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SAN JUAN BASIN COALBED METHANE SPACING STUDY

RESULTS FOR SENSITIVITY ANALYSIS OF THE SAN JUAN BASIN AREA 1 TYPE RESERVOIR

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INTRODUCTION

The primary objective of the Coalbed Methane Committee (CMC) is to develop an appropriate methodology for evaluating well spacing in the development of the coalbed methane resources of the San Juan Basin. ICF Resources has proposed meeting this stated objective by concentrating its efforts on the reservoir characterization of selected field sites and a reservoir simulation sensitivity analysis. Reservoir characterization of selected field sites under active coalbed methane development provides the means by which key parameters can be defined for the basin as a whole. Once the key parameters such as permeability, layering, reservoir pressure, gas content/depth/coal rank, and water saturation have been determined, the sensitivity of gas production to these parameters can be evaluated with an appropriate coalbed methane simulator. The results of such sensitivity analyses can then be utilized to develop families of "type curves" which will allow the determination of gas production rate as a function of well spacing at, for example, various permeabilities, zones of completion, and/or other sensitive parameters. The final step involves the validation of the type curves by comparing results from them with actual production data from selected field sites throughout the basin which exhibit wide ranges in the key parameters. With this approach, the methodology to be employed in implementing the type curves can be illustrated.

The purpose of this report is to provide preliminary results of sensitivity studies completed to date. This study does not include economics as a parameter for spacing considerations. Economics and methods used to evaluate economics varies from operator to operator; and therefore, economics must be considered on a case by case basis. However, this report provides an evaluation of how physical parameters impact performance to which economics can then be applied.

Identification and location of coalbed methane wells in the San Juan Basin has already been conducted by the Texas Bureau of Economic Geology, under contract to GRI, and provides the foundation for site selection of areas already under development.

CONCLUSIONS

The sensitivity analysis of critical reservoir parameters for Area 1, not considering economic parameters, indicates the following:

1. Gas recovery, expressed as a percentage of gas-in-place, increases with decreasing well spacing. Magnitudes of variability for different values of permeability and fracture half-length are indicated in Table 1.

2. Both cumulative gas production and gas recovery increase with decreasing abandonment rates, with a corresponding increase in the production time.

3. Gas recovery increases with both increasing permeability and increasing fracture half-length.

4. Cumulative gas production and recovery are greater for a 2% porosity coal than a 3% porosity coal due to lower water production rates and the shorter time required to dewater the reservoir.

5. Gas production and cumulative recovery increase with increasing gas content.

DISCUSSION

INTRODUCTION

The purpose of the sensitivity analysis portion of the Fruitland Coalbed Methane Study is to determine gas production as a function of various key parameters. These parameters are: permeability, zonation, reservoir pressure, gas content/depth/coal rank, and water saturation. Other properties of importance include desorption pressure/time, gas-water relative permeability, and pore compressibility. Due to the extreme variability in the Fruitland coalbed reservoirs in the San Juan Basin, fields in widely spaced geographic areas had to be selected in order to maximize the representation of differing geologic and reservoir conditions in the definition of these key parameters. Once the geologic and reservoir data have been compiled and correlated, "Type Reservoirs" can be synthesized which are, in general, representative of the more loosely defined pressure and water saturation regions within the basin. A base case has been established for Area 1 of the San Juan Basin (Figure 1), characterized by slightly overpressured coalbed reservoirs which are typically fully saturated with water at initial reservoir conditions. Sensitivity studies have been completed for Area 1 to examine the range of possible reservoir conditions that are expected to occur in that area based on the experience of the members of the CMC.

TECHNICAL APPROACH

COMETPC 3-D[1], a two-phase, three-dimensional, multi-well coalbed methane simulator developed by ICF Resources is being used to perform the sensitivity analyses. The simulator was subsequently tested and benchmarked against other simulators prior to the initiation of the Fruitland study[2]. Future work will include adjustment of reservoir parameters to allow validation of the simulator against actual field conditions.

Through a survey of publicly available data, values for the key parameters were defined for the sensitivity analysis on the Area 1 Type Reservoir, and are shown in Table 2. The COMETPC 3-D model was used to determine the sensitivity of simulated gas production to variations in permeability (1, 5, 10 and 50 md), fracture half-length (100, 300, and 500 feet), and well spacing (160, 320, and 640 acres). A "Base Case" was defined as having permeability of 10 md, fracture half-length of 300 ft, and well spacing of 320 acres.

Several points are worth mentioning about how some of the data in Table 2 were handled for the modelling. The Area 1 reservoir was assumed to be slightly overpressured (0.44 psi/ft), yielding an initial reservoir pressure of 1320 psia at the 3000 foot depth. The coal was assumed to be saturated, so the desorption pressure was also set to 1320 psia. The pore compressibility of 200 x 10^{-6} psi^{-1} is an estimated, rather than a measured value. However, this is not particularly important as it was also assumed that no stress-related change in cleat permeability occurs as the reservoir pressure is reduced at the wellbore. The gas-water relative permeability curves (Figure 2) used as input to the simulator were developed earlier by ICF Resources for a San Juan Basin study[3]. Finally, although the COMETPC 3-D simulator is capable of handling finite conductivity induced fractures via a fine-gridding technique, the fractures simulated were of infinite conductivity.

