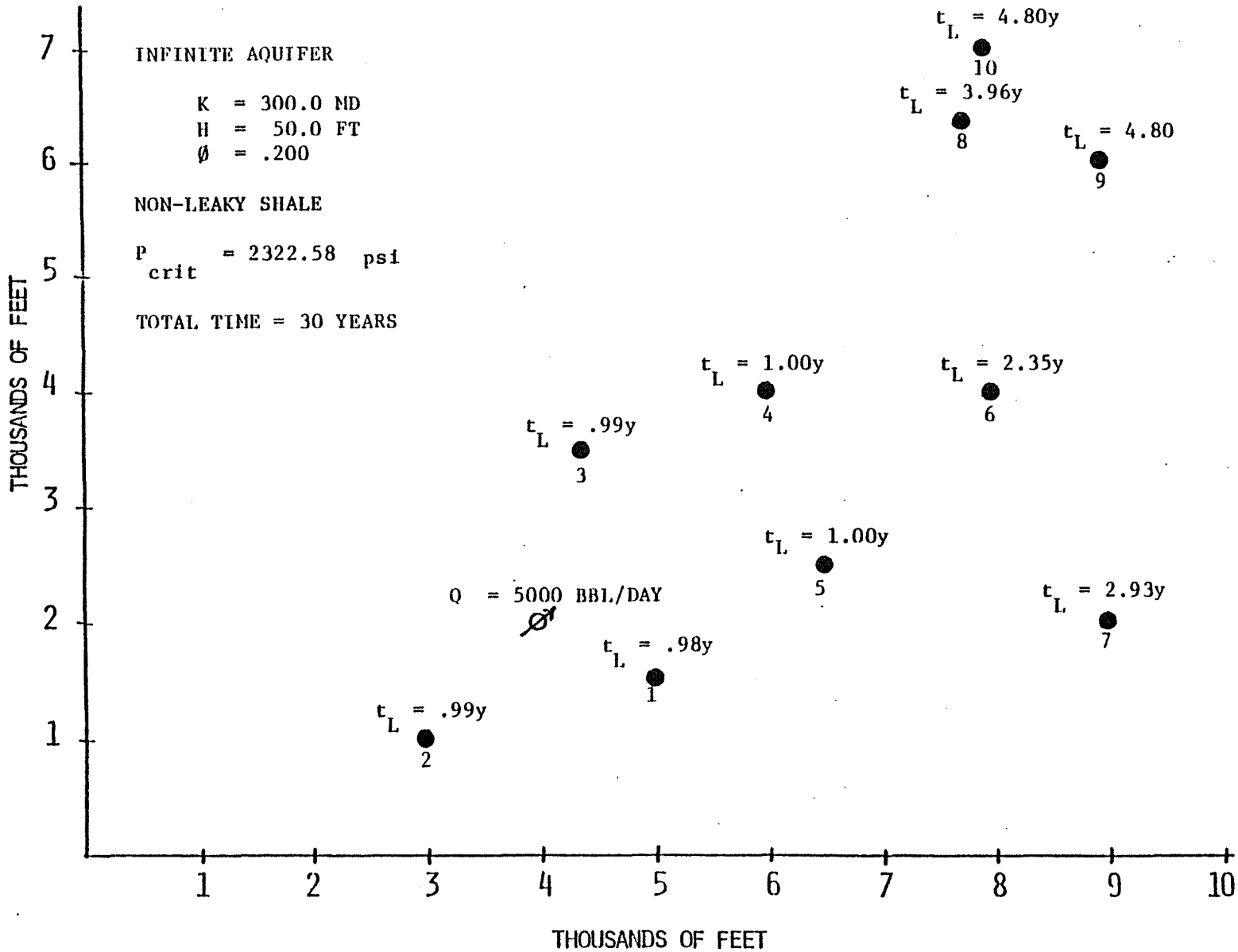
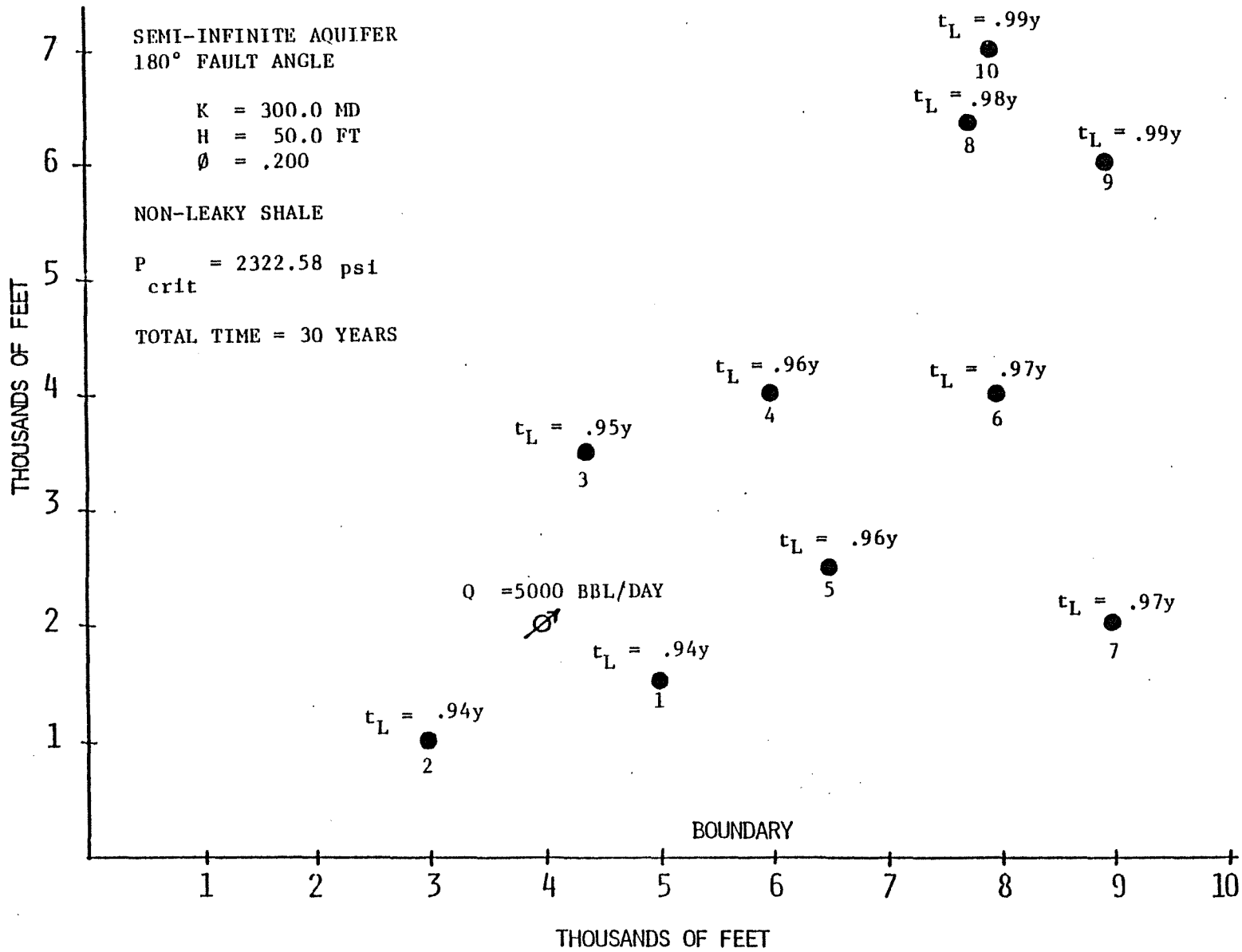
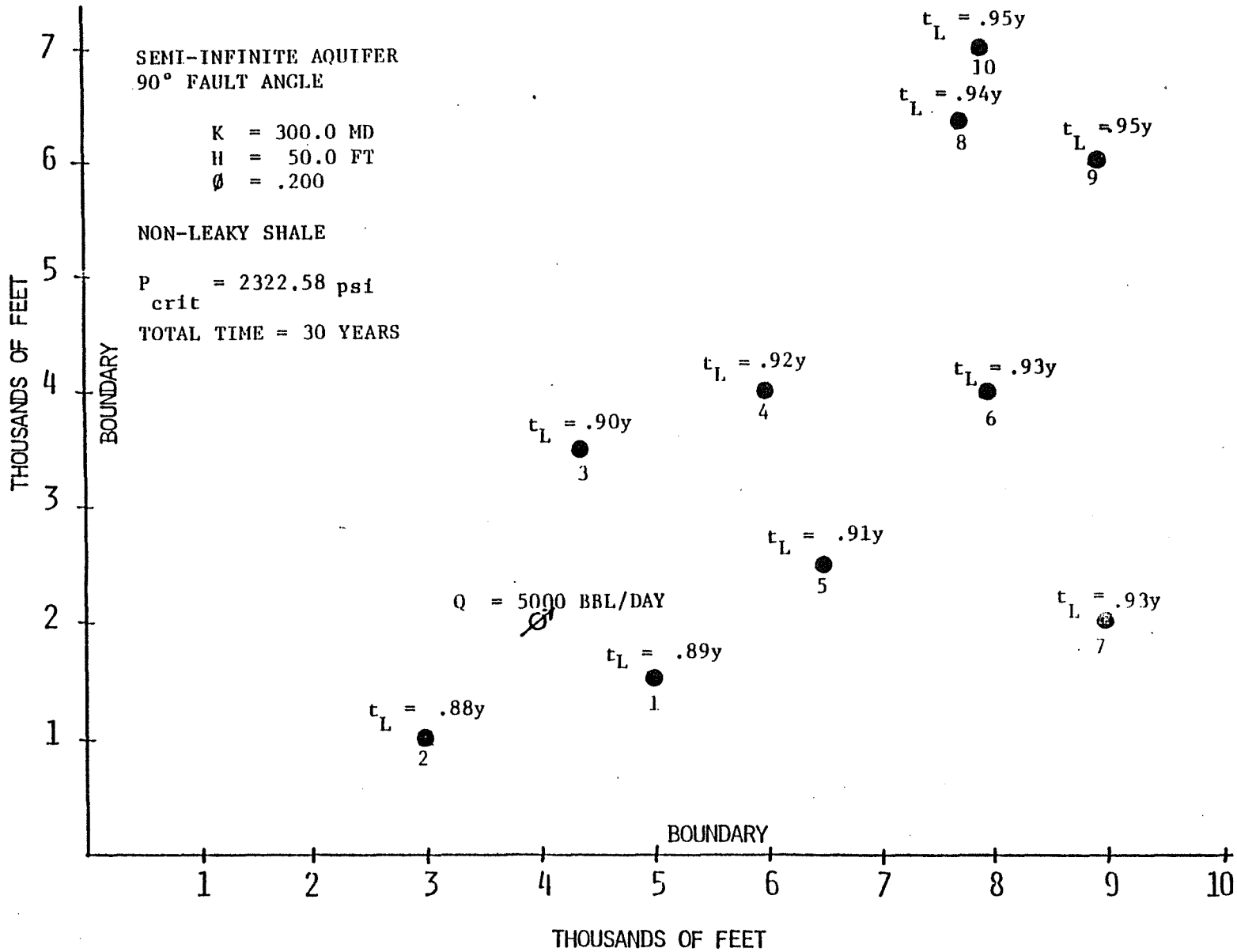


CASE II, GROUP 3, NO. 1



CASE II, GROUP 3, NO. 2



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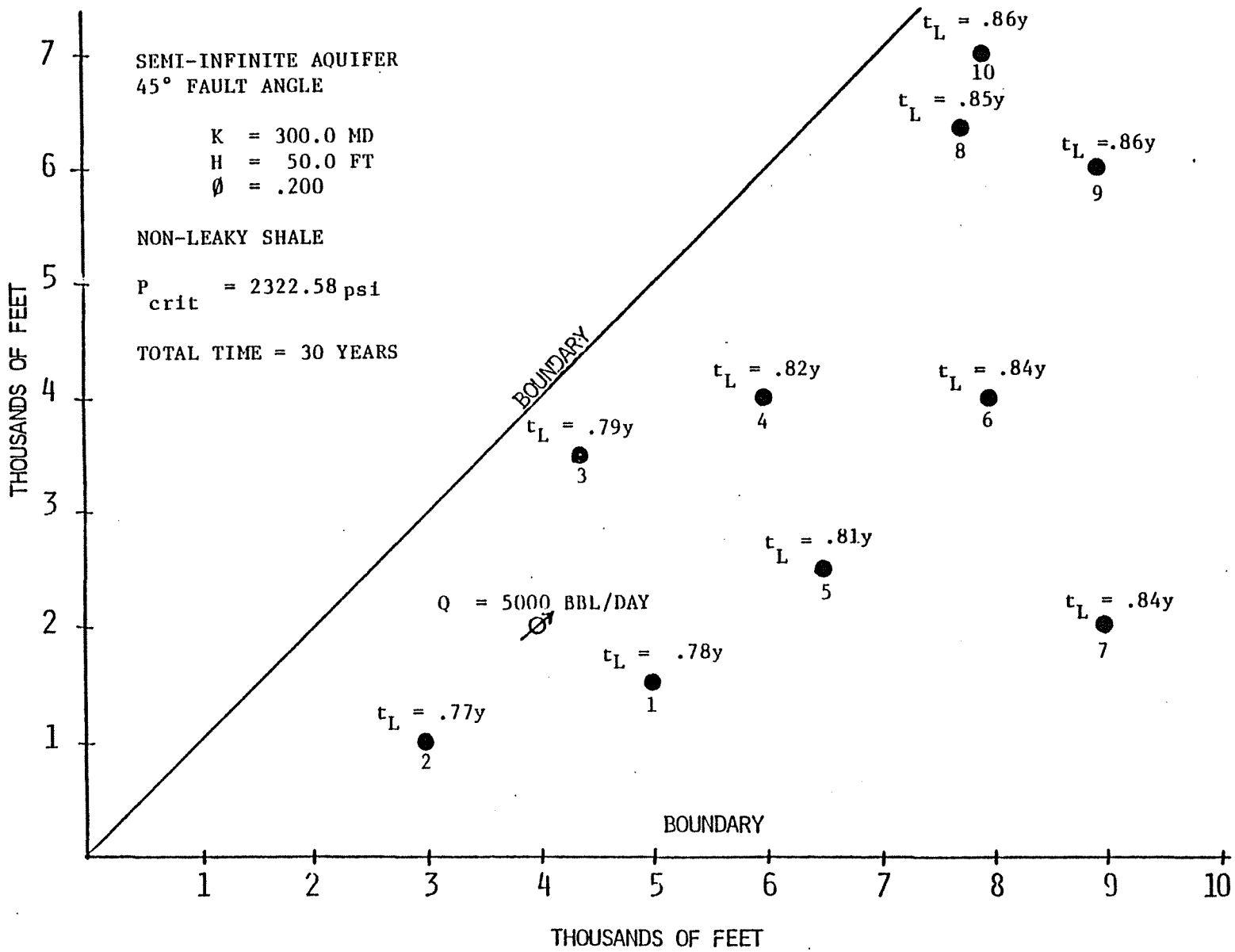
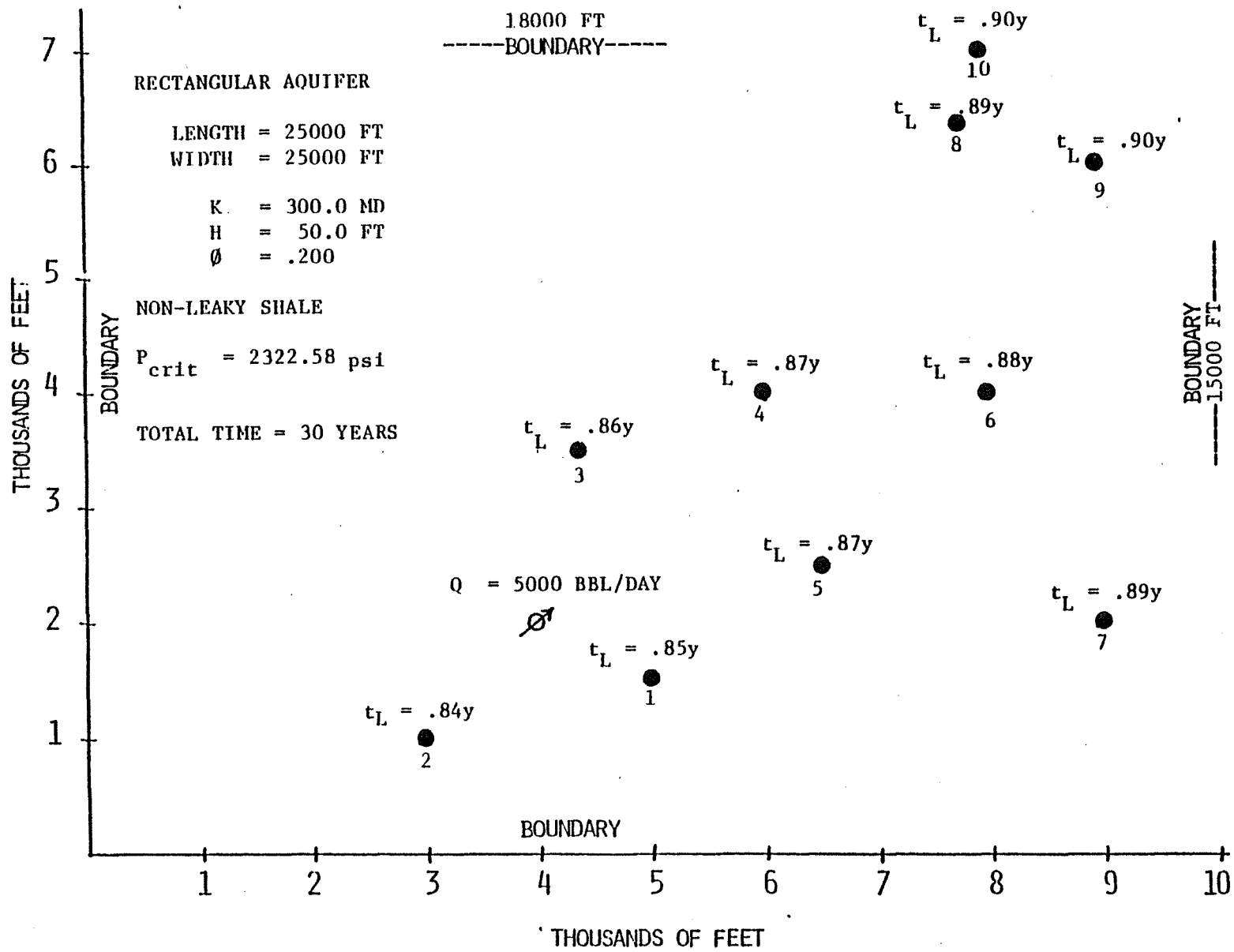


CASE II, GROUP 3, NO. 4



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

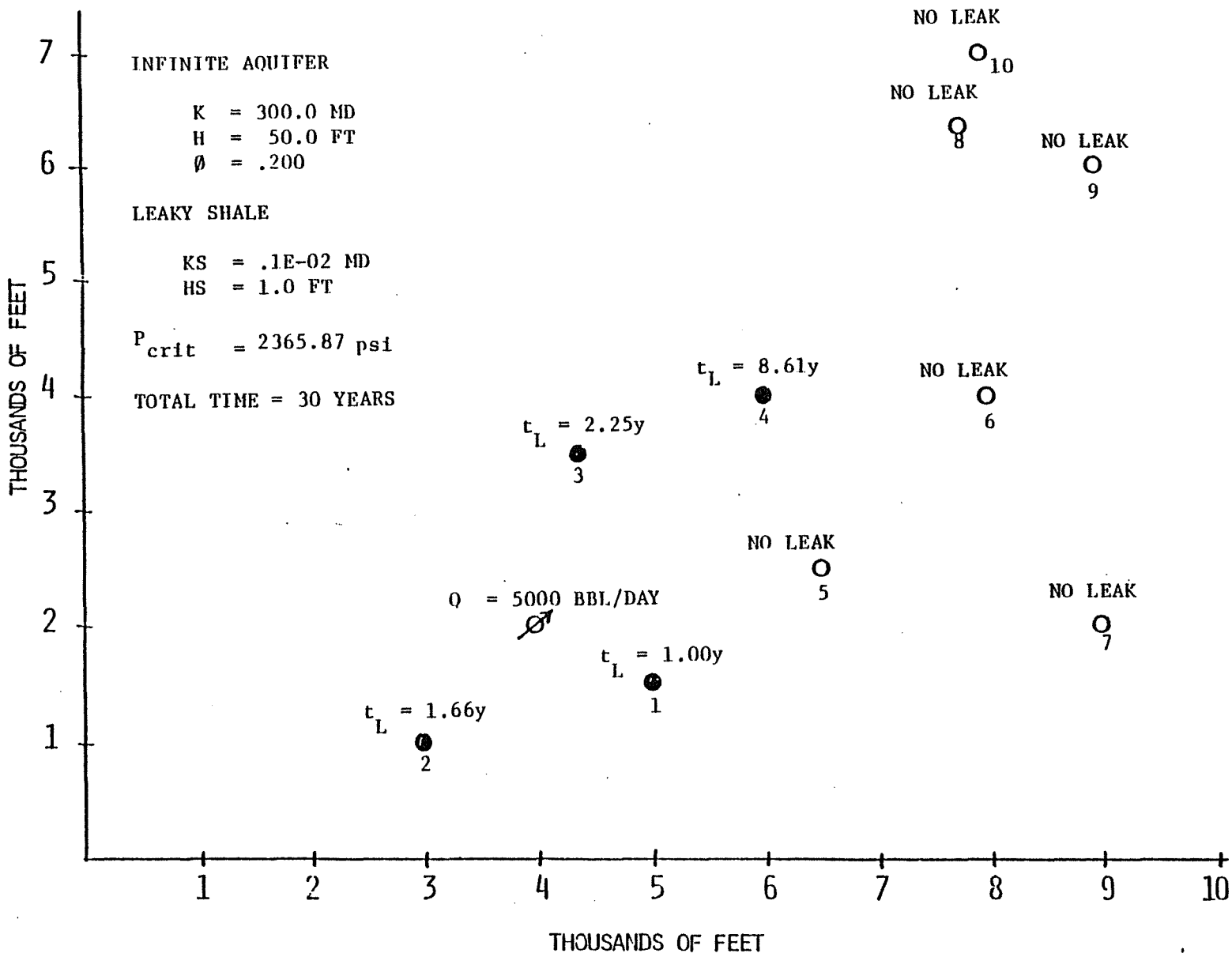
ABAN WELL	WELL DIAM IN	DEPTH TO DISP ZONE FT	DEPTH TO H2O ZONE FT	MUD DENSITY LB/GAL	GEL STRENGTH LB/100FT2	CRITIC PRESSU PSI
1	9.6	5000.00	600.0	8.600	75.00	2365.87
2	9.6	5000.00	600.0	8.600	75.00	2365.87
3	9.6	5000.00	600.0	8.600	75.00	2365.87
4	9.6	5000.00	600.0	8.600	75.00	2365.87
5	9.6	5000.00	600.0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

