *Neuzil and Pollock*, 1983]; (curve 2) constant coefficient, isothermal ($G = 0$), $\zeta = 0$ [*Bradley*, 1975; *Tóth and Millar*, 1983]; (curve 3) constant coefficient, nonisothermal ($G \neq 0$), $\zeta = 1$ [*Domenico and Palciauskas*, 1979]; (curve 4) variable coefficient (ζ variable), isothermal ($G = 0$) [*Neuzil*, 1985]. The dashed curves show representative trends computed using the full form of C (equation (14)): Curve 6 is computed using laboratory determinations of rock properties (see *Neuzil* [1985] for source of data), and curve 5 is computed using α_v derived from *Dickinson*'s [1953] porosity profile.

Examination of Figure 6 suggests that the various simplifications cause the treatments to vary significantly from each other and from the more complete formulation represented in curves 5 and 6. The differences are particularly great at depth. It is of interest to note the difference between curves 4 and 6. These are identical formulations except that thermal effects were ignored in arriving at curve 4. The difference between them therefore represents the possible contribution of thermal effects. Curve 6 suggests that C increases significantly below approximately 2500 m (8000 ft). This results from marked decreases in measured α_v (and thus S_s) with burial and a consequent increase in the final term of (14). These data suggest that fluid pressures in low-permeability sediments undergoing burial can increase significantly below a certain depth. There is, in fact, an often-observed tendency to approach lithostatic values in a "transition zone" after several thousand feet of depth, as, for example, in the data presented by *Dickinson* [1953] and *Sharp* [1976] for the Gulf Coast. This is generally thought to reflect lithology controlled permeability changes [e.g., *Bishop*, 1979; *Bodner et al.*, 1985; *Keith and Rimstidt*, 1985]. However, curve 6 provides an explanation for the tendency of the transition to occur at a certain depth without recourse to lithology-related permeability changes. It suggests that matrix strain is the dominant pressure-producing mechanism at shallow depths, while fluid thermal expansivity is the dominant mechanism at greater depths.

A different interpretation is provided by curve 5, computed using estimates of effective long-term compressibility, here denoted α'_v. Curve 5 suggests that one may ignore water and grain compressibility and, except at great depth, the thermal expansion of water. Under these circumstances, fluid thermal expansion probably would be unable to generate the pressures in excess of lithostatic hypothesized by *Domenico and Palciauskas* [1979]. This is reflected in results of analyses presented by *Walder* [1984] and *Keith and Rimstidt* [1985]. Walder used α_v' values similar to those used to compute curve 5, and Keith and Rimstidt based their analysis on observed porosity-depth relations; both analyses suggested that thermal pressuring would be small.

However, as pointed out earlier, porosity change with depth may not be a good indicator of α_v'. Processes other than mechanical deformation may change porosity. *Walder and Nur* [1984] proposed that pressure solution of minerals at grain contacts and precipitation in the pore space is an important porosity-decreasing process in crystalline rocks at depth. Thus the actual value of α_v' may be smaller than estimates obtained from porosity-depth relations, such as those shown earlier in Figure 4. Any actual difference between values of α_v and α_v' is due to time dependent or viscoelastic deformation of the solid skeleton. Herein lies a difficult problem facing analysts of long-term transient flow. The use of flow models based on assumed elastic behavior of the medium introduces the time scale dependence of specific storage and loading efficiency through the compressibility of the matrix. An additional and perhaps more fundamental problem is whether the behavior of certain systems cannot be analyzed using an elastic model regardless of the choice of parameters. Indeed, there is a range of possible behavior which is depicted schematically in Figure 7.

As indicated in Figure 7, short-term experimental behavior is mostly in the range where deformation is essentially elastic. Viscoelastic deformation may be clearly in evidence, as secondary consolidation, for example, but often at longer time

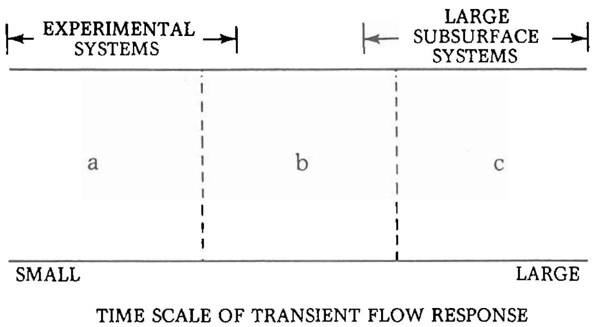

Fig. 7. Diagram illustrating manner in which a pore fluid and a deformable porous matrix interact during transient flow. (*a*) Primarily elastic deformation of the porous matrix in response to effective stress changes, with viscoelastic deformation insignificant during transient flow; a standard transient flow description applies with experimental values of S_s and loading efficiency. (*b*) Viscoelastic deformation significant on time scale comparable with that of transient flow; a complex transient flow description may be necessaary. (*c*) Viscoelastic deformation significant but on time scale smaller than that of transient flow; a standard transient flow description may be used, but effective values of S_s and loading efficiency may be significantly different from those obtained experimentally.

scales than the flow experiment. At the other extreme, in large flow systems with a very slow transient flow response, viscoelastic deformation should be quite significant during the flow. However, it would probably occur over shorter time scales than the flow and thus be additive with, and indistinguishable from, the elastic deformation. *Walder* [1984] suggested this possibility on the basis of theoretical analysis of viscoelastic deformation of clays observed in laboratory tests.

Between extremes of short- and long-term transient flow responses, and represented by the center column of Figure 7, lies a range wherein viscoelastic deformation and the flow response occur on comparable time scales. *Bjerrum* [1967] provides a description of this type of behavior in response to loading. In this range the mechanical interaction between fluid and solid is more complex than represented by (6) and (7), and it may be necessary to incorporate a rheological model of the porous solid into the analysis. Equations (6) and (7) are derived by assuming that a linear elastic (Hookean) constitutive law governs deformation in response to changes in effective stress (see, for example, *van der Kamp and Gale* [1983]). A more complex viscoelastic constitutive law may be used instead; the trick, of course, is ascertaining the appropriate law and parameters. *Gibson and Lo* [1961] were able to describe the behavior following primary consolidation of many media with a model analogous to a Hookean and Kelvin element in series. *Lo* [1961*a*, *b*] discussed a more complex rheologic model.

To briefly summarize the preceding discussion, both short- and long-term transient flow can probably be satisfactorily described with a linear elastic relation for solid deformation in response to changing effective stress. However, the elastic constants applicable at long time scales will be different from those applicable to or measured in the short term. At intermediate time scales a linear elastic description may be inadequate. It is unclear whether flow at intermediate time scales is sufficiently affected by this complexity to warrant a more sophisticated flow model such as that of *Gibson and Lo* [1961]. It is also unclear what time scales are "intermediate" in this context. These questions await further research.

A further complication is presented by the difference between compressibility during compression, α_{vc}, and expansion, α_{ve}, which is manifested as the permanent set suffered by rocks and soils when compressed and allowed to rebound [*Jaeger and Cook*, 1969; *Scott*, 1963]. Both α_{vc} and α_{ve} can be straightforwardly measured in the laboratory. Often, such tests suggest that α_{vc} exceeds α_{ve} by approximately an order of magnitude. *Domenico and Palciauskas* [1979] suggested that the same approximation applies over geologically significant periods. If so, thermal effects may figure much more prominently when effective stress decreases, as when erosion removes overburden.

In experimental soil mechanics, α_{ve} is often found to be approximately equal to α_{vc} in "overconsolidated" media which have borne higher effective stresses in the past [e.g., *Scott*, 1963, p. 175]. *Riley* [1970] found this also to be true for low-permeability lenses which he studied in situ. However, there is no reason to expect that a similar relationship prevails over geologically significant time periods. Estimates of long-term expansion compressibility, α_{ve}', are therefore less readily made than estimates (as in Figure 4) of α_{vc}'. As a result, few attempts have been made to estimate α_{ve}'. *Casagrande* [1949] and *Peterson* [1958] used geotechnical data and geological evidence to study the response of the Cretaceous Bearpaw Shale to past erosional unloading. Their results indicate that α_{ve}' is significantly larger than α_{ve}. Extrapolation of more recent laboratory data by *Lo et al.* [1978] suggests that the ultimate rebound in shales exceed the short-term rebound by 1 to 2 orders of magnitude.

The mechanical behavior of rock is thus problematical but critical for analyzing the fluid flow. To some degree, this is true even in relatively permeable media. However, the shortcomings of existing models are most pronounced for the very prolonged flow transients in environments where the permeability is small.

It is necessary that these problems be recognized and addressed. Current understanding of deformation in geologic materials should be incorporated in analyses. Further experimental work can refine what is known about time dependent deformation over relatively short periods; these data may provide useful bases for extrapolation to long periods. This is particularly true for behavior under stress decrements, for which few experimental data exist. Study of indirect geologic evidence should provide further guidance. For example, the lithospheric structure under certain seamounts led *Watts and Cochran* [1974] to suggest that elastic stresses in these rocks were retained over tens of millions of years. Analogous approaches may provide information in other settings and lithologies.

Physicochemical effects: The long periods of time which are of interest here also dictate consideration of physicochemical phenomena in addition to mechanical and thermomechanical phenomena discussed above. During burial metamorphism, various chemical processes may cause solution, precipitation, and reactions involving the solid and fluid phases. Gas or liquid sources and rock structure and porosity changes can result.

Because argillaceous media are an important low-permeability environment, burial metamorphism of clays is of particular interest. It has long been recognized that clay mineralogy often changes with depth in thick argillaceous sequences and that it differs in old and young shales. *Powers* [1967] and *Burst* [1969] suggested that these data show that smectite to illite transformations occurred with burial, driven by heating. The process releases bound water, and the supposed density reduction of the water upon release would produce a net liquid source. *Powers* [1967] suggested that this caused anomalous pressures. Further work by *Perry and Hower* [1972] and *Hower et al.* [1976] indicated that chemical changes other than simple dehydration of smectite were occurring in the Gulf Coast sediments. Hower et al. also concluded that the reactions could occur in the Gulf Coast shales as a chemically closed system. Apparently, the reactions depend on the chemical environment as well as heating. *Kheizov* [1979] and *Buryakovsky et al.* [1983] report that smectite to illite ratios remain constant to depths of 6000 m (20,000 ft) in sedimentary sequences they studied in the USSR, indicating that the changes did not occur there.

Hanshaw and Bredehoeft [1968] were probably the first to attempt a quantitative analysis of the problem. They considered the release of fluid from a discrete layer at depth by dehydration of gypsum or montmorillonite and simplified the problem by assuming that these processes either led to a step change in hydraulic head in the layer or released fluid from it at a constant rate. While these simplifications are somewhat restrictive, they permitted analytical solutions of the problem and gave the first indication of the significance of the effects.

The significance of smectite transformation as a pressuring mechanism remains controversial. *Magara* [1975] argued that it was unable to produce observed anomalous pressures, although he thought it capable of enhancing anomalous pressures caused by overburden load. *Pritchett* [1980] discussed instances where he believed porosity loss during burial preceded overpressuring; he took this as evidence that smectite transformation later caused the overpressuring. *Morton* [1983] cites isotopic evidence that diagenetic illite in the Texas Gulf Coast sediments formed soon after deposition, suggesting it could not be the result of processes generating pressure at depth. *Walder* [1984] considered the density differences in free and adsorbed water and computed potential pressure increases for a packet of sediment of fixed volume. He concluded that smectite transformation could easily produce lithostatic pressures. However, his assumption of constant volume provided favorable conditions for pressuring just as small compressibility enhances pressure changes from water thermal expansivity. Indeed, aside from structural changes in the solid skeleton, the effect is similar to that from pure thermal expansion of the water; its significance will strongly depend on the mechanical response of the solid skeleton. Further uncertainty is attached to Walder's results by controversy over the density of interlayer and adsorbed water in clays (see *Walder* [1984, p. 114] for a brief discussion). On the basis of an assertion by *Burst* [1969], *Keith and Rimstidt* [1985] assumed that smectite transformation could release a volume of water equal to several percent of the bulk sediment volume. Simulating the transformation gradually between 2500 and 4000 m depth, they concluded that it contributed only small additional pressure.

Other processes during burial metamorphism affect fluid through changes in porosity. *Walder and Nur* [1984] suggested that pressure solution of minerals at grain contacts and precipitation in the adjoining pore space can significantly reduce pore volume in crystalline rocks at depth. They proposed that it causes sporadic excess fluid pressures which are relieved by fracturing. Pressure solution actively affects quartz and so should be operative in quartzitic sediments and might raise pressures in isolated sand lenses. It is unclear whether such a process occurs in clay minerals and, therefore, argillaceous rocks.

Burial metamorphism is probably the single most important process causing transient flow for which an adequate quantitative treatment is not available. Uncertainty about effects of stress and temperature changes lies mainly in the mechanical response of the porous matrix; the uncertainty surrounding the effects of burial metamorphism and diagenesis lies in the processes themselves. Part of the difficulty results from the fact that changes lumped under this term represent several diverse lithology-specific processes. While it may be possible to estimate rates of smectite transformation [*Walder*, 1984], for example, the associated restructuring of the porosity and resulting changes in effective stress and fluid pressure are difficult to account for. Rates of porosity change from pressure solution are equally difficult to estimate; the problem is complicated by the coupling between pressure solution and pore pressure through the effective stress. Moreover, the total suite of processes occurring may be considerably more complex than those yet considered. Incomplete understanding of these phenomena thus limits the ability to analyze prolonged flow phenomena. We need to be able to relate rates of pore fluid production and porosity change to rates of change of temperature, effective stress, and total stress. High-temperature and high-pressure experiments with natural clays and shales, in which strain and fluid pressure are monitored, could provide a basis for obtaining the needed relationships.

Processes in two and three dimensions. The theoretical shortcomings discussed in the previous section apply equally or perhaps more so to two- and three-dimensional analyses which we now consider. While one-dimensional analyses are extremely useful, they are limited in application. It is likely that in most settings the state of stress in rocks evolves in a more complicated fashion than implied by the assumption of negligible horizontal strain in an elastic medium. Indeed, even under the ideal conditions assumed for the one-dimensional analysis some horizontal strain may result from vertical movement normal to the earth's curved surface [*Haxby and Turcotte*, 1976]. In many real settings, moreover, rocks are significantly affected by tectonic and topography related stress changes.

The associated rates of stress change, $\partial\sigma_t/\partial t$, are problematical but can be relatively large. Rates of tectonic stress change as high as 10^3 to 10^4 Pa/yr are not unusual (M. D. Zoback, personal communication, 1984). While this is the high end of the range, it is significantly larger than the 10-Pa/yr rate of overburden stress change associated with representative denudation and erosion rates [*Bredehoeft and Hanshaw*, 1968; *Neuzil and Pollock*, 1983].

Thus tectonic stress may often be expected to affect fluid pressures and flow in tight environments. Tectonic squeezing has been speculated as the cause of "abnormal" pressures in California [*Watts*, 1948; *Berry*, 1973], and North Dakota [*Finch*, 1969]. Because of the uncertainties involved, however, little quantitative analysis of the problem has been possible. Indeed, the problem of tectonic stress may, in many instances, be most profitably posed as a detection problem. In such a context, fluid pressures would be viewed as cumulative stress meters providing information about past tectonic activity.

Some insight into the problem has been gained by extension of the simpler one-dimensional analysis. *Domenico and Palciauskas* [1979] and *Palciauskas and Domenico* [1980] considered the case where the ratio of horizontal to vertical stress is arbitrary, but constant over time. Their results demonstrated that tectonic squeezing enhances burial overpressuring, while tectonic extension subdues it. *Walder* [1984] considered two cases in which horizontal strain was incorporated in a source term in a one-dimensional flow equation. The first case he considered was erosion followed by isostatic uplift as envisioned by *Haxby and Turcotte* [1976]. For the case of erosion, Walder's results suggest that underpressuring, resulting from vertical and horizontal expansion, and cooling, should occur. The second case Walder considered was that of an accretionary sediment wedge at a convergent plate boundary. Under the simplifying assumption that lateral strain dominates over other effects, he derived an equation similar to (6). However, rather than a term accounting for the rate of stress change, $\partial\sigma_t/\partial t$, Walder's equation included a term with the strain rate imposed by the relative plate motion. With the relations implied by the equation he estimated maximum permeabilities at which representative strain rates would significantly perturb pressures. The values he obtained correspond to K of 10^{-11} to 10^{-12} m/s. As these values fall within a reasonable range for fine-grained sediments, Walder's result supports the notion of strain-induced excess pressures in these environments.

Besides simplifying mechanical behavior, one-dimensional analyses force the flow of fluids to be vertical, an approximation which may sometimes be unrealistic [*Bethke*, 1985]. In particular, when laterally continuous permeable units are present, this simplification may be too restrictive [*Magara*, 1976; *Walder*, 1984]. J. D. Bredehoeft and R. D. Djevanshir (manuscript in preparation, 1986) discuss a basin in the Caspian region in which lateral flow in sands appears to be quite significant. *Sharp* [1978] attempted to overcome this problem by solving a one-dimensional equation of the form of (12) coupled with a heat transport equation in a series of one-dimensional profiles to simulate depositional loading and thermal effects in the Ouachita basin. These solutions provided a quasi-two-dimensional simulation of the basin in a vertical plane.

A somewhat different approach has recently been applied to the two-dimensional problem of sedimentary loading in a basin. It uses a statement of fluid mass conservation in a deforming porous medium (such as used in the derivation of (6)). The relation can be expressed as

$$n\alpha_f \frac{\partial p}{\partial t} = -\frac{1}{\rho}\nabla\cdot(\rho q) - \frac{1}{(1-n)}\frac{\partial n}{\partial t} + n\alpha_{Tf}\frac{\partial T}{\partial t} \qquad (15)$$

(see, for example, *Domenico and Palciauskas* [1979], equation 4). The right-hand terms describe fluid flow, porosity change, and thermal expansion of the fluid, respectively. Analyses considered thus far have developed the expression further by relating porosity change to stress and fluid pressure. Thus, for example, Domenico and Palciauskas (1979) used Biot's (1941) constitutive relations to determine that under their assumptions,

$$\frac{1}{(1-n)}\frac{\partial n}{\partial t} = -\alpha\left(\frac{\partial\sigma_t}{\partial t} - \frac{\partial p}{\partial t}\right) \qquad (16)$$

Substitution of (16) in (15) leads to an equation of the form of (12). However, (16) or any similar relation includes all assumptions about long-term mechanical behavior of the solid and requires, as discussed above, knowledge of $\partial\sigma_t/\partial t$, the total stress changes through time. The changes in horizontal as well as vertical stress must be known, or special conditions, such as no horizontal strain, must be assumed to constrain them. In addition, by omitting a term to describe diagenetic porosity changes, (16) implicitly assumes them to be insignificant unless they are embedded in the medium compressibility, α. Thus, in attempting to express porosity changes in terms of other variables much of the uncertainty related to large-scale transient behavior is introduced.

If the porosity changes with time in the region of interest can be ascertained independently, these problems are bypassed, and (15) itself or a comparable equation can be solved. This approach has been used by *Bethke* [1985] to simulate flow in a hypothetical basin fill under continuing sediment input. Bethke considered a slowly subsiding continental basin in which significant transient pressure was unlikely to have been generated; he was thus able to argue that observed porosity-depth relations could be used to determine the temporal changes of porosity, $\partial n/\partial t$, in a sediment packet undergoing burial.

In the cases of interest here, where transient excess pressures are generated, $\partial n/\partial t$ is problematical; the normal porosity decrease is disrupted because the excess pressures do not permit the usual increase in effective stress with depth [e.g., *Magara*, 1969]. In these instances, Bethke suggested what is the only feasible approach, namely, using relations which incorporate the same types of assumptions as (16). By doing this the advantages are lost, and the method becomes equivalent to those described earlier. Indeed, a relation similar to (16) and predetermined $\partial\sigma_t/\partial t$ must be incorporated, in some fashion, in any analysis of stress-induced transient flow.

Cathles and Smith [1983] followed a similar line of reasoning to compute flow from a compacting basin. They used the simplifying assumption that the loss of fluid and accompanying porosity decrease occurred late in basin development and over a short period of time through fractures.

These analyses, together with one-dimensional studies, have begun to address the problem of the concurrent evolution of geologic and groundwater flow systems. An unanswered question at this juncture concerns the significance of the fluid flow-stress coupling in two and three dimensions. Both (6) and (7) are necessary to fully describe transient flow. The one-dimensional analyses described earlier satisfy these relations exactly for the conditions they assume. However, the two-dimensional analyses described have ignored the conditions expressed by (7). While studies have addressed the implications of ignoring (7) in the context of aquifer development [*Gambolati*, 1974] and certain foundation engineering problems [*Schiffman et al.*, 1969], none have addressed its significance in situations where all-around total stress varies in time. As we have seen, such stress changes can be quite pronounced on the time scales of interest. Also, the fully coupled flow-stress description may have importance for an understanding of how the state of stress evolves and its relation to deformation.

A related question concerns visoelastic deformation of the rock, which will be different in response to horizontal and vertical stresses. Inelastic deformation may relieve superimposed tectonic stresses [*Domenico and Palciauskas*, 1979], but the stress due to overburden load remains regardless of the extent of deformation. Indeed, time dependent deformation apparently causes horizontal stresses to tend toward equality with vertical stresses [*Domenico and Palciauskas*, 1979]. The resulting interactions between stress, elastic and viscoelastic strain, and flow are complex but possibly important in a variety of settings. An important area for research now would seem to be investigation of appropriate two- and three-dimensional models for long-term solid matrix deformation and methods for determining parameters for the models.

The problem may be even more complex than these arguments suggest; other forms of inelastic behavior have also been postulated in low-permeability environments. Several authors who have discussed sedimentary deposits [*Sharp*, 1978; *Domenico and Palciauskas*, 1979; *Palciauskas and Domenico*, 1980; *Cathles and Smith*, 1983] and crystalline rocks [*Walder*, 1984; *Walder and Nur*, 1984] have hypothesized that fracturing may cause sporadic periods of increased flow and relief of excess pressures by enhancing the permeability. In some instances, notably as described by *Walder* [1984] and *Walder and Nur* [1984], the process is envisioned as being reversible. The fractures close or heal, reducing permeability to its former low value and initiating another cycle of fracturing.

Palciauskas and Domenico [1980] distinguished between macroscopic fracturing and dilatancy which they considered to result from microfracturing. They described macroscopic fracturing as analogous to hydraulic fracturing in wells, occasioned when the fluid pressure exceeds the least principal stress and tensile strength of the medium. This presumably was the mechanism envisioned by *Sharp* [1978] and *Cathles and Smith* [1983]. *Domenico and Palciauskas* [1979] proposed it specifically as a response to fluid pressures when they begin to exceed the lithostatic load.