After reviewing the results of the Base Case and the 35 additional parametric simulations, the CMC requested that ICF Resources check the sensitivity of gas production to cleat porosity, gas content, and relative permeability. The Base Case, which assumed 3% cleat porosity, was evaluated at 2% porosity to determine the effect on gas production. The sensitivity to gas content was evaluated

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with a dual approach. First, the Base Case Langmuir volume was allowed to vary ±75 scf/ton (approximately an 18% variation), while the initial reservoir pressure (which is equal to the desorption pressure) was held constant at 1320 psia. In the second approach, the adsorption isotherm (i.e., Langmuir constants) were not varied, rather, the desorption pressure was allowed to vary higher or lower from that used in the Base Case. Again, the initial reservoir pressure was held equal to the desorption pressure. This twofold approach was necessary to account for differences in both gas and water production characteristics which result depending on the way gas content is varied. Relative permeability effects were evaluated by replacing the curves used for the Base Case with the curves published by Kamal and Six[4].

Before work could progress on the sensitivity analysis, two issues impacting the sensitivity simulations needed to be resolved. These were the grid configuration to be utilized in COMETPC 3-D for accurate representation of the various well spacings, and a consistent method of grid discretization for the various fracture half-lengths to be evaluated. The results of this work are presented in Appendix A, and the resulting finite difference grids are given in Appendix B.

SIMULATED PRODUCTION PERFORMANCE

Using the grid schematics discussed in Appendix B, COMETPC 3-D simulations were made for 36 cases. The simulation runs were conducted for a 75-year period. The simulated production performance results are graphically presented in two ways: single well cases (Figures 3 - 14) and full section cases (Figures 15 - 26). In the single well cases, the production results reflect only a single well drilled for a given drainage area; that is, one well per 160, 320 or 640 acres. Alternatively, for the full section cases, all performance data has been normalized to a full 640 acre section so that suitable comparisons can be made between the various well spacings evaluated. Thus, in the full section cases, a single well draining 640 acres is contrasted with either two wells draining 640 acres (320 acre well spacing), or four wells draining 640 acres (160 acre well spacing).

For both the single well and full section cases, the presentation format includes the gas production rate (Mscf/D), cumulative gas production (Bcf), gas recovery as a percentage of the initial gas-in-place, water production rate (Bbls/D), and cumulative water production (MBbls) as a function of time (years), with well spacing being the parametric variable (Figures 3 - 26.) In addition, abandonment rate (Mscf/D) is presented as a function of both cumulative gas production and gas recovery, with well spacing being the parametric variable (Figures 27 - 30.) Superimposed on these plots are isochronal lines to provide the production time associated with a given abandonment rate. It should be noted that although fracture half-lengths of 100, 300, and 500 ft were evaluated, only the results from the 300 ft cases have been included in Figures 3 - 30.

Gas recovery is shown as a function of the permeability, at a constant coal thickness of 35 feet, with parametric well spacing for all fracture half-lengths evaluated (Figures 31 - 33). The simulation results presented in Figures 31 - 33 are for 75 years. Simulation results for 10, 20, 30, 40, and 50 years are provided in Appendix C. Plots similar to Figures 31 - 33, but at a 50 Mscf/D cutoff rather than for fixed times, are given in Appendix D.

The results show:

1. For a given value of permeability, production rates and cumulative production increase with decreasing well spacing in early producing time. This effect is more pronounced at higher permeabilities. Ultimate recovery converges in later producing time. (Compare Figures 16 and 25.)

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2. Both cumulative gas production and gas recovery increase as the abandonment rate is reduced. As the abandonment rate approaches zero, ultimate recoveries for the three well spacings converge. However, for a given abandonment rate, the production time required to achieve a particular gas recovery significantly increases with increasing well spacing (Figures 27 - 30).

3. For a given fracture half-length, gas recovery increases with increasing permeability with the greatest differences occurring at lower values of k (Figures 31 - 33). Gas recovery also increases as a function of decreasing well spacing (Figures 31 - 33). A comparison between Figures 31 and 33 indicates that gas recovery increases with increasing fracture half-length, with the greatest sensitivity occurring at the larger well spacing (e.g., 640 acres).

VARIATIONS ON THE BASE CASE

Some limited variations on the Base Case conditions were also simulated for cleat porosity, gas content, and relative permeability. The simulation results are illustrated for both the 2% and 3% porosity cases in Figures 34 - 36, where both gas and water production results are shown. The 33% reduction in cleat porosity yields a corresponding decrease of 33% in the initial water-in-place. This resulted in lower values for both water production rate and cumulative water production (Figure 36). Alternatively, the 0.01 decrease in the cleat porosity resulted in a 1% increase in the bulk volume of coal matrix. Therefore, a slight increase in the gas production rate and the cumulative gas production was observed (Figure 34), with a higher percentage of the initial gas-in-place being recovered for the 2% cleat porosity case (Figure 35). The results of the production analysis are summarized in Table 3. Although the difference in the percentage of recoverable gas is relatively minor, there is less cumulative water production associated with the 2% porosity case than with the 3% porosity case.

Variations in the gas content were also evaluated utilizing the Base Case conditions. In the first approach, the Langmuir volume was allowed to vary 75 SCF/ton (approximately an 18% variation) above and below the Langmuir volume utilized in the Base Case, while the initial reservoir pressure (which is equal to the desorption pressure) was held constant at the "Base Case" conditions. The variations in the desorption isotherm are shown in Figure 37. The results of the COMETPC 3-D simulations are presented in Figures 38 - 40. Although gas production increases with increasing gas content, the water production remains essentially the same (Table 3).