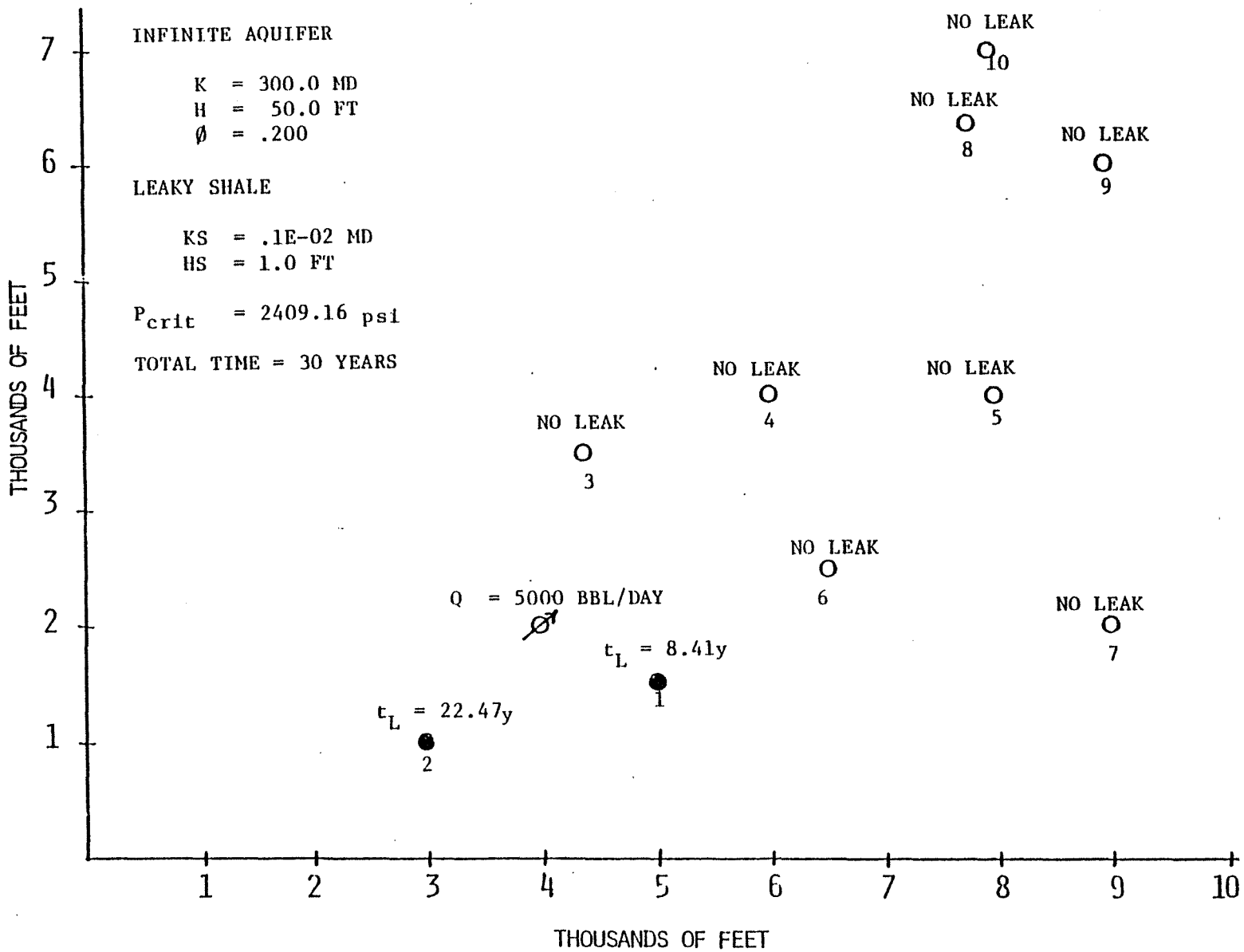
WELL #	X FT.	Y FT.
1	5000.000	1500.000
2	3000.000	1000.000
3	4400.000	3600.000
4	6000.000	4000.000
5	6500.000	2500.000
6	8000.000	4000.000
7	9000.000	2000.000
8	7800.000	6400.000
9	9000.000	6000.000
10	8000.000	7000.000

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

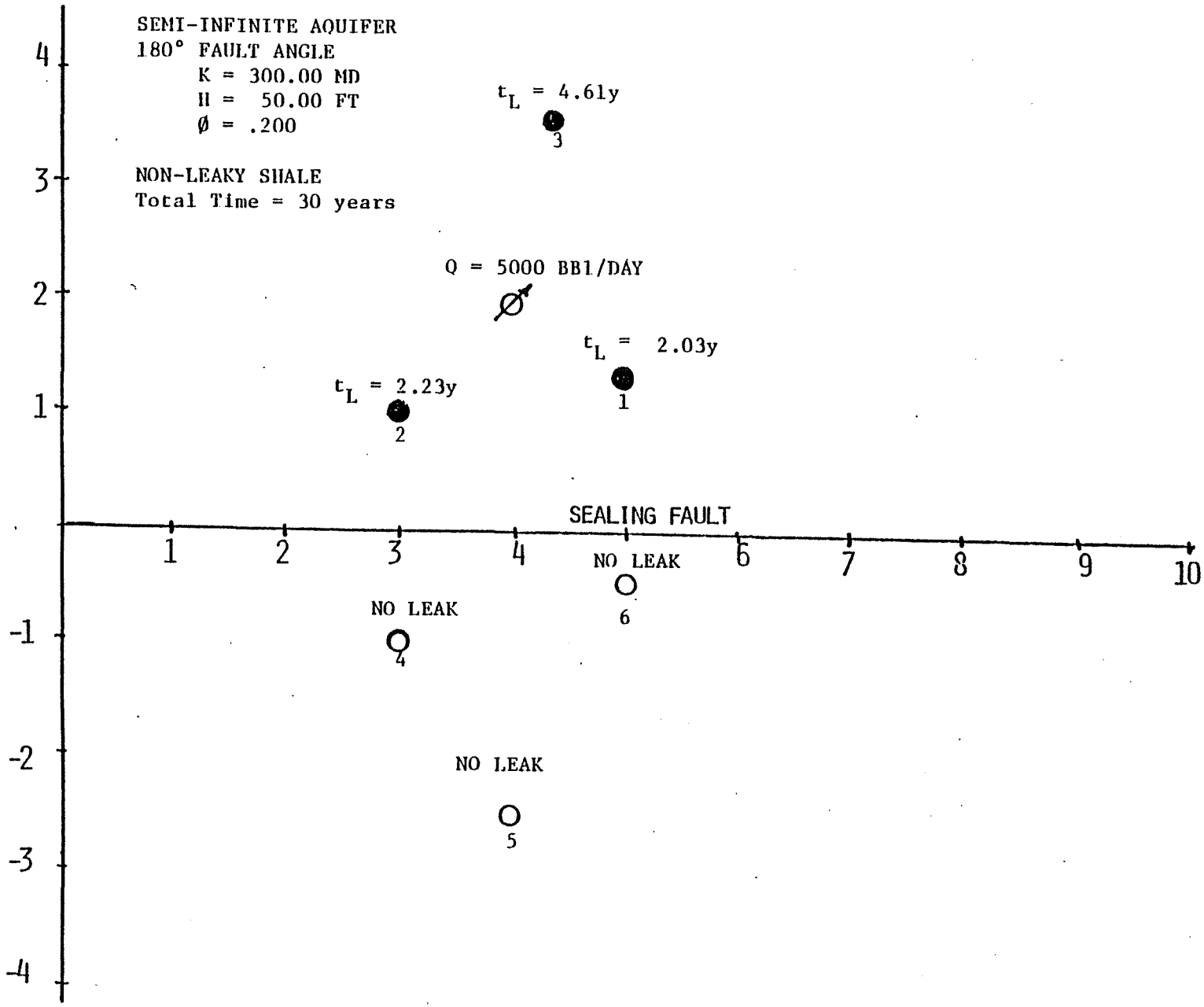
ABAN WELL	WELL DIAM IN	DEPTH TO DISP ZONE FT	DEPTH TO H2O ZONE FT	MUD DENSITY LB/GAL	GEL STRENGTH LB/100FT2	CRITIC PRESSU PSI
1	9.6	5000.00	600.0	9.000	100.00	2513.16
2	9.6	5000.00	600.0	9.000	100.00	2513.16
3	9.6	5000.00	600.0	9.000	100.00	2513.16
4	9.6	5000.00	600.0	9.000	100.00	2513.16
5	9.6	5000.00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

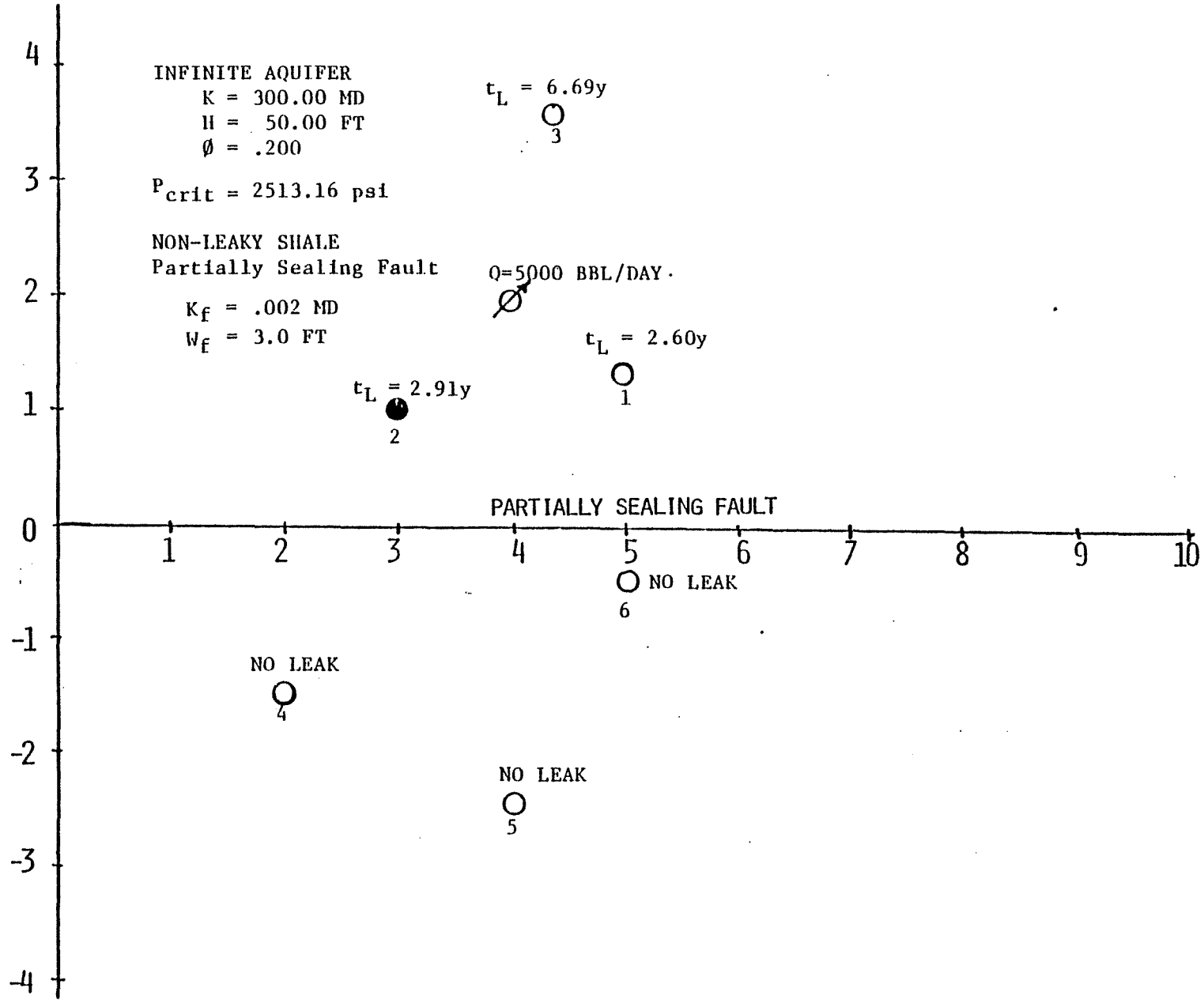
COORDINATES OF THE ABANDONED WELLS

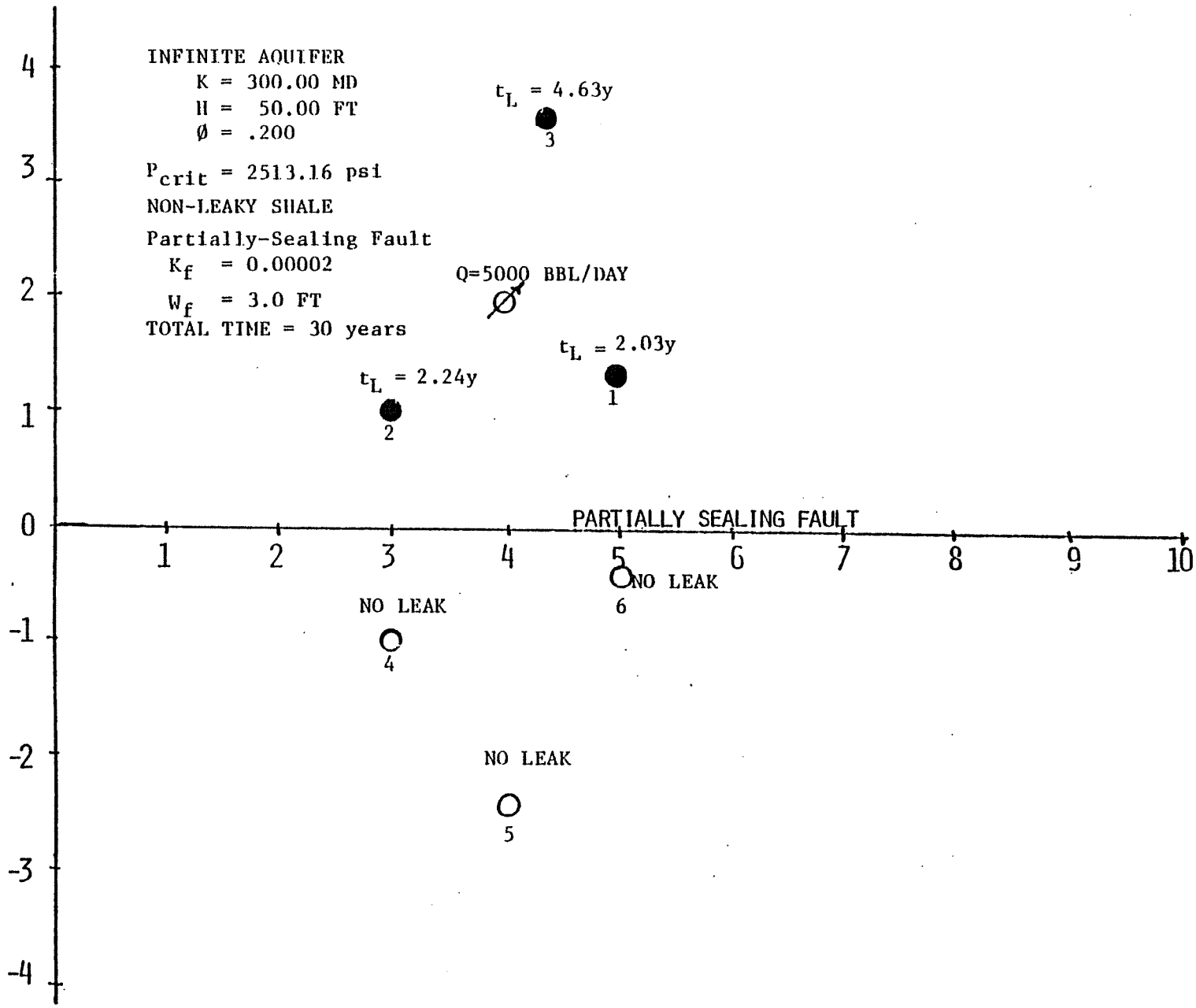
WELL #	X FT.	Y FT.
1	5000.000	1500.000
2	3000.000	1000.000
3	4400.000	3600.000
4	3000.000	-1000.000
5	4000.000	-2500.000
6	5000.000	-500.000

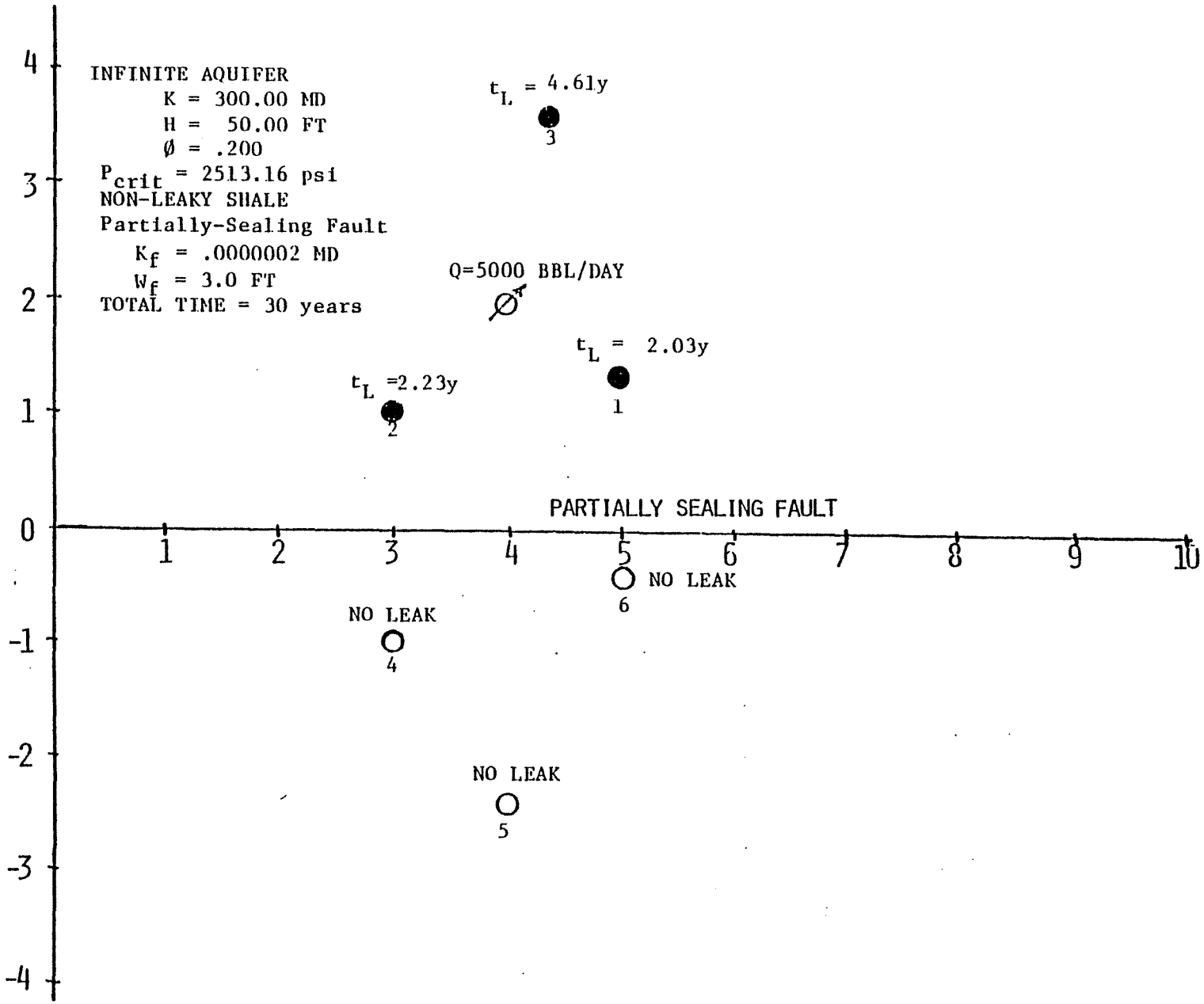
COORDINATES OF THE INJECTION WELL

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
Q = 5000 BBl/DAY
t_L = 4.61y
3
t_L = 2.03y
1
t_L = 2.23y
2
SEALING FAULT
NO LEAK
6
NO LEAK
4
NO LEAK
5
4
3
2
1
-1
-2
-3
-4
1
2
3
4
6
7
8
9
10


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
3
Q=5000 BBL/DAY
t_L = 2.03y
1
t_L = 2.24y
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 = .0000002 MD
W_f = 3.0 FT
TOTAL TIME = 30 years
t_L = 4.61y
3
Q=5000 BBL/DAY
t_L = 2.03y
1
t_L =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
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CASE IV

EFFECTS OF LEAKY SHALE AQUICLUDES

Group 1, Comparison of leaking and non-leaking shale aquicludes for 45° 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

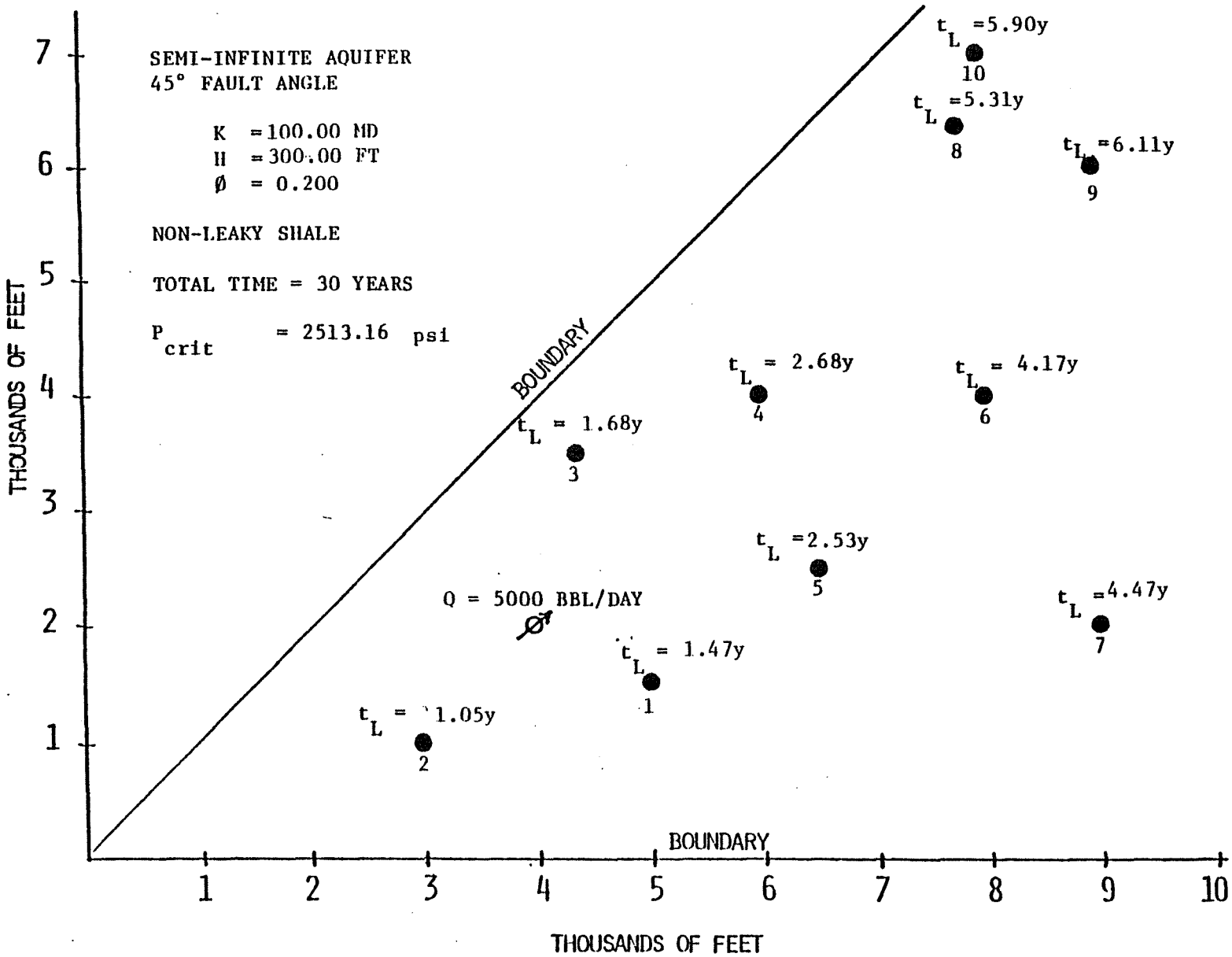
ABAN WELL	DIAM	DISP ZONE	H2O ZONE	MUD DENSITY	GEL STRENGTH	CRITIC PRESSU
	IN	FT	FT	LB/GAL	LB/100FT2	PSI
1	9.6	5000.00	600.0	9.000	100.00	2513.16
2	9.6	5000.00	600.0	9.000	100.00	2513.16
3	9.6	5000.00	600.0	9.000	100.00	2513.16
4	9.6	5000.00	600.0	9.000	100.00	2513.16
5	9.6	5000.00	600.0	9.000	100.00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