Dilatancy is a porosity and bulk volume increase known from experimental work in sedimentary rocks [*Handin et al.*, 1963] and crystalline rocks [*Brace et al.*, 1966]. *Domenico and Palciauskas* [1979] and *Palciauskas and Domenico* [1980] proposed that dilatation is proportional to deviatoric stress and included a term for it in their version of (12). They suggested that significant permeability increases accompany dilatation.

The mechanical behavior in these processes is not well understood, particularly in the long term. As *Palciauskas and Domenico* [1980] themselves acknowledge, we do not yet have an experimentally based constitutive relation for dilatation. Further, there are no data concerning the effect of dilatation on permeability. Resolution of these problems is necessary to evaluate the role of such inelastic phenomena in low-permeability settings.

An interesting geologic setting, exemplifying the complex behavior discussed above, is found in accretionary wedges at convergent plate boundaries. Containing large volumes of sediment, these features are only now being explored. It has been suggested that excess pressures created in the sediments by the tectonic strains and overthrust loading facilitate further thrust faulting [*von Huene and Lee*, 1983; *Westbrook and Smith*, 1983].

Changes in hydraulic boundary conditions. Besides the types of changes already described, geologic processes affect flow in tight environments by altering the hydraulic boundary conditions. The geometry of rock bodies and hydraulic heads at their boundaries is changed by processes such as tectonic folding and tilting, faulting, and erosional exposure of aquifers. This occurs in any tectonically active region, whether undergoing tectonic extension, such as developing rift zones, or compression. The possibilities are varied and difficult to generalize; it is perhaps useful to consider a specific example.

Tóth [1978] describes an aquifer in Alberta which was probably exposed by valley erosion approximately 3×10^5 years ago. Exposure presumably caused a relatively rapid head decline in the aquifer as it became unconfined. Underlying the aquifer is a 500-m-thick confining layer with a hydraulic diffusivity estimated by Tóth as 5×10^{-9} m^2/s. Had flow in the system originally been at steady state, the head decline in the aquifer would have acted like a nearly instantaneous change at the confining layer boundary. The resulting one-dimensional flow in the confining layer can be analyzed with a solution to (1) for these boundary conditions. The solution is graphed by *Hanshaw and Bredehoeft* [1968, Figure 2], from which it can be seen that transient flow should persist, in this case, for approximately 5×10^5 years; the groundwater flow in the underlying confining bed may therefore still be in a transient state.

An analogous situation occurs in formations confining aquifers when the aquifer head declines because of development. Recently, *Bredehoeft et al.* [1983] showed that during development of the Dakota artesian aquifer, most of the water released from storage came from the adjoining tight shales. Moreover, the properties of the confining Cretaceous shales [*Bredehoeft et al.*, 1983] suggest that transient leakage to the aquifer should continue for approximately 10^6 years.

Nonhydraulic Flow in Large-Scale Systems

Two distinct flow phenomena which may be classed as nonhydraulic were considered in the earlier discussion of small-scale experimental work, namely, non-Darcian flow in response to hydraulic gradients and coupled flow in response to nonhydraulic driving forces. In this section we consider the implications of these phenomena for flow in geologic systems on a large scale.

Speculations on the effects of non-Darcian flow. The applicability of Darcy's law, as we have seen, is usually a fundamental assumption of large-scale flow studies. This is entirely appropriate in view of the lack of convincing evidence to the contrary. However, it is also well to recall that the applicability of Darcy's law, in the media of interest and under in situ hydraulic gradients, is strictly an assumption (see Figure 2).

A small number of investigators have considered the effects of specific types of non-Darcian behavior. Because of the lack of consistent experimental evidence for non-Darcian behavior of any kind, analyses based on an assumed specific non-Darcian flow law can only be regarded as highly speculative. *Florin* [1951] and *Elnagger et al.* [1971] analyzed consolidation, and *Pascal* [1981] analyzed the response to hydraulic stresses with a threshold gradient. They showed that under the flow laws they assumed, apparently transient head distributions would become "frozen" and represent a new steady state. *Schmidt and Westmann* [1973] analyzed consolidation using a nonlinear flow law. *Remson and Gorelick* [1982] proposed considering the problem more generally and discussed the potential importance of non-Darcian flow in waste repository design. They argued that the existence of a threshold gradient for flow, for example, would render waste contaminant analyses more conservative than realized, leading to overdesign of repositories.

Geologic membranes in large-scale systems. In contrast with non-Darcian flow, coupled flow in certain geologic materials is clearly demonstrable experimentally. However, speculation about coupled flow in the subsurface predates experimental work on geologic materials. According to *Hanor* [1983], the problem of accounting for the origin of subsurface brines led to speculations by *Russell* [1933] and *De Sitter* [1947] that ultrafiltration by shales was operative. Attempts to explain certain ore deposits led *Mackay* [1946] to publish similar speculations. Subsequently, as experimental evidence for significant coupled flow in certain geologic materials began to accumulate, numerous studies addressed the possibility of large-scale osmosis and ultrafiltration in the subsurface.

Most discussions of membrane phenomena in the subsurface paralleled experimental experience and considered the interaction of reservoirs (aquifers) and membranes (confining layers). By experimental criteria, the presence of salt-bearing groundwater separated from fresher groundwater by a shale or similar medium provides the conditions for osmotic flow of the fresh water toward the salty. If the salty water occurs in a reservoir surrounded by tight shales, it was reasoned that the osmosis may produce observable excess pressures there. *Berry* [1959], *Hanshaw* [1962], and *Hanshaw and Hill* [1969] suggested this mechanism to explain highs in the piezometric surface in the San Juan Basin region of Utah, Colorado, and New Mexico, and *Berry and Hanshaw* [1960] interpreted high heads in the San Joaquin Valley, California, as being due to osmosis. *Hanshaw and Zen* [1965] proposed osmosis as a mechanism for generating excess pressures and facilitating thrust faulting.

The role of ultrafiltration in the subsurface has also been widely discussed. *Berry* [1966, 1967] suggested that ultrafiltration helped create brines in the Imperial Valley, California, and *Hitchon et al.* [1971] argued that the composition of sedimentary formation fluids in western Canada should also be explained this way. *White* [1965] discussed the relative abundances of various ions in brines in connection with their different mobilities in membranes. Based on their experimental studies of filtering efficiencies for different ions [*Kharaka and Berry*, 1973], *Kharaka and Berry* [1974] interpreted the geochemistry of formation fluids in the Kettleman Dome area of California as indicating that extensive ultrafiltration had occurred. *Graf* [1982] has reviewed these and other studies. More recently, *Gautier et al.* [1985] summarized the geochemical criteria that they consider indicative of membrane filtration. They indicated that on this basis, filtration is indicated in Central Valley, California, the Alaskan North Slope, and the Gulf of Mexico.

As noted above, these discussions are distinguished by the fact that they conceptualize the system as being discontinuous and usually consider effects in aquifers adjacent to membranes without considering behavior in the membrane itself. This may partly reflect the influence of experimental work which has been limited to reservoir-membrane interaction. Perhaps a more important reason, however, is that membrane effects in the subsurface are likely to be detected only in permeable reservoirs; these are the source of nearly all data on subsurface fluid chemistry and pressure.

The question of behavior within geologic membranes, in the laboratory as well as in situ, has received much less attention. The data for investigations of this sort are difficult to obtain. One such investigation is that by *Marine* [1974] and *Marine and Fritz* [1981], who measured high hydraulic heads within the low-permeability fill of the Triassic Dunbarton Basin, South Carolina. They interpreted their data as indicating that the high heads occur within the fill as a result of osmotic flow from surrounding permeable rocks with fresher waters.

All of the studies cited are mainly qualitative. Few quantitative analyses of in situ coupled flow have been made. Exceptions include analyses by *Bredehoeft et al.* [1963, 1983] which combined quantitative flow analyses with simple models of ultrafiltration. However, even these studies adopted the simplification of ignoring osmosis and considered only steady flow conditions.

A more general quantitative description of coupled flow in the subsurface can be obtained with the constitutive relations between flows and forces expressed by the phenomenologic equations (2) combined with statements of mass and energy conservation. The important flows in geologic environments are those of pore fluid, solute, electric charge, and, in certain environments, heat. Electrical effects usually result from chemical forces and flows and thus are effectively embedded in the chemical effects. Thus a useful simplification is to consider only flows of pore fluid and solute.

Greenberg [1971] combined the phenomenologic equations for fluid and solute flow with equations of conservation for fluid and solute mass to develop one-dimensional equations describing the transient flow of fluid and solute in a membrane. Hydraulic flow, osmosis, ultrafiltration, and diffusive solute flux are described by the equations. Similar equations were independently suggested by P.C. Trescott (unpublished manuscript, 1975). Using the one-dimensional equations, *Greenberg* [1971] and *Greenberg et al.* [1973] numerically simulated osmotic consolidation of aquitards in a groundwater basin experiencing saltwater intrusion.

Mitchell et al. [1973] [see also *Mitchell*, 1976, pp. 370–373] solved Greenberg's equations numerically for a representative problem involving a layer of clay or shale. The simulation results provide important insight into possible transient flow behavior in large membranes. The shale was considered to lie adjacent to aquifers in which the salt concentration abruptly increased to a value that remained constant. Values for the coefficients were derived from the experimental data for clay cakes discussed earlier. Osmotic flow out of the shale produced a pattern of low hydraulic heads similar to that indicated for other processes and qualitatively depicted in Figure 5b. Thus in practice, osmotic effects would be difficult to distinguish on the basis of hydraulic head measurements alone. Because the shale in the simulation did not act as a perfectly efficient filter, it was slowly invaded by the salt. Substantial concentration differences within the shale were indicated. Thus measurement of pore fluid chemistry variations together with hydraulic head measurements within a shale would be more diagnostic of coupled flow than head measurements alone. Membrane behavior is a distinct possibility if solute concentration and hydraulic heads both decrease or both increase inward from the boundaries.

The time scales implied by the simulation results are also highly significant. Minimum pressures from osmotic flow were attained at $t^* \approx 4$, where t^* is dimensionless time as previously defined. This response time is comparable to that for purely hydraulic transient flow considered in previous sections. As shown there, response times of this order may represent long periods of time. For a perfectly efficient filter this condition would have represented a new steady state. However, time dependent changes occurred at yet a slower rate as salt slowly leaked into the shale, and salt concentrations and fluid heads continued to evolve until $t^* > 10^3$. The extreme longevity of these "secondary" transient conditions suggests that in systems containing membranes, the chemically driven flow may rarely reach a fully steady, equilibrium condition. Moreover, secondary transient conditions would be difficult to detect because they change so extremely slowly that even in tight media the flow would be quasi-steady. *Bredehoeft et al.* [1983] have suggested that just such a situation, the incomplete invasion of shales by dissolved salts, may in part explain the geochemistry of the Dakota aquifer system.

This theoretical work represents a relatively primitive understanding of how geologic membranes may function in actual groundwater systems. The complexity of the flow processes lends uncertainty to mathematical models. Unlike the case of hydrodynamic flow, there is very little experience with application of the equations suggested by *Greenberg* [1971] and P. C. Trescott (unpublished manuscript, 1975) with which to judge their appropriateness. *Greenberg* [1971] notes numerous assumptions of uncertain validity which were necessary to simplify his model to a workable form. The complexity of the geologic environment also poses difficult problems. Rather than being homogeneous, uniform bodies, geologic membranes undoubtedly exhibit inhomogeneity and anisotropy with respect to membrane properties. A single argillaceous formation might consist of several layers of more or less efficient membranes. The entire sediment package might act like several membranes in series, increasing the filtration efficiency of the formation as a whole. *Bredehoeft et al.* [1983] incorporated this concept in their simulations. Transmissive fractures, on the other hand, can probably be expected to "short-circuit" membranes and prevent significant osmotic flow while permitting movement of solutes.

Many of the conceptual problems related to membranes in groundwater systems are manifestations of the difficulty of extrapolating small-scale experimental experience to a large scale. There is great controversy concerning the significance of coupled flow in groundwater systems, even though the requisite conditions for it, such as significant concentration gradients, are common in the subsurface. Some investigators [e.g., *Hanshaw and Hill*, 1969; *Marine and Fritz*, 1981] have argued that the existence of membrane effects in certain locales is indicated by a process of elimination. In other words, certain anomalous hydraulic heads are due to osmosis because they are not explicable by other causes. However, as should have been apparent in earlier discussions, it is extremely difficult to exclude any number of geologic processes as causes of transient flow. While the evidence may suggest large-scale osmosis, it can hardly be considered unequivocal. Likewise, the evidence for in situ ultrafiltration has been questioned by *Hanor* [1983], who also argued that it apparently has not occurred in Gulf Coast sediments. Studies of sandstone diagenesis in the Gulf Coast by *Land* [1984] suggest a more open geochemical system than one would expect if ultrafiltration were significant. *Graf* [1982], on the other hand, has argued for extensive ultrafiltration in subsurface environments such as those in the Gulf Coast. While the existence of signficant coupled flow in the subsurface is difficult to demonstrate, its absence is equally difficult to show, and for the same reason; real systems are quite complex with cause and effect not easily determined.

The problem of in situ behavior is further complicated by the difficulty of characterizing the driving forces in the subsurface. The chemistry of natural waters is complex; there are generally both solute composition and concentration gradients in groundwater. To compound the difficulty, chemical and electrical potential gradients capable of causing osmosis apparently may also be generated internally by chemical reactions [*Olsen et al.*, 1985] and strains in the solid skeleton [*Kemper et al.*, 1972]. *Hilbert* [1981] attributed significant electrical potential gradients to weathering reactions and suggested they caused electroosmosis.

In the opinion of the writer the question of the significance of coupled flow in the subsurface has not been resolved despite the belief by some, as described by *Freeze* [1985], for example, that it can be ignored. The persisting uncertainty is a result of several factors which may be enumerated as (1) incompleteness of small-scale test data, particularly from undisturbed geologic samples, (2) the lack of understanding of scale sensitivity of the phenomenologic parameters, (3) the difficulty of linking cause and effect in complex real environments, and (4) the tendency to focus on effects external to membranes in adjacent reservoirs, which may be less significant than those within low-permeability bodies with membrane properties.

Resolution of the problem of the significance of geologic membranes in groundwater systems will require the synthesis of diverse methods of investigation. The need for laboratory experimental data on coupling coefficients in undisturbed geologic media has already been discussed. Development of in situ testing techniques for low-permeability membrane media could be expected to provide useful data. A general in situ test strategy can be outlined: Waters of different chemistry are pumped into packer-isolated or open boreholes terminated in a suspected membrane unit. Significant osmotic flow would be indicated by a tendency toward different hydraulic heads in the boreholes. A synthesis of laboratory and borehole data might elucidate the scale sensitivity of membrane properties. Theoretical investigations using mathematical models can shed light on the expectable effects of inhomogeneity and anisotropy of coupling coefficients. Again, laboratory work is required to characterize these qualities. Field characterization of formations thought to be acting as membranes, while likely to be difficult, can be expected to provide important answers.

The Field Problem

Ultimately, the problem of interest is that of analyzing the flow in a particular low-permeability system. It will be necessary to characterize current conditions in the system, particularly the hydraulic head, and if membrane phenomena are to be considered, the pore fluid chemistry. These characterizations are difficult in tight media.

Determination of undisturbed hydraulic head. Very few measurements of hydraulic head in low-permeability formations have been made. Generally, anomalous pressures are detected in formations intimately associated with tight formations (which maintain the pressures) but which themselves are permeable enough to permit significant flow when penetrated by drilling. As *Smith* [1971], *Bradley* [1975], and *Bishop* [1979] have noted, pressures in shales are generally inferred from these reservoir pressures rather than measured. As a result, our view of the occurrence of transient conditions is probably biased by the fact that anomalous pressures are usually detected only in permeable reservoirs. For this reason, and to be better able to map hydraulic head distributions, measurements of fluid head within low-permeability formations are often desirable.

Indirect indicators of fluid pressure have been used for some time. Several borehole logging measurements respond in a qualitatively predictable manner in regions of abnormal pressure [*Fertl*, 1976, p. 226]. Some [e.g., *Magara*, 1969] have carried the concept further by estimating porosity or other properties from borehole logging data and relating them quantitatively to effective stress and fluid pressure. Difficulties with this approach lie in the empirical nature of the relation between log response and fluid pressure caused by lithologic and other variations. These shortcomings are discussed, for example, by *Reynolds et al.* [1973] and *Pritchett* [1980]. However, in certain instances it may be possible to draw reliable inferences about fluid pressure indirectly. The tendency of certain overpressured shales to flow [*Musgrave and Hicks*, 1968; *Pritchett*, 1980] presumably indicates fluid pressures near lithostatic load. Along similar lines, *Walder and Nur* [1984] have suggested that seismic low-velocity zones in the crust may indicate regions of crystalline rock with nearly lithostatic fluid pressures.

Direct measurement of formation fluid pressures using boreholes is difficult largely because of the slow response of tight formations to a hydrodynamic disturbance. The simplest measurement technique, simply letting the fluid level in the borehole reach equilibrium, is usually impractical because of the long time required. Such a procedure, in fact, is similar to an open slug test. *Marine* [1974, also personal communication, 1984] and *Marine and Fritz* [1981] have observed the slow return to equilibrium in wells completed in low-permeability Triassic sediments. A period of several years was required to gain an accurate estimate of the predrilling head.

As when conducting slug tests, the process may be hastened by shutting in the borehole, usually with inflatable packers. This procedure, however, brings the attendent problems of eliminating small leaks past the packer or in the piping. Connection via leaks between the shut-in portion and other parts of the borehole may be sufficient to cause the pressure to stabilize at an unrepresentative value. *Neuzil and Pollock* [1983] avoided this problem by isolating a pressure transducer with a shale slurry which self-consolidated to form a low-permeability plug. *Wolff and Olsen* [1968] developed a pointed piezometer which could be pushed into soft clays; it was designed to have small storage and thus respond quickly to pore pressure changes. The system was successfully used in the field for small penetrations into a clay confining bed [*Wolff*, 1970]. The instrument was isolated with an inflatable packer.

Assuming that the section to be tested can be successfully isolated, a sufficient period of time must be allowed for drilling-caused disturbance to dissipate. Generally, part of the disturbance results from the imposition of an arbitrary fluid head at the borehole walls during drilling. The distance this effect penetrates the surrounding rock depends on the period the disturbance is applied; it is described by *Hantush*'s [1964] *A* function. In the case that the well has been "produced" at a reasonably constant rate for some time, the equilibrium head can sometimes be estimated from early shut-in data using a method developed by *Horner* [1951]. *Anderson and Zoback* [1982] used this technique to estimate the equilibrium head in a tight underpressured formation. In principle, industry drill stem tests could be used to measure original formation pressure using this technique [*Bredehoeft*, 1965]. However, few, if any, measurements of this type have been made in the commercial sector. Another problem is that early shut-in data may be strongly affected by thermal disequilibrium introduced by drilling, as *Grisak et al.* [1985] found in crystalline rocks.

Stress distortion caused by drilling the hole also disturbs surrounding fluid pressures. An analysis by C. E. Neuzil (unpublished manuscript, 1982) based on the plane-strain solution of *Hubbert and Willis* [1957] for the mechanical response of elastic media to a borehole indicates that induced pore pressure changes in the vicinity of the borehole will be symmetrical and cancel out. However, experience with boreholes in the Pierre Shale (C. E. Neuzil, unpublished data, 1985) and in a shale in Saskatchewan (G. van der Kamp, personal communication, 1985) indicates that recovery of the hydraulic head in the boreholes was delayed. The delayed response suggests that fluid pressures in the vicinity of the borehole may have been depressed. Inelastic deformation may play an important role in this process. *Florence and Schwer* [1978] analyzed the mechanical response to a circular hole of an elastic–perfectly plastic medium; plastic dilatation, which would lower fluid pressures, was predicted near the hole. In tight materials this presumably could affect fluid pressure in the borehole for long periods of time.

Thus, once shut-in occurs, flow must not only overcome storage in the shut-in volume, it must also dissipate disturbances induced by drilling. Analysis of the interaction between the fluid flow and the complex mechanical behavior near a borehole is needed in order to assess the validity of current measurements and to devise improved measurement strategies.

In the case of shales and other media which may have membrane properties a further potential complication, in the form of osmotically generated pressures, must be considered. For example, were the borehole filled with water substantially fresher than the pore fluid in a surrounding shale, osmotically driven flow into the shale could result. The apparent equilibrium pressure reached in a shut-in borehole would then be less than the equlibrium pore pressure in the shale. The possibility of such a process makes it advisable to determine the pore water chemistry and to duplicate its gross properties in any water injected into the borehole.

Determination of pore fluid chemistry. The porosity of crystalline rocks is so small that, except when they are fractured, recovery of analyzable amounts of pore fluid from them is not practical. Argillaceous media generally have high porosity but yield their pore fluid with difficulty. Relatively small quantities (of the order of tens of milliliters) can be obtained from shale and clay cores by squeezing. H. W. Olsen (personal communication, 1982) has extracted pore fluid samples from Cretaceous shale of approximately 30% original porosity by squeezing under high loads. This approach is not entirely satisfactory because some fraction of the water obtained may not have been mobile under normal conditions; the chemistry of the sample thus may not be representative of the free pore water.

OVERVIEW

> When the phenomena of any class are in general ambiguous, and admit of being explained by different or even opposite theories; if few of those exclusive facts are known, which admit but one or a few solutions, then we have no right to expect much from our endeavors to generalize, except the knowledge of the points where our information is most deficient, and to which our observations ought chiefly to be directed.
>
> *Playfair* [1802, pp. 515–516]

The task of analyzing groundwater flow in general is a difficult one. This is indicated by a retrospective examination by *Konikow and Patten* [1985] of attempts to simulate flow accurately enough to make usable predictions. They showed that the degree of success was quite varied. Analysis of flow in low-permeability environments can be even more challenging in many respects. In this review I have attempted to analyze the aspects which contribute to the difficulty of quantitative analysis. The major ones are summarized in Table 1. Many of the phenomena alluded to in the tabulation are incompletely understood. Perhaps more fundamentally, the significance of some of the phenomena in subsurface systems is unknown or controversial. The questions raised by these uncertainties are important subjects of future research in order to improve the ability to understand groundwater flow in these environments.

Historical Bias

Our present understanding of low-permeability environments reflects how the problem has been approached. Soil mechanics and soil physics have long held flow in low-permeability media, particularly clays, to be of major interest. However, in hydrology and hydrogeology most work in tight media has been preceeded by that on more permeable media.