Another way in which sensitivity of the production to variations in the gas content was evaluated was to vary the desorption pressure (set equal to the initial reservoir pressure) while the desorption isotherm (i.e., Langmuir constants) was held constant at the Base Case conditions. The variation in the desorption pressure/initial reservoir pressure was chosen such that the resulting cumulative gas production for the upper and lower desorption pressure cases would be equivalent to the corresponding upper and lower Langmuir volume cases utilized in the first approach (Table 3). In this way, the variations in water production could be more meaningfully evaluated. The simulation results are shown in Figures 41 - 43. In these cases, both gas and water production increase with increasing gas content. Increases in gas content due to an increase in desorption pressure also yield greater water production (Table 3).

Variations in the relative permeability were also evaluated. The Base Case gas-water relative permeability curves[3] are shown contrasted with the San Juan Basin curves as published by Kamal and Six[4] in Figure 44. The k_{rg}/k_{rw} ratio curves for both sets of relative permeability data are presented in Figure 45. The simulation results are shown in Figures 46 - 48 and are summarized in Table 3. As would be expected from an examination of the relationship between the two k_{rg}/k_{rw} curves in Figure 45, conditions are more favorable to the flow of gas at very high initial water saturations with the Kamal and Six curves than with the Base Case curves. Alternatively, as water saturation declines due to

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water production, the Base Case k_{rg}/k_{rw} curve crosses over that of the Kamal and Six curve at approximately 98-99% S_w (Figure 45). Once this occurs, conditions become more favorable to gas flow for the Base Case relative permeability curves as compared with those of Kamal and Six. The resulting gas and water production curves further illustrate this behavior (Figures 46-48). Although the gas production from the Base Case is initially lower, it does not decline as rapidly as that resulting from the Kamal and Six curves (Figure 46). The initial water production for the Kamal and Six curves is higher than that for the Base Case but then declines to the same level early in the production history (Figure 48). The net result is that the greatest differences are seen in the cumulative water production (Figure 48) as contrasted to the relatively minor differences in the gas production (Figures 46 - 47).

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3. "Ignacio Blanco Field Fruitland Formation Coalbed Methane Gas Recovery Estimates for U. S. Exploration Company Leases," Exhibit presented to Colorado Oil and Gas Conservation Commission, Cause 112-73, September 18, 1989.

4. Kamal, M. M., and Six, J. L.: "Pressure Transient Testing of Methane Producing Coalbeds", paper SPE 19789 presented at the 1989 SPE Annual Technical Conference and Exhibition in San Antonio, TX, Oct. 8-11.

TABLE 1

SUMMARY OF SIMULATION RESULTS FOR AREA 1 TYPE RESERVOIR

Permeability	Fracture Half-Length (Feet)	Well Spacing (Acres)	Assuming 50 MSCF/D Cut-Off in Gas Production Rate: Time (Years)	Assuming 50 MSCF/D Cut-Off in Gas Production Rate: Recoverable Gas Reserves (% IGIP)	% IGIP @ 25 Years
1	100	160	0.3	0.2	8.7
1	100	320	0.3	0.1	3.3
1	100	640	0.3	0.0	1.3
1	300	160	28.8	18.1	16.0
1	300	320	41.8	11.1	6.4
1	300	640	2.1	0.5	2.5
1	500	160	40.1	31.4	22.1
1	500	320	68.2	23.4	9.5
1	500	640	6.2	1.4	3.7
5	100	160	40.1	46.3	35.7
5	100	320	80.9	44.7	19.5
5	100	640	165.0	42.7	3.7
5	300	160	34.3	54.2	47.9
5	300	320	72.4	52.0	28.7
5	300	640	151.0	49.4	13.6
5	500	160	30.4	58.0	54.7
5	500	320	65.3	55.8	35.8
5	500	640	140.0	53.2	17.7
10	100	160	33.5	56.2	50.6
10	100	320	67.7	55.0	33.6
10	100	640	140.1	53.6	17.5
10	300	160	26.9	61.2	60.2
Base Case 10	300	320	56.8	59.7	44.0
10	300	640	121.4	58.1	24.9
10	500	160	22.6	63.3	64.5
10	500	320	49.7	62.1	50.5
10	500	640	108.4	60.5	30.7
50	100	160	15.7	66.5	69.1
50	100	320	32.5	66.4	63.7
50	100	640	67.8	66.0	50.9
50	300	160	11.8	68.0	69.9
50	300	320	24.6	67.6	67.7
50	300	640	53.7	67.2	58.1
50	500	160	9.6	68.5	70.0
50	500	320	20.7	68.2	69.0
50	500	640	45.6	67.8	62.0

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TABLE 2

RESERVOIR PARAMETERS FOR AREA 1 SENSITIVITY ANALYSIS

FIXED PARAMETERS

Depth	=	3000 ft.	) Assume slightly overpressured
			) 3000 ft * 0.44 psia/ft
$P_{initial}$	=	1320 psi	) = 1320 psia.
$P_{desorption}$	=	$P_{initial}$	
C_{pore}	=	200×10^{-6} psi^{-1}	(uncoupled from stress sensitive k)
Gas Content	=	345 SCF/Ton	
Porosity	=	0.03	
h, ft		35	
Sorption time, days		10	
V_L	=	610 SCF/Ton (427 @ 30% Ash)	
P_L	=	315 psi	
FBHP	=	100 psi	
Temperature	=	$T_{3000\ ft.}$ (= 120°F)	
k_{rw}, k_{rg}		(Figure 2)	