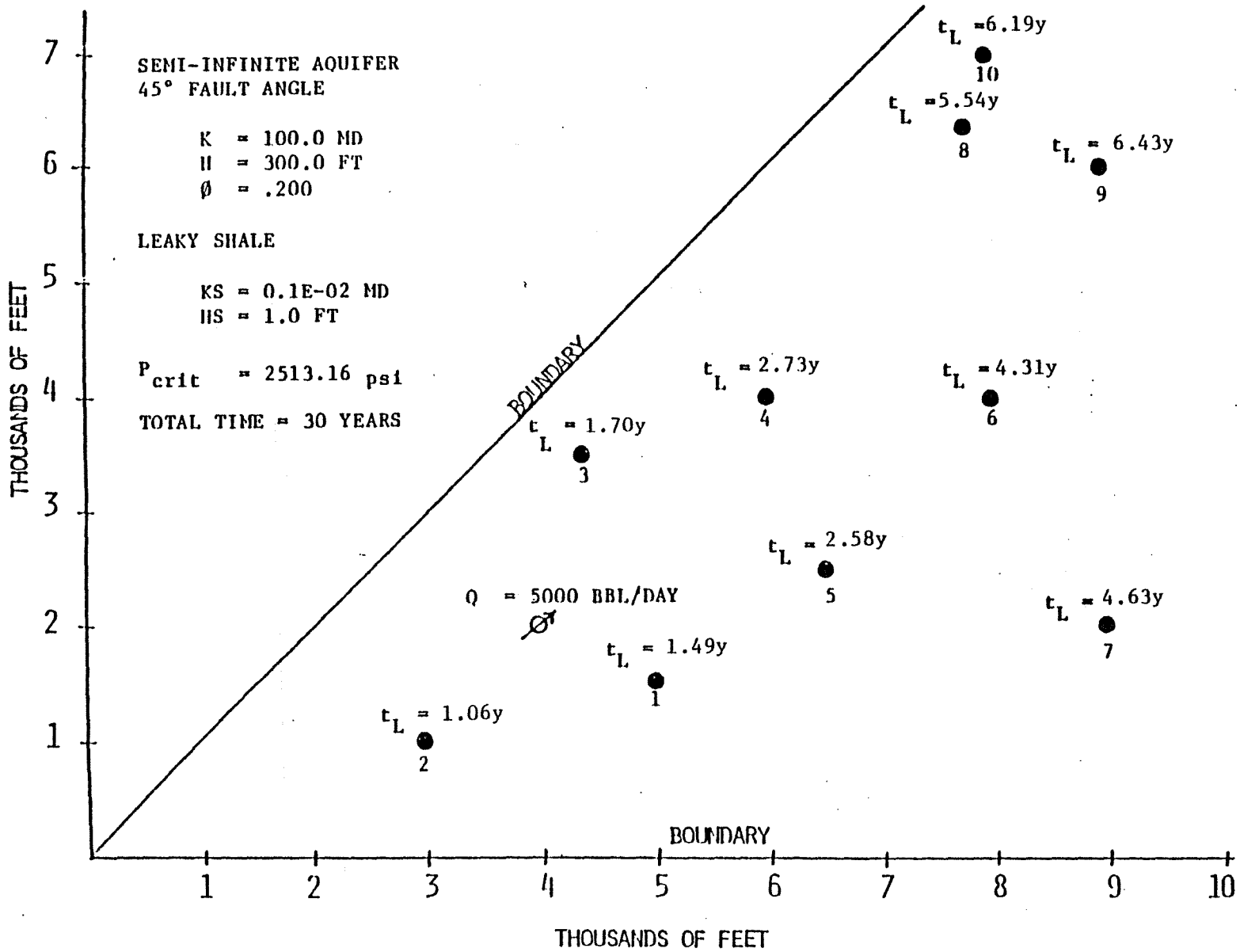
WELL #	X FT.	Y FT.
1	5000.000	1500.000
2	3000.000	1000.000
3	4400.000	3600.000
4	6000.000	4000.000
5	6500.000	2500.000
6	8000.000	4000.000
7	9000.000	2000.000
8	7800.000	6400.000
9	9000.000	6000.000
10	8000.000	7000.000

COORDINATES OF THE INJECTION WELL

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



CASE IV, GROUP 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

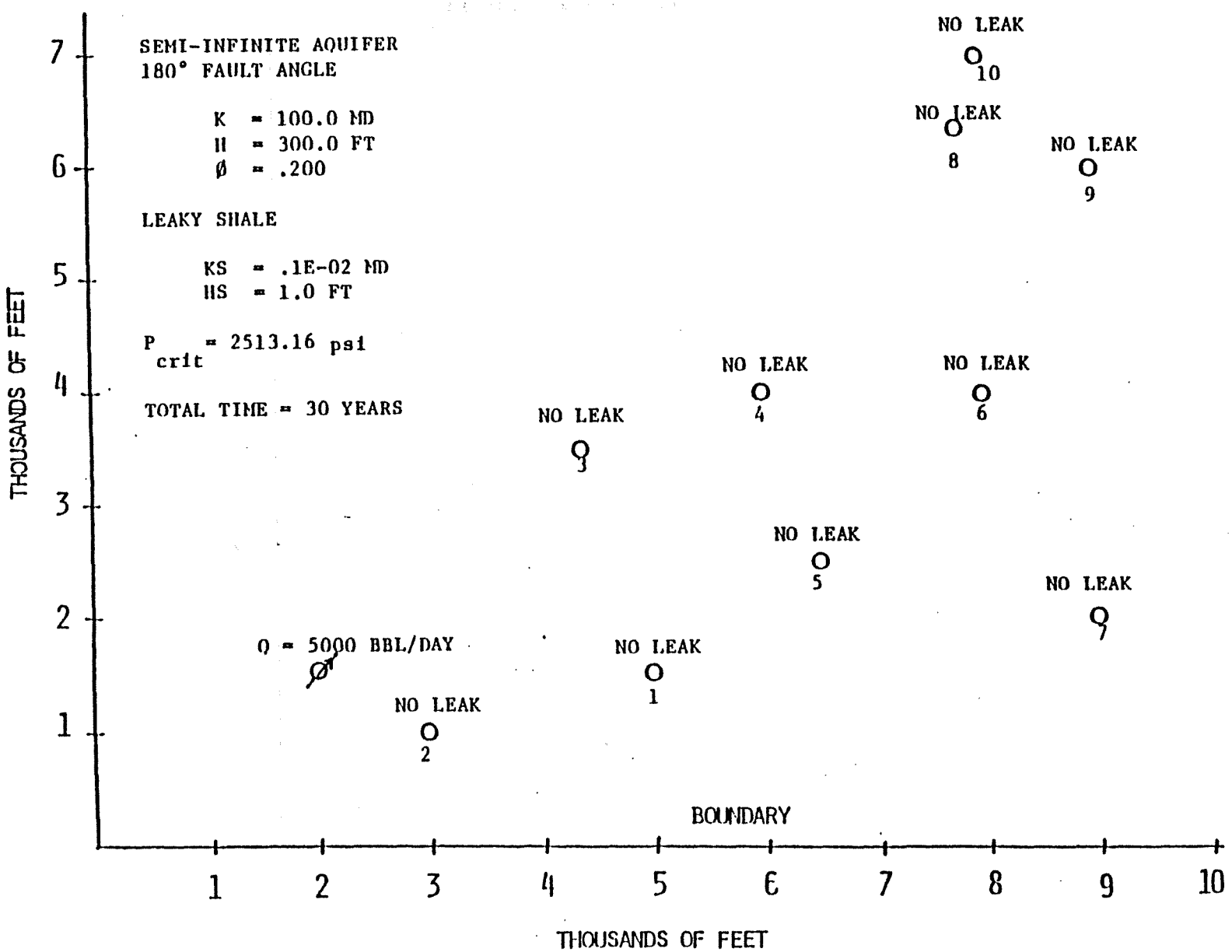
ABAN WELL	WELL DIAM IN	DEPTH TO DISP ZONE FT	DEPTH TO H2O ZONE FT	MUD DENSITY LB/GAL	GEL STRENGTH LB/100FT2	CRITIC PRESSU PSI
1	9.6	5000.00	600.0	9.000	100.00	2513.16
2	9.6	5000.00	600.0	9.000	100.00	2513.16
3	9.6	5000.00	600.0	9.000	100.00	2513.16
4	9.6	5000.00	600.0	9.000	100.00	2513.16
5	9.6	5000.00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

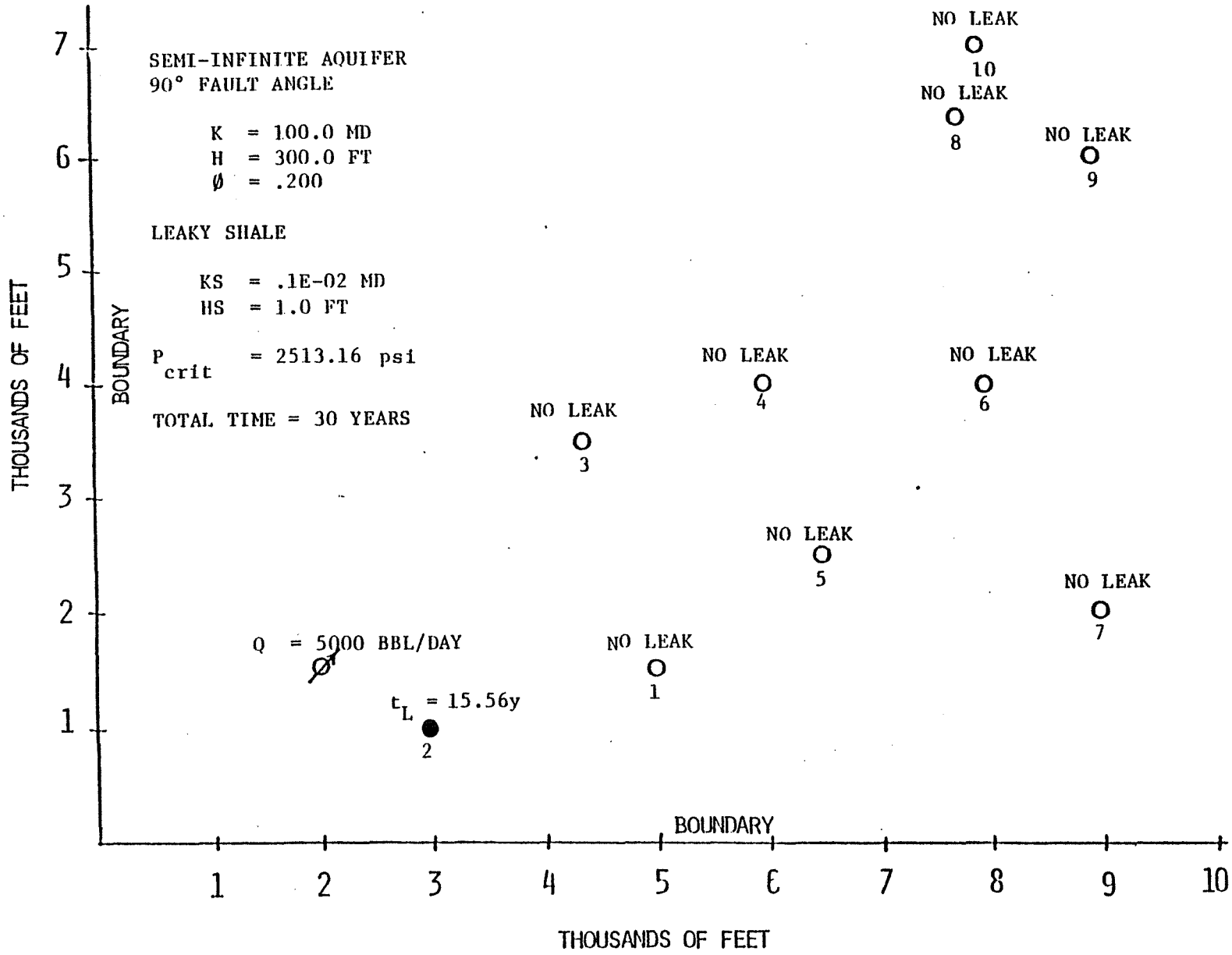
WELL #	X FT.	Y FT.
1	5000.000	1500.000
2	3000.000	1000.000
3	4400.000	3600.000
4	6000.000	4000.000
5	6500.000	2500.000
6	8000.000	4000.000
7	9000.000	2000.000
8	7800.000	6400.000
9	9000.000	6000.000
10	8000.000	7000.000

COORDINATES OF THE INJECTION WELL

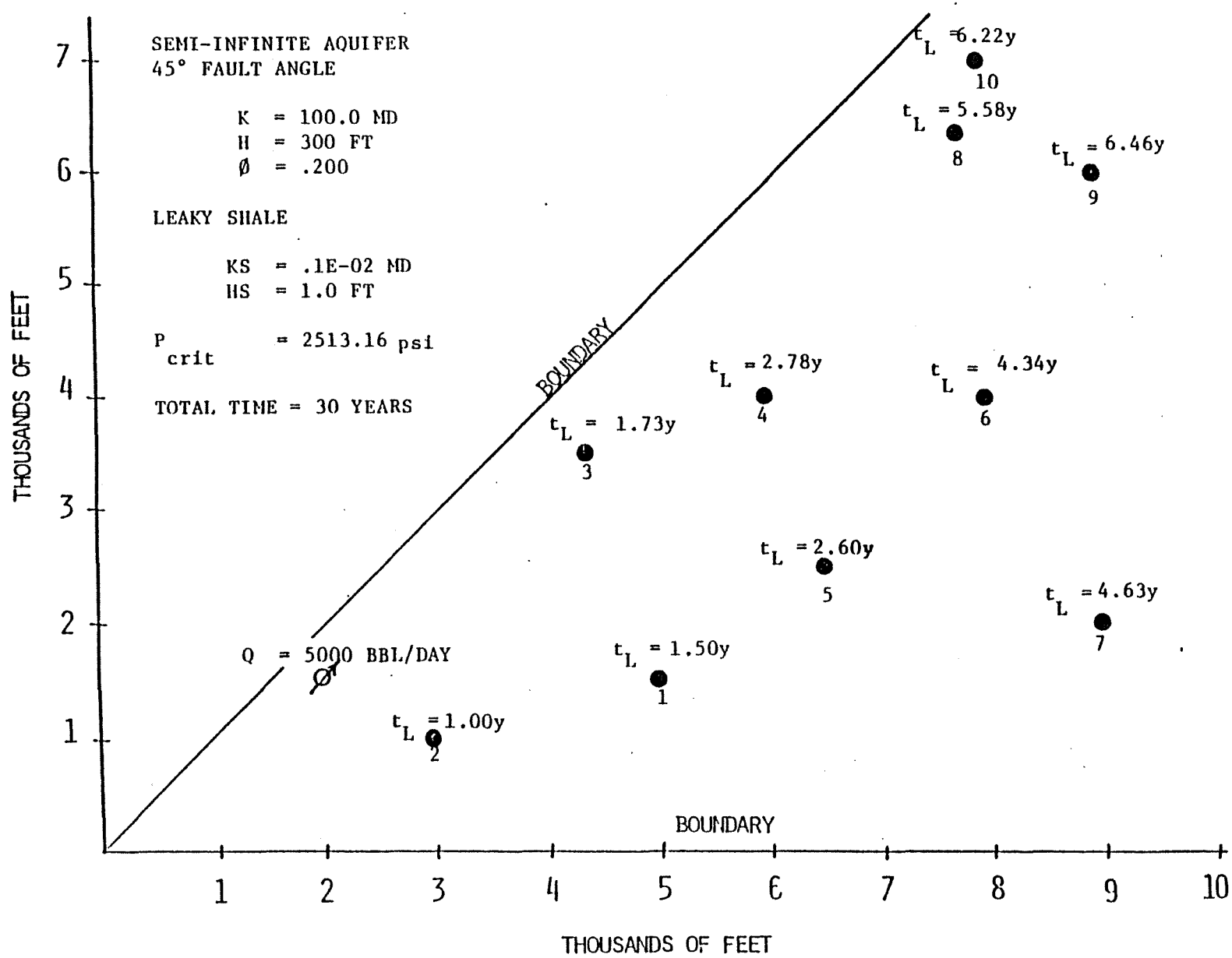
X= 2000.000 Y= 1500.000 FT.
INJECTION RATE =5000. BBL/DAY



CASE IV, GROUP 2, NO. 1



CASE 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

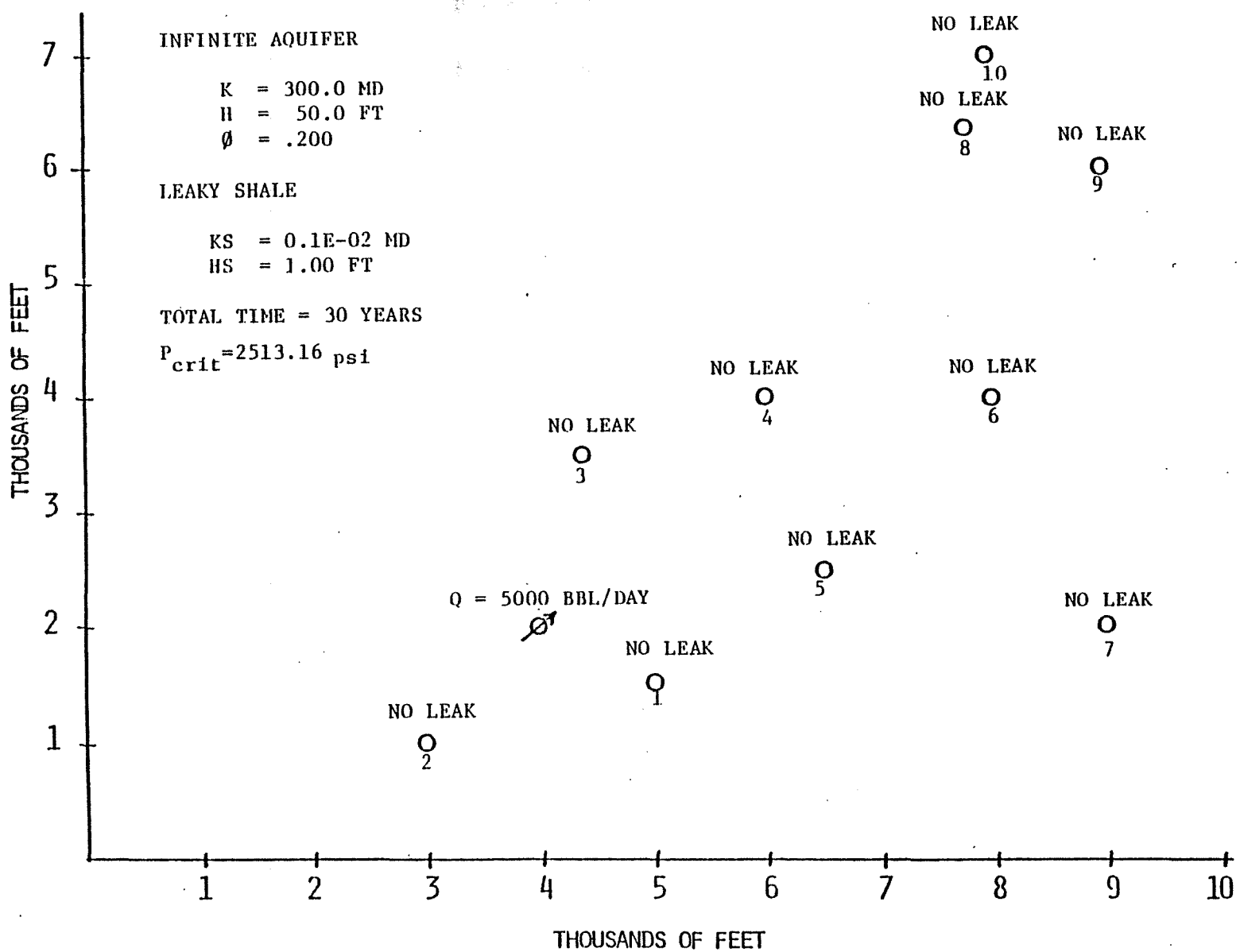
ABAN WELL	DIAM IN	DEPTH TO DISP ZONE FT	DEPTH TO H2O ZONE FT	MUD DENSITY LB/GAL	GEL STRENGTH LB/100FT2	CRITIC PRESSU PSI
1	9.6	5000.00	600.0	9.000	100.00	2513.16
2	9.6	5000.00	600.0	9.000	100.00	2513.16
3	9.6	5000.00	600.0	9.000	100.00	2513.16
4	9.6	5000.00	600.0	9.000	100.00	2513.16
5	9.6	5000.00	600.0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

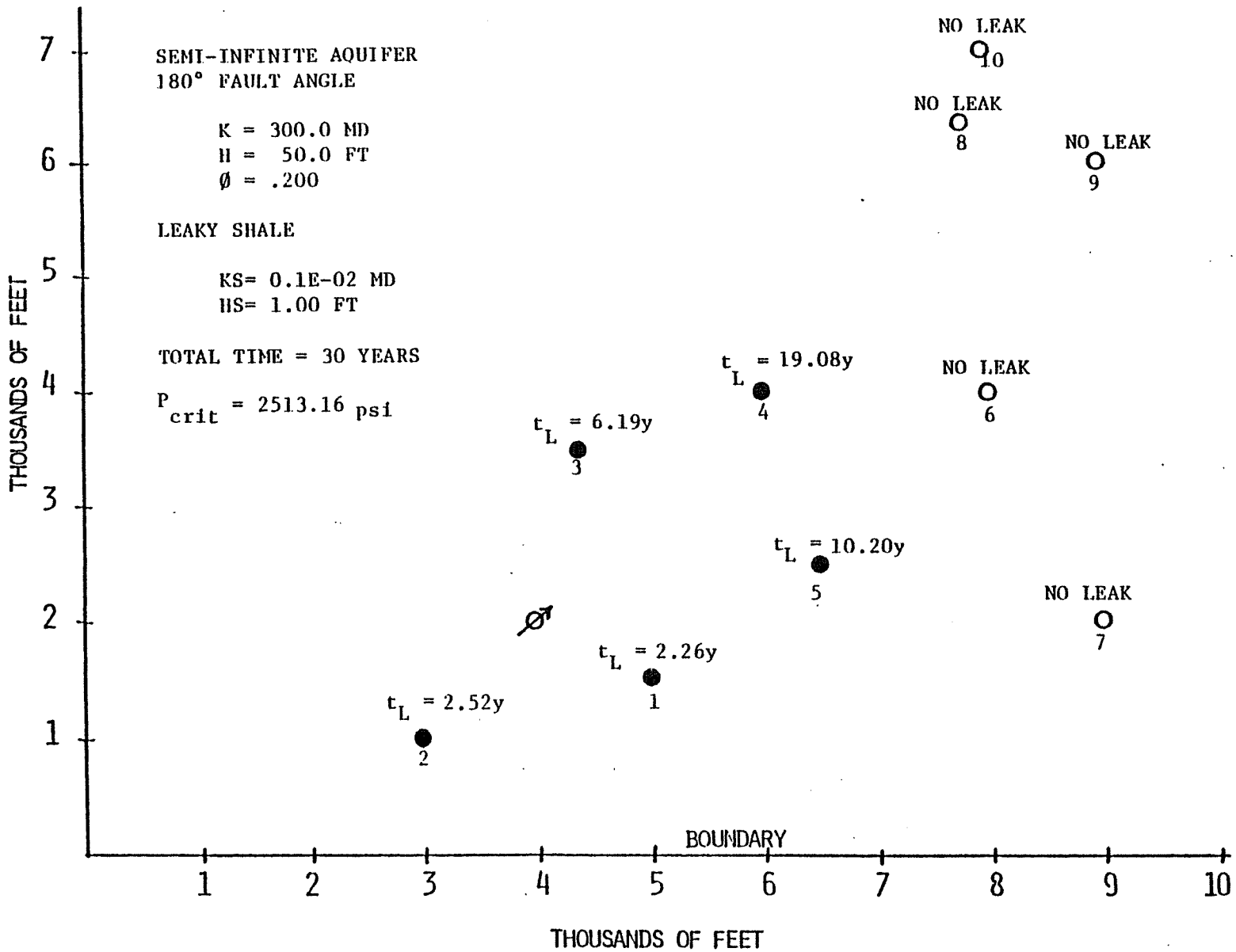
WELL #	X FT.	Y FT.
1	5000.000	1500.000
2	3000.000	1000.000
3	4400.000	3600.000
4	6000.000	4000.000
5	6500.000	2500.000
6	8000.000	4000.000
7	9000.000	2000.000
8	7800.000	6400.000
9	9000.000	6000.000
10	8000.000	7000.000