TABLE 1. Factors Adding Uncertainty to Nature of Large Scale Groundwater Flow in Low Permeability Environments

Factor	Significance
Extrapolation of Darcian relation to in situ hydraulic gradients	Unknown
Coupled flow (osmosis and ultrafiltration)	Importance in subsurface disputed, potentially capable of causing extremely long lived transient conditions
Geologic processes occurring on time scales comparable with flow	Geologic processes can apparently be the dominant control of flow in certain settings
Time scale dependence of storage parameters and size scale dependence of hydraulic and nonhydraulic conductivity.	Long term and laboratory S_s may differ by one or more orders of magnitude, large and small scale diffusivity and conductivity by several orders of magnitude
Three-dimensional coupling between stress and flow (equations (6) and (7))	Unknown, probably most significant where tectonic stresses are important
Viscoelastic deformation of solid skeleton and groundwater flow on comparable time scales (intermediate range in Figure 7)	Unknown

In addition, collective experience with more permeable media is much greater in these disciplines. Consequently, there appears to be a historical bias attached to the study of tight systems, particularly in a hydrogeological context. This seems to explain, in part, certain current approaches to low-permeability problems. For example, it is ironic that few question the applicability of Darcy's law in tight media at small hydraulic gradients, for which we lack experimental justification, while most quantitative flow analyses have ignored coupled flow, for which ample experimental evidence exists. The experimental evidence for coupled flow is sufficiently extensive that its failure to influence flow in large systems, if true, requires explanation. Further progress will be helped by recognizing this bias.

Such a bias may also play a role in the readiness with which mathematical models based on elastic theory have been extrapolated to describe transient flow over geologically significant time periods. With successful application of transient flow theory on a regional scale in developed aquifers, applying the theory in large, naturally transient low-permeability systems seems a natural extension.

Fundamental Difficulties and the Scientific Method

The study of groundwater flow has generally been characterized by the advancement of theoretical models whose usefulness or "correctness" is subsequently tested by application. As examples, one may cite *Terzaghi*'s [1923] theory as a description of consolidation and *Jacob*'s [1940] equation as a description of transient flow in aquifers. Both contain numerous simplifications and assumptions and yet have been shown, through application, to provide useful descriptions in a wide range of problems. As a more recent counterexample, consider the classic convective-diffusive description [e.g., *Ogata*, 1970] of solute transport in groundwater; recent work, including experimental studies, have shown it to have important limitations [e.g., *Simmons*, 1982].

The ability to test conceptual models of flow in low-permeability environments is severely limited by the constraints of time; response on a large scale takes too long to observe. Even if monitoring efforts were to extend over decades, the changes would often be unobservably small. In effect, even under the most ideal conditions for data collection all we can obtain is a "snapshot" of the dynamic behavior. In practical terms this means it is difficult to ascertain the appropriate mathematical descriptions and parameters through experience with application to actual systems. Uncertain size scale dependence of hydraulic and membrane conductivities and uncertain time scale dependence of storage parameters are the manner in which this problem is manifested in the current theoretical framework.

The difficulties here are fundamental; they cannot be readily overcome by technological or analytical advances. One way around the problem is to seek indirect evidence for long-term behavior of porous media by studying the geologic evidence of processes which have been operative for a long time. The nature of the problem is such, however, that significant uncertainty is likely to remain a component of most analyses encompassing large spans of time.

In actual geologic environments one is likely to be faced with a multitude of former and present geologic processes occurring at rates comparable with rates of pressure dissipation in tight rocks. Stress, temperature, chemical, and other effects can all play a part in hydrodynamically stressing the system; the lack of quantitative understanding of these processes presents difficulties. It has so far proved very difficult to identify the significant and insignificant processes with confidence.

Viewing in the context of scientific inquiry [*Bredehoeft et al.*, 1983] one attempts to explain observed conditions by constructing rational physical models of the processes causing them. Rational models for several causal processes can often be proposed. The scientific method therefore requires that the models be testable to premit rejection if they are inappropriate. Unfortunately, low-permeability systems are distinguished by the fact that indicative experimental tests are extremely difficult in practice.

NOTATION

C dimensionless coefficient.
C_A, C_B solute concentration at sample boundaries (M/L^3).
C_s solute concentration at a point (M/L^3).
E electrical potential (L^2M/QT^2).
G geothermal gradient (deg/L).
h hydraulic head (L).
h' hydraulic head above or below hydrostatic (L).
J_i flux of ith component (various dimensions).
K hydraulic conductivity (L/T).
K_c chemicoosmotic conductivity (L^2/T).
K_e electroosmotic conductivity (QT/M).
L ground elevation (L).
L_{ik} coupling conductivity (various dimensions).
l representative size dimension (L).
n porosity (L^3/L^3).
q groundwater flux (L^3/T).
S_s "one-dimensional" specific storage, equal to $\hat{S}_s(1-\lambda\beta)$ (L^{-1}).

$\hat{S}_s$ "three-dimensional" specific storage, equal to $\gamma_f[(\alpha - \alpha_s) + n(\alpha_f - \alpha_s)]$ (L^{-1}).
T temperature (degrees Celsius).
t time (T).
t^* dimensionless time.
v fluid volume (L^3).
X_k kth thermodynamic driving "force" (various dimensions).
z vertical distance.
α bulk compressibility of porous medium (LT^2/M).
a_f compressibility of groundwater (LT^2/M).
α_s bulk compressibility of solids (LT^2/M).
α_{Tf} thermal expansivity of groundwater (1/deg).
α_v vertical compressibility (no horizontal strain) of porous medium, equal to $\{(1 + \nu)/[3(1 - \nu)]\}\alpha(LT^2/M)$.
α_{vc} vertical compressibility (no horizontal strain) of porous medium for compression only (LT^2/M).
α_{vc}' effective vertical compressibility (no horizontal strain) which accounts for long-term compressional deformation (LT^2/M).
α_{ve} vertical compressibility (no horizontal strain) of porous medium for expansion only (LT^2/M).
α_{ve}' effective vertical compressibility (no horizontal strain) which accounts for long-term expansional deformation (LT^2/M).
β "three-dimensional" loading efficiency, equal to $\{(\alpha - \alpha_s)/[(\alpha - \alpha_s) + n(\alpha_f - \alpha_s)]\}$ (dimensionless).
γ specific weight of saturated medium, equal to $(1 - n)\gamma_s + n\gamma_f$ (M/L^2T^2).
γ_s specific weight of solids (M/L^2T^2).
γ_f specific weight of groundwater (M/L^2T^2).
γ' $\gamma - \gamma_f$.
ζ "one-dimensional" loading efficiency, equal to $\{[\beta(1 + \nu)]/[3(1 - \nu) - 2(1 - \alpha_s/\alpha)\beta(1 - 2\nu)]\}$ (dimensionless).
κ "one-dimensional" hydraulic diffusivity, equal to K/S_s (L^2/T).
$\hat{\kappa}$ "three dimensional" hydraulic diffusivity, equal to $K/\hat{S}_s$ (L^2/T).
λ dimensionless coefficient, equal to $\{[2(1 - \alpha_s/\alpha)(1 - 2\nu)]/[3(1 - \nu)]\}$.
ν Poisson's ratio for the porous medium (dimensionless).
σ_t mean total stress (M/T^2L).
σ_v vertical total stress (M/T^2L).

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Long Term Properties of Clay Water Based Drilling Fluids

LONG-TERM PROPERTIES OF CLAY, WATER-BASED DRILLING FLUIDS

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Abstract

Although drilling fluids play a major role in preventing vertical fluid migration from deep injection zones into underground sources of drinking water (USDW), very little long-term data are available concerning the properties of these fluids after they have been in the subsurface environment for an extended period of time.

In an effort to gain a more definitive view of actual long term mud properties, 735 feet of an undisturbed, 29 year old, mud column were removed from an abandoned well at the request of the Texas Water Commission (TWC). This continuous 735 foot mud sample was analyzed in the Envirocorp laboratory to determine mud density, gel strength, and shear strength as a function of depth.

As expected from laboratory and operational field data, mud density remained relatively unchanged over the 29 years, gel strength increased to 267 lbs/100 ft^2, and the mud remained fluid, even for samples with a gel strength of 7000 lbs/100 ft^2.

Introduction

The intent of this paper is to show that water-based drilling fluids, which contain bentonite or natural clays, provide adequate long-term protection against vertical fluid migration in abandoned wellbores along the Texas, Louisiana Gulf Coast and in other areas where similar geology is encountered. The basic approach taken in this paper is to provide a brief review of those mud properties relevant to the issue of vertical fluid migration, to predict the long-term behavior of these relevant mud properties from the available literature, and finally, to compare the predicted long-term mud properties with actual mud properties from a 29 year old field mud column. This mud sample was removed in a single continuous operation from a previously plugged and abandoned wellbore. The field mud column was obtained in August of 1988 from an abandoned dry hole drilled in November of 1959. The well was located near Corpus Christi, Texas.

As will be seen throughout this paper, a significant number of references are used from George R. Gray and H. C. H. Darley's 1980 revised text, Composition and Properties of Oil Well Drilling Fluids. The reason for referencing this text, rather than the underlying literature, is to demonstrate that many of the topics addressed in this paper are fundamental to the drilling industry and have been the subject of investigations over the past 50 years. Although the perspective presented in this paper is slightly different, the data collected by previous investigators are relevant to the current concerns about the ability of drilling fluids to prevent vertical fluid migration in abandoned wellbores. The major mud properties discussed in this paper include:

- Fluid Density
- Gel Strength
- Mud Dehydration Potential
- Filtercake Buildup

Formation stresses and their effect on a mud column will also be discussed with respect to the ultimate forces acting within a mud column over an extended period of time.

Drilling Fluid Properties

As indicated by Gray and Darley (1980, p.4), drilling fluids serve a variety of functions in the drilling industry. However, from the standpoint of resistance to vertical migration, the most relevant functions performed by a drilling fluid are those that:

- Prevent the flow of reservoir fluids into the wellbore,
- Stabilize the uncased section of the wellbore,
- Prevent solids settling during quiescent periods, and
- Develop a filtercake to prevent excessive fluid loss from the wellbore into the formation.

These drilling fluid functions are controlled by fluid density, gel strength, and mud solids.

Fluid Density

Drilling fluid density is the only short-term property of a drilling mud which can prevent reservoir fluids from entering the wellbore. Fluid density is also the only mud property that can prevent formation collapse due to tectonic stresses or unconsolidation of the formation. In general, as indicated by Mitchell, Goodman, and Wood (1987), and by Gray and Darley (1980, p. 355) drillers commonly use a mud weight that will overbalance the highest formation fluid pressure encountered by a "safe margin" which will commonly range between 200 to 400 psi. The overbalanced mud weight is used to provide a conservative margin of error to prevent fluid flow into the wellbore.

Along the Gulf Coast, increased mud weight is also used to prevent the unconsolidated formation from sloughing into the well. As an example, a well recently drilled in the Upper Texas Coast under the supervision of Envirocorp required an 8.8 pound/gallon (lb/gal) mud to balance the formation fluid pressure during a gravel pack operation. However, the mud weight needed to be increased above 9.4 lb/gal to prevent the sides of the open hole from sloughing into the wellbore.

The above example, and the data provided by Mitchell, Goodman, and Wood (1987) demonstrate that the original mud column will commonly overbalance the highest static reservoir pressure encountered by 100 psi or more. The average overbalance pressure indicated by the data provided by the above authors is approximately 350 psi.

Mud weight can be increased by either increasing the salinity of the brine, or by adding insoluble solids to the mud. For onshore Gulf Coast drilling operations, barite ($BaSO_4$) is the weighting material of choice due to its comparatively low cost and ease of handling. Long-term maintenance of the mud weight is controlled by the gel strength developed in the mud.

Gel Strength

Gel strength serves two important functions in terms of preventing vertical fluid migration. First, gel strength is the mud property necessary for keeping the solid weighting materials suspended in the mud for extended periods of time. Second, long-term gel strength provides additional resistance to vertical migration due to the increased pressure required to initiate fluid movement.

To understand the buildup of gel strength within muds and why it occurs, it is necessary to review briefly the basic concepts which have been proposed to account for the gel strength of clay mud systems. As discussed by Gray and Darley (1980, Chapter 4), and the studies referenced in their text, the development of gel strength in a mud is associated with the charged surfaces of the clay particles used to develop mud viscosity. These authors point out that the edges of the clay particles have a different charge than their crystal or platelet faces. The difference in the charges on the faces and edges cause both electrostatic repulsive and attractive forces between the individual clay particles. During drilling operations, the mud is subjected to high shear forces which disturb the electrostatic interactions and allow only localized interactions to occur between individual platelets. The shearing action results in a lowering of the operating viscosity.

During static periods, when the drilling fluid is not being sheared, the charged surfaces cause the clay particles to align according to natural kinetic, steric, and thermodynamic forces. This natural development of a "gel" structure between the clay particles and the surrounding water can extend over a considerable distance. It is the formation of a structured relationship between clay particles and the water molecules which gives rise to the gel strength. Again, solid particle alignment, i.e. the gel structure, is due to the natural thermodynamic tendency to maximize the electrostatic attractive forces and minimize the repulsive forces. Thus, gel strength in clay, water-based drilling fluids is seen to be a natural phenomenon that can be explained using the basic chemical and physical laws of nature.

With the understanding that the formation of a gel structure is a natural and fundamental property of clay, water-based drilling fluids, it is easier to address the importance of gel strength from an empirical perspective. Empirical studies of gel strength have been performed by a variety of investigators and have been partially summarized by Davis (1986).

The intent of the following paragraphs is to briefly demonstrate that gel strength naturally increases with time, far exceeds the gel strength required to maintain the original fluid density, and will reach an ultimate strength approaching or in excess of 100 pounds/100 square feet (lbs/100 ft^2) in a matter of days.

The time dependence of gel strength was reported over 50 years ago. Garrison's original work, published in 1939, showed the gel strength of a montmorillonite clay, water system could be empirically correlated with time using the following equation:

$$t/S = t/S' + 1/S'k$$

Where:
- t = Time After Shearing Stopped
- S = Gel Strength at Time, t
- S' = Ultimate Gel Strength
- k = Rate of Gelation

Figure 1 is a plot of Garrison's data in Table 1 for gel strength versus time. Figure 2 presents the same data plotted as t/S versus t. As a point of reference, a gel strength of 1.0 dyne/cm^2 is equal to 0.21 lbs/100 ft^2.

TABLE 1

GEL STRENGTH MEASUREMENTS

BENTONITE PERCENT IN WATER	CURVE	ADDITIVES	GEL STRENGTH AFTER 135 MINUTES dynes/cm^2	GEL STRENGTH AFTER 135 MINUTES lbs/100 ft^2
4.5	1	-------	34.4	7
5.5	2	-------	74.4	16
6.5	3	_______	114.0	24
5.5	4	0.1% Na Tannate	104.0	22
5.5	5	Sodium Hydroxide	99.7	21

(Revised from Garrison, 1939)

FIGURE 1

GEL STRENGTH IN RELATION TO TIME
AND RATE OF REACTION
(FROM GARRISON 1939)

SEE TABLE 1

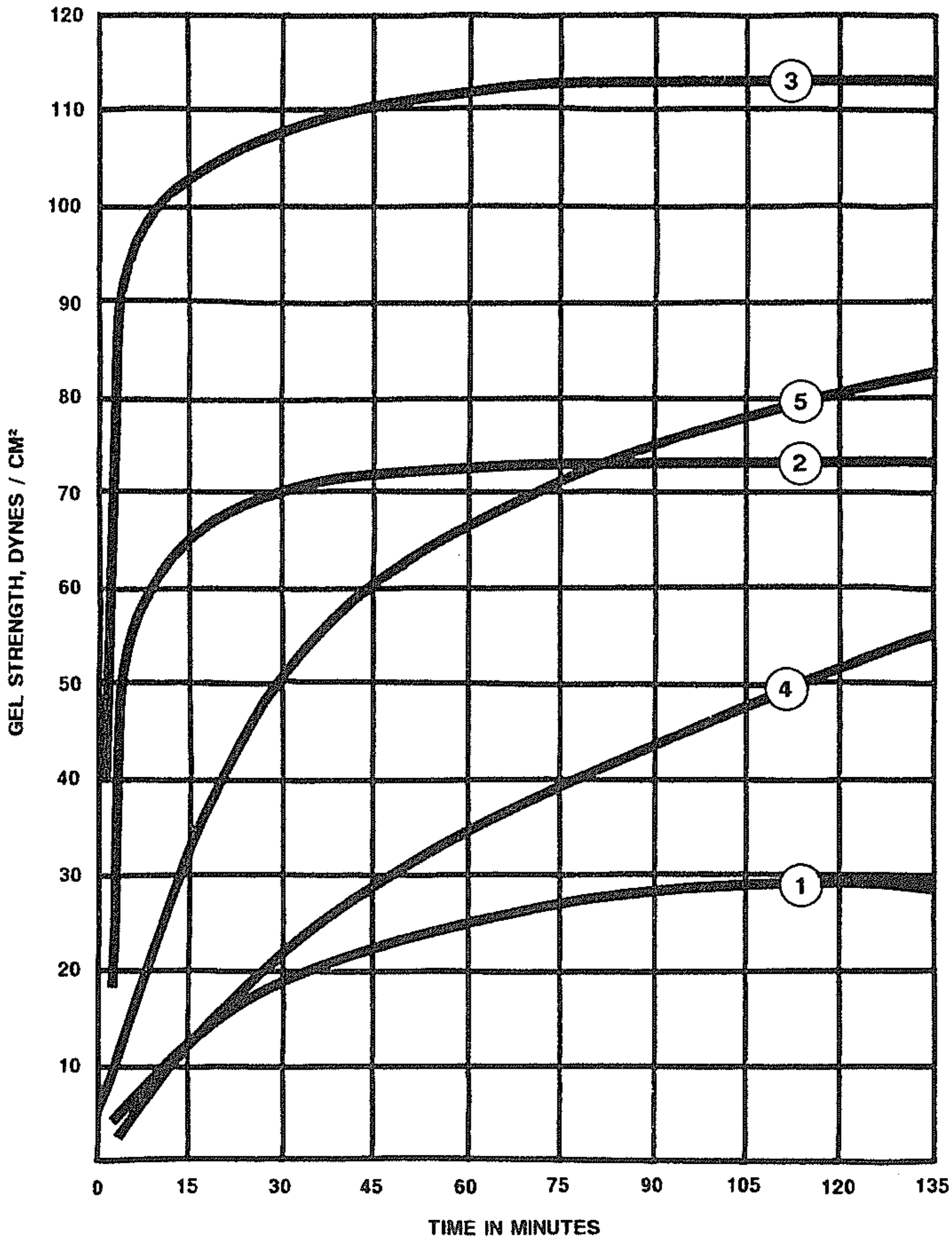
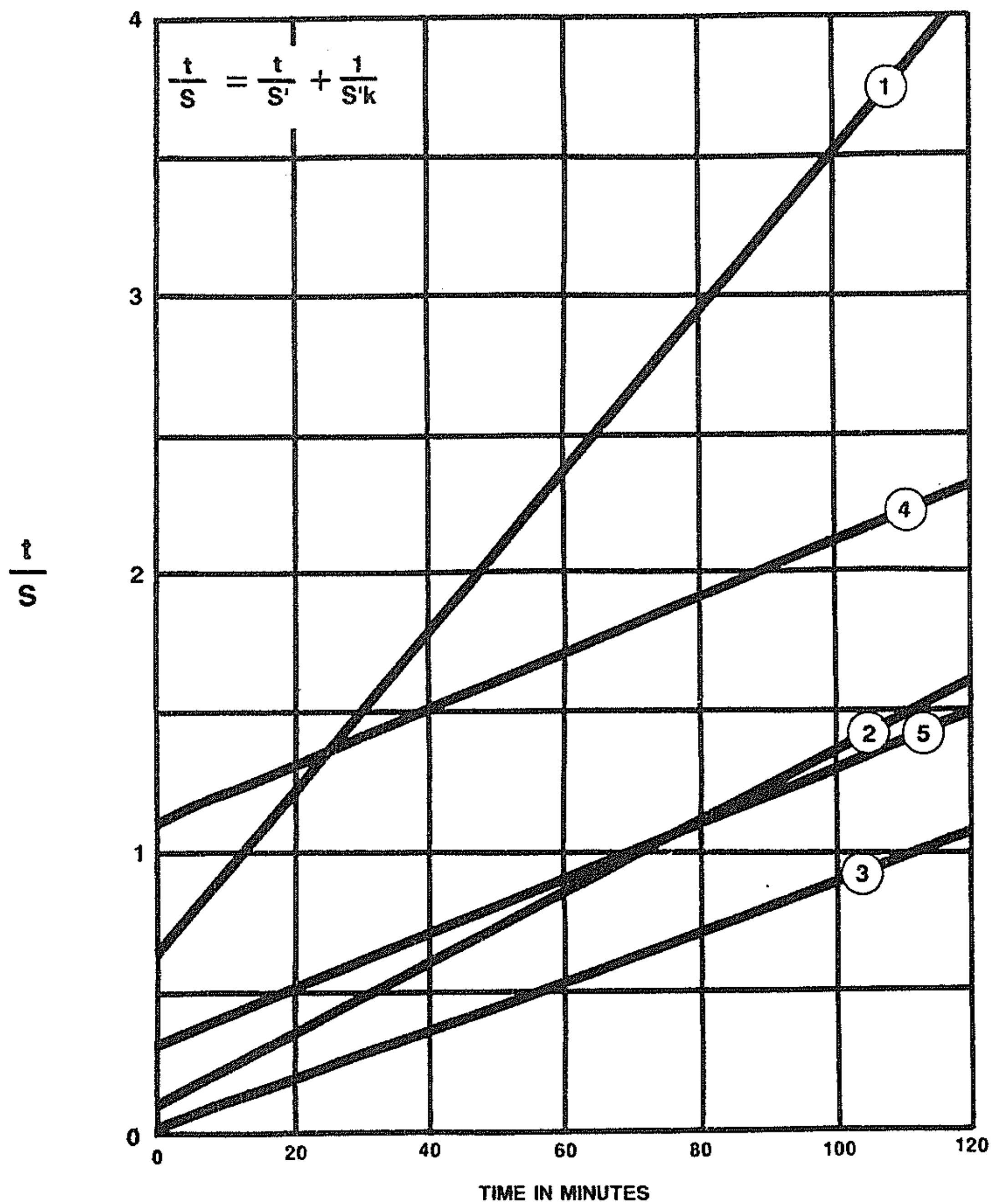


FIGURE 2
GEL STRENGTH AND RATE CONSTANTS
(FROM GARRISON 1939)

SEE TABLE 1



Weintritt and Hughes (1965) measured the gel strength of three field muds as a function of time. As mentioned by Gray and Darley (1980, p. 205), Weintritt and Hughes' data follow Garrison's model only at early times. For longer time periods, the gel strength continues to increase at a rate in excess of what Garrison's model would predict. Weintritt and Hughes' data, Table 2, are graphically presented in Figure 3 which demonstrates that for these field muds, gel strength is approximated more closely by a linear relationship with time after the first two hours. The importance of these data is not the exact relationship between gel strength and time, but rather, gel strength increases with time, and that a gel strength for clay-based field mud systems will normally exceed 25 lbs/100 ft^2 in a matter of days, if not hours.