VARIABLE PARAMETERS

k, md	1, 5, 10*, 50
X_f, ft	100, 300*, 500
Spacing, acres	160, 320*, 640

Total Simulations Required: 36

* Base Case

TABLE 3

PRODUCTION SUMMARY OF VARIATIONS ON BASE CASE FOR AREA 1

CASE DESCRIPTION	GAS Cumulative BCF	GAS % Recovery	WATER Cumulative MSTB	WATER % Recovery
Base Case*	4.3	63.5	947	36.4
Base Case w/2% porosity	4.5	65.6	655	37.8
Base Case w/V_L = 14.46 scf/cf	3.6	64.5	940	36.1
Base Case w/V_L = 20.66 scf/cf	4.9	62.6	952	36.6
Base Case w/P_D = 932 psia	3.8	60.5	772	29.7
Base Case w/P_D = 1960 psia	4.7	66.0	1,235	47.4
Base Case w/Kamal & Six k_r	4.2	62.6	1,164	44.7

* Base Case: Ø = 3%, V_L = 17.64 scf/cf, P_D = 1320 psia, and k_r from Fig. 2. Assumes 75 year life and 320 acre spacing.

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Figure 1

AREAS 1, 2 AND 3 - SAN JUAN BASIN

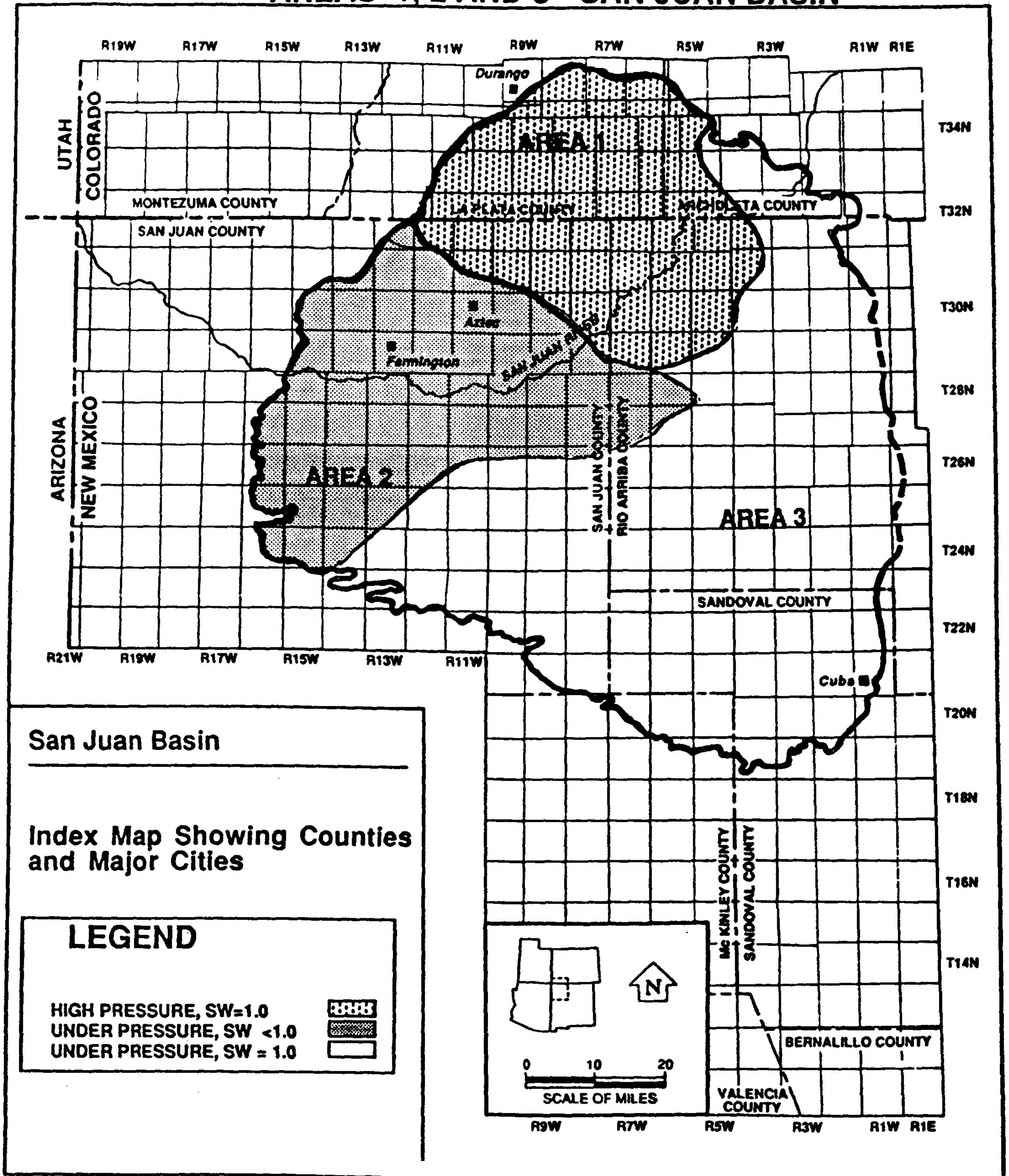

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Figure 2

San Juan Basin Sensitivity Analysis
Area 1 Type Reservoir
Relative Permeability Function
For Base Case