COORDINATES OF THE INJECTION WELL

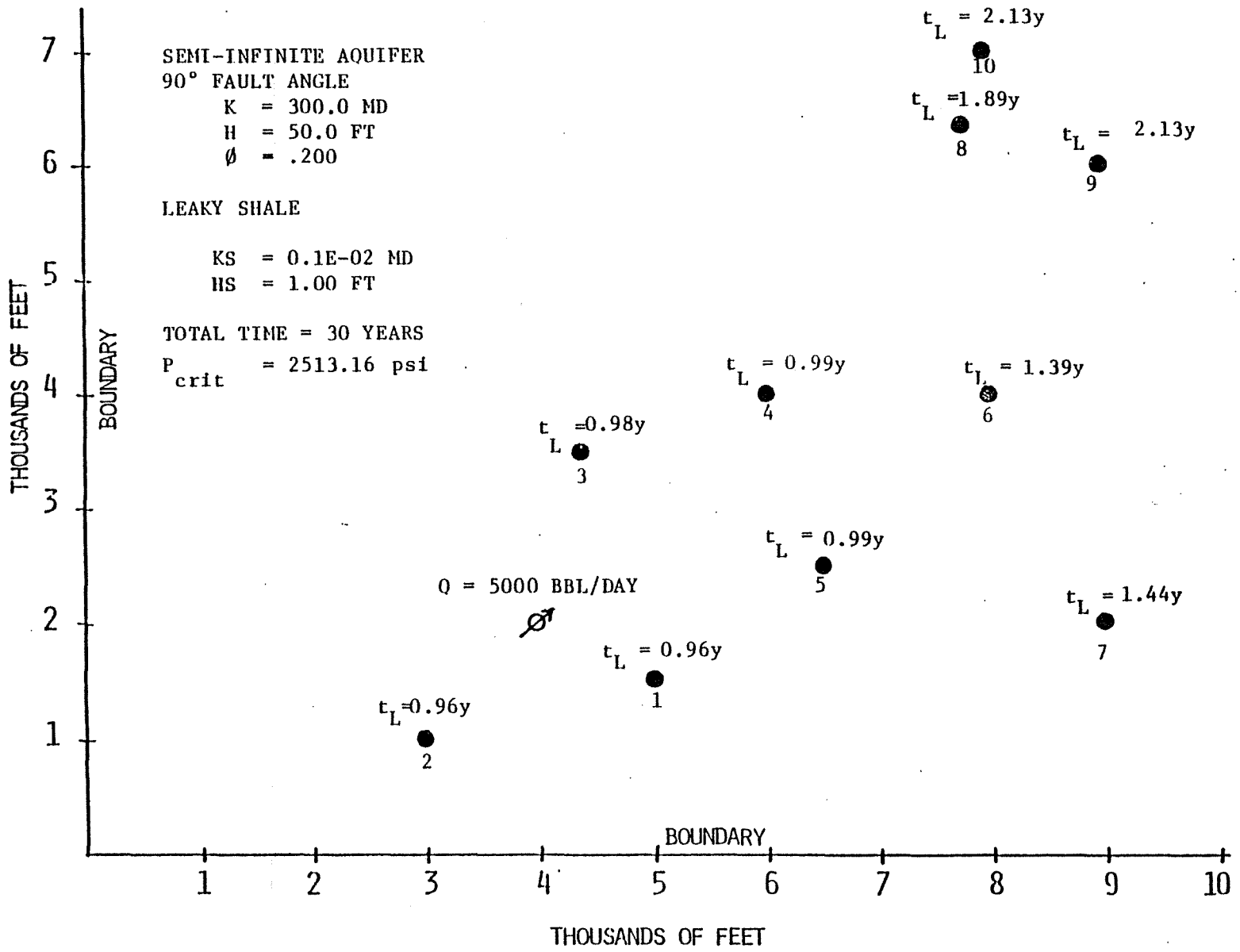
X= 4000.000 Y= 2000.000 FT.
INJECTION RATE =5000. BBL/DAY



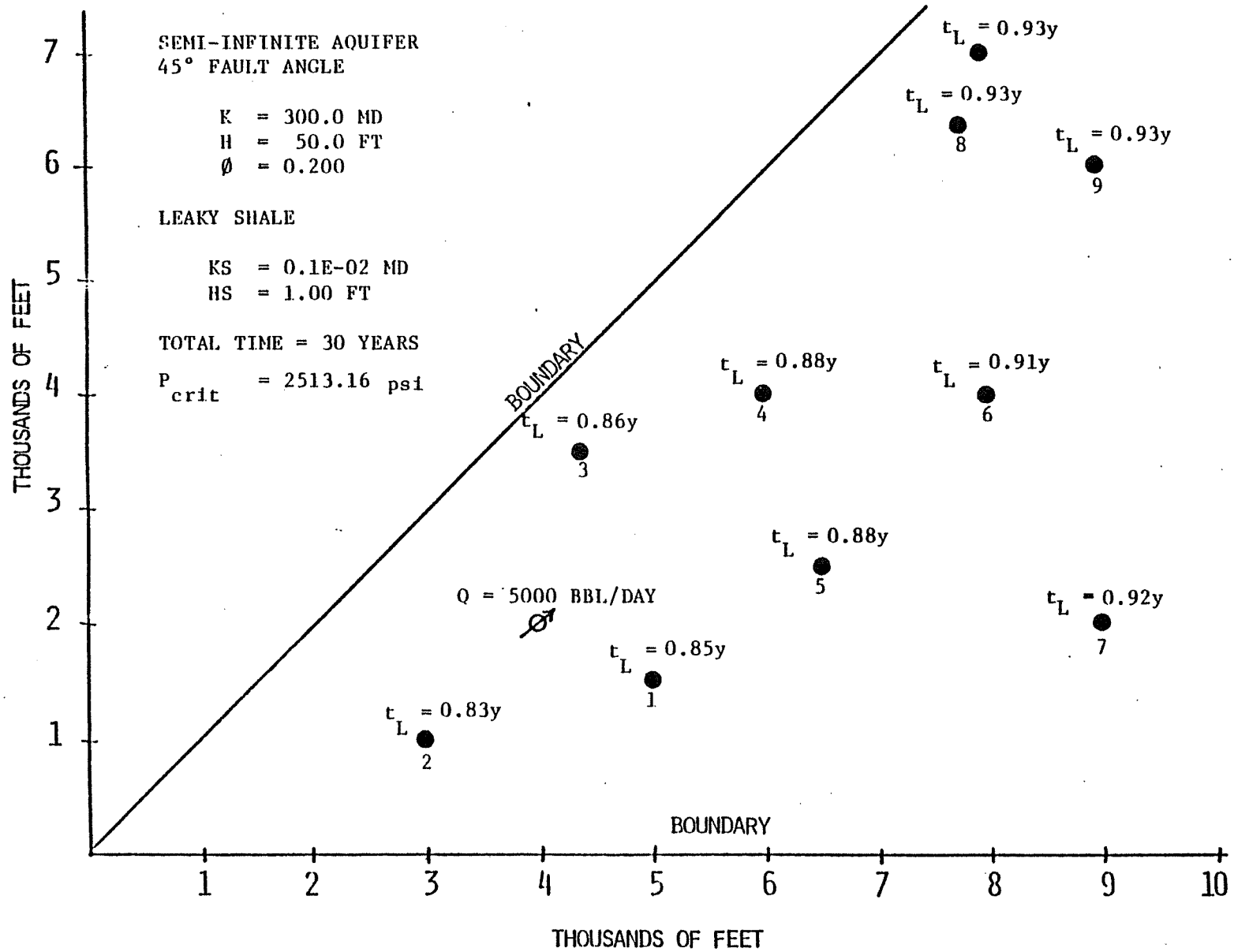
CASE IV, GROUP 3, NO. 1



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

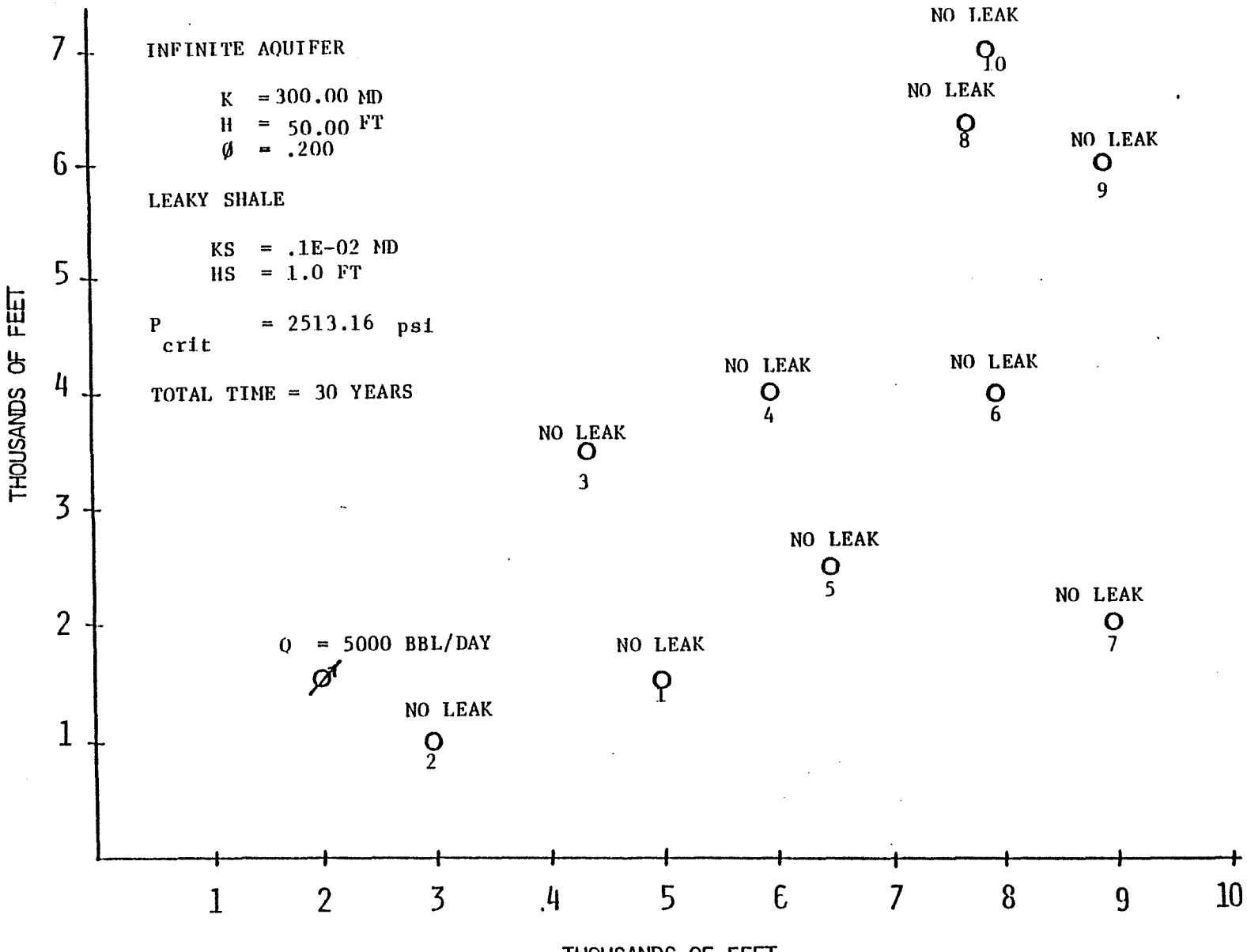
ABAN WELL	WELL DIAM IN	DEPTH TO DISP ZONE FT	DEPTH TO H2O ZONE FT	MUD DENSITY LB/GAL	GEL STRENGTH LB/100FT2	CRITIC PRESSU PSI
1	9.6	5000.00	600.0	9.000	100.00	2513.16
2	9.6	5000.00	600.0	9.000	100.00	2513.16
3	9.6	5000.00	600.0	9.000	100.00	2513.16
4	9.6	5000.00	600.0	9.000	100.00	2513.16
5	9.6	5000.00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

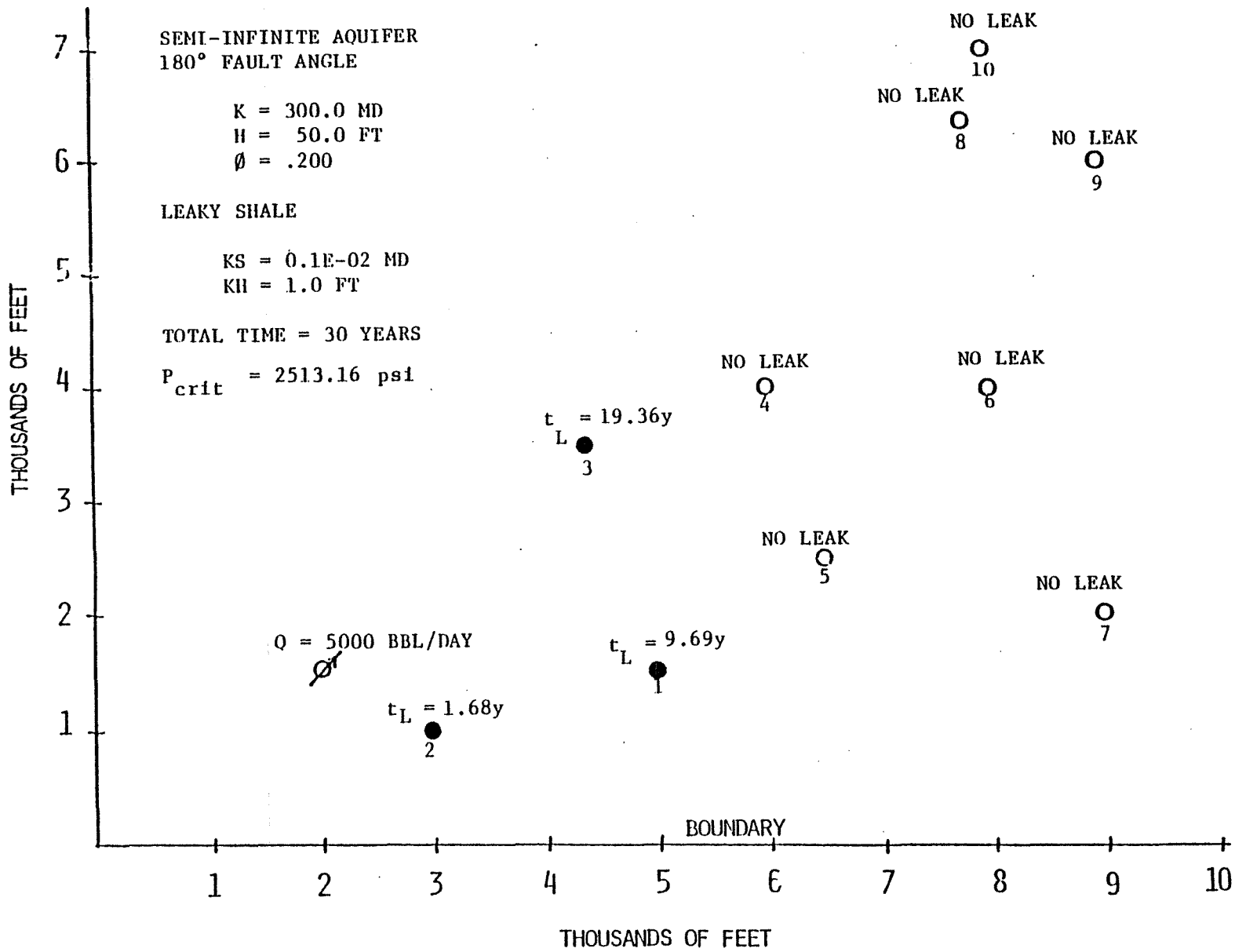
WELL #	X FT.	Y FT.
1	5000.000	1500.000
2	3000.000	1000.000
3	4400.000	3600.000
4	6000.000	4000.000
5	6500.000	2500.000
6	8000.000	4000.000
7	9000.000	2000.000
8	7800.000	6400.000
9	9000.000	6000.000
10	8000.000	7000.000

COORDINATES OF THE INJECTION WELL

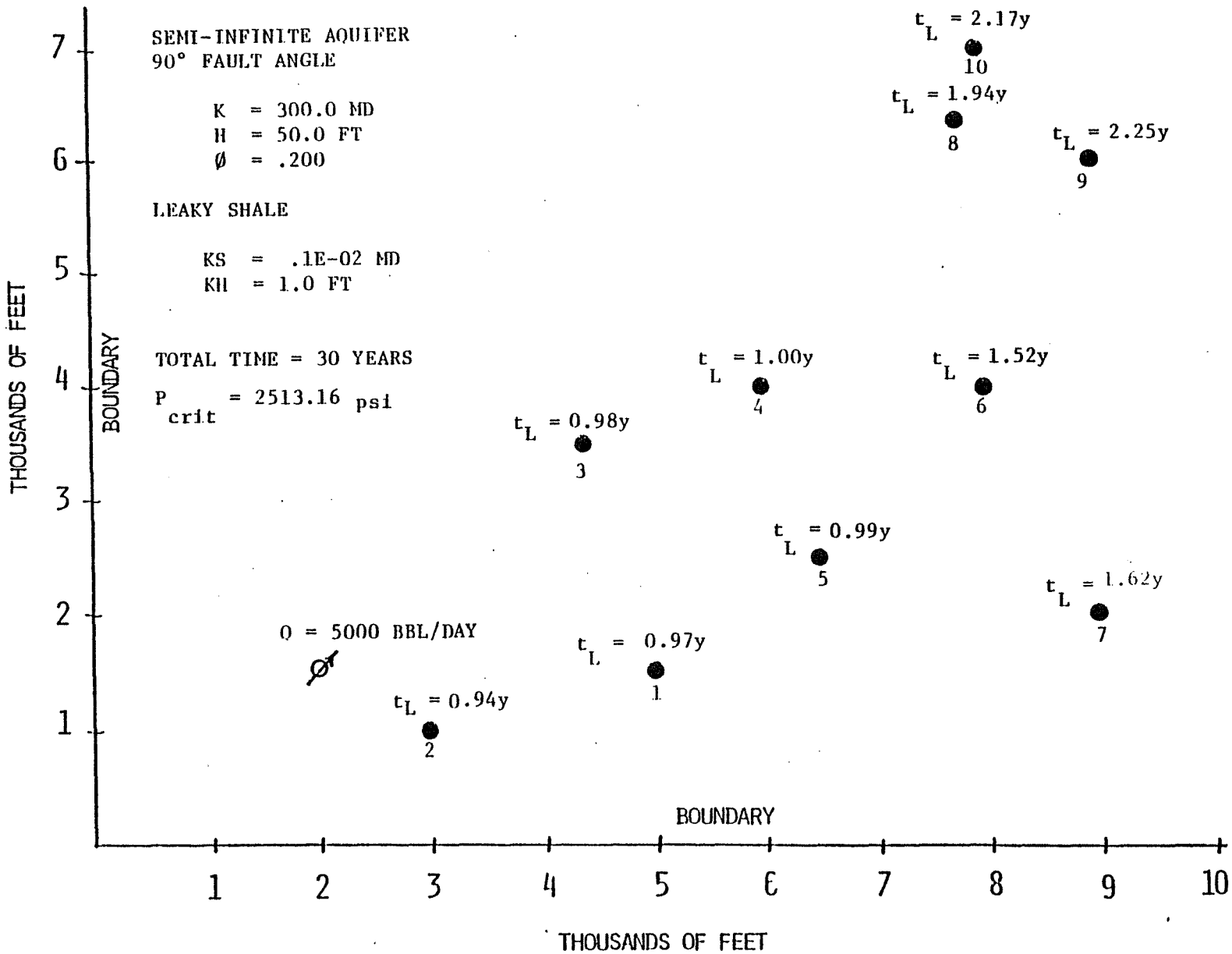
X= 2000.000 Y= 1500.000 FT.
INJECTION RATE =5000. BBL/DAY