The next step in the evaluation of the resistance a mud column provides against vertical fluid migration is the estimation of the minimum gel strength required to suspend solid weighting material indefinitely in the drilling fluid. The gel strength required to prevent a spherical solid of radius r from settling can be estimated using the following equation:

$$(\rho_b - \rho_f) g (4\pi r^3/3) = G\ (\pi r^2)$$

or

$$G = 4\ (\rho_b - \rho_f) g r/3$$

where:

ρ_b	=	density of barite (4.2 g/cm^3)
ρ_f	=	density of water (1.0 g/cm^3)
g	=	acceleration due to gravity (981 cm/sec^2)
r	=	radius of barite particle (cm)
G	=	Gel Strength (dynes/cm^2)

If the maximum radius of barite is assumed to be 0.00635 cm (0.0025 inches) or larger, the largest 3% of the solids allowed in standard API barite (Gray and Darley, 1980, p. 533), the gel strength is calculated to be 26.6 dynes/cm^2 or 5.6 lbs/100 ft^2. This calculation shows that only a minimal gel strength is required to keep over 97% of the barite weighting material suspended. Since barite density is 4.2 g/cm^3, bentonite density is 2.8 g/cm^3, and the density of sandstone is 2.65 g/cm^3, it is clear that the gel strength in field muds will reach a value in excess of the gel strength required to maintain mud density in less than an hour. Only the larger drilled solids and the largest 3% of the barite have any potential for settling during this time period.

As indicated by the above calculation, a gel strength of 5.6 lbs/100 ft^2 is adequate to suspend the largest 3% of the barite particles in the mud. It should be noted that the development of a sufficient gel strength to prevent barite from settling does not mean that drilled solids do not settle from the mud. An examination of the settled solids, as discussed later in this paper, shows that the settled solids are composed mainly of drilled solids that are significantly larger than the barite used as weighting material. During the first twenty to thirty minutes of quiescence, these particles may be large enough to settle to the bottom. It may even be possible that the largest barite particles will also settle. However, the loss of these materials will not alter the mud weight significantly, since the large drill solids are removed at the surface, and are not included in the measured mud density. Furthermore, the largest barite particles with any potential to settle constitute less than 3% of the total

TABLE 2

COMPARISON OF MUD PROPERTIES WITH PROGRESSIVE GEL-STRENGTH TESTS
GYP-FERROCHROME LIGNOSULFONATE EMULSION MUDS

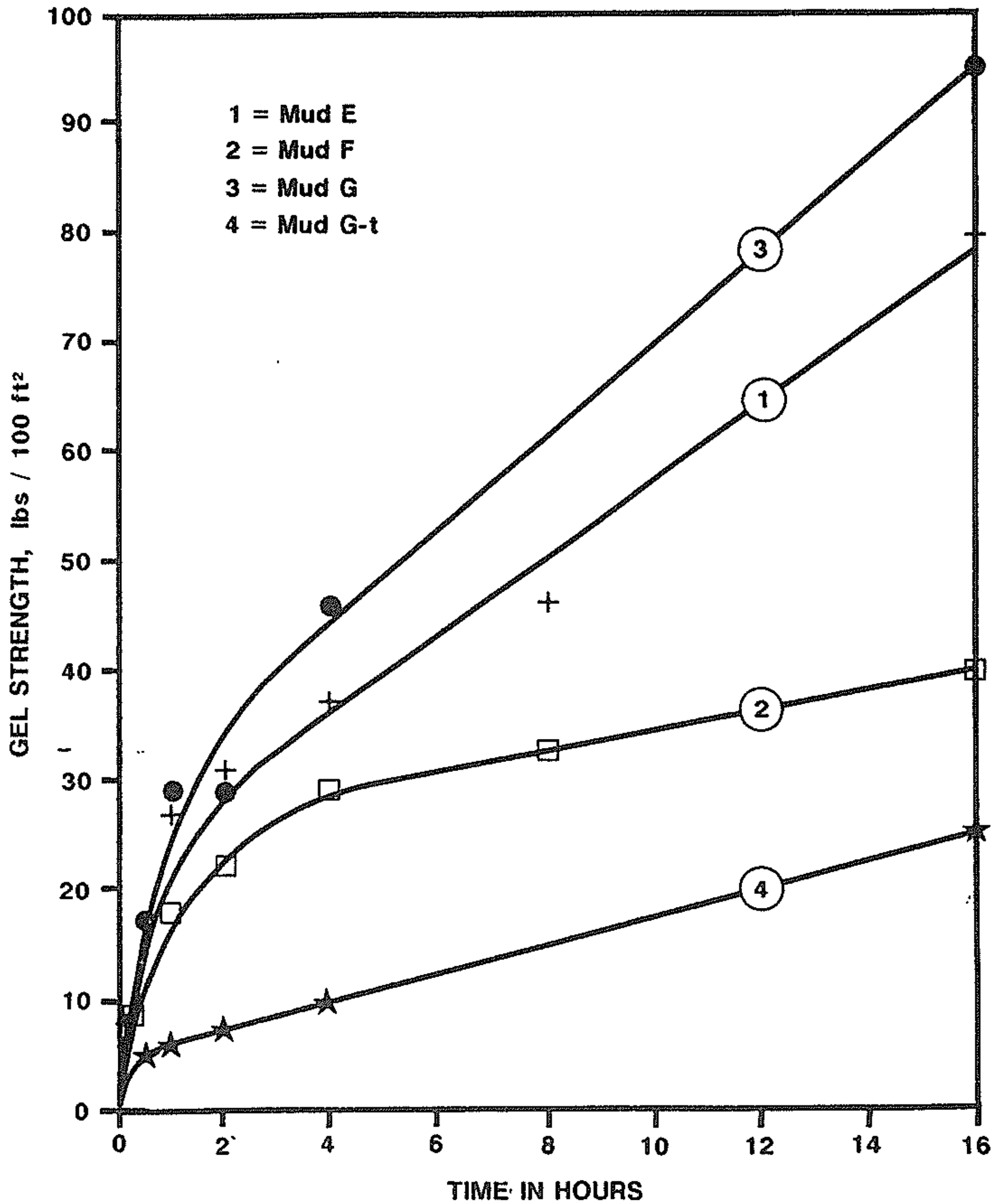
	SAMPLE			
	Mud E	Mud F	Mud G	
			No Treatment	3 lb/bbl PCL
Weight, unstirred, lb/gal	11.0	10.7	10.6	
Weight, stirred, lb/gal	11.0	10.3	10.7	
Plastic Viscosity, cp	14	23	16	15
Yield Point, lb/100 sq ft	3	6	2	1
10-sec gel, lb/100 sq ft	1	2	1	0
10-min gel, lb/100 sq ft	8	8	7	3
API filtrate, sl	6.2	3.3	5.2	2.9
pH	10.9	10.6	10.5	10.4
Composition:				
Water % by vol	76	63	75	
Oil, % by vol	5	11	9	
Solids, % by vol	19	16	16	
Solids, % by vol	39	36	37	
Solids, SG	2.7	2.9	3.0	
Filtrate Ion Analysis:				
Chlorides, ppm	3500	400	3000	
Sulfates, epm	250	300	130	
Carbonate, epm	24	28	12	
Bicarbonate, epm	12	160	12	
Calcium, epm	44	52	44	

Progressive Gel Strengths lb/100 sq ft	Temperature (°F)							
Time	75°	180°	75°	180°	75°	180°	75°	180°
0 minutes	1	1	2	2	1	1	0	0
3 minutes	2	3	2	5	3	8	1	1
10 minutes	8	18	8	12	7	26	3	3
30 minutes	15	40	11	18	17	58	5	5
60 minutes	27	90	18	16	29	91	6	6
2 hours	31	145	22	22	29	104	7	7
4 hours	37	190	29	42	46	172	10	10
8 hours	46	190	33	42				
16 hours	80	320	40	57	95	320	25	25

(From Weintritt and Hughes, 1965)

FIGURE 3
GEL STRENGTH vs. TIME
FOR 3 FIELD MUDS AT 75°F
(FROM WEINTRITT AND HUGHES, 1965)

SEE TABLE 2



barite in the mud. Therefore, the loss of these larger barite particles will not alter the mud density by more than 0.3%.

As an example consider a 10 lb/gal, mud system with the following formulation:

Component	Specific Gravity	Concentration (lbs/bbl)	Volume Percent
Bentonite	2.8	18	1.84
Barite	4.2	77	5.26
H_2O	1.0	325	92.9

A loss of 3% barite would lead to the following mud system:

Component	Specific Gravity	Concentration (lbs/bbl)	Volume Percent
Bentonite	2.8	18.1	1.84
Barite	4.2	74.7	5.08
H_2O	1.0	326	93.1

The weight of this second system is 9.97 lb/gal, which reflects a total reduction in mud weight of 0.3% or 4 psi per 1000 feet of mud column. This number is a conservative value since less than 3% of the barite is expected to settle, the radius of the largest particles has been over estimated, and the minimum gel strength required to prevent solids from settling will be reached in less than thirty minutes (Table 2).

Other areas which need to be reviewed concerning long-term mud properties are associated with the following relationship between the drilling fluid and the formation:

- Formation Stresses
- Mud Dehydration
- Filtercake Formation

Formation Stresses

Three phenomena, faulting, hole stability, and hydraulic fracturing; contribute to our knowledge of formation stresses. General experience and theoretical models continually demonstrate the existence of stresses in the underground which always act in a direction to close a borehole in unconsolidated formations along the Gulf Coast (Gray and Darley, 1980, Chapter 8). The existence of these stresses in Gulf Coast formations requires that, over a long period of time, the following relationship must hold:

Formation Friction + Mud Hydrostatic Forces + Gel Strength = Formation Stress

Since the general experience associated with deep wells is that the diameter of wellbores along the Gulf Coast will shrink due to plastic flow of shales, and long-term shale creep (Gray and Darley, 1980, Chapter 8 and Mitchell et al, 1987), an enclosed mud column must acquire the increased stresses imposed by the surrounding formation. Since the mud is a gelled fluid, these forces will be transmitted as an increase in hydrostatic pressure throughout the mud column. The eventual limit of this increased stress will be the same force per unit area required to maintain an open fracture in the weakest exposed formation. The resistance offered by a drilling fluid to upward migration of fluids will approach or exceed that of the formation itself due to the hydrostatic nature of the mud.

Mud Dehydration

Some concern has been raised that drilling fluids can eventually be dehydrated and cracked. If this were to occur, it is speculated that an open conduit would exist for fluid flow up a wellbore. Again, the literature data provided by Gray and Darley (1980, p. 366) demonstrate that clays in general, and smectite clays in particular, are prone to adsorb water, and that these clays can develop significant swelling pressures due to water adsorption. This process of brine adsorption by bentonite has been demonstrated numerous times, and a most spectacular presentation of this swelling process can be observed in the 1972 Drilling Fluid Engineering Manual provided by Macobar (1972). It is interesting to note that compaction of these clay systems, due to compressing the water out of the clay samples, can result in fluid permeabilities on the order of 10^{-9} darcies (10^{-6} md) (Gray and Darley, 1980, p. 271).

The data provided by Gary and Darley and their cited references demonstrate that clay muds will remain hydrated while in contact with a source of water. Therefore, at a minimum, all the drilling fluid clays must remain hydrated below the top of the first continuous aquifer. Since the first aquifer in the Gulf Coast region is only tens of feet below the surface, it is improbable that dehydration will have any measurable effect on resistance to flow offered by the mud column, especially if a conservative estimate for gel strength of 25 lbs/100 ft^2 is used in an additive manner to calculate resistance. It is important to point out that if a dehydrated mud is later contacted with an aqueous fluid, the above data indicate that the mud would swell as it gained water. The swelling would close all cracks in the dehydrated mud, and therefore close off the existing path for fluid migration. This would also add hydrostatic pressure to the mud column once the clays were again fluidized.

In more inland areas, the top of the mud column can be conservatively located at the top of the first aquifer encountered below the surface. The effect of this correction will be site specific, and dependent upon the mud weights used, the gel strength of the mud, and the amount of formation stresses transferred to the mud column.

Filtercake Buildup

The ability of the mud column to resist upward flow of fluids is most dependent on the long-term density of the fluid. It has been suggested that drilling fluid solids may be squeezed into permeable formations, and therefore, a significant reduction in the hydrostatic head could occur. The loss of hydrostatic head would then allow fluids to flow more easily from the injection zone to a USDW.

A review of the filtration properties of clay-based drilling fluids and an understanding of gel strength can be used to alleviate this concern. One of the primary designed properties of a drilling mud is fluid loss control for fluid flow into the formation. The clay-based systems use bentonite or the natural clays to provide viscosity, gel strength, and filtercake formation to control fluid loss. The fact that a filtercake forms with little invasion of solids into the formation (Gray and Darley, 1980, Chapter 6) demonstrates that the loss of drilling fluid solids into the reservoir is minimal under ordinary conditions. Basically, the solids are too large to migrate into the formation, and they must remain in the wellbore unless they are naturally fractured into the formation due to the accumulation of formation stresses encountered over a long period of time.

Since the solids must remain in the wellbore as demonstrated by filtercake buildup, the only mechanism available for relieving the formation stress accumulated in the mud column is the compaction of the mud column, and the movement of water into the formation. However, the loss of water into the formation must naturally be followed by three changes in the mud properties. First, the mud column will increase in density due to the loss of the lower density water. Second, the gel strength of the mud will increase, as the solids are brought into closer contact with each other. Third, the actual low permeability of the mud column to fluids must decrease. The reduced permeability reached by compaction of the clay mud could be as low as 10^{-9} darcies, although two to three orders of magnitude higher permeability would be sufficient to prevent significant vertical fluid migration (Gray and Darley, 1980, p. 271).

Expected Long-Term Mud Properties

The review of known mud properties for clay, water-based drilling fluids presented thus far leads to the following expectations for long-term mud properties:

1. The density of a clay, water-based drilling fluids should not be altered by more than 0.3% over an extended period of time, since adequate gel strength will be developed to prevent solids settling.

2. The mud density will overbalance original formation pressure by at least 100 psi or more.

3. Gel strength will reach a minimum of 25 lbs/100 ft^2 and will most likely exceed 100 lbs/100 ft^2 over an extended period of time.

4. For cased holes, the top of the mud column in abandoned wells will be close to the surface, since the mud must remain inside the hole after it is abandoned.

5. For an open hole in hard rock country, the major conservative consideration will be the location of the first water aquifer below ground level due to potential dehydration and cracking of the drilling fluid. Dehydration of muds below this point is highly improbable, if not impossible, due to the water adsorption properties of the clay. It should be realized that the point where dehydration causes loss of density and cracking of the mud could occur significantly higher in the mud column due to the water adsorping properties of the clay and capillary forces.

6. Recontacting a dehydrated mud with water will cause the clays to swell and close off any potential cracks in the dry cake.

7. For an open hole in regions such as the Gulf Coast, the stresses in the formation should load the mud column and increase the hydrostatic head with time. The expected increase in hydrostatic head is caused by a reduction in the wellbore diameter due to wellbore closure without a commensurate loss of material from the drilling fluid. The increase in hydrostatic head will provide resistance to vertical migration that approaches the pressure required to fracture the weakest exposed interval.

8. The solids in the mud cannot be forced into the formation by means other than fracturing of the weakest exposed formation.

9. Loss of water to the formation due to wellbore closure will increase both mud density and gel strength. If total compaction of the fluid in the wellbore occurs, the permeability of the compacted column could approach 10^{-9} darcies.

In all cases, for the mud systems reviewed, except for dehydration effects which have not yet been quantified in the literature, the long-term mud properties are expected to be more resistant to vertical migration of fluid than the original mud. Since the original mud density typically overbalances formation pore pressure by 100 psi or more, it is realistic to expect that mud filled wellbores will not provide a conduit for fluid flow from the injection zone to a USDW under the vast majority of operating conditions.

Measured Long-Term Drilling Fluid Properties

Before presenting the data for the mud properties of the 29 year old mud obtained from the abandoned well located near Corpus Christi, Texas, it is valuable to review the mud properties and the well schematic for the well after it was plugged and abandoned (Figure 4).

As the data in Figure 4 indicate, the mud density was recorded to be approximately 11.0 lb/gal. The 10 sec and 10 min gel strengths were recorded to be 0 and 3 lbs/100 ft^2. From the preceding arguments, the density of the mud would be expected to remain 11 lb/gal, and the gel strength should be at least 100 lbs/100 ft^2 as suggested by the data provided by Weintritt and Hughes (1965).

The data presented in Table 3 and Figure 4 show that the average density of the mud over the 740+ feet recovered was 11 lb/gal, and the average gel strength of the mud was 267 lbs/100 ft^2. The shear strength of the mud was also measured using the standard technique mentioned by Gray and Darley (1980, p. 101). The average shear strength was determined to be 260 lbs/100 ft^2.

It should be remembered when evaluating these data, that the operators are disposing of their mud at the end of the job and are no longer interested in maintaining the quality of the mud system at the same level required for drilling. The variations in density observed in Figure 4 are likely due to the final variation in mud properties in the mud pit as the mud was pumped downhole, and not to solids settling. This reasoning is supported by the fact that the mid level mud densities were the lightest encountered in the mud column. If

FIGURE 4

WELL : NORA SCHULZE No. 2

LOCATION : CORPUS CHRISTI AREA

MUD TYPE : LIGNOSULFATE ?

MUD DENSITY : 11.0 POUNDS/GALLON

GEL STRENGTH : 0/3 POUNDS FORCE/100 FEET^2

DRILLING COMMENCED : NOVEMBER 13, 1959

WELL P&A : NOVEMBER 25, 1959

DATE OF MUD SAMPLE : AUGUST 26, 1988

DEPTH OF MUD SAMPLES : 12' TO 754' BGL

WELL DIAGRAM

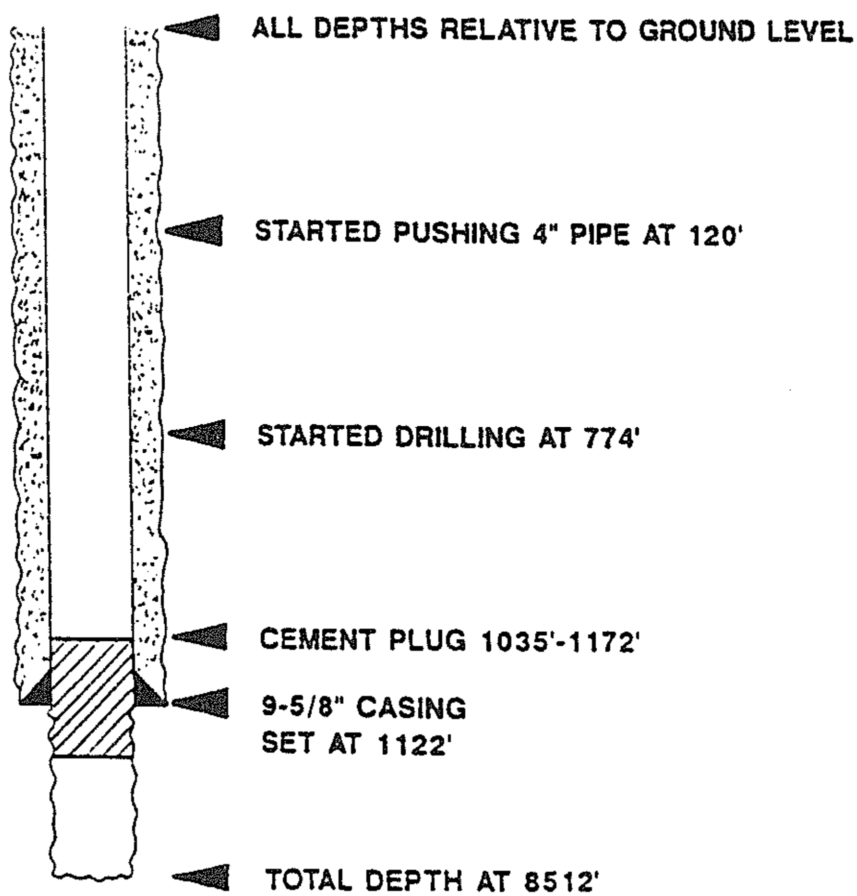


TABLE 3

RECOVERED MUD PROPERTIES FOR NORA SCHULZE NO. 2 WELL

SAMPLE NO.	DEPTH (ft)	MUD WEIGHT (lb/gal)	SHEAR STRENGTH (lbs/100 ft^2)	GEL STRENGTH (lbs/100 ft^2)
1	---	---	---	---
2	60	12.0	540	304
3	111	10.9	230	296
4	174	11.0	310	295
5	207	11.2	190	>320
6	240	10.9	170	284
7	273	10.7	180	237
8	306	10.9	285	254
9	339	10.5	190	288
10	372	10.9	245	272
11	405	11.1	280	220
12	438	11.1	255	222
13	471	11.1	301	292
14	504	11.1	300	230
15	537	11.0	490	292
16	570	11.0	225	217
17	603	10.9	240	236
18	636	11.3	650	>320
19	609	11.4	750	---
20	702	11.5	2100	---
21	719	10.9	4700	---
22	725	10.7	890	---
23	731	11.3	7000	---

Average mud weight using all samples - 11.1

Shear strength averaged for samples 3 through 17 - 260 lbs/100 ft^2

Average gel strength of samples 3 through 17 - 267 lbs/100 ft^2

settling was responsible for the density variation, then a regular increase in density from the top of the column to the bottom of the column would have been expected. This phenomenon was not observed.

The data presented in Figure 4 demonstrate that the long-term extrapolation of the short-term laboratory and field data is reliable for the clay-based mud systems. Currently available data do not indicate that the behavior of these mud systems over an extended time period should be anything other than what the current extrapolation of mud properties would indicate. In fact, all current data suggest that the use of the short-term measured properties of a clay, water-based mud system will provide a conservative long-term prediction of the actual mud properties.

Two important points remain to be discussed. First, all samples flowed from the collection tubing in the field except for the samples isolated in the last three pup joints. The shear strength of the last three samples ranged between 890 and 7000 lbs/100 ft^2. When these three samples were placed in 5 gallon pails in the laboratory, they showed the properties of a fluid, since they slowly flowed into the bottom of the pail rather than retaining the shape of tubing. Second, it was evident that a large amount of drill solids had settled to the 700 foot range, since large fragments of drill cuttings could be felt in the mud samples below this depth. The bottom samples felt gritty, while samples taken above this point did not have a gritty texture.

The first observation discussed in the previous paragraph shows that the mud removed from the hole remained fluid, demonstrating the ability of this mud to transmit hydrostatic pressure. This was true even for samples with 2000 to 7000 lbs/100 ft^2 shear strengths. Since the average density remained approximately 11 lb/gal, it was evident that the hydrostatic forces associated with the original mud were not altered. The second observation correlates with past observations in the oil field. Basically, some drilled solids, and potentially some barite will settle upon standing. However, the settling of these solids is not sufficient to cause a major change in the average mud density, although they will contribute to a significant increase in gel strength in the region where solids finally settle. The final settling point may not necessarily be the bottom of the hole.