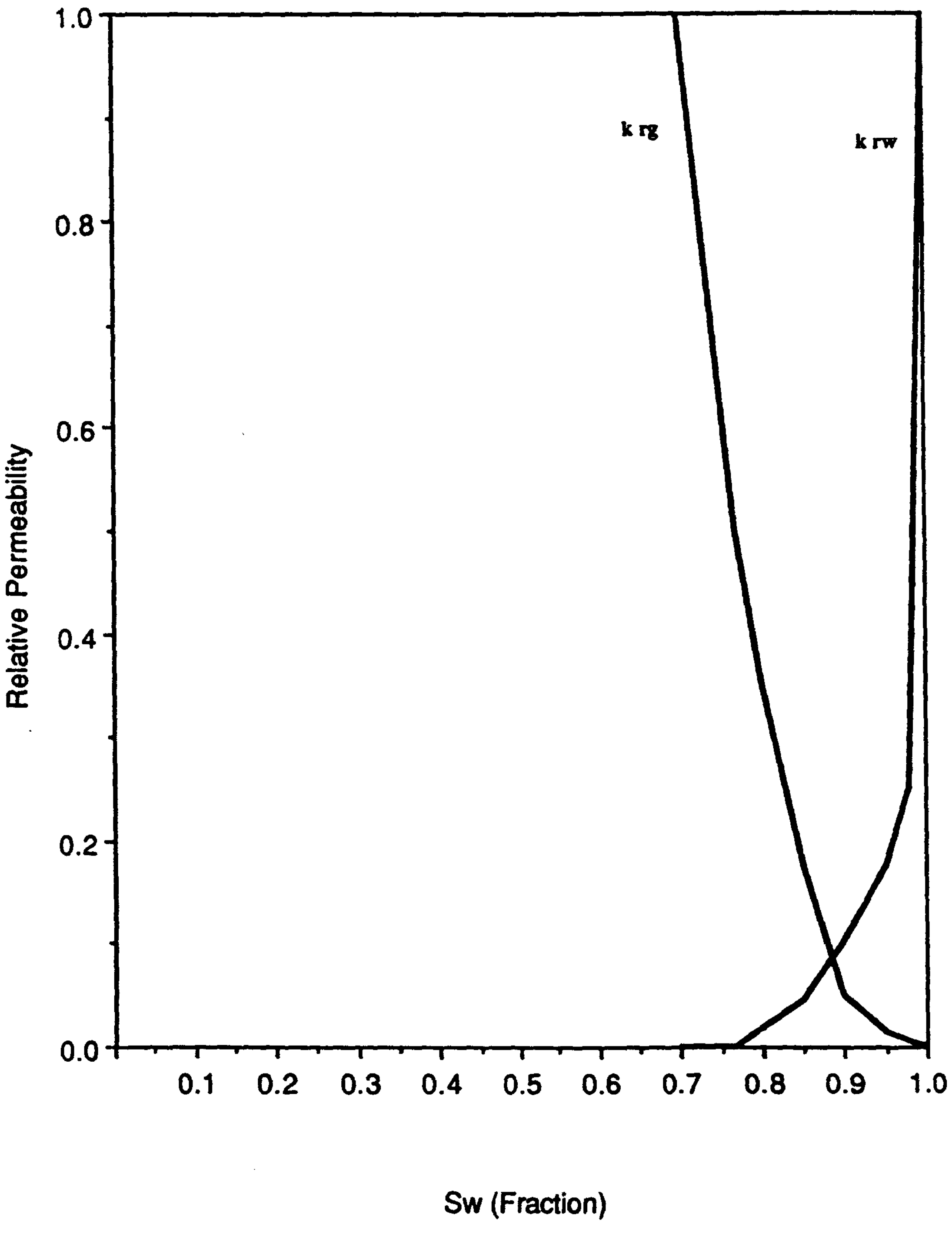

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Figure 3

San Juan Basin Sensitivity Analysis

Area 1 Type Reservoir - Single Well Case