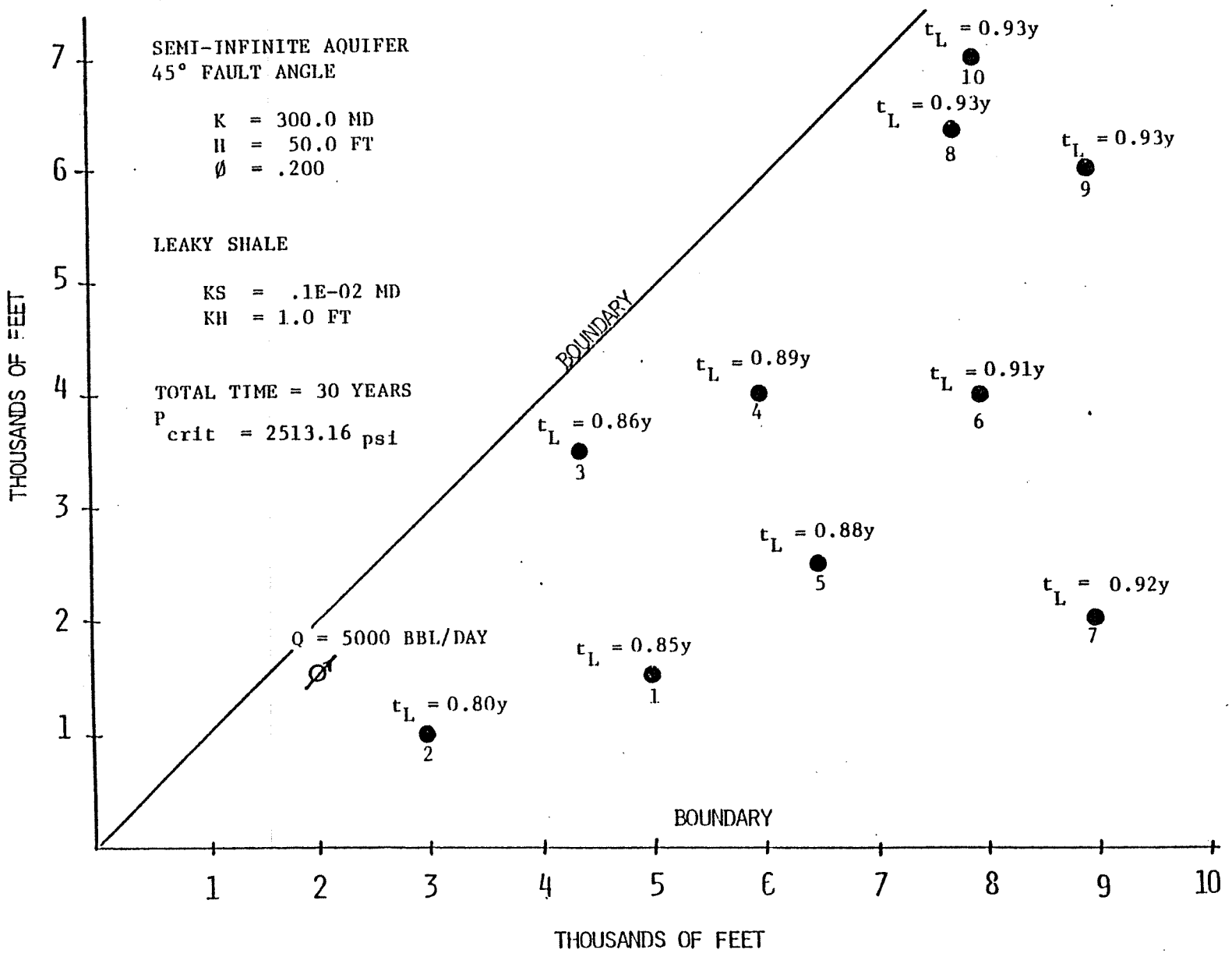
CASE IV, GROUP 4, NO. 1



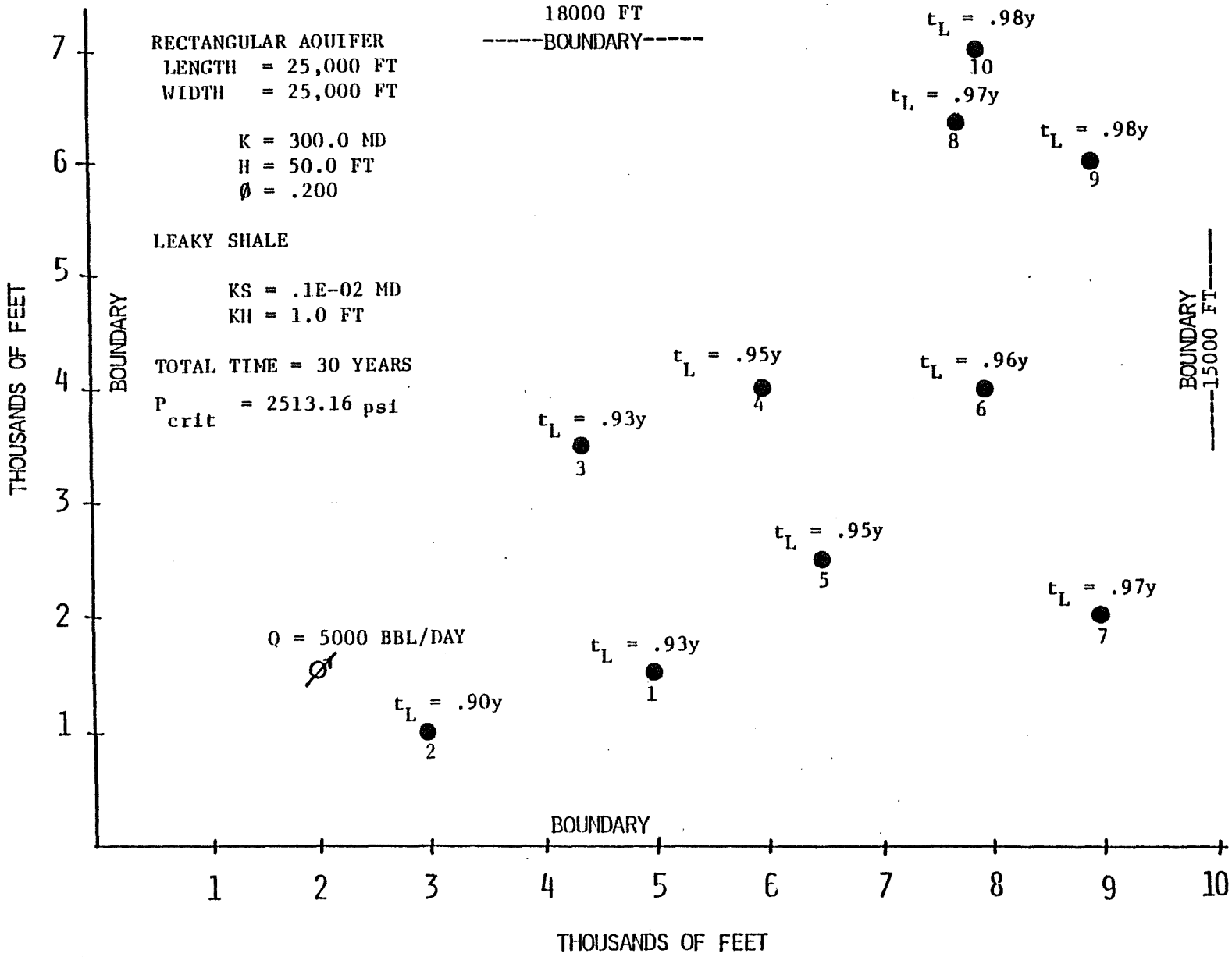
CASE IV, GROUP 4, NO. 2



CASE IV, GROUP 4, NO. 3



CASE IV, GROUP 4, NO. 4



CASE 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

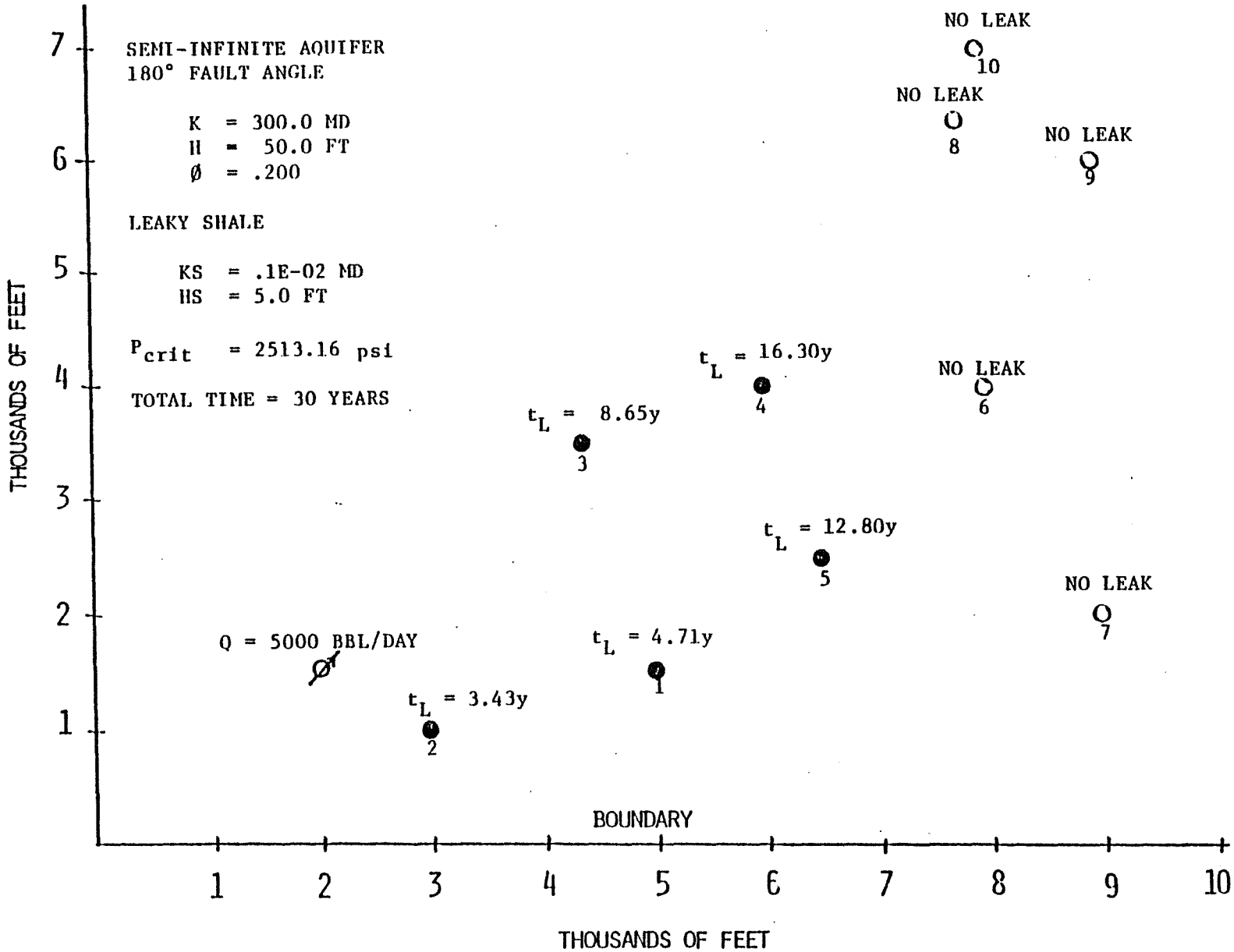
ABAN WELL	WELL DIAM IN	DEPTH TO DISP ZONE FT	DEPTH TO H2O ZONE FT	MUD DENSITY LB/GAL	GEL STRENGTH LB/100FT2	CRITIC PRESSU PSI
1	9.6	5000.00	600.0	9.000	100.00	2513.16
2	9.6	5000.00	600.0	9.000	100.00	2513.16
3	9.6	5000.00	600.0	9.000	100.00	2513.16
4	9.6	5000.00	600.0	9.000	100.00	2513.16
5	9.6	5000.00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

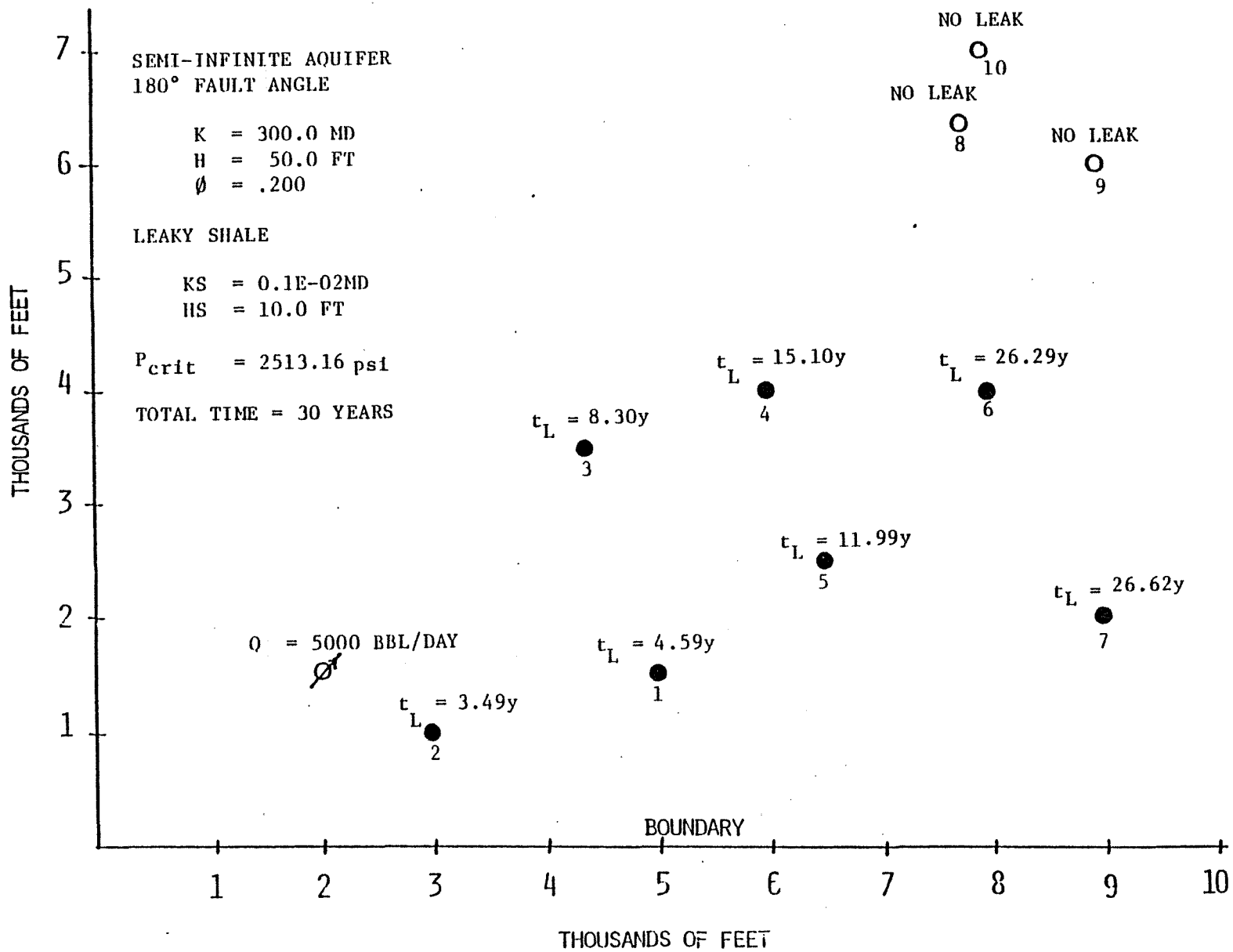
WELL #	X FT.	Y FT.
1	5000.000	1500.000
2	3000.000	1000.000
3	4400.000	3600.000
4	6000.000	4000.000
5	6500.000	2500.000
6	8000.000	4000.000
7	9000.000	2000.000
8	7800.000	6400.000
9	9000.000	6000.000
10	8000.000	7000.000

COORDINATES OF THE INJECTION WELL

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



CASE 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

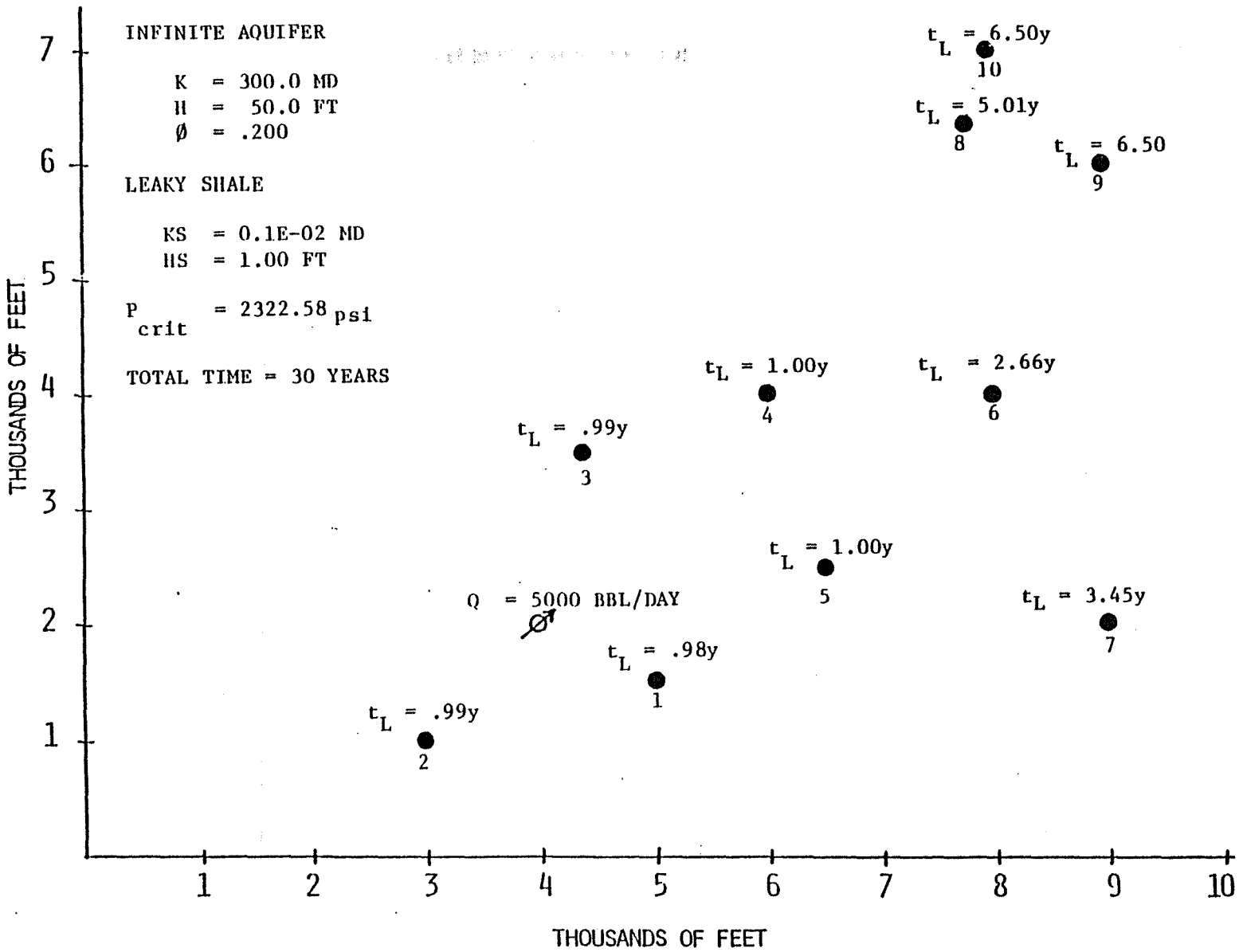
ABAN WELL	WELL DIAM IN	DEPTH TO DISP ZONE FT	DEPTH TO H2O ZONE FT	MUD DENSITY LB/GAL	GEL STRENGTH LB/100FT2	CRITIC PRESSU PSI
1	9.6	5000.00	600.0	8.600	50.00	2322.58
2	9.6	5000.00	600.0	8.600	50.00	2322.58
3	9.6	5000.00	600.0	8.600	50.00	2322.58
4	9.6	5000.00	600.0	8.600	50.00	2322.58
5	9.6	5000.00	600.0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

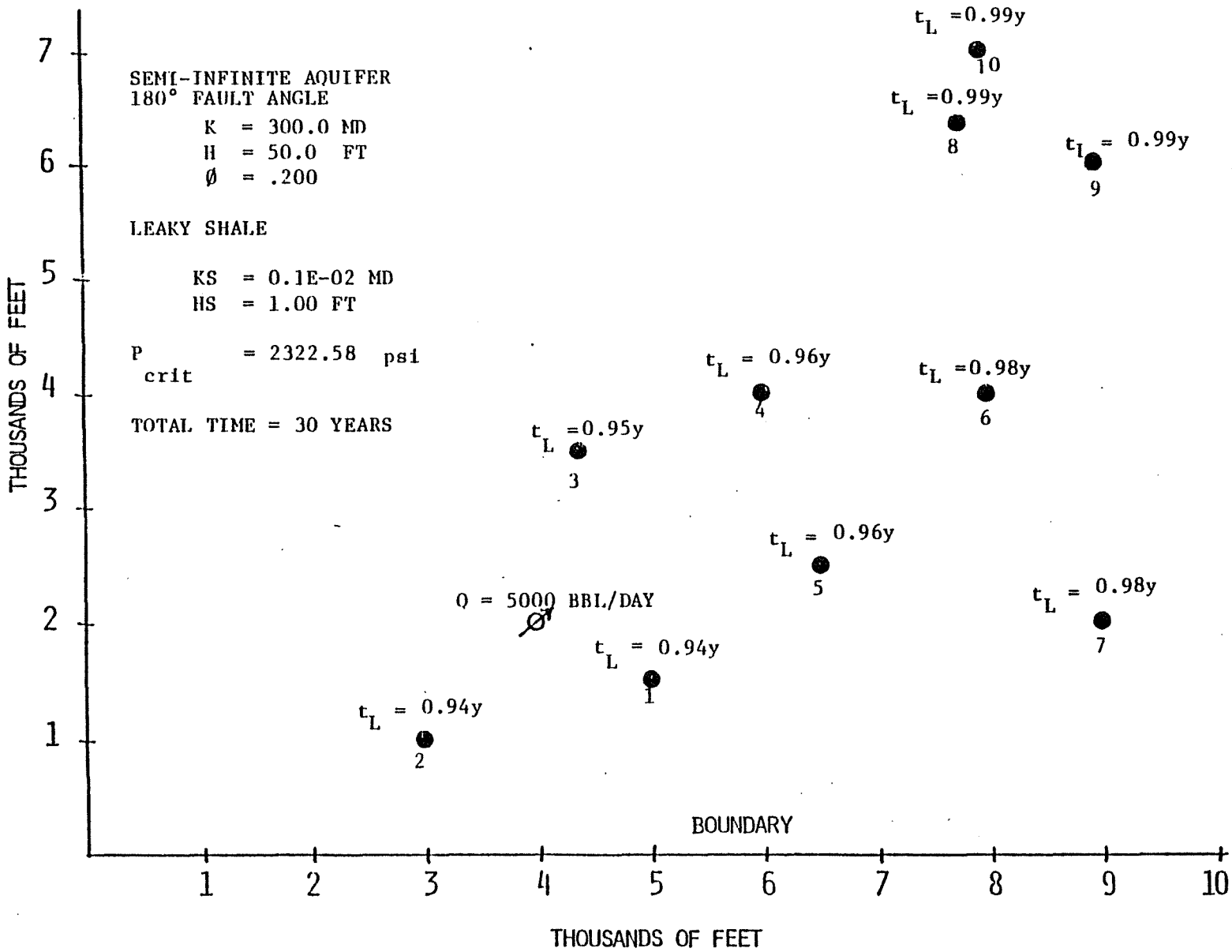
WELL #	X FT.	Y FT.
1	5000.000	1500.000
2	3000.000	1000.000
3	4400.000	3600.000
4	6000.000	4000.000
5	6500.000	2500.000
6	8000.000	4000.000
7	9000.000	2000.000
8	7800.000	6400.000
9	9000.000	6000.000
10	8000.000	7000.000

COORDINATES OF THE INJECTION WELL

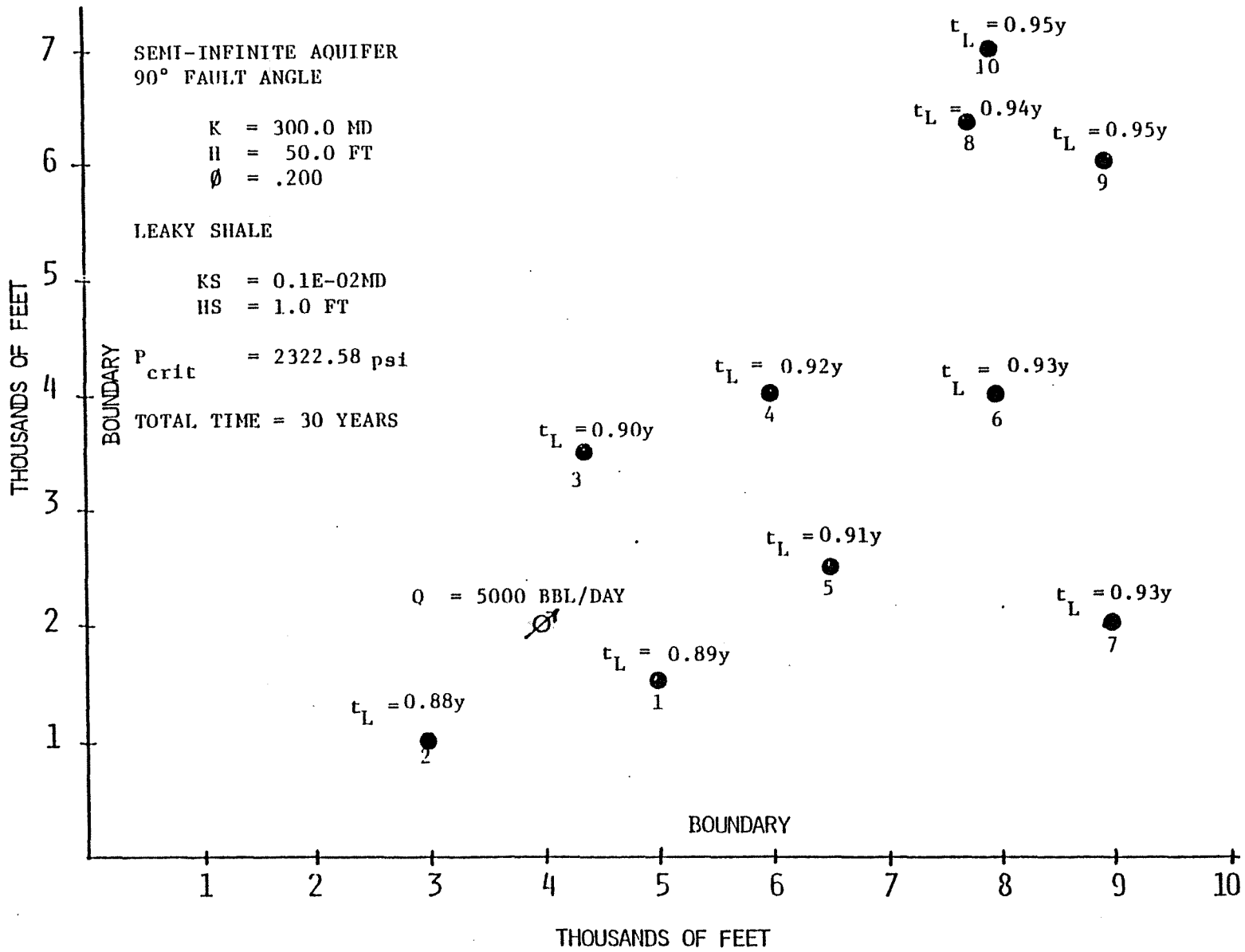
X= 4000.000 Y= 2000.000 FT.
INJECTION RATE =5000. BBL/DAY