<u>Sample Collection</u>

The samples from the reentered well were obtained by forcing 2-7/8 inch tubing into the well with a special coring device attached to the driving edge of the tubing. From a depth of 120 feet to approximately 740 feet, the tubing had to be pushed into the wellbore, because the tubing weight alone did not apply enough force to move the tubing through the mud. At a depth of approximately 740 feet, the tubing could no longer be pushed into the wellbore. The tubing was pulled from the well at that point, and the mud in each joint was allowed to flow into a 5 gallon plastic pail which was quickly sealed. The bottom three pup joints, each 6 feet in length, were sealed for shipment back to the laboratory because the mud in these joints did not flow easily from the tubing. From ±740 feet to ±1100 feet, the mud could not be cored using the above techniques, and it was therefore necessary to drill and circulate the remaining drilling fluid out of the hole.

Conclusions

The 29 year old mud properties measured in this study support the expectations associated with extrapolating short-term mud properties over an extended period of time. Mud density remained essentially unaltered, gel strength exceeded 100 lbs/100 ft^2, and, even for the most highly gelled samples, the mud remained fluid. This last property is extremely important since it supports the concept that formation stresses can be transmitted through the drilling fluid column over extended periods of time. All evidence gathered to date indicates clay, water-based drilling fluids provide adequate protection against vertical fluid migration over a 10,000 year time period.

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The Effect of Temperature on the Flow Properties of Clay Water Drilling Muds

TECHNICAL NOTE 2025

The Effect of Temperature on the Flow Properties of Clay-Water Drilling Muds

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INTRODUCTION

In the past few years the hydraulic aspects of rotary drilling have received considerable attention. It is generally recognized that accurate prediction of circulating pressures is desirable, particularly in those areas where a delicate pressure balance is necessary to prevent both blowouts and lost circulation. For calculation purposes the standard hydraulic equations for the pipeline flow of Newtonian fluids have been altered to facilitate similar calculations for non-Newtonian or plastic fluids.[1,2] This latter classification includes most colloidal types of drilling muds.

Two properties: plastic viscosity, μ_p, and Bingham yield value, Y_B, are commonly used to define the flow characteristics of a plastic fluid. These are commonly obtained with multispeed viscosimeters such as the Fann V-G meter.[3] Normally these measurements are obtained at some surface temperature, and are not corrected to circulating temperatures for calculation purposes. This may result in considerable error, particularly in the laminar flow calculations which commonly apply to the drill pipe-borehole annulus. The purpose of this study was to investigate the effect of temperature on the flow properties of some water-base muds.

EXPERIMENTAL PROCEDURE

A laboratory model Fann V-G meter was used for measurement of viscosities, yield values and gel strengths. An aluminum water jacket with O-ring seals was machined to fit around the mud cup of the Fann meter.

All mud samples were prepared by thorough mixing in a Hobart mixer. Viscosity and gel strength measurements were made with the Fann meter using standard procedures. Flow properties of muds were studied at 80, 120, 160 and 180°F.

The compositions of the test samples are given in Table 1.

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**Currently studying for PhD as a graduate fellow at Pennsylvania State U., State College, Pa.
[1]References given at end of paper.

SPE 975-G

RESULTS

EFFECT OF TEMPERATURE ON FLOW PROPERTIES

The typical effect of temperature on the flow properties of these drilling muds is illustrated by Fig. 1. It was found that plastic viscosity and apparent viscosity decreased with an increase of temperature. However, the curves were not linear, and did not appear to follow any definite trends or patterns. Yield point data showed much more scattering.[4]

Since a usable method for predicting drilling mud flow behavior with temperature was desired, an attempt was made to find a simple relationship between these variables. The basic approach used by Havenaar[5] for predicting the same effect on turbulent viscosity resulted in Fig. 2, which shows that

TABLE 1—COMPOSITION OF MUD SAMPLES TESTED

Sample No.	Composition
32	8 per cent bentonite mud
34	3 per cent bentonite mud
35	4 per cent bentonite mud
36	8 per cent bentonite mud
39	10 lb/gal, 4 per cent bentonite, barite mud
42	15 lb/gal, 4 per cent bentonite, barite mud
43	10 lb/gal, 10 per cent (by volume) diesel oil, 4 per cent bentonite, barite emulsion mud
45	15 lb/gal, 10 per cent (by volume) diesel oil, 4 per cent bentonite, barite emulsion mud
47	10 lb/gal, 4 per cent bentonite, barite, surfactant (DMS) mud
48	15 lb/gal, 4 per cent bentonite, barite, surfactant (DMS) mud
49	10 lb/gal, low lime treated (1 lb/bbl), 4 per cent bentonite, barite mud
50	15 lb/gal, low lime treated (1 lb/bbl), 4 per cent bentonite, barite mud
51	8 per cent bentonite mud

Note: All mud samples referred to are water-base muds; per cents are by weight unless otherwise specified.

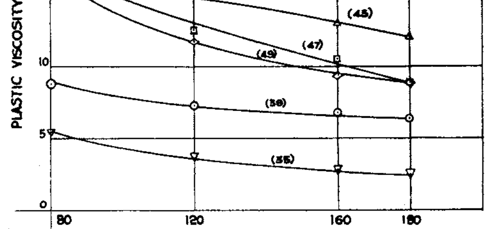

FIG. 1—PLASTIC VISCOSITY VS TEMPERATURE.

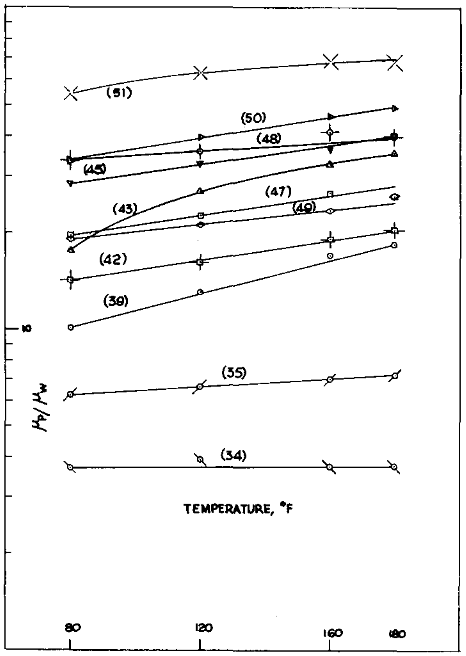

FIG. 2—μ_p/μ_w VS TEMPERATURE.

$$\log \frac{\mu_p}{\mu_w} = a + bT \quad , \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where μ_p is plastic viscosity of mud at temperature, T; μ_w is water viscosity at same temperature, T; a,b are intercept and slope of line, respectively; and T is temperature, °F.

All muds tested fit this relationship closely except the emulsion mud (No. 43). Its deviation was probably due to changes in emulsion quality which would not have occurred in a completely stabilized system. A similar plot of apparent (600 rpm) viscosity is shown in Fig. 3.

These observations make it possible to predict the flow properties (μ_p and Y_B) of these or similar muds at common borehole temperatures; if they are known at two lower temperatures. Data from this study indicate that this relationship is valid to at least 200°F. Yield values may be calculated from plastic and apparent viscosity values using the following relationship.

$$Y_B = 2\ (\mu_a - \mu_p) \ , \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where Y_B is Bingham yield value, lb/100 ft^2; and μ_a, μ_p are apparent and plastic viscosities of the mud in question at the desired temperature, cp.

Knowledge of flow property behavior to 200°F will cover pressure drop predictions in wells as deep as 15,000 ft in the Gulf Coast area. This assumes that the average flow temperature in the annulus is approximated by the arithmetic average of bottom-hole circulating and discharge temperatures. Data on down-hole circulating temperatures are available in API RP-10B, or from a convenient curve prepared by Smith.[6]

EFFECT OF TEMPERATURE ON GEL STRENGTH

Gel strength behavior is shown in Fig. 4. As expected, each mud had its own characteristic behavior and no correlation was attempted.

CONCLUSION

Flow property variation with temperature to 200°F of clay-water muds may be predicted by the method presented in this paper. This of course does not apply to other systems which might undergo appreciable chemical alteration at the temperatures in question.

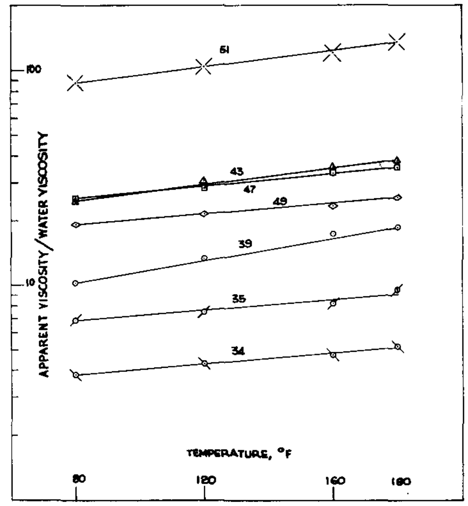

FIG. 3—APPARENT VISCOSITY/VISCOSITY OF WATER VS TEMPERATURE.

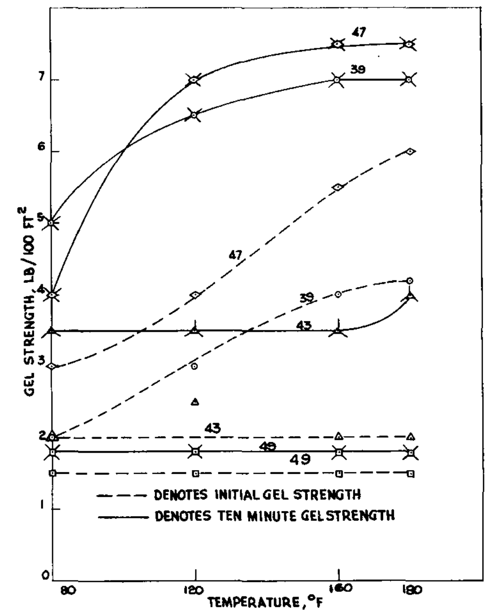

FIG. 4—GEL STRENGTH VS TEMPERATURE FOR DIFFERENT MUDS.

ACKNOWLEDGMENTS

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★★★

Understanding the Temperature Effect on the Rheology of Water Bentonite Suspensions

Understanding the Temperature Effect on the Rheology of Water-Bentonite Suspensions

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ABSTRACT

A successful drilling operation is heavily dependent on the effectiveness of the drilling fluid in use. Exploration of new hydrocarbon fields in complex subsurface environments under high pressure and high temperature (HPHT) conditions, requires the development and use of exceptional drilling fluids, which maintain their rheological properties even at such hostile environments. Drilling fluids are complex, non-Newtonian systems and bentonite is a key component for their formulation. The understanding of its physico-chemical properties that is related to different clay particle linking processes, can lead to the development of "smarter" and more effective drilling fluid systems. This work examines the effect of temperature on the rheological behavior of aqueous bentonite suspensions by performing extensive rheological analysis which can contribute to the understanding of the interfacial and surface phenomena that take place, as well as the modes of interaction between bentonite particles in an aqueous environment.

INTRODUCTION

Clay materials are widely used in several industries such as oil and gas, pharmaceutical and cosmetics, food, agriculture and ceramics. Bentonite is an aluminium phyllosilicate clay consisting mostly of montmorillonite and is a key component for drilling applications. It is mainly used to control the rheological and filtration properties in water-based fluid systems. Due to its high swelling capacity, it provides exceptional flow capabilities by forming a gel-like structure, which is responsible for the yield stress of the suspension giving superior cuttings suspension when circulation of the drilling fluid is stopped. However, montmorillonite clay begins to chemically break down at temperatures higher than 121°C[1], thus restricting its application for HPHT wells without the use of high temperature additives.

In drilling a well, it is essential to know the effect of temperature on the rheological properties of the drilling fluid at operational conditions[2]. The successful prediction of frictional pressure drops is dependent on an accurate knowledge of the drilling fluid rheology[3]. As the fluids travel around the wellbore, their rheological profile is undergoing significant alterations. This can be attributed to the HPHT downhole conditions encountered, which can cause the degradation of the drilling fluid additives as well as to the chemical modification of the fluid when it comes in contact with other formations on its way to the surface[4].

The combination of temperature, pressure, time- and shear- history dependence of the rheological properties makes the characterization and forecasting of drilling fluids rheological profile more complicated. Good knowledge of the synergistic interaction of different drilling fluid additives, can lead to the development of "smarter" drilling fluid systems with optimal and made-to-order rheological properties[5]. In our preceding studies[6,7], we used water-bentonite suspensions as the base fluid for the formulation of complex drilling fluid systems, giving superior rheological and filtration characteristics. The different additives used each time necessitate a deep understanding of their strengths and limitations in order to control the rheology of the fluid and subsequently the drilling operations performance.

Yet, despite some studies that were carried out over the previous years[2,8,9], which have tried to understand the temperature effect on the rheological properties of aqueous bentonite suspensions, there is still a lot of room for a deeper understanding of the temperature dependence of the flow properties and especially of the contribution of microstructure mechanisms.

This paper presents data showing the effect of temperature (up to 70°C) at atmospheric pressure on the rheological properties of water-bentonite suspensions. The experimental results point out that there is a complex particle to particle interaction at ambient temperature which is enhanced at higher temperatures and that the produced suspensions have reversible thermal/shear history characteristics. Numerous physico-chemical analysis techniques were employed to reveal this phenomenon in order to examine such complex inter-particle structures.

EXPERIMENTAL

Materials and Sample Preparation

The bentonite (Aquagel-Gold Seal) was supplied by Halliburton in powder form with specific gravity 2.6 and without any polymer additives, according to vendor specifications. It is tan in colour with a pH range 8-10.

X-Ray Diffraction (XRD) and X-Ray Fluorescence (XRF) analysis were employed to reveal its mineralogical and chemical composition, respectively. XRD analysis was carried out using a Rigaku Ultima IV multipurpose X-ray diffractometer. XRD pattern was collected at 2theta (2θ) angle from 3 to 80 degrees with a sampling width of 0.01 degree and scanning speed of 0.5 degree/minute, and was analysed using the Rigaku PDXL2 analysis software. The elemental analysis of the Bentonite powder was carried out using a Rigaku ZSX Primuss II wavelength dispersive X-ray Fluorescence (XRF) spectrometer (WD-XRD). The powder sample was loaded on an aluminium cup and a pellet is prepared using 20T power press without adding any binder.

A Beckman Coulter Laser Scattering Particle Size Analyzer with dry-powder module was used to study particle size distribution of the bentonite powder.

Finally, a FEI QUANTA 400 Environmental Scanning Electron Microscope (SEM) equipped with EDAX Apollo Energy Dispersive X-ray Spectroscopy (EDS) system, was used for surface structure and chemical analysis, respectively. For SEM analysis, the samples were coated with gold using a Leica EM SCD050 coating machine.

Bentonite (45.16 g) was added to 600 ml of de-ionized water to give us 7.0 wt.% suspension with pH range 7.8-8.2, and mixed at 11000 rpm in a Hamilton Beach mixer for 20 min in order to create the samples. The samples were prepared according to American Petroleum Institute (API) procedures[10,11]. The suspension was left to hydrate for 16 h in plastic containers. All rheological measurements for all tested samples were taken one day after the initial preparation of the samples. Before making the rheological measurements the samples were stirred for five minutes in the Hamilton Beach mixer in order to achieve the same shear history for each sample[10]. The preparation and measurement protocols for each sample was followed strictly, in order to ensure consistency and to minimize any biases of our results.

Rheological Measurements

The impact of temperature on the rheological profiles of the water-bentonite suspensions (7 wt.%) was examined at various temperatures (25-70°C) and ambient pressure using a Couette type viscometer (Grace M3600). Viscometric data were obtained at fixed speeds of 600, 300, 200, 100, 60, 30, 6, 3 rpm, which give Newtonian shear rates of 1021.38, 510.67, 340.46, 170.23, 102.14, 51.069, 10.21 and 5.11 s^{-1}, respectively[12]. The yield stress is estimated from the obtained rheograms after extrapolating the shear stress – shear rate curve to zero shear rate and fitting an appropriate rheological model. The readings were taken from high to low speeds, while rotation lasted for 60s at each rotational speed, with readings being recorded every 10s, thus giving six measurements for each rotational speed with a total duration of 8 min per cycle. These six values were averaged and recorded. The rheological parameter estimation was done according to the Herschel-Bulkley (HB) model, given by Eq. 1:

$$\tau = \tau_{HB} + K(\dot{\gamma})^n \qquad (1)$$

which uses three rheological parameters, the Herschel-Bulkley yield stress (τ_{HB}), the flow consistency index (K), which is an indication of viscosity, and the flow behaviour index (n). The Herschel-Bulkley rheological model has proven to give the most accurate fitting results for water-bentonite suspensions used in these experiments.

Methodology

The rheological measurements of the water-bentonite suspensions were performed in the rotational viscometer, which was connected to a circulating water bath being able to maintain temperature with an accuracy of ±0.5˚C. The water bath allowed the water to circulate around the viscometer cup, while the viscometer would run the experiment. The range of the tested temperatures was 25˚C-70˚C. Preceding each test, we started the circulating water bath and waited until the desired temperature was reached. The gradual increase of temperature, was performed with a rate of 1˚C/min. Once the desired temperature was achieved, the sample was stirred for 5 min using a mechanical stirrer (Hamilton Beach) prior to each measurement, in order to achieve the same shear history. Then, the sample was placed into the measuring cup and the experiment started immediately, with an initial step of 200s at 600rpm, before any values to be recorded. This step was added in the experimental procedure in order to achieve a temperature equilibration of the sample. The temperature of the experiments was monitored by a temperature sensor embedded into the viscometer cup. Before starting the experiment the exact temperature of the sample inside the viscometer cup was measured with an external thermometer in order to double check temperature accuracy. When a test was done, the tested sample was transferred to the closed container and the measurements with the same procedures were repeated for other temperatures.

Three sets of experiments were carried out with 5 samples in total. In particular:

a) 2 samples (S1 and S2) were measured at a continuous temperature cycle (25˚C→40 ˚C→60 ˚C→70 ˚C), referred as continuous samples.

b) 2 samples (S3 and S4) were measured directly at 40˚C and 60˚C, those being referred as direct samples.

c) 1 sample (S5) was measured at 25˚C after natural aging for 1, 30 and 60 days.

RESULTS AND DISCUSSION

Physico-Chemical Analysis of Bentonite

XRD analysis of the raw bentonite powder is shown in Figure 1. The major mineralogical component of the bentonite is montmorillonite, an absorbent aluminium phyllosilicate clay. Other bentonite clay species such as illite and a small amount of Quartz are also present as minor phases.

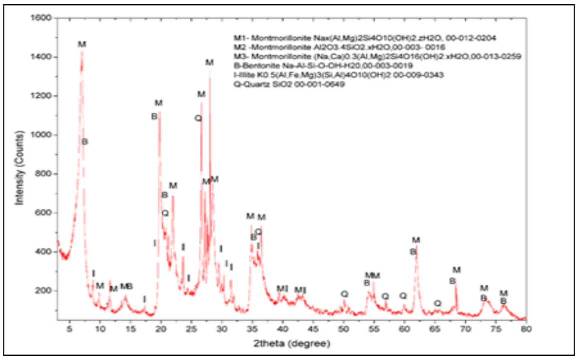

Figure 1. X-Ray Diffraction (XRD) analysis of bentonite.

XRF elemental analysis revealed that the main elements in the powder are Si, Al, Fe, Na, Mg and Ca, which are in accordance with the chemical composition of bentonite clays and quartz, identified by the XRD analysis (Fig. 1). The weight percentage of the major elements are reported in Table 1.

Table 1. X-Ray Fluorescence (XRF) elemental analysis (%) of bentonite.

SiO_2	Al_2O_3	Fe_2O_3	Na_2O	MgO	CaO
65.30	20.30	5.75	2.38	2.24	1.30

Particle Size Analysis (PSA), showed that the mean particle size of the bentonite is 36μm (Fig. 2). This is in agreement with the observed particle size from the SEM analysis (Fig. 3).

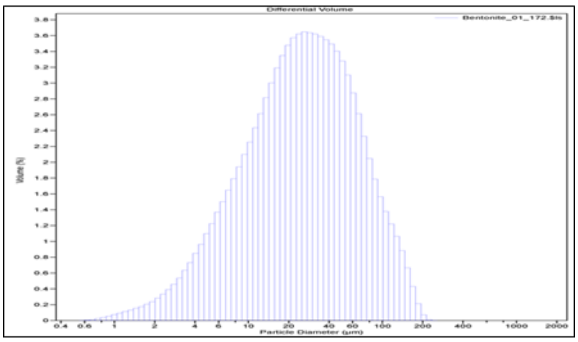

Figure 2. Particle Size Analysis of bentonite powder.

We compare SEM images at 100μm, while insets are taken at 40μm of the same sample, from suspensions at 25˚C (Fig. 3a), then directly to 40˚C (Fig. 3b) and 60˚C (Fig. 3c) and raw bentonite powder at 20μm (Fig. 3d). Similarities and differences for their size and morphology are evident when comparing the suspensions with SEM. The main conclusion that can be drawn from Fig. 3, is that the suspensions have a smoother uniform surface and better dispersion compared to other samples. At higher temperatures (40˚C and 60˚C), the surfaces of samples became rougher with higher concentrations of porous muffin-shaped particles on their surfaces. This morphology can probably affect their rheological characteristics, which requires further investigation in order to gain a deeper understanding. Higher magnification (Fig. 3d), reveals the particle size of the bentonite, probably being composed of single platelets with an average length of 20μm. The EDS elemental analysis of the bentonite powder (Fig. 4) shows the presence of major elements such as Si, Al, Na, Mg, K, Ca, and confirms the results obtained from XRF (Table 1).

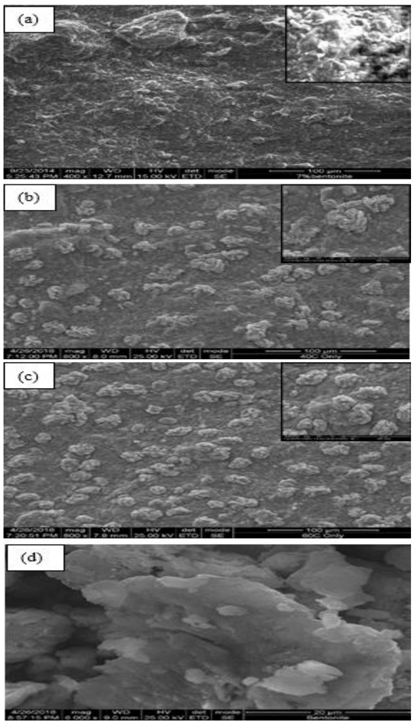

Figure 3. SEM images at 100μm and insets at 40μm, from top to bottom: a) water-bentonite suspension at 25˚C, b) water-bentonite suspension tested directly at 40˚C, c) water-bentonite suspension tested directly at 60˚C and d) bentonite powder at 20μm.