Permeability = 1md and Fracture Half Length = 300 Ft

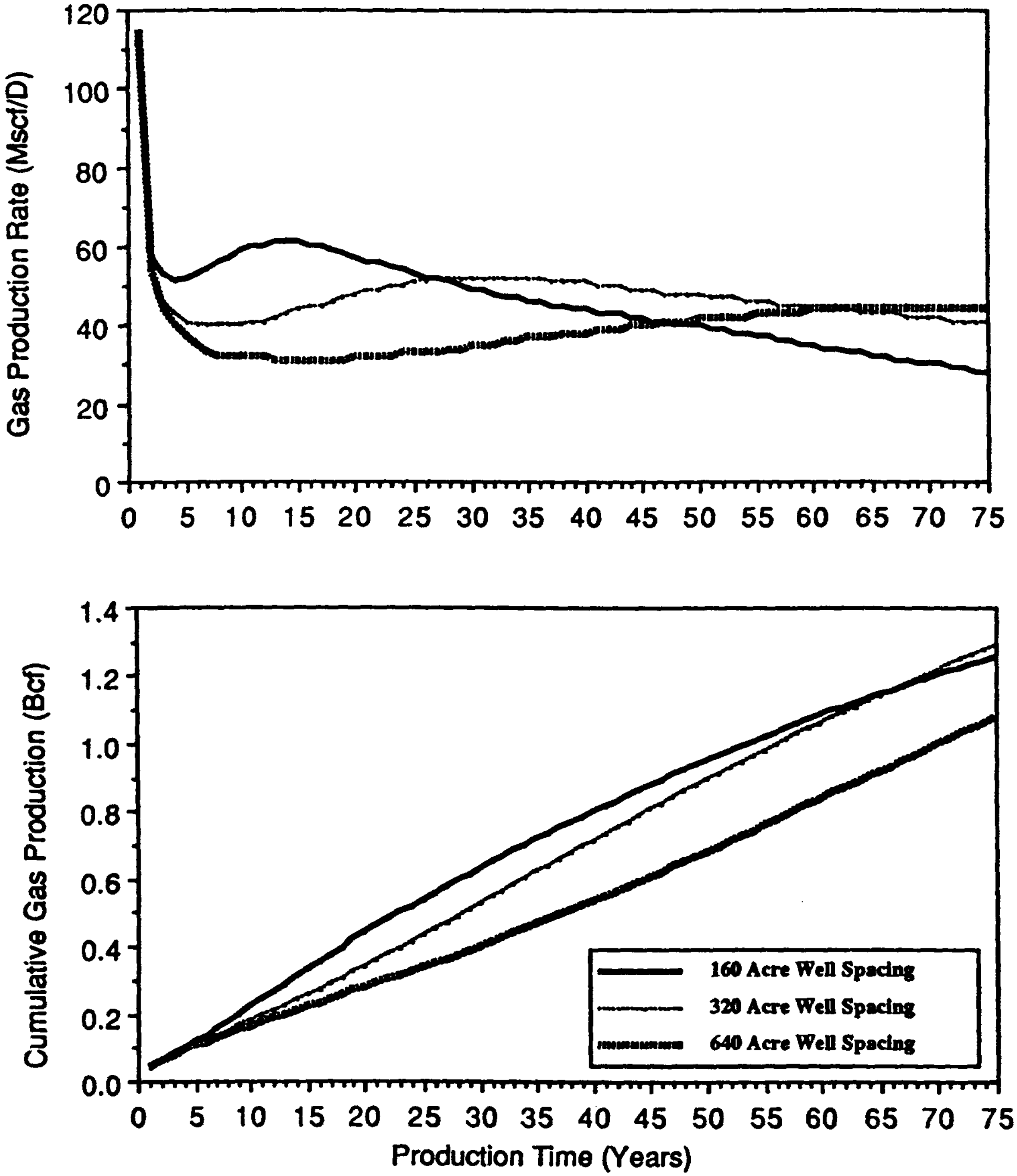

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Figure 4

San Juan Basin Sensitivity Analysis