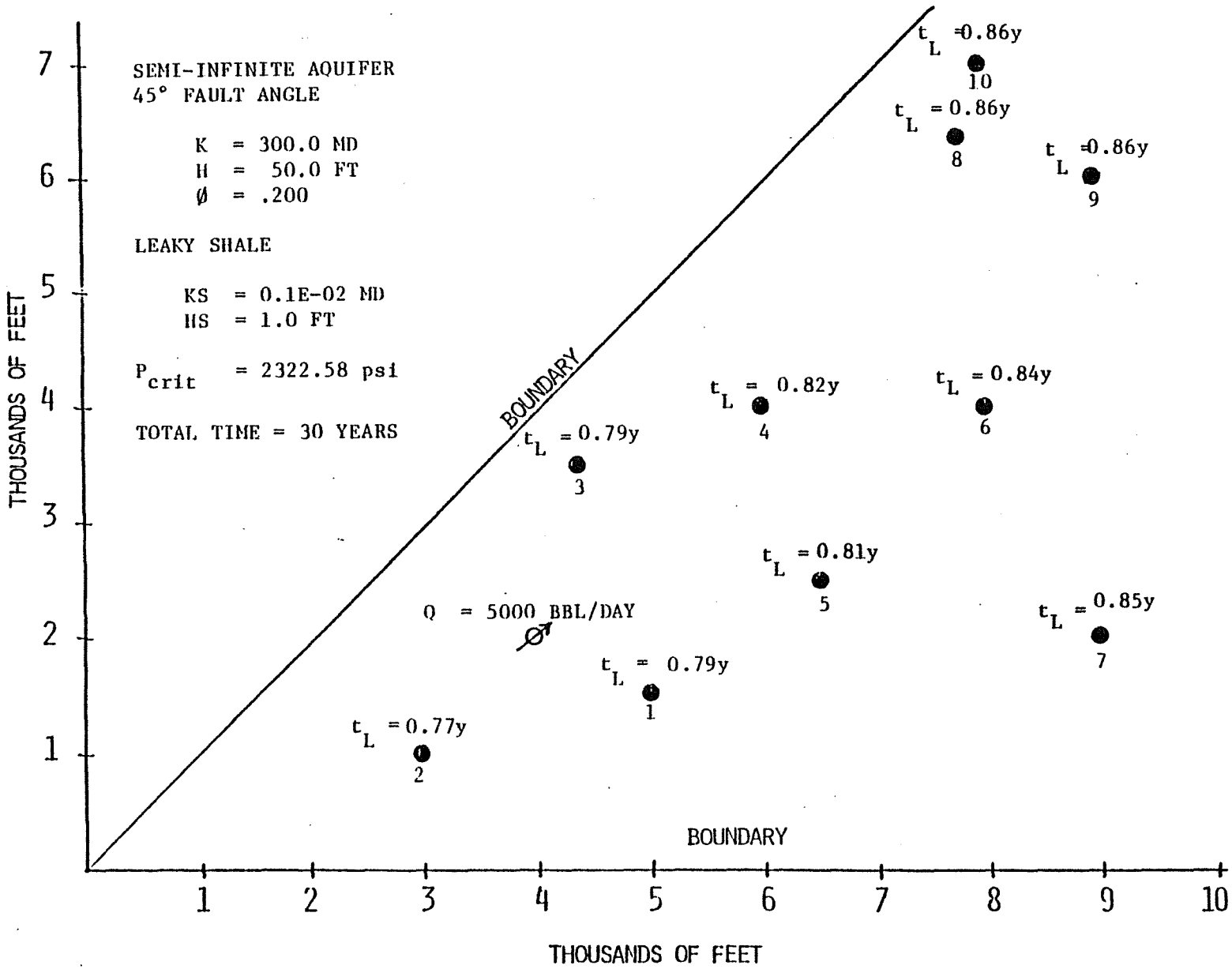
CASE IV, GROUP 6, NO. 1



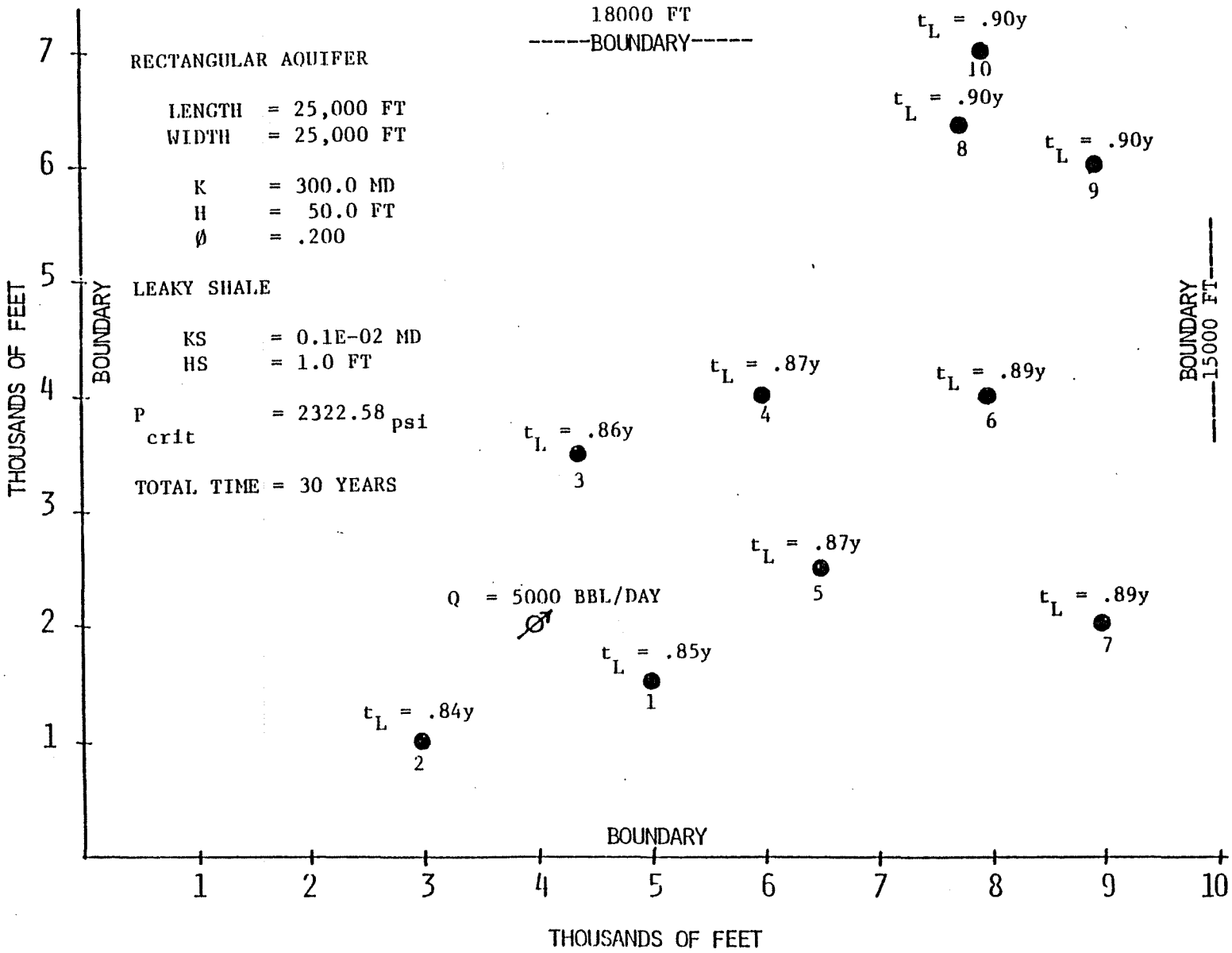
CASE IV, GROUP 6, NO. 2



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

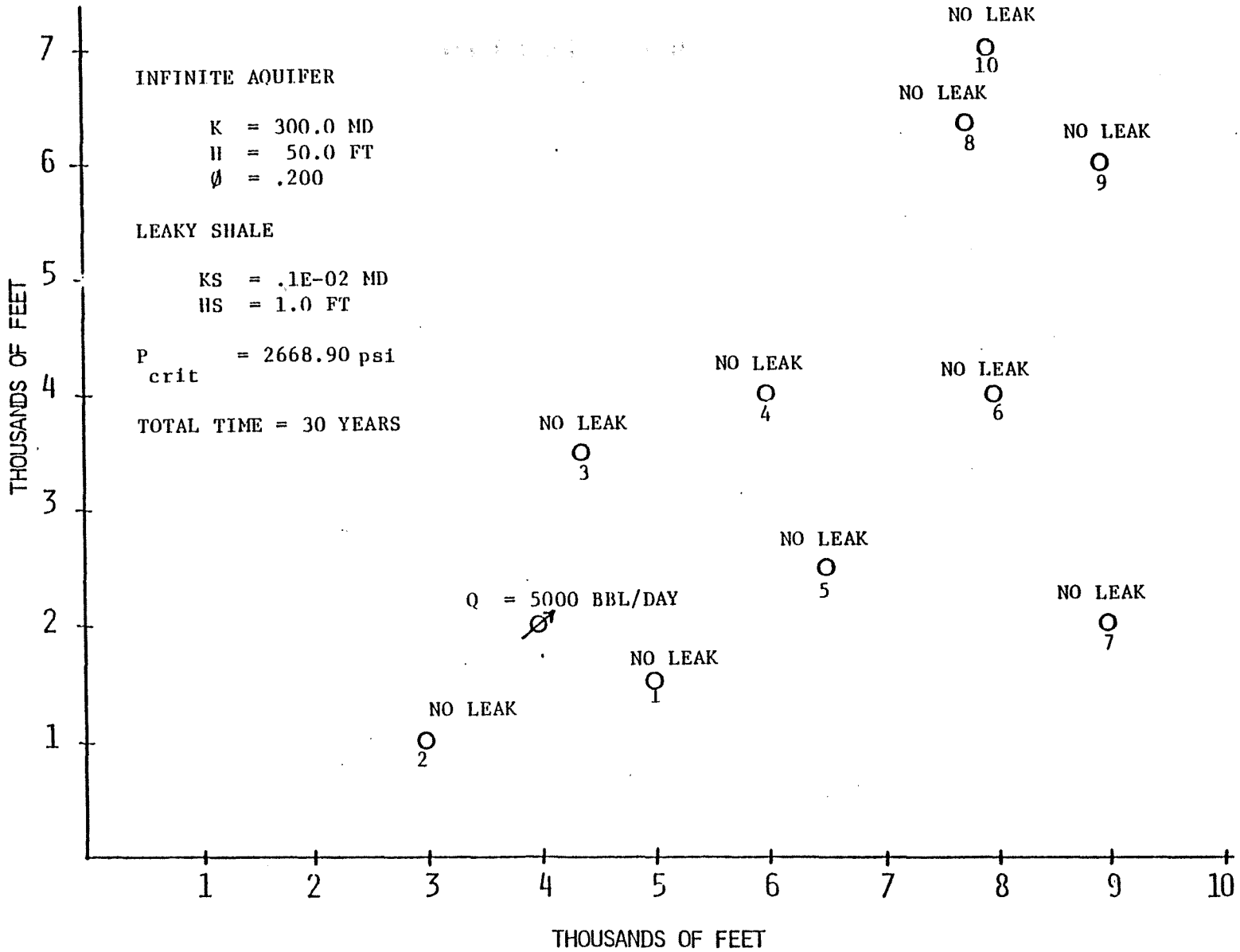
ABAN WELL	WELL DIAM IN	DEPTH TO DISP ZONE FT	DEPTH TO H2O ZONE FT	MUD DENSITY LB/GAL	GEL STRENGTH LB/100FT2	CRITIC PRESSU PSI
1	9.6	5000.00	600.0	8.600	250.00	2668.90
2	9.6	5000.00	600.0	8.600	250.00	2668.90
3	9.6	5000.00	600.0	8.600	250.00	2668.90
4	9.6	5000.00	600.0	8.600	250.00	2668.90
5	9.6	5000.00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

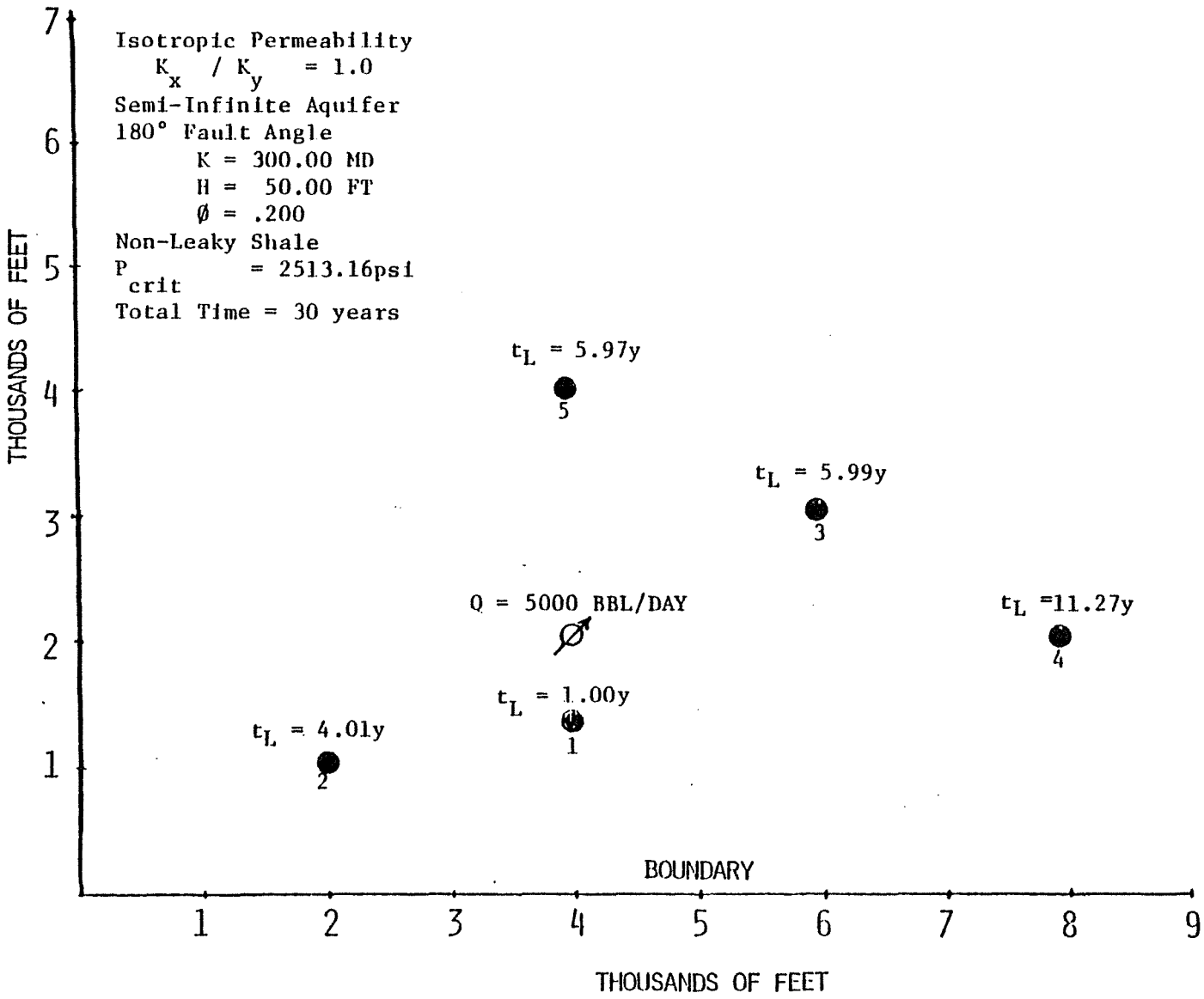
ABAN WELL	DIAM IN	DEPTH TO DISP ZONE FT	DEPTH TO H2O ZONE FT	MUD DENSITY LB/GAL	GEL STRENGTH LB/100FT2	CRITIC PRESSU PSI
1	9.6	5000.00	600.0	9.000	100.00	2513.16
2	9.6	5000.00	600.0	9.000	100.00	2513.16
3	9.6	5000.00	600.0	9.000	100.00	2513.16
4	9.6	5000.00	600.0	9.000	100.00	2513.16
5	9.6	5000.00	600.0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

COORDINATES OF THE ABANDONED WELLS

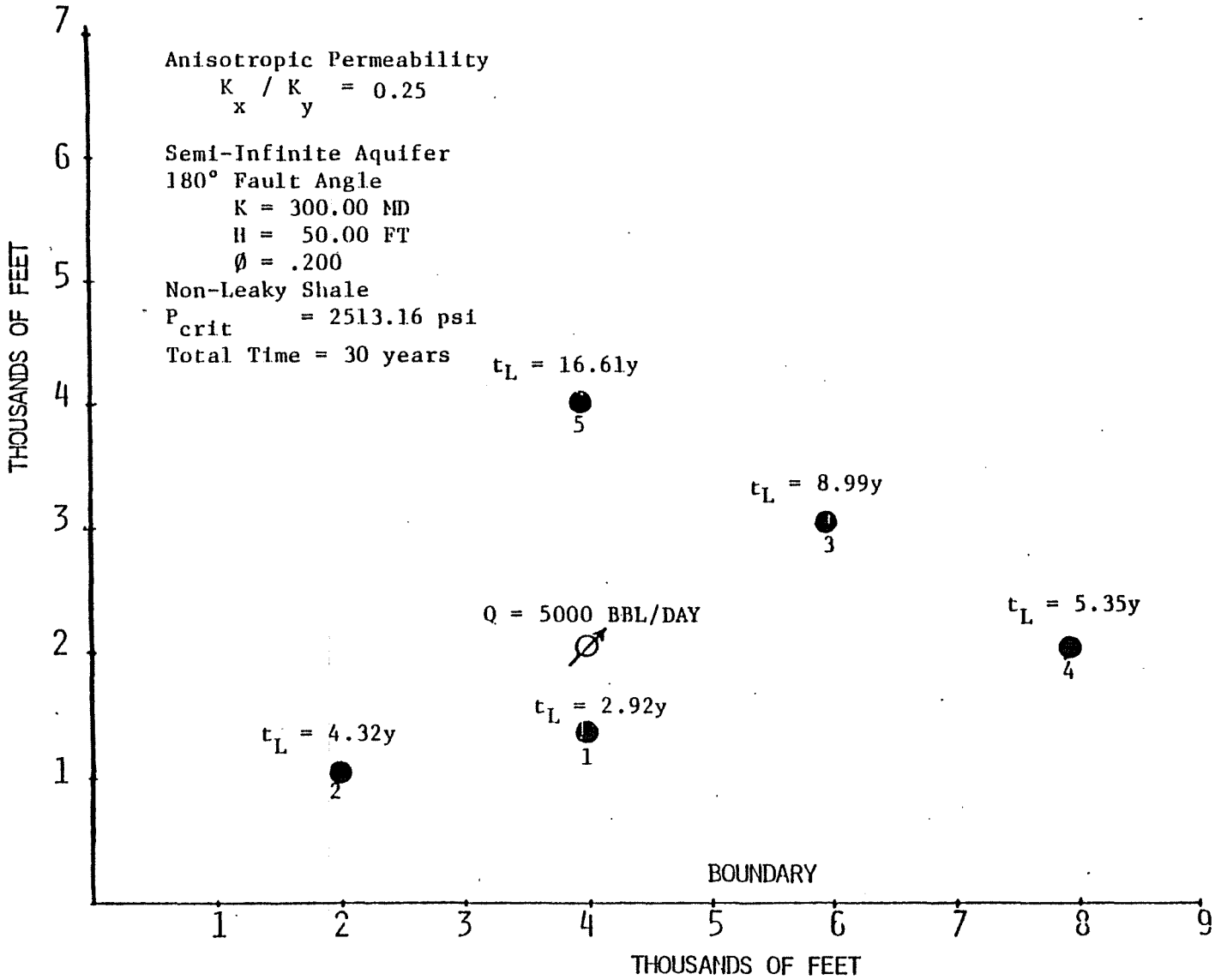
WELL #	X FT.	Y FT.
1	4000.000	1500.000
2	2000.000	1000.000
3	6000.000	3000.000
4	8000.000	2000.000
5	4000.000	4000.000

COORDINATES OF THE INJECTION WELL

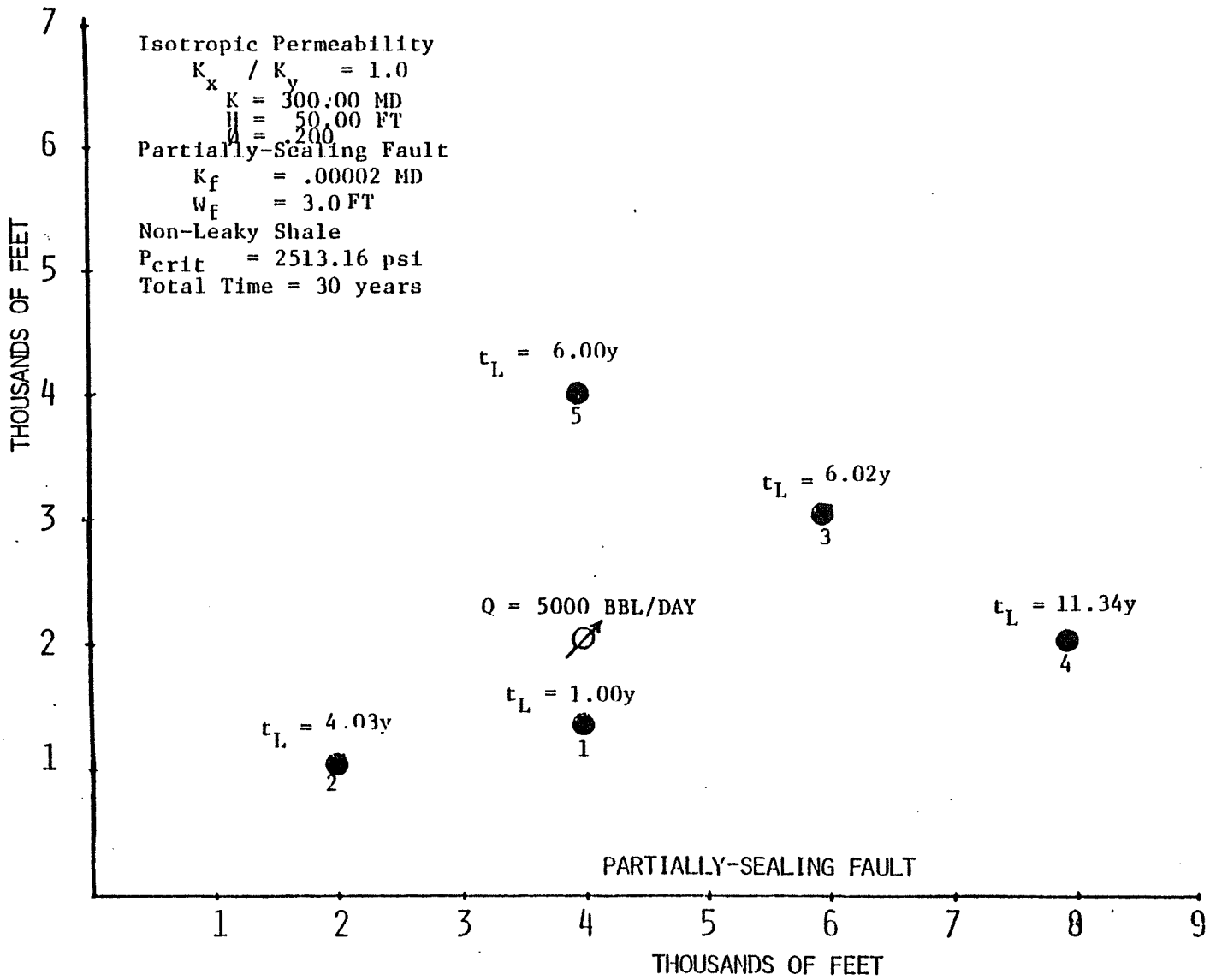
X= 4000.000 Y= 2000.000 FT.
INJECTION RATE =5000. BBL/DAY


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

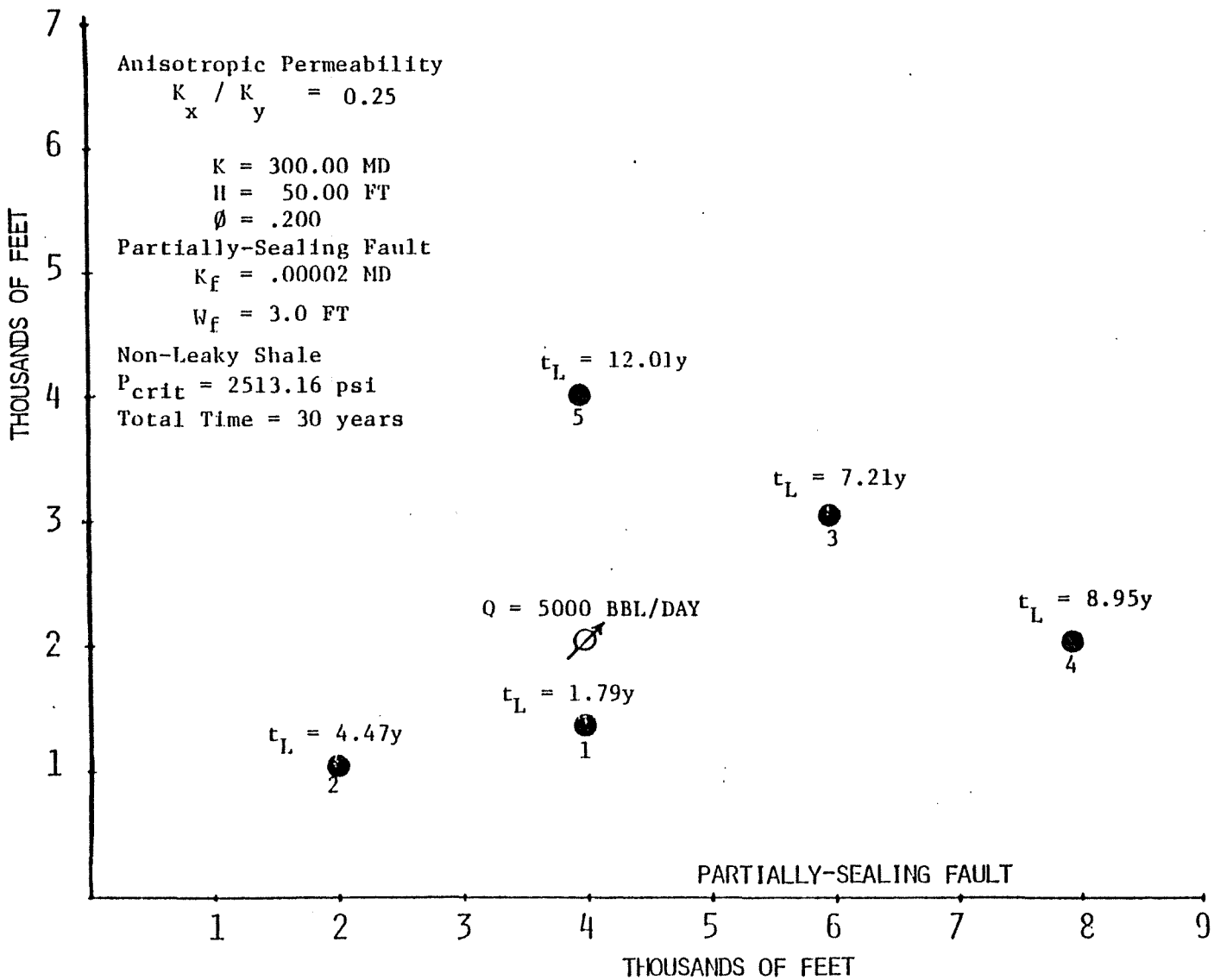
CASE V, NO. 1


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 = 1.00y
1
t_L = 4.03y
2
PARTIALLY-SEALING FAULT
THOUSANDS OF FEET
THOUSANDS OF FEET
1
2
3
4
5
6
7
8
9