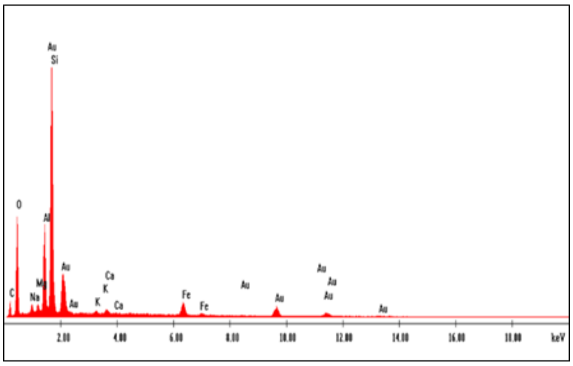

Figure 4. Energy Dispersive X-Ray Spectroscopy (EDS) analysis of raw bentonite powder.

Rheological Analysis

It is apparent from the rheograms in Fig. 5 and 6, that the samples of water-bentonite suspensions which were tested continuously (S1 and S2), are highly sensitive at all tested temperatures. The two samples display similar rheological behaviour with maximum shear stress differences ±5%. The fluids exhibit a yield stress, followed by a shear thinning behaviour with higher shear stress values for increased temperatures. Furthermore, there are larger differences of the stress values at ambient temperature at lower shear rates compared to higher shear rates. More specifically, at low shear rates (5.1-170 s^{-1}) both S1 and S2 samples, have almost doubled their shear stress values at all tested temperatures, while at high shear rates (510.69 and 1021.38 s^{-1}) the maximum difference in the obtained stress values is ±10%. Fig.6 shows the rheogram of S2 sample, which tested back to 25˚C after a continuous testing at 25˚C, 40˚C and 60˚C. One can observe an interesting trend here. At high shear rates, stress values increased by an average of 40% compared to the initial values obtained at 25˚C, while at 6 and 3 rpm the stress values are similar to those obtained at 25˚C, giving a similar yield stress value as shown later. This can be plausibly attributed to the microstructural network and gel-like structure of bentonite suspensions, which is broken at higher shear rates, while becomes stronger at lower shear rates, giving rise to the build-up of an interconnected network structure in the aqueous suspension. Van Olphen[13], reported that gelation of bentonite particles is mainly governed by electrical forces and as shear rate is decreased these electrical interactions play a more prominent role and affect the rheological properties to a greater extent.

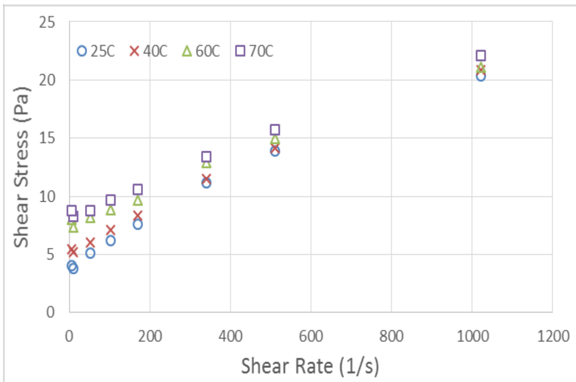

Figure 5. Rheograms of 7 wt% water-bentonite suspensions at different temperatures (S1).

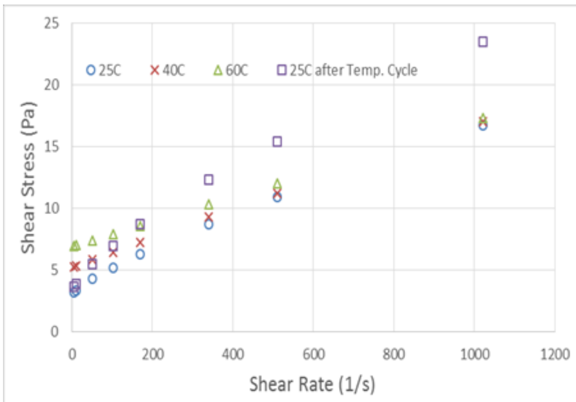

Figure 6. Rheograms of 7 wt% water-bentonite suspensions at different temperatures (S2).

Fig. 7 and 8 compare the apparent viscosity of the suspensions (S1 and S2) at the different tested temperatures (25˚C-70˚C). It can be seen that higher temperatures cause an increase of the viscosity at all shear rates, for both S1 and S2 with shear thinning characteristics. This is in contrast to the base fluid (water) behaviour, where high temperatures cause a decrease in viscosity values. A possible explanation for this behaviour is that exposure of the suspensions at higher temperatures has caused a better dispersion of the bentonite, therefore increasing the number of individual platelets in suspension. Our results are in good agreement with these presented by Annis[2], who observed a significant increase in the viscosity for higher temperatures and argued that high shear rate viscosities are mainly due to mechanical interaction of the solids and the liquid. The low shear rate viscosities are greater than the viscosity at higher shear rates and this difference becomes greater as temperature increases[14]. This can be possibly attributed to the fact that particle aggregates were broken down into smaller flow units by the applied forces, leading to lower viscosity values at higher shear rates. Under high shear rates the fluid is not able to build a strong inter-particle network which arises from the gelation of water-bentonite suspensions upon exposure at high temperatures. The S2 (Fig. 8) was tested back to 25˚C, after a continuous testing from 25˚C to 60˚C, showing that apparent viscosity was not significantly affected when exposed to a higher temperature (60˚C), with a maximum of 5% changes at higher shear rates and 15% at lower rates.

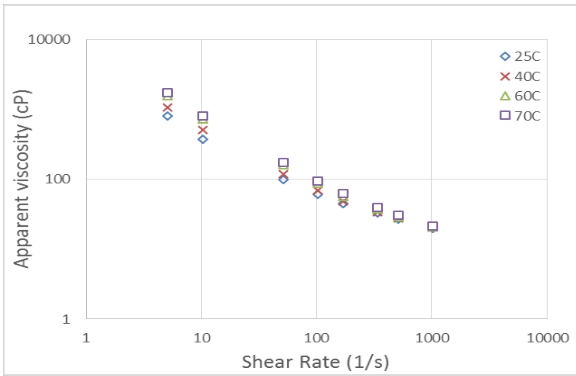

Figure 7. Apparent viscosity of 7 wt% water-bentonite suspensions as a function of shear rate at different temperatures (S1).

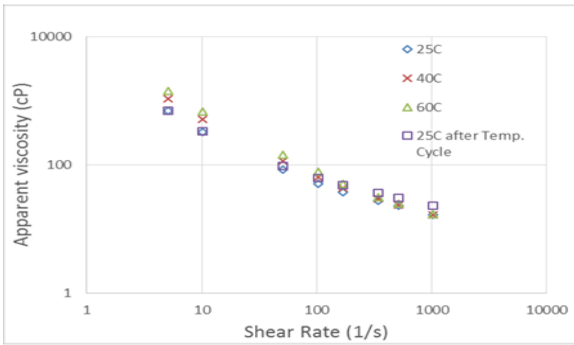

Figure 8. Apparent viscosity of 7 wt% water-bentonite suspensions as a function of shear rate at different temperatures (S2).

Tables 2 and 3, give the rheological Herschel-Bulkley (HB) parameters at different temperatures for the S1 and S2 samples. It can be clearly seen that there is an excellent fit of the HB model because of the very high regression coefficient (R^2) values and the very small variation of the sum of square errors (ΣQ^2) achieved, with R^2 to be higher than 0.99 in all cases and the range of ΣQ^2 between 0.35–1.43 Pa^2.

Table 2. Herschel-Bulkley Model parameters fitted at different temperatures for 7 wt% water-bentonite suspensions (S1).

Temperature (°C)	Herschel-Bulkley Model				
	τ_o (Pa)	K (Pa·s^n)	n	R^2	ΣQ^2 (Pa)^2
25	3.38	0.097	0.747	0.9990	0.45

40	4.92	0.050	0.833	0.9992	0.35
60	7.36	0.026	0.907	0.9972	0.88
70	8.19	0.022	0.931	0.9985	0.47

Table 3. Herschel-Bulkley (HB) Model parameters fitted at different temperatures for 7 wt% water-bentonite suspensions (S2).

	Herschel-Bulkley Model				
Temperature (°C)	τ_o (Pa)	K (Pa·s^n)	n	R^2	$\sum Q^2$ (Pa)^2
25	3.04	0.053	0.802	0.9973	1.43
40	5.18	0.015	0.963	0.9967	1.43
60	6.92	0.009	1.017	0.9973	0.82
25*	3.19	0.130	0.728	0.9993	1.14

*Rheological analysis at 25˚C after a full temperature cycle (25˚C-60˚C).

Fig. 9 presents a comparison of the HB yield stress values over a range of temperatures (25˚C – 70˚C) for S1 and S2 samples. Determining a trend of the yield stress development across elevated temperatures is of great importance, especially in drilling operations, in order to understand the complex fluid flow properties and optimize cuttings transport efficiency. The existence of yield stress is related to the Van der Waals forces, which promote the formation of flocs that provoke a resistance to flow. In water-bentonite suspensions higher temperatures cause the flocculation and dispersion of the bentonite platelets. Yield stress values increase with temperature for both samples. The first sample (S1) showed an almost linear increase with 3.38 Pa at 25˚C, 7.36 Pa at 60˚C and 8.19 Pa at 70˚C. This represents a change of 118% and 142%, respectively. The second sample (S2) presented an increase in the yield stress values at the tested temperatures from 3.04 Pa at 25˚C to 6.92 Pa at 60˚C (127% change). The values of the yield stress for the two samples are very close with a maximum deviation of ± 5% until 60˚C. As the temperature increases, the bentonite flocculates giving rise to the formation of edge-to-edge or edge-to-face associations, thus giving higher yield stress and viscosity values[2]. It can also be seen that the change in yield stress after the end of the continuous temperature cycle is small, with values of 3.04 Pa and 3.19 Pa before and after the temperature cycle, respectively. This proves the reversibility of the produced suspension (S2), which regains its original yield stress value after an exposure at 60˚C with small variations of ±10%, in its viscosity values (Fig. 8).

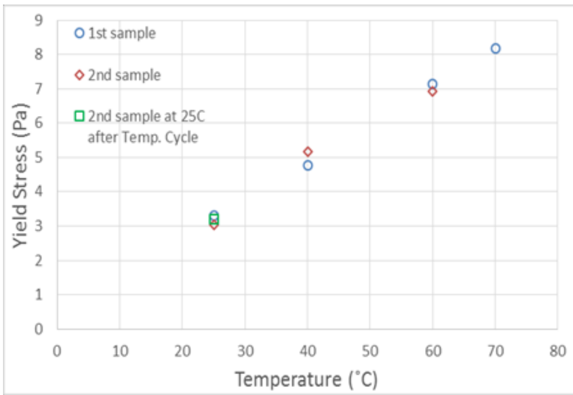

Figure 9. Comparison of yield stress for the tested samples (S1 and S2) at different temperatures.

Fig. 10 presents the variation of flow consistency (K) and flow behaviour (n) index across a temperature range of 25˚C - 70˚C, for the S1 sample. Analysis for the S2 sample is not presented graphically for clarity purposes, however the detailed values can be seen in Table 3. One can observe the decrease in K as the temperature increases, which probably represents the decrease of water viscosity. The flow behaviour index (n) showed an increase which dictates that the fluids tend to the Newtonian behaviour at high shear rates, which can also be observed when looking at the slope of the rheograms at high shear rates (Fig. 5 and Fig. 6).

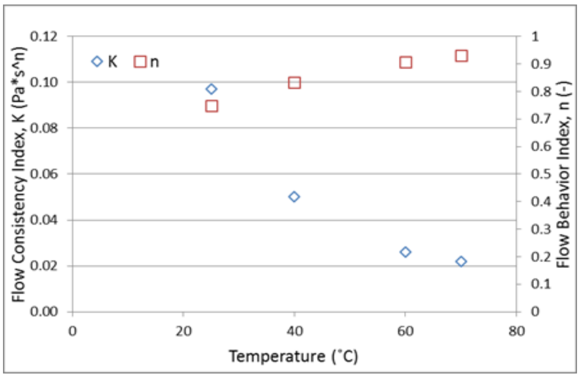

Figure 10. Variation of Herschel-Bulkley flow consistency (K) and flow behaviour (n) index with temperature for the S1 sample.

Another interesting issue is the effect of temperature in the produced suspensions under varying conditions (time, temperature) of exposure. For this reason, two new samples (S3 and S4) were prepared, and tested directly to 40˚C and 60˚C. From Fig. 11 and Table 4, it can be observed that the samples which were tested directly at 40˚C and 60˚C showed lower yield stress values than these of the continuous cycle (25˚C-60˚C), with an average decrease of 30%. This difference is larger as the temperature increases, which reveals the great impact of temperature history profile on their rheological characteristics. Alderman et al.[9], reported that the rheological properties of clay suspensions are extremely time, temperature and shear-history dependent.

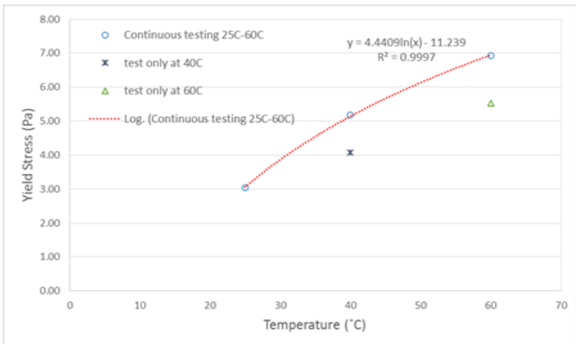

Figure 11. Comparison of yield stress values of the S2 with samples that tested directly to 40˚C and 60˚C.

Table 4. Herschel-Bulkley (HB) Model parameters fitted for samples directly measured at 40˚C and 60˚C (S3 and S4).

Temperature (°C)	Herschel-Bulkley Model				
	τ_o (Pa)	K (Pa·s^n)	n	R^2	$\sum Q^2$ (Pa)^2
Only 40˚C	4.07	0.024	0.884	0.9963	1.29
Only 60˚C	5.54	0.007	1.037	0.9949	1.44

The rheological stability of the produced suspensions under different aging time was evaluated by testing a new sample (S5) at fresh conditions (1 day), after 30 days and after 60 days at 25˚C. Table 5 and Fig. 12 present the variation of the HB parameters and the rheogram, respectively. It is observed that there is a small increase in the yield stress after 30 and 60 days with a value of 3.69 Pa and 3.76 Pa, respectively, compared to its initial value of 3.41 Pa. This can be attributed to the formation of a stronger particle network due to an enhanced clay platelet dispersion over time. The variations in K and n are small, while R^2 is higher than 0.99 in all cases. Our results indicate that the prepared suspensions were rheologically stable with minor rheological changes after 60 days of natural aging.

Table 5. Herschel-Bulkley (HB) Model parameters fitted for the S5 sample at 25˚C after a) 1 day b) 30 days and c) 60 days.

25˚C	Herschel-Bulkley Model				
Aging (days)	τ_o (Pa)	K (Pa·s^n)	n	R^2	$\sum Q^2$ (Pa)^2
1	3.41	0.083	0.770	0.9992	0.74
30	3.69	0.095	0.754	0.9985	1.42
60	3.76	0.093	0.759	0.9983	1.73

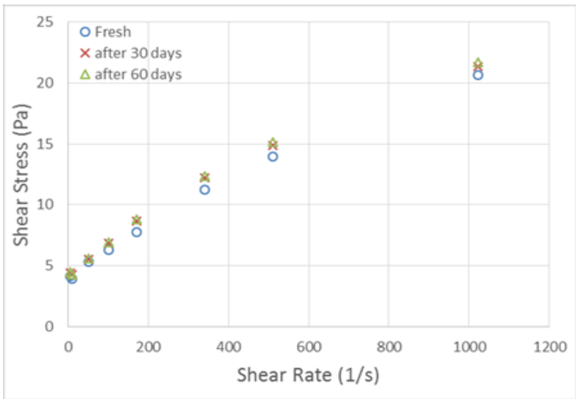

Figure 12. Rheograms of the S5 sample at 25˚C for a) fresh conditions, b) after 30 days and c) after 60 days.

CONCLUSIONS

In the present study, we investigated the impact of temperature on the rheological profile of the water-bentonite suspensions (7 wt.%) at various temperatures (25-70°C) and ambient pressure. A comprehensive physico-chemical characterization of the bentonite was presented using XRD, XRF and SEM analysis and coupled with rheological data in order to reveal microstructural qualities affecting the suspensions rheological properties. SEM images of the suspensions after different exposure temperatures, revealed that the association of the particles in different configurations plays a critical role in their rheological profile. The prepared water-bentonite suspensions were examined for their rheological characteristics over a shear-rate range of 5 to 1021 s^{-1} and exhibited a yield stress followed by a shear thinning behaviour, which tends to become Newtonian at higher temperatures. The three parameter Herschel-Bulkley model was proved to have an excellent fit of the experimentally derived data. Yield stress and viscosity become increasingly sensitive to temperature, as temperature increases. Higher yield stress and viscosity values were obtained for higher temperatures, which can be attributed to the flocculation of bentonite particles. High-shear viscosities are less sensitive to temperature variations, which can be due to the gel-like structure of water-bentonite suspensions, which breaks at higher shear-rates, while they form a strong microstructural network at lower shear rates. The temperature history profile has a great impact on rheological characteristics of the suspensions, which proved to be rheologically stable after an aging period of 30 and 60 days with minor changes in their rheological properties measured at 25˚C. It has been shown that by using standard sample preparation and measuring procedures, it is possible to achieve reproducible data for the temperature dependence shear rheology behaviour of water-bentonite suspensions. Further investigations are already under way in order to elucidate the complex inter-particle interactions which govern the rheological behaviour of water-bentonite suspensions at higher temperatures[15].

ACKNOWLEDGMENTS

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ABANDONED OIL AND GAS INDUSTRY WELLS AND THEIR ENVIRONMENTAL IMPLICATIONS

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ABANDONED OIL AND GAS INDUSTRY WELLS AND THEIR ENVIRONMENTAL IMPLICATIONS

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Washington, D.C.

February 1988

CONTENTS

ABANDONED OIL AND GAS INDUSTRY WELLS AND THEIR ENVIRONMENTAL IMPLICATIONS

FIGURES

I. SUMMARY AND CONCLUSIONS

Many thousands of wells have been drilled and abandoned during the 130 year history of the U.S. petroleum industry. Regulations for plugging of such wells were nonexistent in the early days of the industry and have evolved, over the years, to their present effective level. Thus, an unknown but large number of abandoned wells exist that are unplugged or inadequately plugged by today's standards.

As a result of incidents in which abandoned wells have been implicated as sources of ground water contamination, such wells are often considered, without discrimination among them, to be potential pathways for contamination of an underground source of drinking water (USDW). Such contamination can result from interaquifer flow of natural formation water or by transmission of injected fluids from the injection reservoir to an USDW.

In fact, the relative contamination potential of such wells ranges from highly likely to impossible, depending on a complex set of geologic and hydrologic circumstances. The relative contamination potential of an abandoned well or wells in a particular geologic and hydrologic setting can be analyzed qualitatively by an understanding of the factors involved and can be quantitatively analyzed with available numerical computer models. An example of such a model analysis is given for a case where the abandoned well is judged to not be a potential source of contamination to an USDW, even in the presence of a nearby injection well.

It can be concluded that abandoned unplugged or improperly plugged wells may or may not pose a potential for contamination to underground sources of drinking water, depending on a complex set of geologic and hydrologic circumstances. Therefore, it seems reasonable that regulation of oil and gas industry activities should take into account the wide range of contamination potential of individual abandoned wells when establishing specific operating restrictions in their vicinity.

II. INTRODUCTION

During the 130 year history of the U.S. petroleum industry hundreds of thousands of oil and gas[1] exploration and production wells have been drilled, many of which are abandoned. For many years, effective requirements for the plugging of wells upon abandonment did not exist and, thus, an unknown but very large number of unplugged or inadequately plugged wells exists in the country. Such abandoned wells have been observed to be conduits by which

1. Under the Underground Injection Control regulatory programs of the U.S. EPA, petroleum industry injection wells are defined as Class II wells.

natural formation waters and, perhaps, injected fluids have migrated between subsurface formations (Figure 1) and in some cases, to the ground surface (Figure 2). This is a particular threat where injection wells are present that increase reservoir pressures and can induce such fluid movement as is shown in Figures 1 and 2.

As a result of such known or suspected incidents involving abandoned wells, some can be expected to believe that all abandoned wells pose a contamination potential to USDW's. This paper is intended to briefly outline the circumstances under which abandoned unplugged or improperly plugged wells may and, on the other hand, may not be a pathway for contamination of an USDW. The paper will show that the circumstances that determine the extent of hazard of an abandoned well are very complex and have, only recently, become subject to analysis by computer modeling. A case example of such modeling is given in which an abandoned well is analyzed and judged to not be a threat to an USDW.

III. GEOLOGY AND HYDROGEOLOGY OF OIL AND GAS PRODUCING REGIONS

A. General Geologic Frameworks

The vast majority of oil and gas production is from sequences of sedimentary rocks that occur in geologic basin areas and range in thickness from a few thousand to over 50,000 feet. Oil and gas wells that penetrate these sedimentary rocks range from several hundred to over 20,000 feet in total depth. Types of sedimentary rocks containing oil and gas include sand and sandstone, siltstone, shale, limestone, dolomite, salt, gypsum and, occasionally, other less common ones. Sand, sandstone, limestone and dolomite are commonly porous and permeable enough to act as oil and gas producing reservoir rocks whereas siltstone, shale salt and gypsum are more likely to act as cap rocks or confining beds.

The various sedimentary rock types occur in intercalated sequences, depending on the environment in which they are deposited and the nature of the supply of the depositional material. In the United States, particular geologic basins are characterized by the rock sequences that they contain. For example, the Texas-Louisiana Gulf coastal region contains principally interbedded sand-siltstone-shale, whereas various interior basins are dominated by carbonate (limestone and dolomite) rocks with occasional sandstones and shales. These consolidated to semiconsolidated oil and gas bearing rocks are from Cambrian to Tertiary in age.

In many areas, the sedimentary rocks described above are overlain by thin layers of unconsolidated gravels, sands, silts and clays of alluvial, glacial or other origin that are of Recent or Pleistocene age and are generally fresh-water bearing.