Area 1 Type Reservoir - Single Well Case

Permeability = 1md and Fracture Half Length = 300 Ft

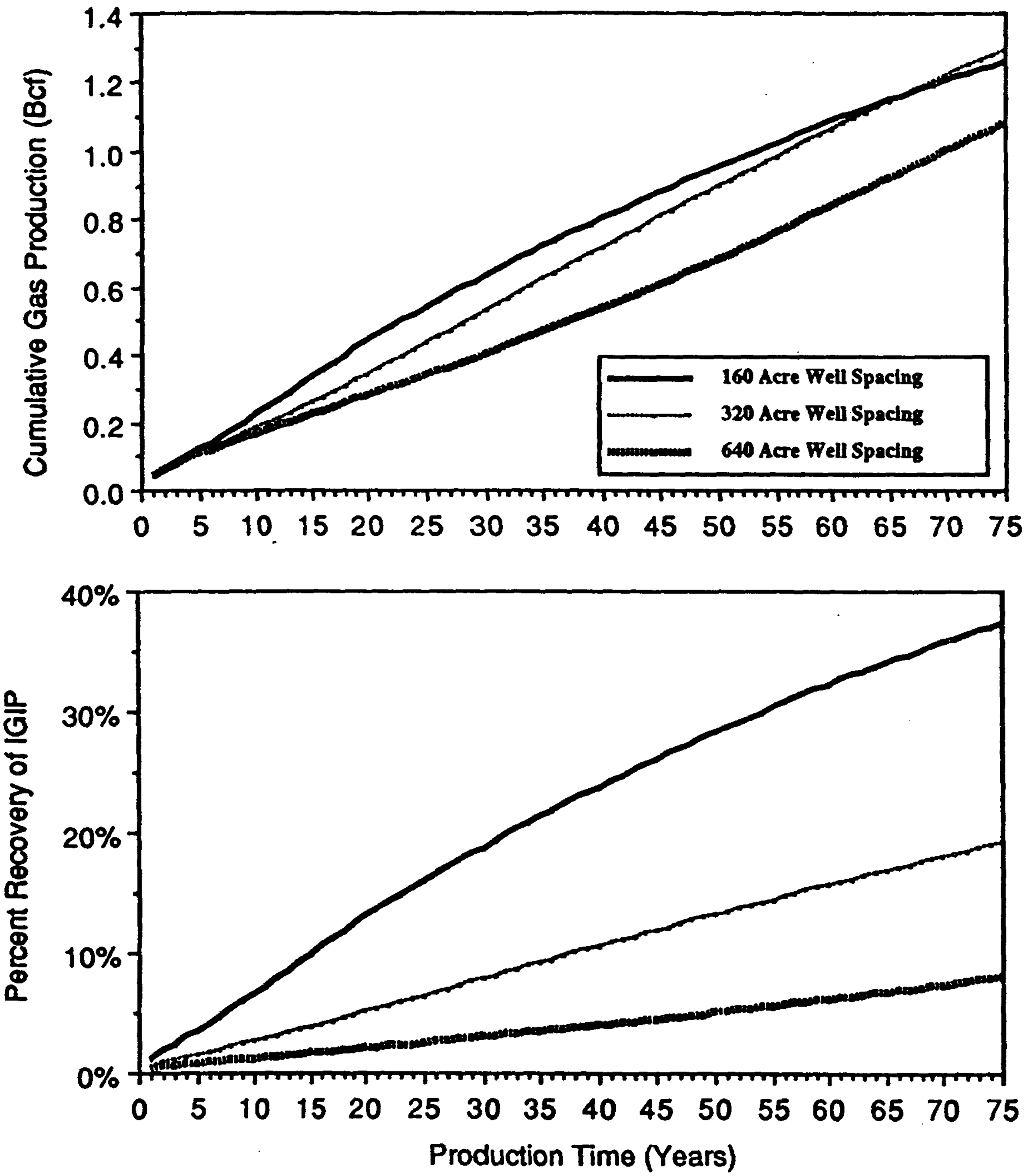
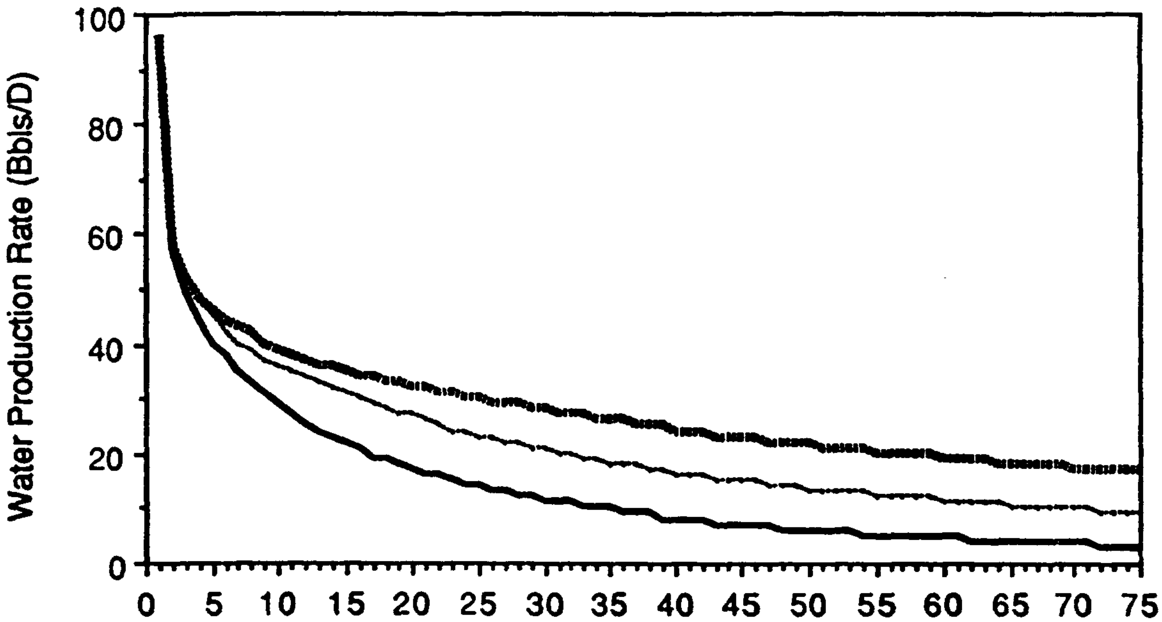