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
1
2
3
4
5
6
7
8
9

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

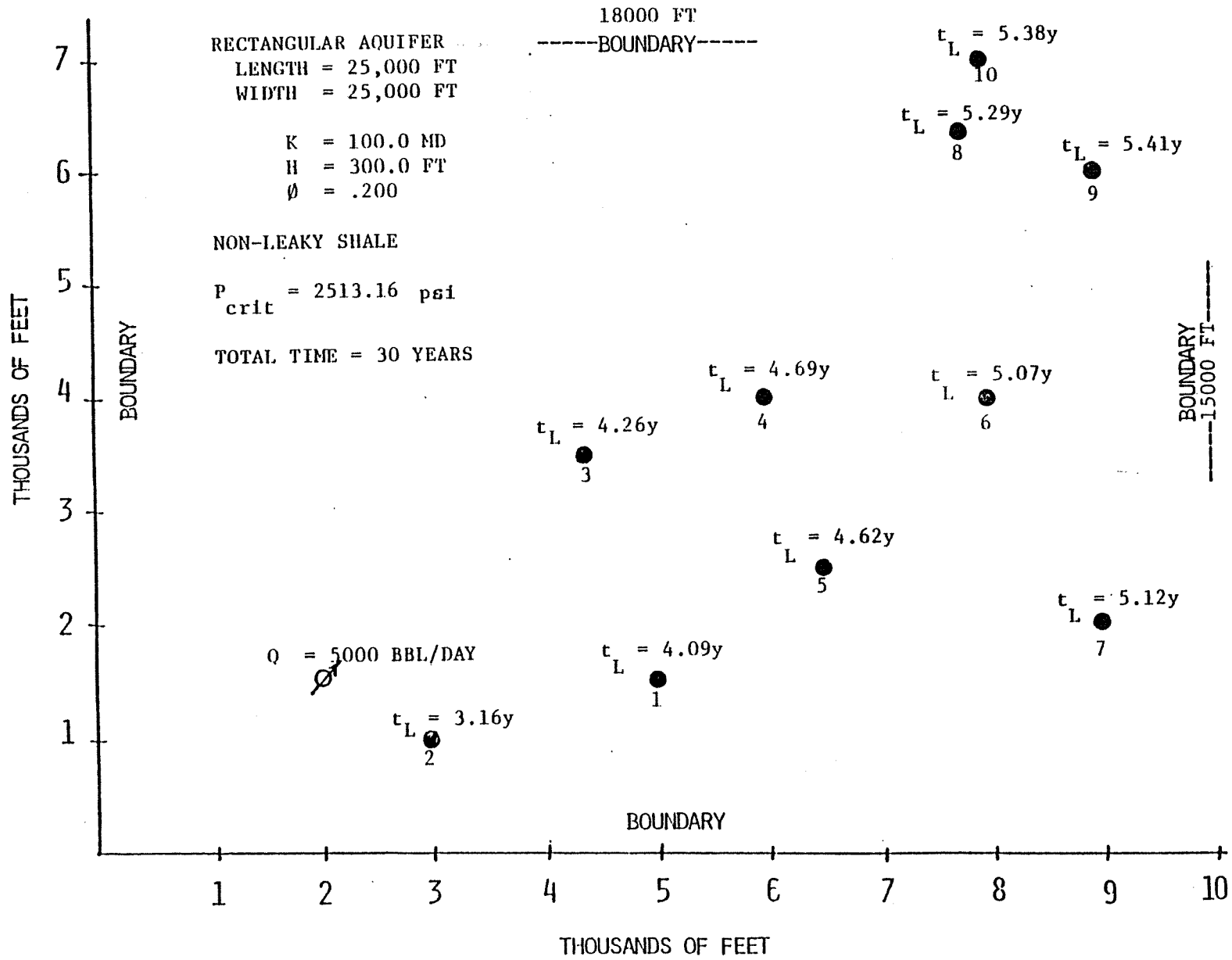
SYSTEM CONFIGURATION

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


18000 FT
-----BOUNDARY-----
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
Q = 5000 BBL/DAY
t L = 3.16y
2
t L = 4.09y
1
t L = 4.26y
3
t L = 4.69y
4
t L = 4.62y
5
t L = 5.07y
6
t L = 5.12y
7
t L = 5.29y
8
t L = 5.38y
10
t L = 5.41y
9
BOUNDARY
BOUNDARY
BOUNDARY
15000 FT
THOUSANDS OF FEET
THOUSANDS OF FEET
1
2
3
4
5
6
7
8
9
10

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

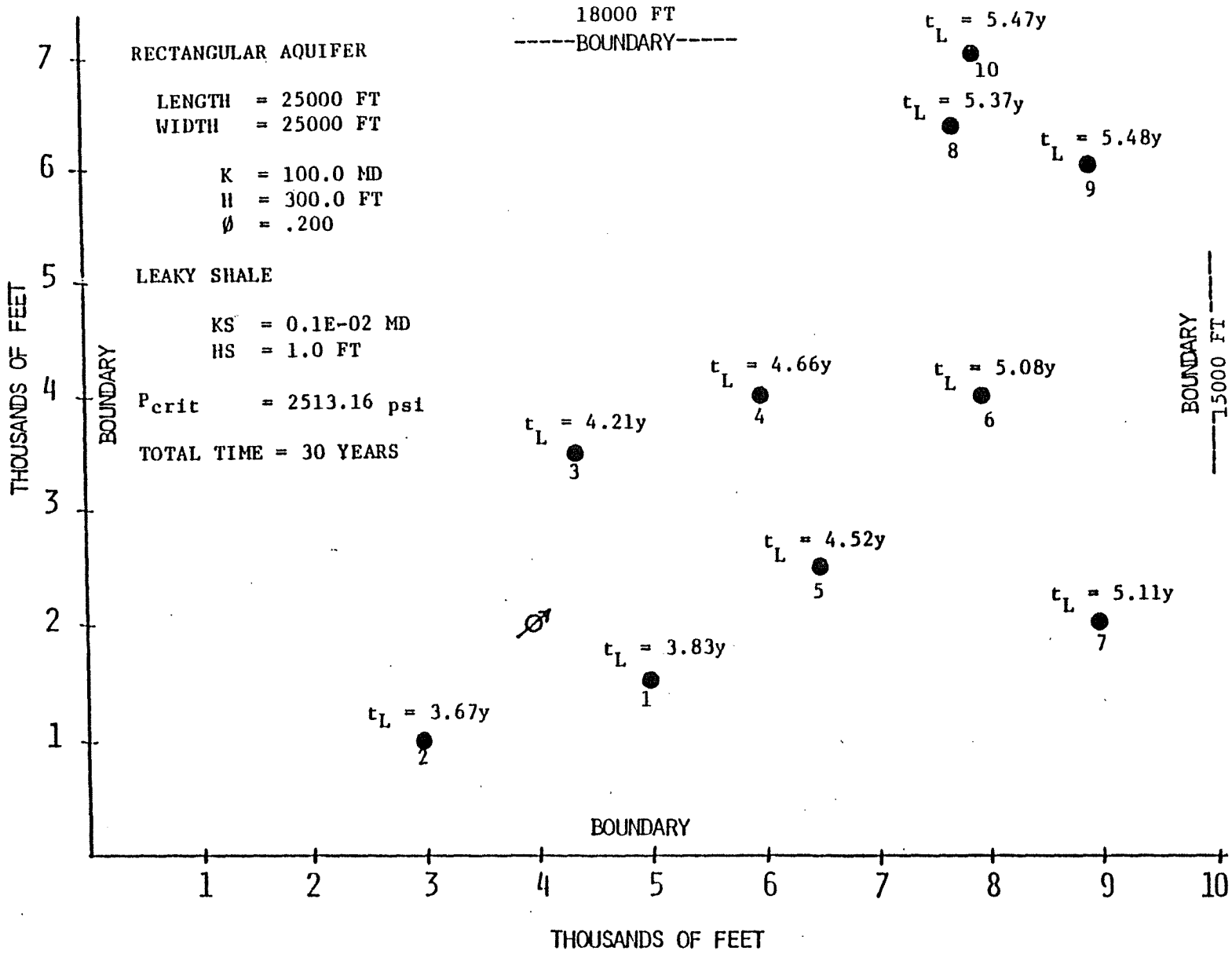
LEAKY SHALE LAYER

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


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
18000 FT
-----BOUNDARY-----
BOUNDARY
15000 FT
BOUNDARY
BOUNDARY
THOUSANDS OF FEET
THOUSANDS OF FEET
tL = 3.67y
tL = 3.83y
tL = 4.21y
tL = 4.66y
tL = 4.52y
tL = 5.08y
tL = 5.11y
tL = 5.37y
tL = 5.48y
tL = 5.47y
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

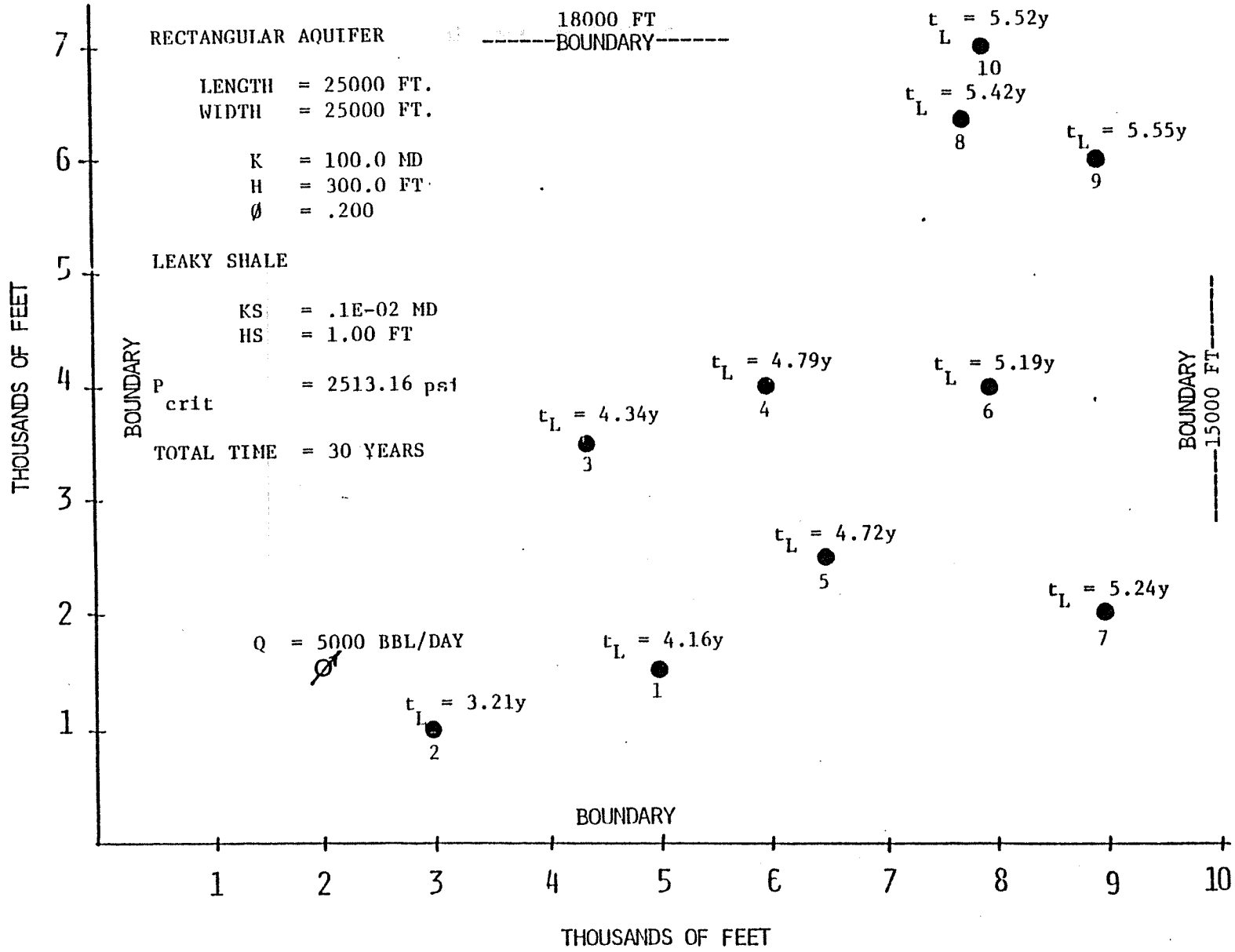
LEAKY SHALE LAYER

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
Q = 5000 BBL/DAY
Ø
18000 FT
BOUNDARY
BOUNDARY
BOUNDARY
15000 FT
BOUNDARY
t L = 3.21y
2
t L = 4.16y
1
t L = 4.34y
3
t L = 4.79y
4
t L = 4.72y
5
t L = 5.19y
6
t L = 5.24y
7
t L = 5.42y
8
t L = 5.55y
9
t L = 5.52y
10
THOUSANDS OF FEET
1
2
3
4
5
6
7
8
9
10
THOUSANDS OF FEET
1
2
3
4
5
6
7

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

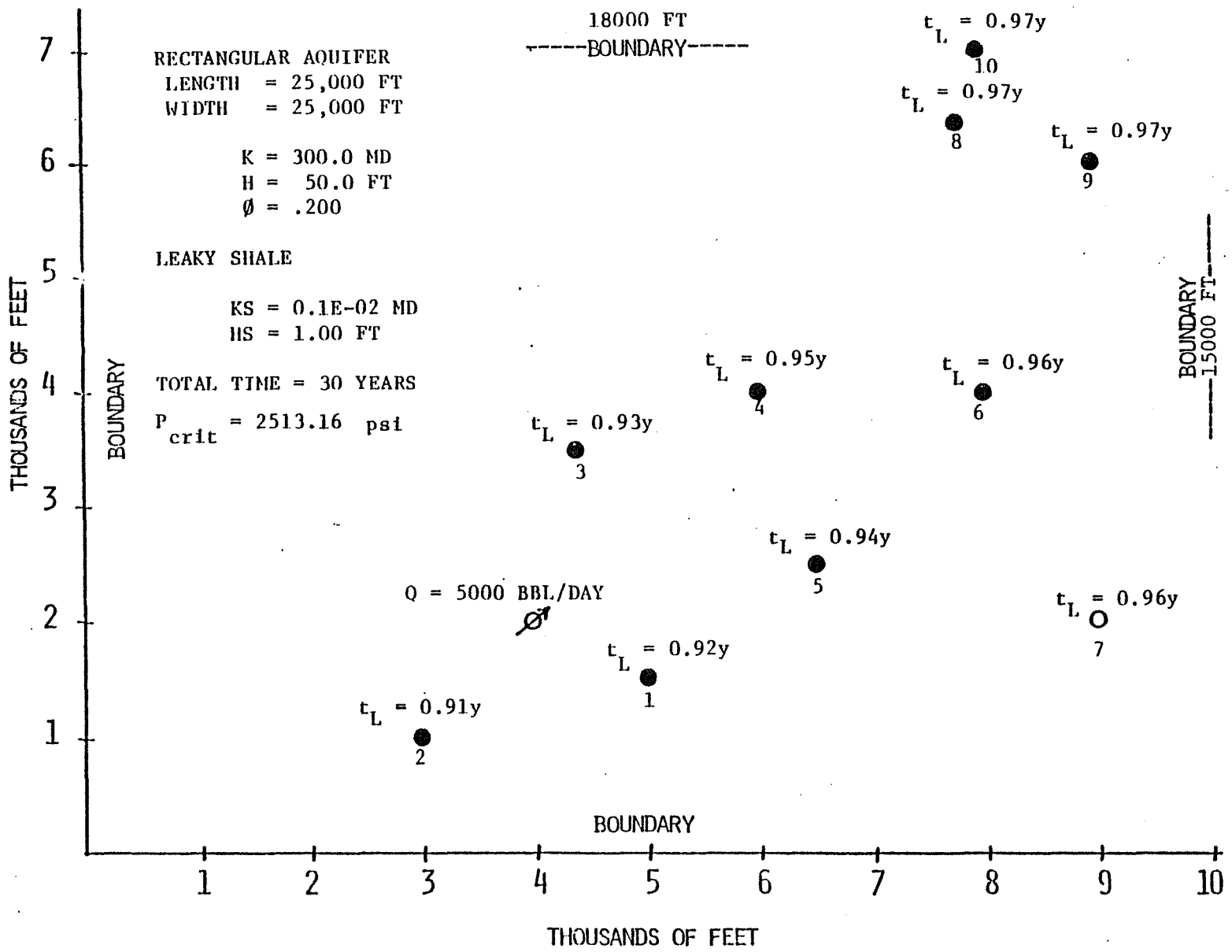
LEAKY SHALE LAYER

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
tL = 0.92y
tL = 0.93y
tL = 0.94y
tL = 0.95y
tL = 0.96y
tL = 0.96y
tL = 0.97y
tL = 0.97y
tL = 0.97y
1
2
3
4
5
6
7
8
9
10
THOUSANDS OF FEET
THOUSANDS OF FEET

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

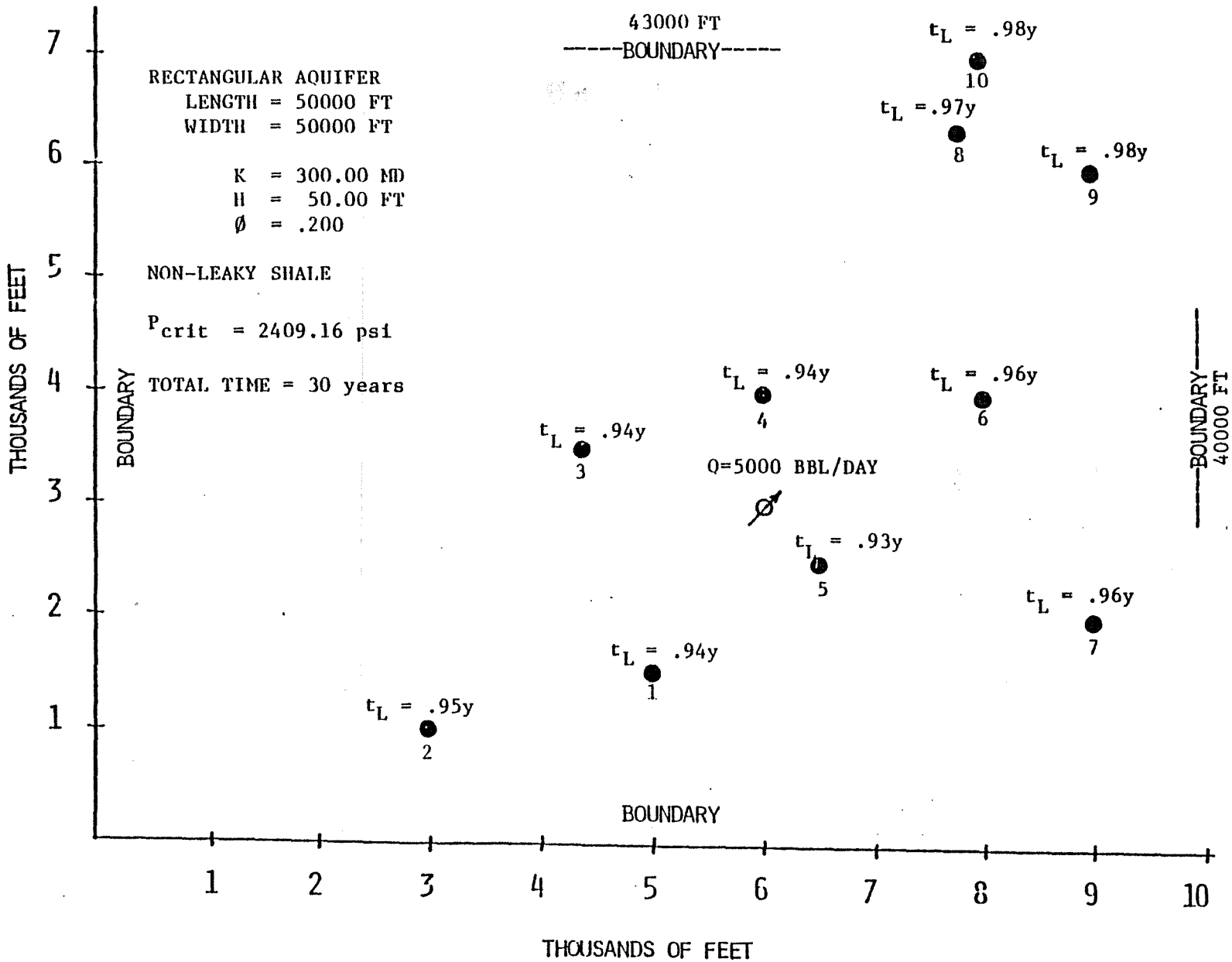
SYSTEM CONFIGURATION

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
Pcrit = 2409.16 psi
TOTAL TIME = 30 years
43000 FT
BOUNDARY
BOUNDARY
BOUNDARY
BOUNDARY
40000 FT
Q=5000 BBL/DAY
tL = .95y
tL = .94y
tL = .94y
tL = .94y
tL = .93y
tL = .96y
tL = .96y
tL = .97y
tL = .98y
tL = .98y
1
2
3
4
5
6
7
8
9
10
THOUSANDS OF FEET
THOUSANDS OF FEET

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

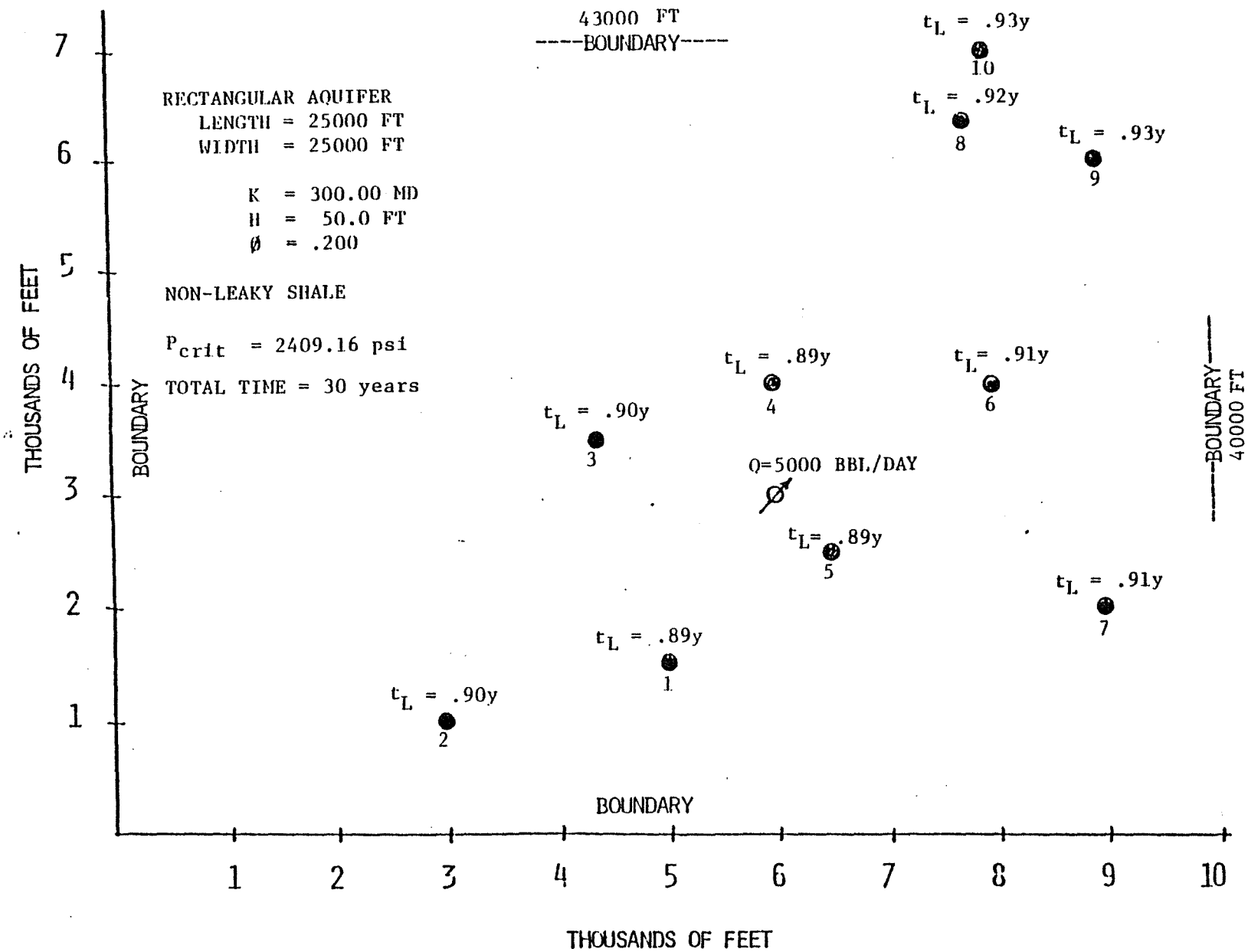
SYSTEM CONFIGURATION

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
P_{crit} = 2409.16 psi
TOTAL TIME = 30 years
t_L = .93y
10
t_L = .92y
8
t_L = .93y
9
t_L = .89y
4
t_L = .91y
6
t_L = .90y
3
Q=5000 BBL/DAY
t_L = .89y
5
t_L = .91y
7
t_L = .89y
1
t_L = .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

APPENDIX 4-12

Appendix 4-12

Confining Layer Study – Supplemental Report (Warner et al., 1986)

Confining Layer Study - Supplemental Report

Prepared for

U.S. Environmental Protection Agency

Region V, Chicago, Illinois

SUBMITTED BY:

ENGINEERING ENTERPRISES, INC.