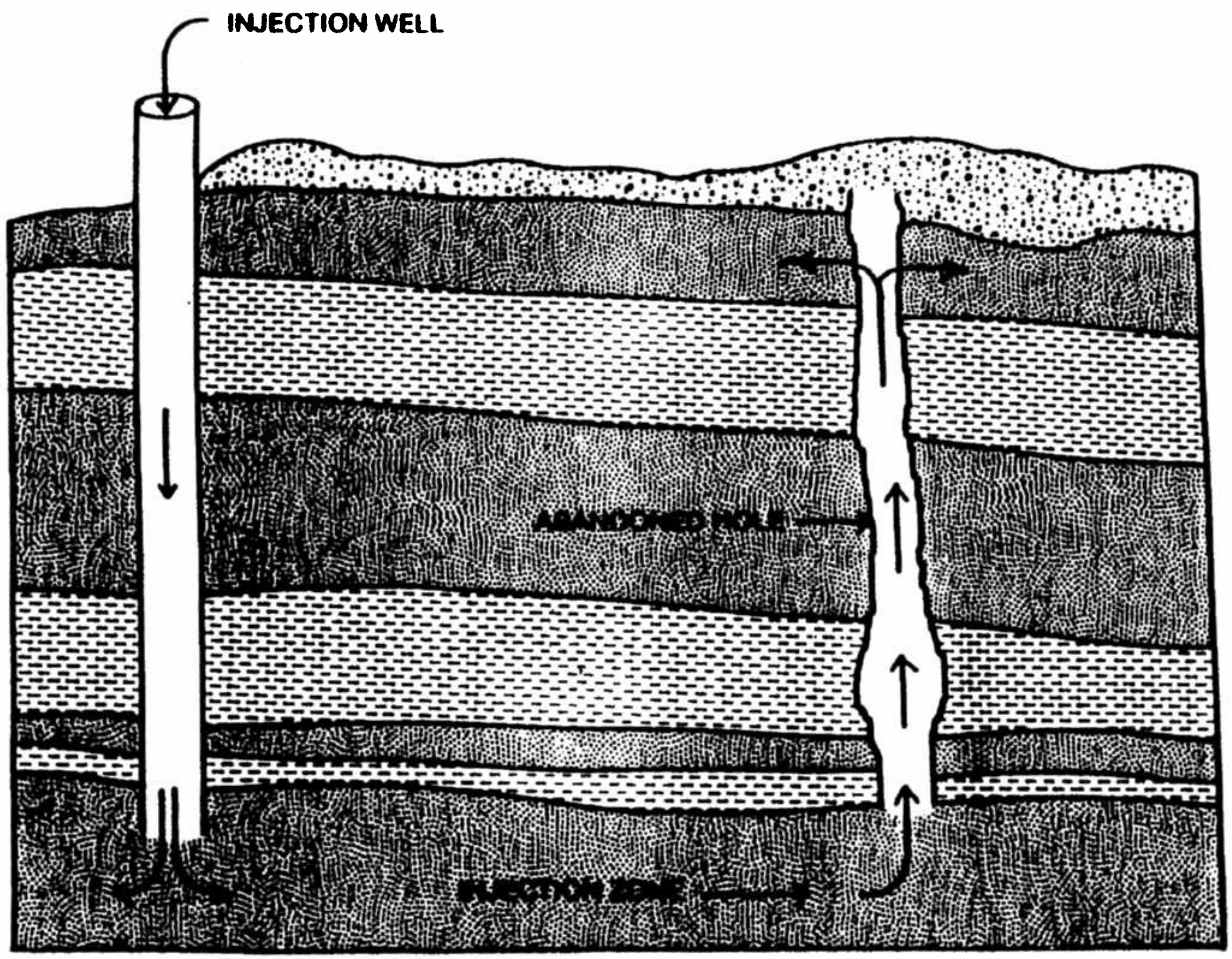


Figure 1 - Schematic diagram of interaquifer flow through the borehole of an abandoned well (Aller, 1984).

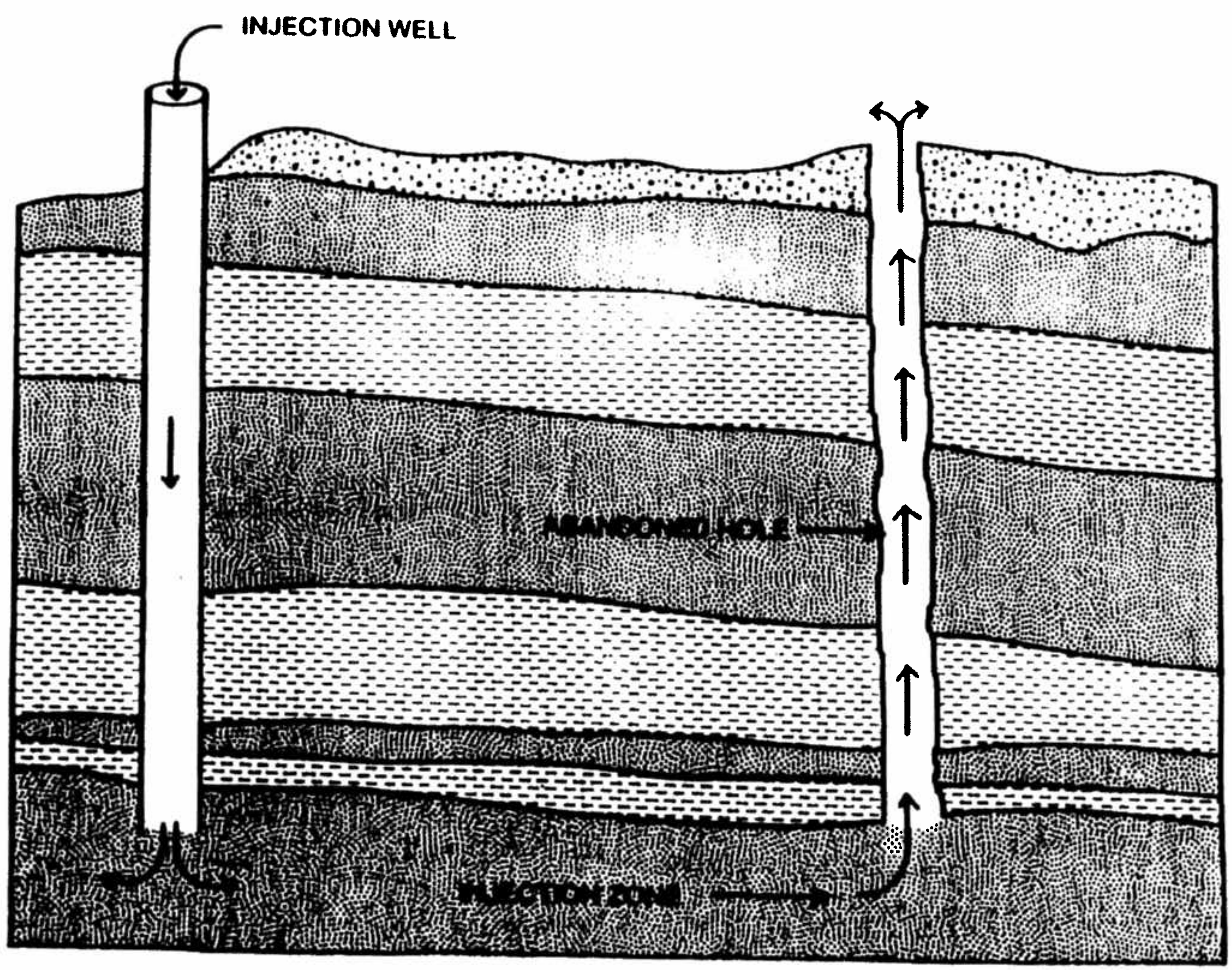


Figure 2 - Schematic diagram of flow to the ground surface through the borehole of an abandoned well (Aller, 1984).

B. Groundwater Occurrence and Movement

All soils and rocks contain water, in the subsurface. At depths of from a few feet to, at most, a few hundred feet, there is sufficient water present to completely saturate the soil or rock. The depth, at which saturation occurs is termed the ground-water table. Below that depth, all soil or rock is saturated and the contained water is termed ground water. Shallow ground water is often unconfined, that is, precipitation is able to infiltrate directly to the water table and recharge the water-containing aquifer. At greater depths, ground water becomes confined or semiconfined by the less permeable rocks in the sedimentary sequence. Oil and gas occurs and is accumulated in deep confined aquifers or reservoirs in very limited locations where structural and stratigraphic geologic conditions are favorable. All of the remaining subsurface rocks are entirely water filled.

Ground water circulates in response to the hydrologic cycle of precipitation, infiltration, recharge, ground water flow and discharge. Shallow ground water may flow relatively rapidly, as much as several feet per day, whereas very deep confined ground water may be almost stationary, flow rates being so slow as to be unmeasurable with the methodology available and in the time framework in which man operates.

In areas of relatively gentle topography, water in confined aquifers at the location of a single drilled well would rise in that well to nearly a common elevation, when adjusted for the differing density of the water in different aquifers. This condition is referred to as hydrostatic and simply means that there is little or no potential for the water to move vertically from one confined aquifer to another. In other cases, vertical equilibrium does not, naturally, exist and flow is occurring, though usually slowly, among confined aquifers. The status of the local ground water system, hydrostatic or not, is determined by drilling a borehole and measuring the level of the piezometric surface in each successively deeper aquifer by one or more of the various measurement methods available.

C. Groundwater Chemistry

The chemical quality of natural ground water is characterized by its content of the common cations, sodium, potassium, calcium and magnesium and the common anions; chloride, bicarbonate and sulfate and by the total dissolved solids comprised by these constituents. Fresh waters contain up to 1,000 mg/l of TDS, brackish waters 1,000-10,000 mg/l, saline waters 10,000-100,000 mg/l and brines greater than 100,000 mg/l of TDS.

The salinity or TDS content of a ground water is determined by its age and location and by the minerals that it has contacted during its lifetime. Young shallow waters tend to be low in TDS and deep old waters high in TDS. Often, a progressive increase in salinity occurs, with depth, in the aquifers intersected by a borehole in an oil producing area. Increased salinity also means increased density. Fresh water weighs

62.4 lb/ft^3 (has a specific gravity of 1.0) whereas a brine with a TDS content of 100,000 mg/l will weigh about 66.5 lb/ft^3 and have a specific gravity of 1.066. The hydrostatic pressure gradient of the fresh water would be 0.433 psi per foot of depth and of the brine would be 0.469 psi per foot of depth. An "average" hydrostatic gradient might be about 0.46 psi per foot of depth.

D. Hydrogeologic Parameters

To make quantitative assessments of ground water flow patterns and any consequent transport of contaminants in the subsurface, it is necessary to measure or estimate a number of hydrogeologic parameters or characteristics of the fluids and rocks involved. Fluid properties are density, viscosity compressibility and chemistry. Rock properties include porosity, permeability, thickness and compressibility.

These fluid and rock properties are obtained by a variety of geologic, geophysical and engineering methods or, where not measured, are estimated. Calculations are then made with analytical equations or numerical models to analyze and predict patterns of subsurface water flow and possible associated ground water contamination.

IV. ENVIRONMENTAL IMPLICATIONS OF ABANDONED WELLS

When a borehole is drilled through a series of subsurface geologic formations that contain waters of differing chemical quality, it immediately becomes a potential pathway for movement of those waters among formations. This is one reason why wells are cased with steel casing and why cement is forced into the open area (annulus) between the casing and the wall of the borehole. It is the principal reason for the careful plugging of well bores with cement and drilling mud before well abandonment.

A. Properly Plugged and Abondoned Wells

In recent years, the Federal Government and the states have adopted increasingly stringent requirements for the methods and procedures for plugging and abandonment of oil and gas wells. It is assumed that, when wells have been plugged and abandoned under current procedures, the well bores are sealed and do not allow movement of fluids among subsurface formations and, thus, are not potential sources of ground water contamination.

B. Improperly Plugged and Abandoned Wells

During the early history of the oil and gas industry, the potential danger to usable ground water from abandoned unplugged or improperly plugged oil and gas wells was not recognized and many thousands of such wells were either not plugged at all or were inadequately plugged to prevent interformational water flow. In the earliest days of the oil and gas industry, scant or no recording requirements existed and the numbers and locations of many wells abandoned during that era are unknown.

As regulation improved, well permits were required and numbers and locations are on record. The details of plugging are, however, still often unknown and it must be assumed that effective plugs were often not emplaced. Modern wells are required to have permits for drilling and for abandonment and plugging methods and procedures are carefully supervised so that abandoned plugged wells are not a hazard to ground water.

From this brief history, it can be concluded that the potential for contamination to an USDW from abandoned wells is closely related to the era during which they were constructed, the hazard being from wells drilled prior to enactment of effective plugging and abandonment regulations. An important aspect of this conclusion is that the depth to which wells are drilled has steadily increased with time. Early wells were very shallow, often only a few hundred feet but seldom more than 2,000-3,000 feet in depth. Few wells today are less than 3,000 feet in depth. This means that most wells being drilled today will not be in direct conmmunication with many older unplugged or improperly plugged wells.

1. Exploration Wells vs. Development Wells

It is useful to distinguish among the types of wells drilled by the oil and gas industry when considering their possible contamination potential. Exploration wells are drilled outside of producing fields or are drilled to targets deeper than known production in producing fields. In either case, they are of lesser environmental concern than development wells drilled inside producing areas, since well density will be less and there is, therefore, less possiblity of interaction among wells that would lead to interformational fluid flow.

2. Variables Affecting Contamination Potential of an Abandoned Well

The variables that determine the contamination potential that an abandoned unplugged or improperly plugged well poses to underground sources of drinking water are many and complex. Let it first be said that some such abandoned wells do pose a threat to USDW's while many are believed not to, for reasons that will be examined.

a. Pressure Status of the Geologic Sequence Penetrated

In considering the potential environmental effects of unplugged or improperly plugged abandoned wells it is essential to characterized the pressure regimes that may exist in the formations penetrated by such wells. The possible detailed scenarios are too extensive for it to be practical to attempt to discuss them all. It was mentioned earlier that reservoirs or aquifers in a geologic sequence may naturally be under hydrostatic or normally pressured conditions or may be overpressured or underpressured relative to hydrostatic conditions. Considerable debate exists over the reasons for these varying natural pressure conditions but there is no question of their existence. Superimposed upon these natural reservoir or aquifer pressure conditions are the effects of petroleum production, groundwater pumpage, oilfield brine disposal by reinjection, secondary and enhanced oil recovery projects and other man-induced effects.

Whatever the original pressure status of a gelogic sequence of aquifers and reservoirs, petroleum production will lower the original pressure of the producing reservoir so that it will often be underpressured relative to the rest of the sequence. When petroleum production ceases, the reservoir will begin to return to its original natural pressure status. The rate of this pressure recovery depends upon the geologic and engineering reservoir characteristics but should require a time period comparable to that during when the reservoir was produced. The cycle of pressure depletion and recovery of an oil field will be affected by oilfield brine reinjection for pressure maintenance by waterflooding for secondary oil recovery and by enhanced-oil-recovery projects. Ground water pumpage will affect the pressures in drinking water aquifers similarly to production of petroleum reservoirs as described above.

The variety of possible flow patterns that can occur among aquifers and reservoirs with differing pressure conditions is, thus, very extensive and the local circumstances will have be examined in order to reach a conclusion concerning the threat of an abandoned well to an USDW. For example, there is no hazard of flow from a pressure-depleted petroleum reservoir to a normally pressured water-supply aquifer. In fact, flow would be into the pressure-depleted reservoir rather than from it. Even when reservoir pressure has recovered, no threat would exist in a normally pressured sequence. A hazard only exists when a saline-water bearing aquifer or reservoir is at a higher flow potential than an overlying fresh water aquifer connected with it by an unplugged or improperly plugged abandonded well. Even in that circumstance, movement of saline water into an USDW may not occur for reasons that will be described below.

b. Abandoned Well Flow Mechanics

Given the presence of an abandoned well that is improperly plugged or unplugged, is open to a geologic sequence of aquifers and which penetrates a petroleum producing reservoir or reservoirs, the analysis of the potential for flow of natural saline water or injected fluids into underground sources of drinking water is a complex but tractable problem. Among the variables of the problem are:

i. Flow potential status of all aquifers and reservoirs in the sequence penetrated by the abandoned well. This is discussed under a. above.

ii. Status or condition of the borehole of the abandoned well - Even though a well may have not been plugged or may have been inadequately plugged at abandonment, most boreholes will contain impediments to interaquifer fluid flow. These include drilling muds, partially effective cement or mud plugs, collapsed or sloughed formations, formations that have expanded into the borehole and, possibly, drilling equipment or well completion equipment lost in the hole. Only under unusual circumstances will abandoned wells not contain such flow impediments. A possible case of that type would be a cable-tool well drilled in a sequence of competent strata in which drilling mud was not used and in which no form of plug was ever employed. Such wells probably exist in early field areas in several geologic provinces but will, typically, be shallow and not in communication with present producing formations. Probably all rotary drilled wells will contain, at least, drilling mud as a flow impediment.

iii. Details of the operation of petroleum or water producing activities in formations intersected by the borehole - The effects of any injection and/or production wells that are completed in formations intersected by the boreholes of an abandoned well must be superimposed upon the flow gradients that exist under non-operational conditions. For example, if an abandoned well is bottomed in a petroleum reservoir that is undergoing waterflooding, the pressure effects of waterflood injection and production wells at the point where the abandoned well penetrates the reservoir must be determined so that the total differential pressure available to move fluids up the abandoned well is known. Effects of pumping from or injection into other aquifers must also be accounted for. For example, pumping from a fresh-water bearing aquifer would create a pressure decrease that would encourage fluid movement into that aquifer.

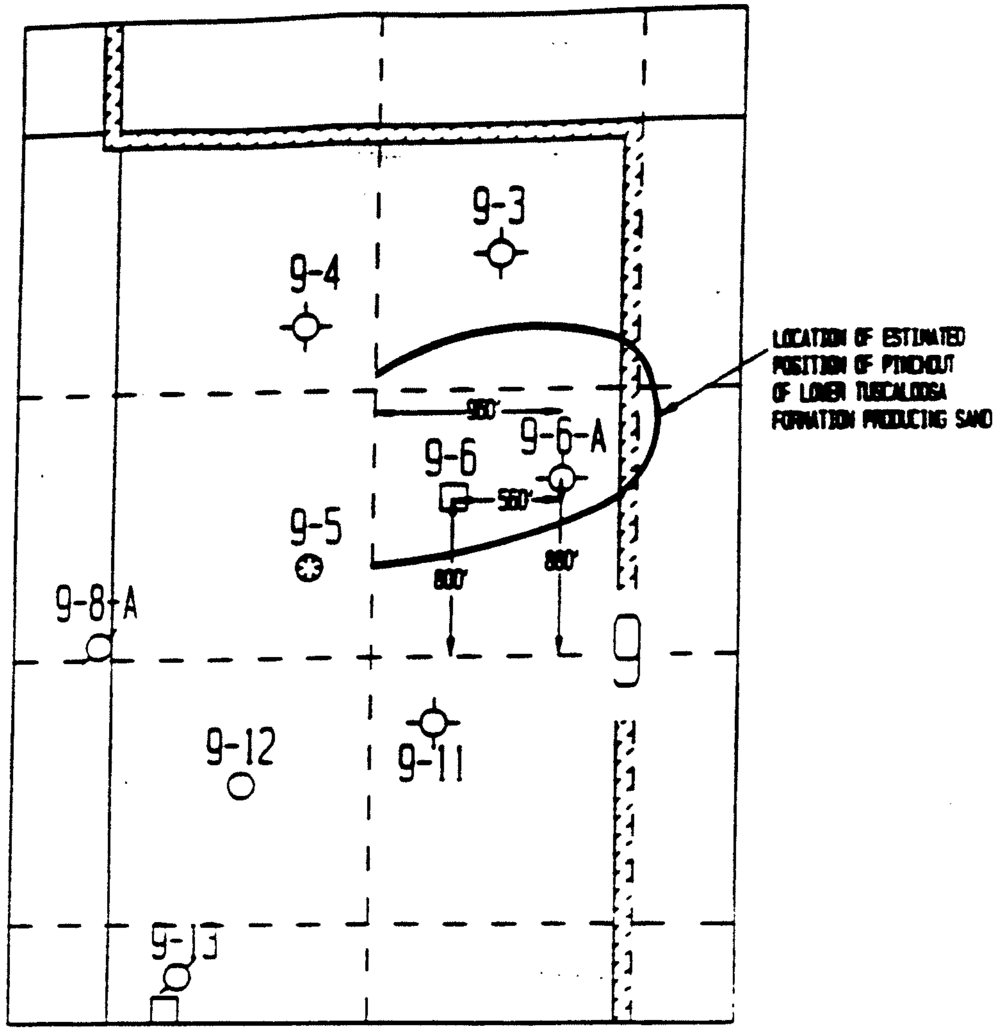
iv. Subsurface geologic conditions - Essential to determining the environmental hazard potential of an abandoned well is the subsurface geologic framework in the vicinity of the well. For example, if the abandoned well is drilled through formations that exhibit extreme lateral variability, the well may not be an effective pathway for fluid movement from an oil producing formation into a fresh water aquifer because the well may miss either t petroleum producing or water yielding units in the respective formations.

v. Engineering characteristics of all units in the geolog sequence and their contained fluids - The rate of flow and flow path that will be taken by formation waters o injected fluids in response to flow gradients that exi among formations in communication through an abandoned well will depend on the engineering properties of the formations and their contained fluids. Formation properties include porosity, permeability thickness an compressibility. Fluid properties include density, viscosity and compressibility. Both formation and flu properties and the differential flow gradient are ente into the appropriate analytical equations or numerical models in order to calculate flow paths and flow quantities. Such calculations are an accepted means c modeling subsurface flow problems and provide relative practical means of evaluating hazard of an abandoned well.

V. CASE EXAMPLE

The case example that will be described is based on a recent unpublisl study of the possible environmental effects of an abandoned well located n a proposed water injection well. The wells are located in an oilfield undergoing an enhanced oil recovery project in Mississippi. Figure 3 show portion of the oilfield with the two wells studied. Well 9-6 is the propo water injection well. Well 9-6A is the abandoned well. The producing san for the oilfield pinches out by facies change to the north, east and south the two wells, as shown in Figure 3. Figure 4 shows a generalized stratigraphic column for the field. The Lower Tuscaloosa Sand is the producing sand for the field. It occurs at a depth of 10,490 feet in well and is 26 feet thick. The base of the deepest underground source of drink water occurs at a depth of 3100 feet, in sands of the Sparta Formation, wh is about 700 feet thick.

The predicted hydraulic effects in abandoned well 9-6A resulting from proposed injection into Well 9-6 were studied with a numerical model, SWIF III (Ward, 1987). SWIFT III is a revised and improved version of a code originally developed for the U.S. Geological Survey specifically for inje well modeling. The original code and its successors have received extens verification, validation and use. Figure 5 depicts the finite difference used in the simulations. Figure 6 is another representation of the grid showing the line of cross-section A-A', which is used to display the resu of selected simulations.