WATER RESOURCES SPECIALISTS

UNDER CONTRACT NO. 68-01-7011

CONFINING LAYER STUDY - SUPPLEMENTAL REPORT

PREPARED FOR U.S. EPA REGION V
UNDER CONTRACT NO. 68-01-7011

RESPECTFULLY SUBMITTED
DON L. WARNER, INC.
ROLLA, MISSOURI
ENGINEERING ENTERPRISES, INC.
NORMAN, OKLAHOMA

AUGUST, 1986

DISCLAIMER

Although the information in this document has been funded wholly or in part by the United States Environmental Protection Agency under Contract No. 68-01-7011 to Engineering Enterprises, Inc., it does not necessarily reflect the views of the Agency and no official endorsement should be inferred.

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CHAPTER 9

FLOW THROUGH CONFINING LAYERS

The entire purpose of the evaluation of a confining layer or layers for containment of injected wastewater is to provide assurance against vertical migration of wastewater or saline water from the injection unit into overlying fresh water bearing aquifers. Such vertical movement could occur as a result of:

1. Intergranular flow through unbreached confining strata,
2. Flow through naturally fractured or faulted confining strata,
3. Flow through confining strata with solution porosity and permeability,
4. Flow through artificially fractured confining strata,
5. Flow through abandoned unplugged or improperly plugged wells.

Flow under each of these conditions is discussed below.

9.1 Natural Intergranular Flow

If the confining layer is a clastic sedimentary rock, that is, it is composed of discrete sedimentary particles and is unfractured, then fluid flow will be through intergranular spaces. Shales and siltstones and gradations between them are examples of such rocks. Flow through the intercrystalline spaces in chemically deposited rocks such as limestones is also intergranular flow.

Darcy's law for the flow of water through a granular rock is:

$$v = \frac{\bar{K} \Delta P}{\mu \Delta L} \qquad (9\text{-}1)$$

where:

v = darcy velocity [cm/sec]

$\bar{K}$ = permeability [darcys]

μ = viscosity [centipoise]

ΔP = pressure differential across the flow distance [atmosphere]

ΔL = flow distance [centimeters]

Furthermore, the actual average intergranular liquid velocity is:

$$\bar{v} = \frac{v}{\phi_e} \qquad (9\text{-}2)$$

where:

$\bar{v}$ = average intergranular velocity [cm/sec]

ϕ_e = effective porosity

The fluid pressure in a reservoir into which liquid is being injected is greatest at the injection well face and declines approximately logarithmically away from the borehole. The pressure will also vary with time, increasing as injection continues or declining if injection ceases or the rate is reduced. For purposes of illustration, however, a maximum constant pressure can be assumed to exist at the injection well in order to calculate the rate at which wastewater might be moving vertically through a confining layer. While Equation 9-1 is strictly correct only for horizontal flow, it can be used here for purposes of illustration, if ΔP is considered to be a pressure differen-

tial across the confining layer that was induced by fluid injection and where no cross-formational flow potential existed prior to injection. Using Equations 9-1 and 9-2, the values in Table 9-1 were, then calculated. Table 9-1 shows illustrative rates of movement expressed in feet/year, for a range of pressures and permeabilities. For these cases, the confining layer was assumed to be 100 feet thick, the effective porosity to be 10 percent and the viscosity one centipoise.

TABLE 9-1 Distance of vertical travel of injected wastewater in feet/year through a 100-foot-thick confining stratum with various permeabilities and injection-induced pressure gradients. The effective porosity was assumed to be 10 percent and the viscosity to be one centipoise.

K (darcys)	P (psi) 500	1,000	2,000	5,000
1×10^{-3}	114 ft/yr	228 ft/yr	456 ft/yr	570 ft/yr
1×10^{-5}	1.14	2.28	4.56	5.7
1×10^{-7}	1.14×10^{-2}	2.28×10^{-2}	4.56×10^{-2}	5.7×10^{-2}
1×10^{-9}	1.14×10^{-4}	2.28×10^{-4}	4.56×10^{-4}	5.7×10^{-4}

A vertical wastewater travel of 114 feet/year would probably be unacceptably high but the assumed permeability in this case (1×10^{-3} darcys) is at the upper end of values that one might encounter in a confining stratum, whereas a value of 1×10^{-9} darcys is at the other extreme. The travel rates shown in Table 9-1 are only meant to be illustrative and not comprehensive. Additional computations can be made, quite simply, if so desired.

No mention has, so far, been made of the chemical quality of water that might be forced to flow from the injection unit to an overlying aquifer by injection pressure buildup. If the vertical flow is within the radius of spread of wastewater in the injection unit, then the water that would initially enter the overlying aquifer would be from the confining stratum and that would eventually be followed by injected wastewater. Outside of the radius of spread of the wastewater, the water initially entering the overlying aquifer would be from the confining stratum eventually to be followed by natural water from the injection unit.

An example of the type of analysis described above was documented by Hickey (1984) for an injection well facility at St. Petersburg, Florida. The stratigraphic and hydrogeologic section for the St. Petersburg injection site is given in Figure 9-1. Injection was carried out during a period of 32 months beginning in September, 1979, to determine the impact of long-term injection. During the first year of the test, the mean injection rate was 2,750 gpm through a single well into injection zone C and by a postulated wellbore interconnection into injection zone B. Hickey (1984) calculated the vertical velocities in the semiconfining bed between injection zones A and B and also the pressures at various monitor well locations using analytical equations similar to those given here.

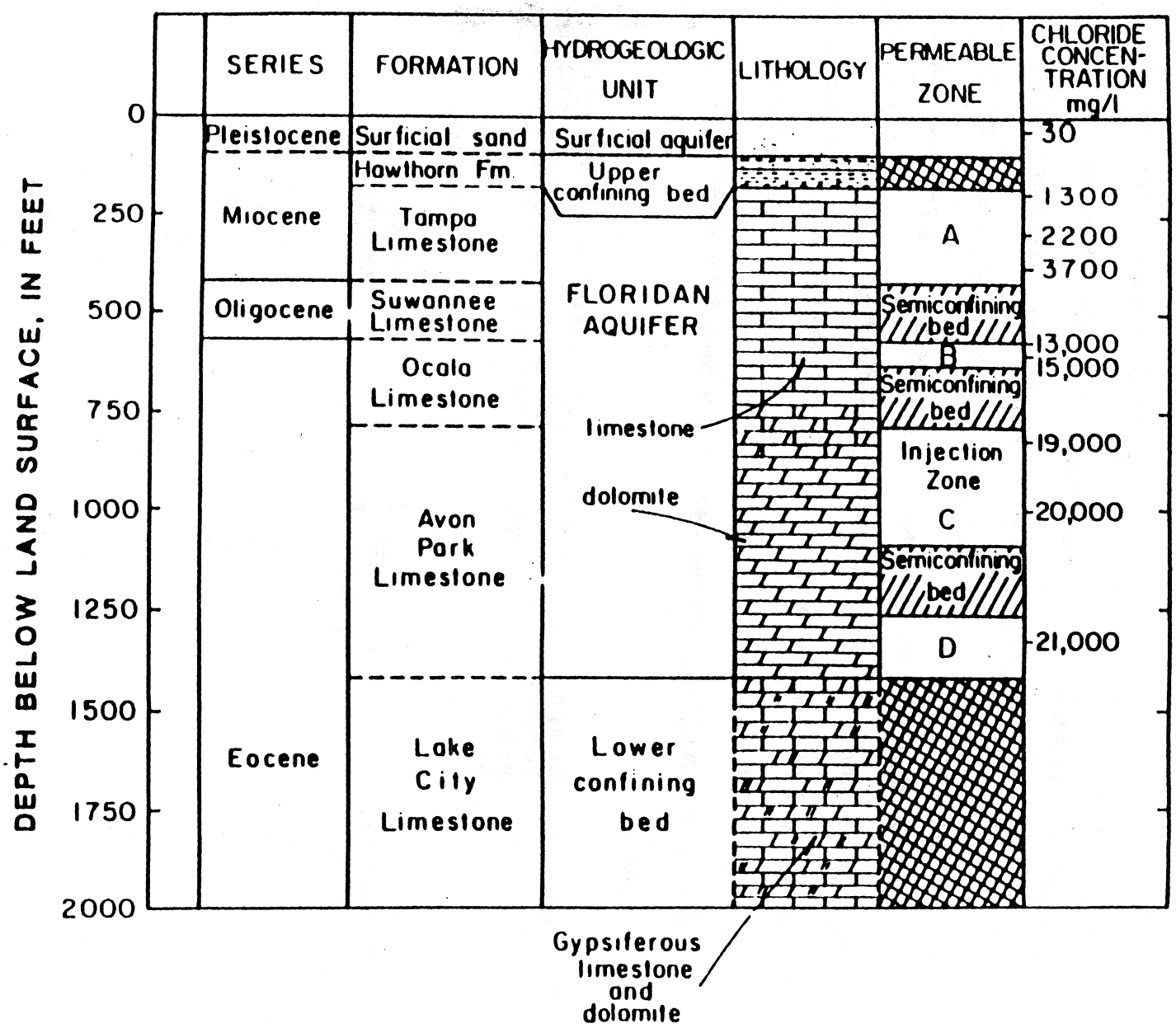

Figure 9-1 Stratigraphic and hydrogeologic section, St. Petersburg injection site (Hickey, 1984)

A much more powerful and revealing method of analysis, for a problem as complex as that at St. Petersburg, is the use of a numerical model such as the U.S. Geological Survey Saline Water Injection Program or SWIP (INTERCOMP Resource Development and Engineering, Inc., 1976). The SWIP model was used to obtain predicted pressures, vertical velocities and saline water displacements in the injection zones and semiconfining units at St. Petersburg for comparison with Hickey's (1984) results. Table 9-2 shows a comparison of pressures at selected monitoring points at the St. Petersburg injection well site as calculated by Hickey (1984) using analytical equations and as calculated for this study by use of the SWIP model. No field data were given by Hickey to allow comparison between observed and calculated pressures.

TABLE 9-2 Comparison of pressure buildups at observation well locations at St. Petersburg, Florida as calculated by Hickey (1984) and as calculated for this study using SWIP.

		Pressure Buildup	
Observation Well	**Distance from Injection Well**	**From Hickey**	**From SWIP**
A3	0	4	2.9
B6	45	1.6	2.5
B7	66	2.4	2
B8	100	0.5	1.0
B9	115	0.1	.08
B1	660	0.1	1.0
B2	660	0.1	1.0
B3	660	1	1.2
B4	660	1.4	1.3
B5	660	0.5	.3
C2	1300	0.8	.8
C3	1390	0.3	1.8

Figure 9-2 shows upward vertical velocities of pore water in the confining layer between injection zones B and A. The velocities are those computed by the SWIP model to exist after one year of injection at 2,750 gpm into zones B and C as explained above. For comparison, Hickey (1984) calculated velocities, using analytical equations, of 0.005 to 0.05 ft/day at a distance of about 733 ft. from the injection well and 0.01 to 0.1 ft/day immediately adjacent to the injection well. Figure 9-3 shows the calculated concentration fraction (C/C_o) of dissolved chemicals in zone A as forced upward from the semiconfining layer into zone A from injection into zone B. For example, if the semiconfining layer were to contain water with a chloride concentration of 13,000 mg/l (Figure 9-1), then the chloride concentration in the lower 20 feet of zone A would be increased by about:

$$(13{,}000 \text{ mg/l})\ (0.056) = 728 \text{ mg/l}$$

immediately adjacent to the injection well after one year of injection.

9.2 Naturally Fractured Strata

The effect of naturally occurring fractures in a confining layer is, commonly, to greatly increase the permeability and to create a secondary form of porosity which is small in magnitude but effectively interconnected. The net result is that wastewater transport through a fractured caprock may be tens or hundreds of times more rapid than through the same rock in the unfractured state.

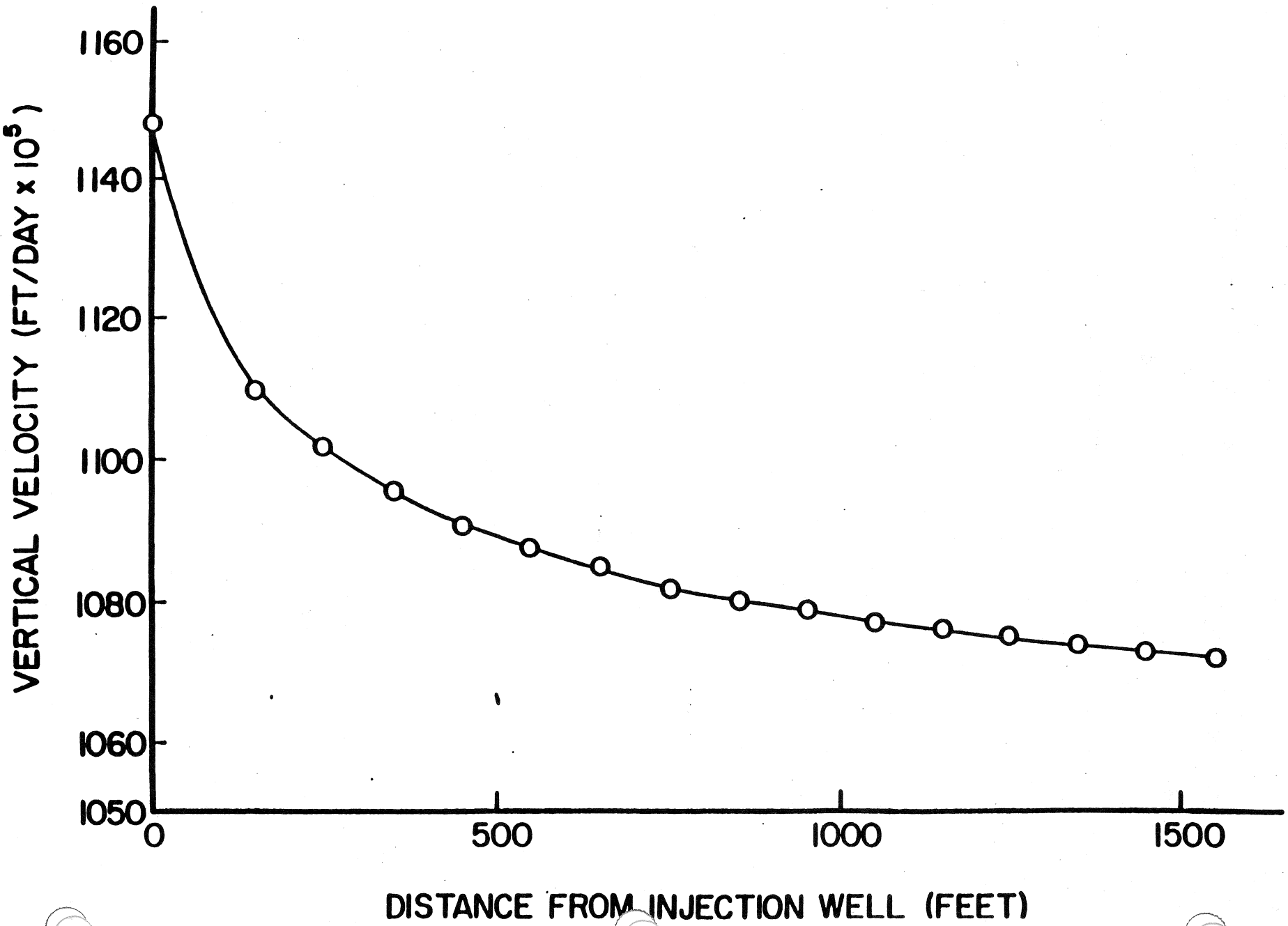

Figure 9-2 Vertical upward ve[illegible]ities of pore water in the confining layer

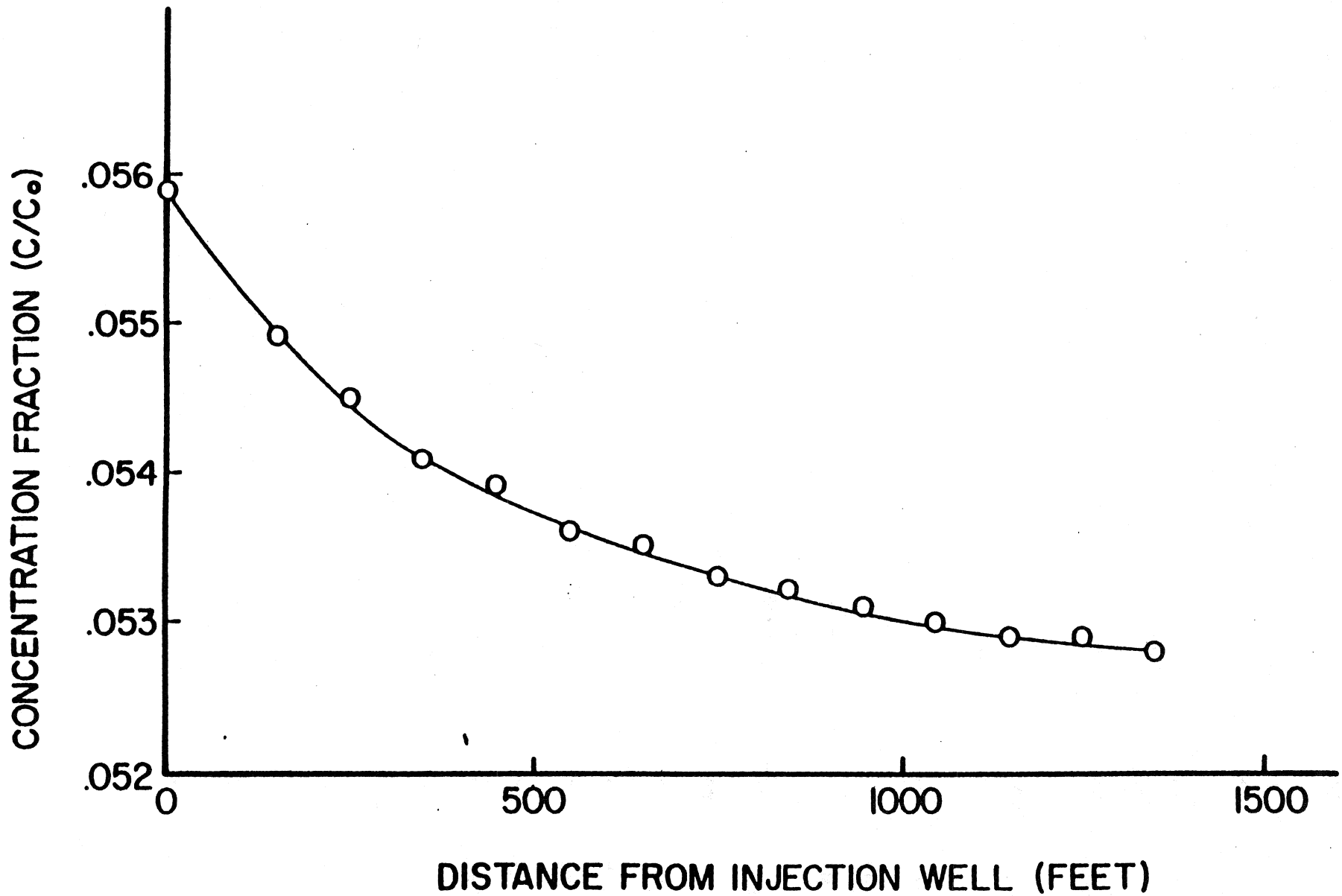

Figure 9-3 Concentration fraction C/C_0 of dissolved chemicals in zone A as forced upward from the semiconfining layer into zone A by injection into zone B at St. Petersburg, Florida

The analysis of flow through fractured rock is often treated no differently than flow through granular media. This approach is probably acceptable in many cases; but, where fractures are widely spaced, are of wide aperture or have a particular directional trend other mathematical methods may be needed (Freeze and Cherry, 1979, p. 73-74).

9.3 Strata With Solution Porosity

Solution porosity is often developed in conjunction with fractures and in soluble rocks and the above statements concerning fracture porosity will, thus, commonly be true where solution porosity exists.

9.4 Artificially Fractured Strata

Artificial fractures differ from naturally occurring ones in that they are more likely to be represented by a single vertical or horizontal fracture as opposed to a network of fractures. Also, if the artificial fracture has been deliberately induced, it will be propped open with sand, glass beads or other propping agents. Equations have been developed to predict fluid pressure distribution patterns in the vicinity of a well injection into single vertical or a horizontal fracture (Gringarten and others, 1974; Gringarten and Ramey, 1974). However, it is not likely that such equations would find application to the flow of fluid through a confining layer, since injection would be precluded if it were known that the confining layer was breached by an induced fracture.

9.5 Abandoned Unplugged or Poorly Plugged Wells

An abandoned, unplugged or poorly plugged well, penetrating the injection unit, within the radius of pressure influence of the injection well can act as a point leak from the injection unit to overlying aquifers. This is, of course, the main basis for the area of review determination required in the UIC regulations promulgated under the Safe Drinking Water Act.

While development of analytic equations to predict rates of interaquifer flow through a wellbore should not be particularly difficult, this has apparently not been done. However, work is currently in progress toward the formulation of analytic equations for this purpose in the Earth Sciences Division of the Lawrence Berkeley Laboratory, Berkeley, California (written communication P.A. Witherspoon, 1986).

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CHAPTER 9

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APPENDIX 4-13

Appendix 4-13

Abandoned Oil and Gas Industry Wells and Their Environmental Implications (Warner, 1988)

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