XYZ FIELD
MISSISSIPPI

WELL STATUS
JULY 1987

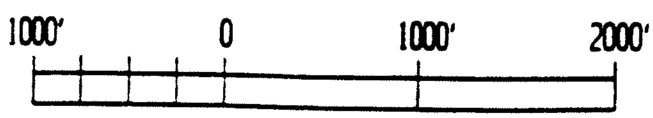
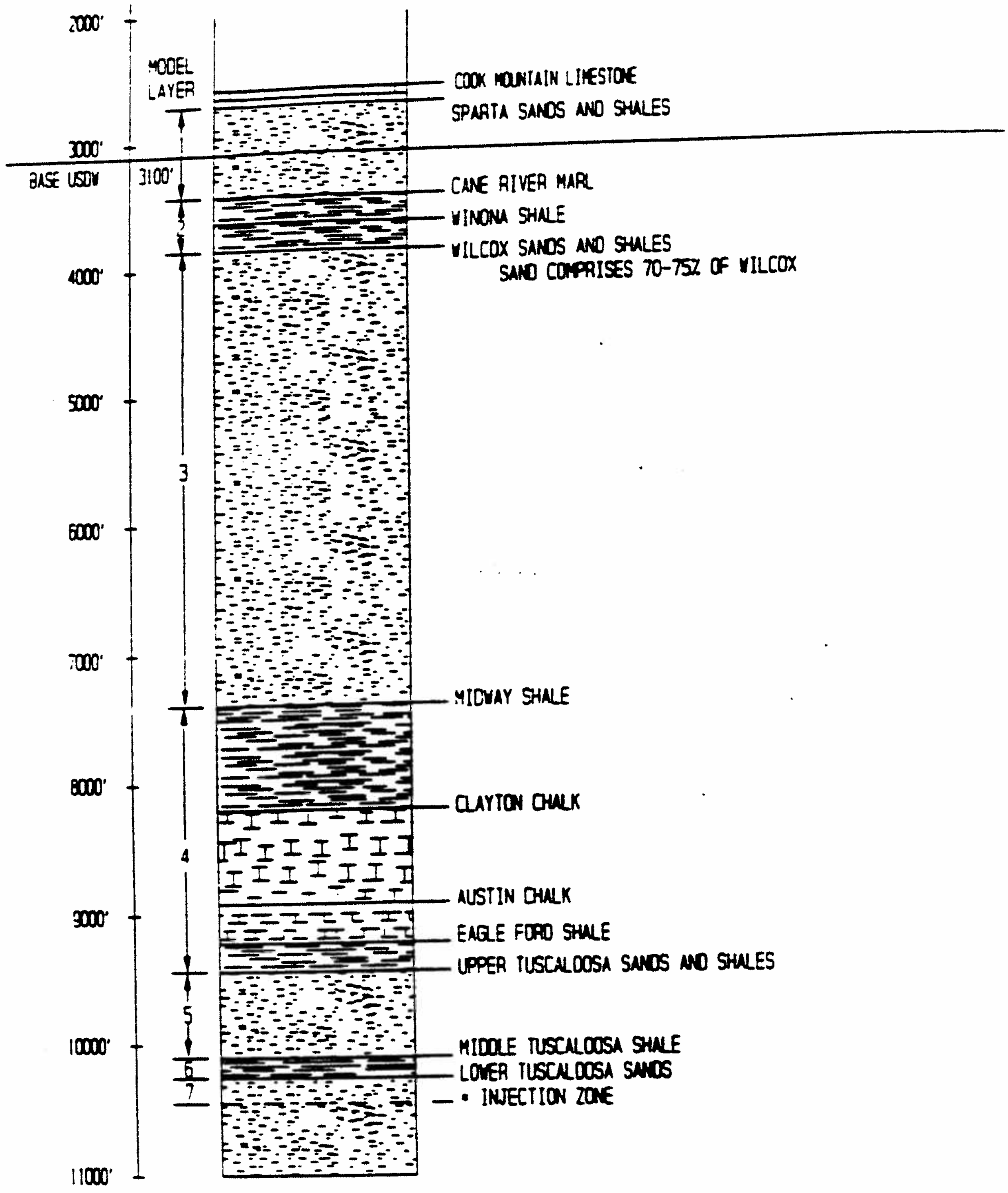


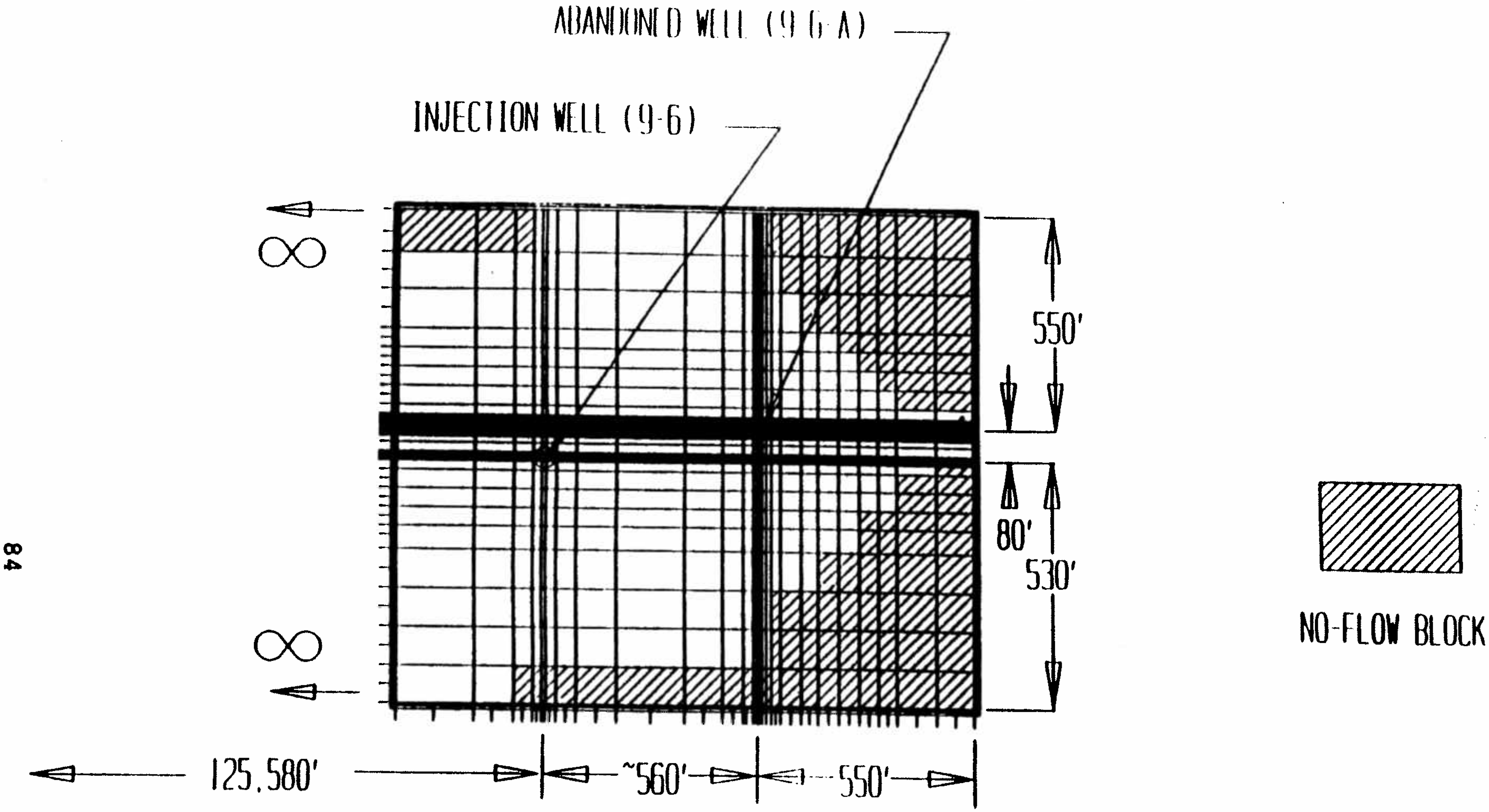
FIGURE 3

FIGURE 4

GENERALIZED STRATIGRAPHIC COLUMN

XYZ FIELD
MISSISSIPPI



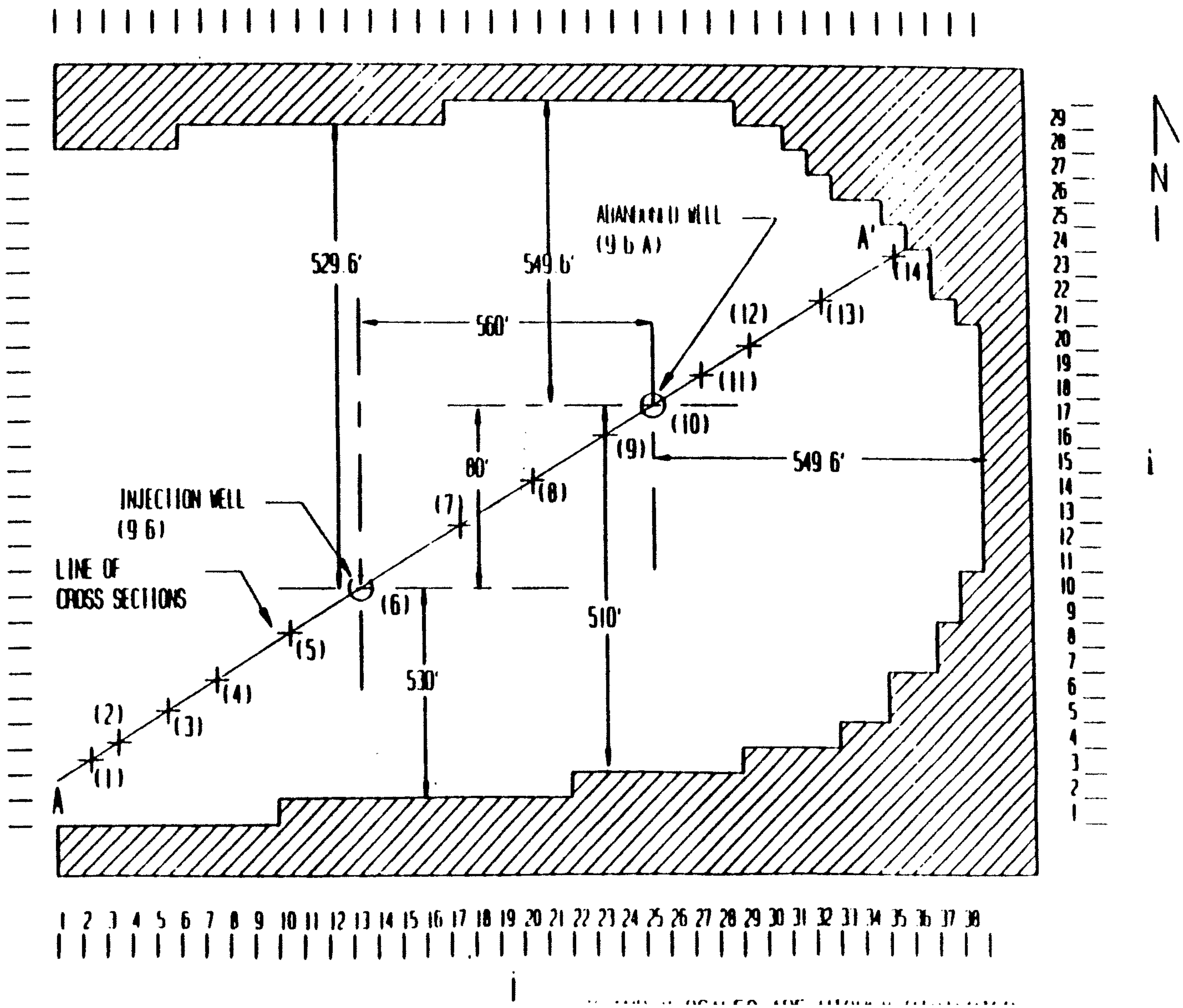


SCALED SIMULATION GRID

FIGURE 5

FIGURE 6

DETAIL OF THE SIMULATION GRID (7 LAYERS)



The energy company that operates the oilfield under study provided the geologic and engineering parameters and operating schedule for Well 9-6, needed as input to the numerical model. It was assumed that the injection well would operate at near its maximum injection capacity, the constraint being the local fracture gradient of about 0.7 psi per foot of depth. The permeability of the Lower Tuscaloosa Sand was assumed to be a maximum probable 30 millidarcys and a minimum probable 2 millidarcys. The large range is the result of uncertainty concerning the effect of residual oil on the permeability to water. A total of about 20 simulation runs were made to calibrate the model and 10 final simulations were run to test various borehole and reservoir conditions. The results of representative simulations are discussed below.

Figure 7 displays the results of a simulation in which the borehole of Well 9-6A was considered to be unplugged.[1] The Lower Tuscaloosa Sand was considered to have a permeability of 30 millidarcys and the injection rate in Well 9-6 considered to be 200 bbl/day. Reservoir pressure at the wellbore of Well 9-6 increased 908 psi over the 10-year simulation period and increased about 752 psi in the Lower Tuscaloosa Sand at the borehole of abandoned Well 9-6A. This pressure increase was transmitted through the Middle Tuscaloosa and through the borehole of Well 9-6A to the extent that up to a 7.2 psi pressure increase occurred in the Upper Tuscaloosa. Transmission of pressure through Well 9-6A also caused a buildup of up to 4.8 psi in Model Layer 4 but no pressure increase could be observed in the Wilcox Formation or units above the Wilcox. This result indicates that upward flow through abandoned Well 9-6A was insufficient to cause an observable pressure increase in the Wilcox and that no transmission of water to units above the Wilcox would be expected to occur. All subsequent simulations in which the permeability of the Lower Tuscaloosa Sand and the injection rate of Well 9-6 were proportionately varied, yielded the same result.

Cases were also studied where a plug composed of precipitated drilling mud solids was hypothesized to have developed. Figure 8 displays the results of one such simulation in which a plug of only 10-feet in length was considered to have developed in the interval of the Middle Tuscaloosa Formation. The 10-foot plug was assigned a permeability of 10^{-3} millidarcys. As shown in Figure 8, no observable pressure increase developed in layers above the Middle Tuscaloosa.

1. As has been discussed, it is believed that all rotary drilled boreholes will have some hydraulic resistance to flow. In this study, permeabilities of from about 40 to 4000 darcys were assigned to the borehole of Well 9-6A with no observable difference in the results.

FIGURE 7

INCREASE IN PRESSURE (PSI) ABOVE HYDROSTATIC ALONG SECTION A-A' AFTER 10 YEARS OF INJECTION

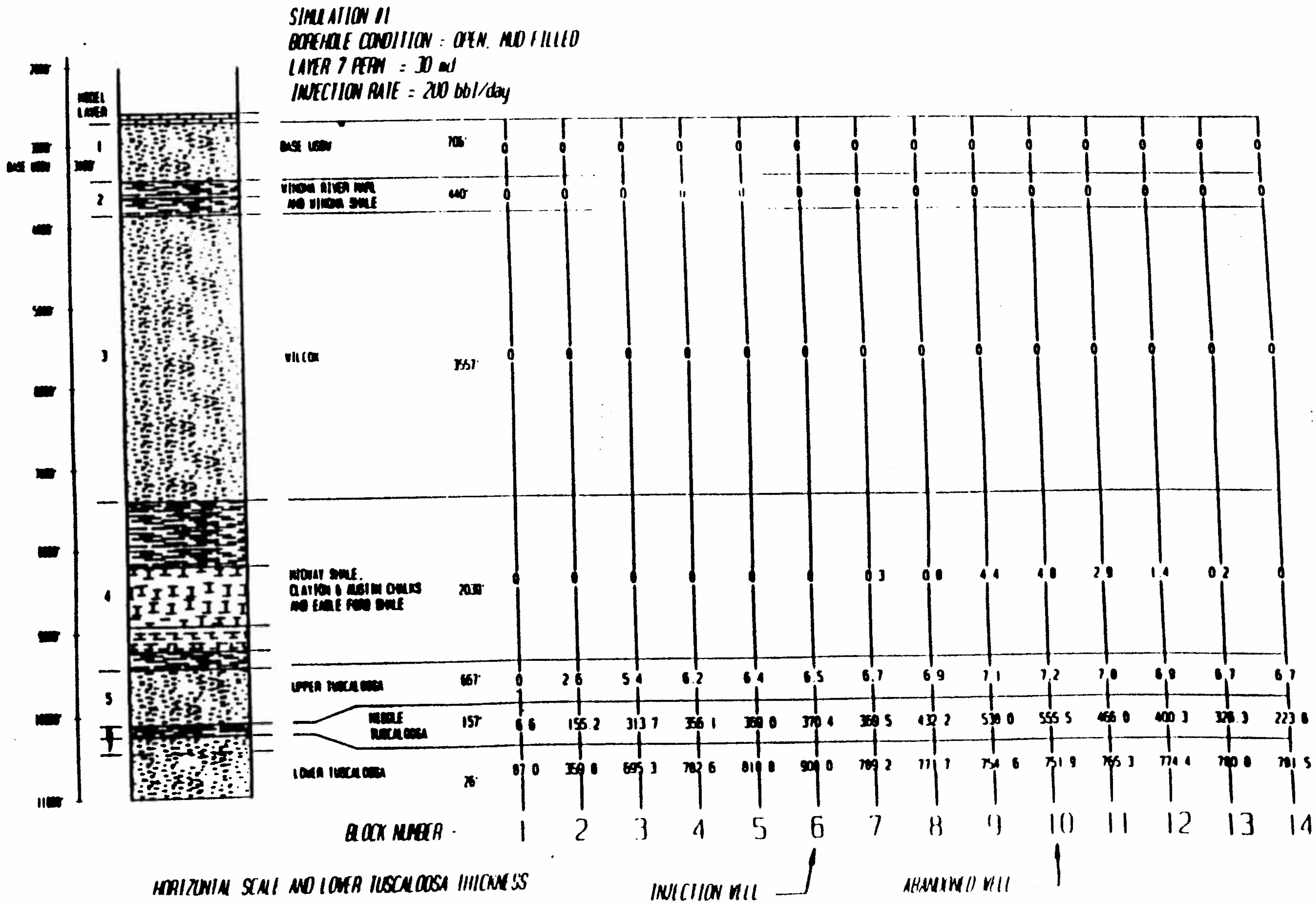
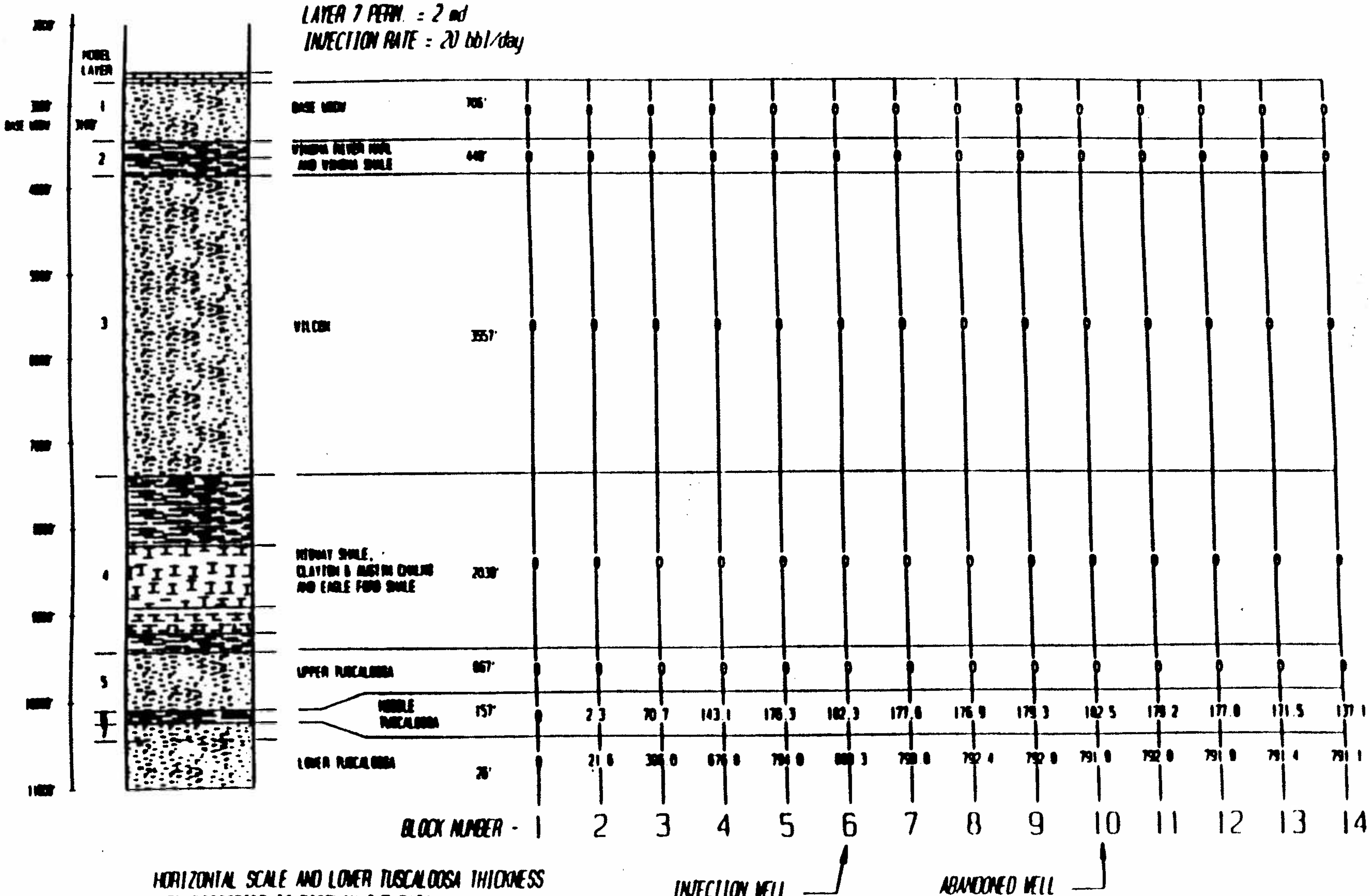


FIGURE 8

INCREASE IN PRESSURE (PSI) ABOVE HYDROSTATIC ALONG SECTION A-A' AFTER 10 YEARS OF INJECTION

SIMULATION #5
BOREHOLE CONDITION : 10 FT PLUG w/PERM. = 10^{-1} md
LAYER 7 PERM. = 2 md
INJECTION RATE : 20 bbl/day



HORIZONTAL SCALE AND LOWER TUSCALOOSA THICKNESS ARE DISTORTED TO DISPLAY THE DATA