Figure 5

San Juan Basin Sensitivity Analysis

Area 1 Type Reservoir - Single Well Case

Permeability = 1md and Fracture Half Length = 300 Ft



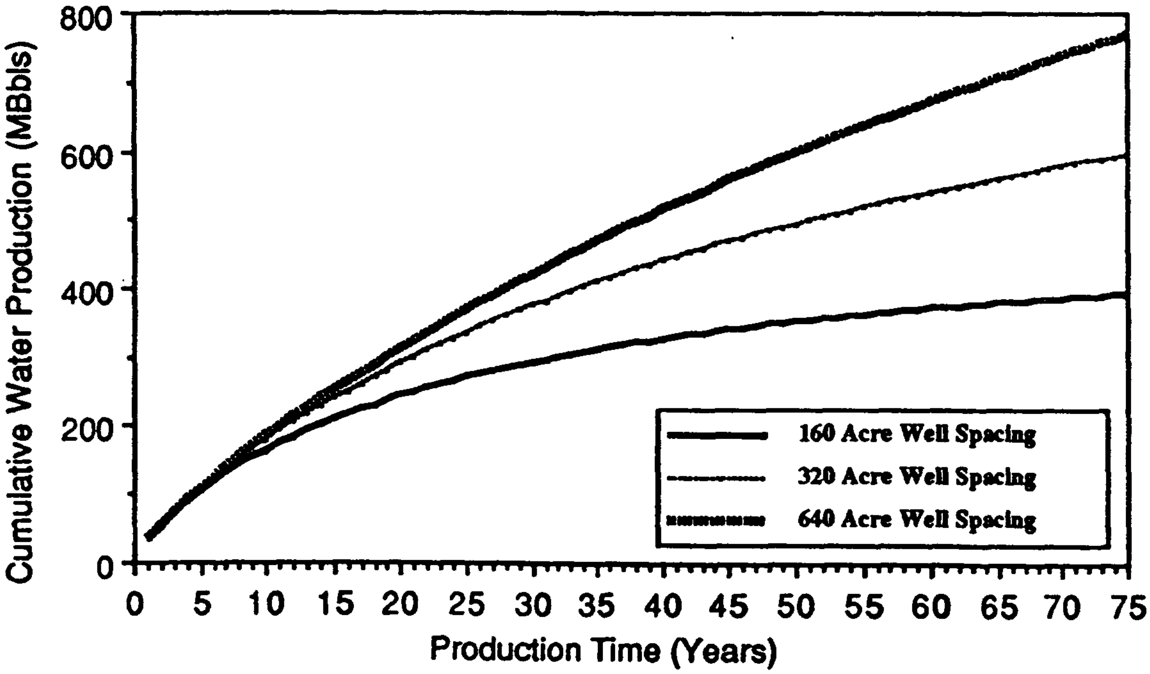


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Figure 6

San Juan Basin Sensitivity Analysis

Area 1 Type Reservoir - Single Well Case

Permeability = 5md and Fracture Half Length = 300 Ft

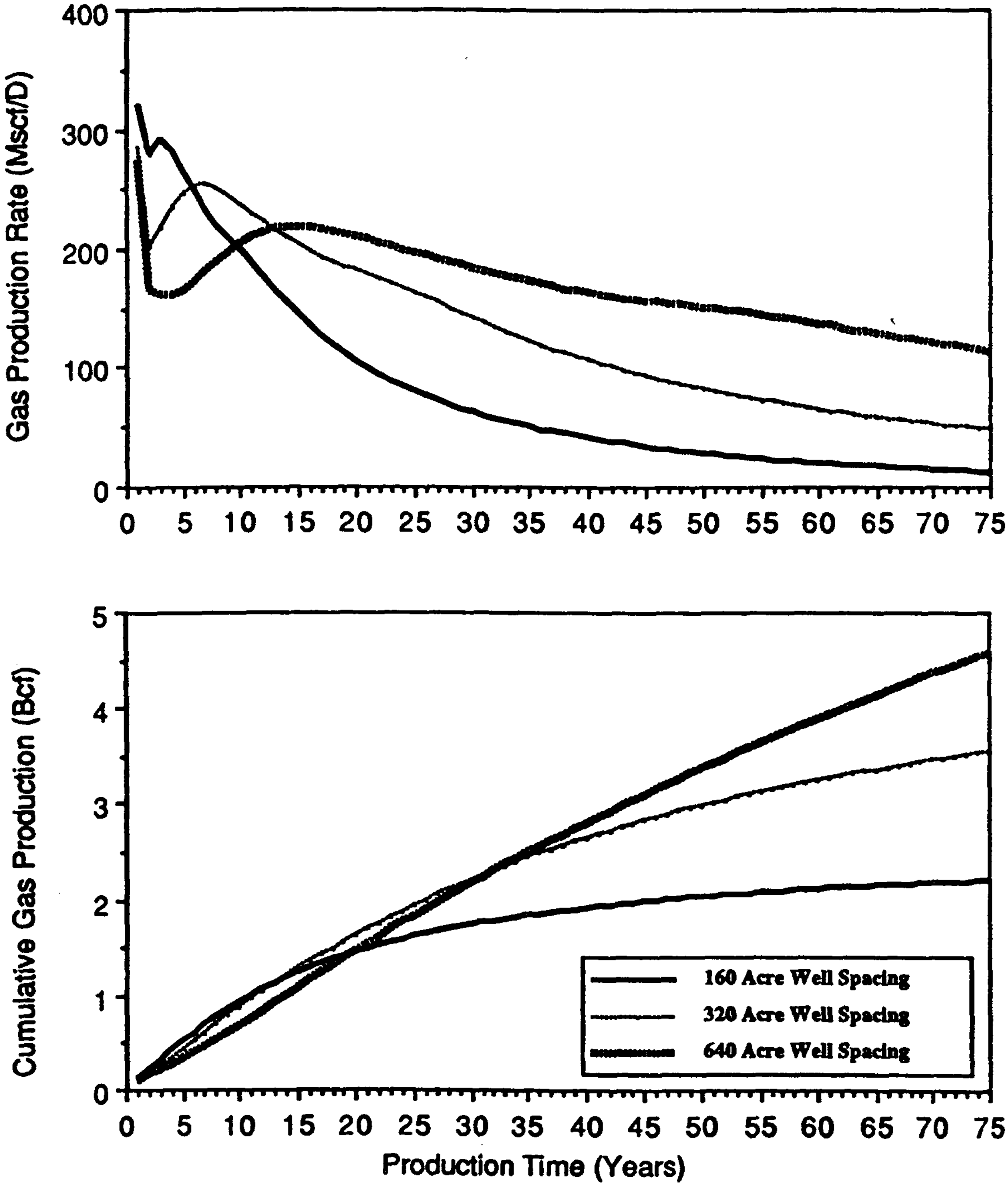

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Figure 7

San Juan Basin Sensitivity Analysis
Area 1 Type Reservoir - Single Well Case
Permeability = 5md and Fracture Half Length = 300 Ft

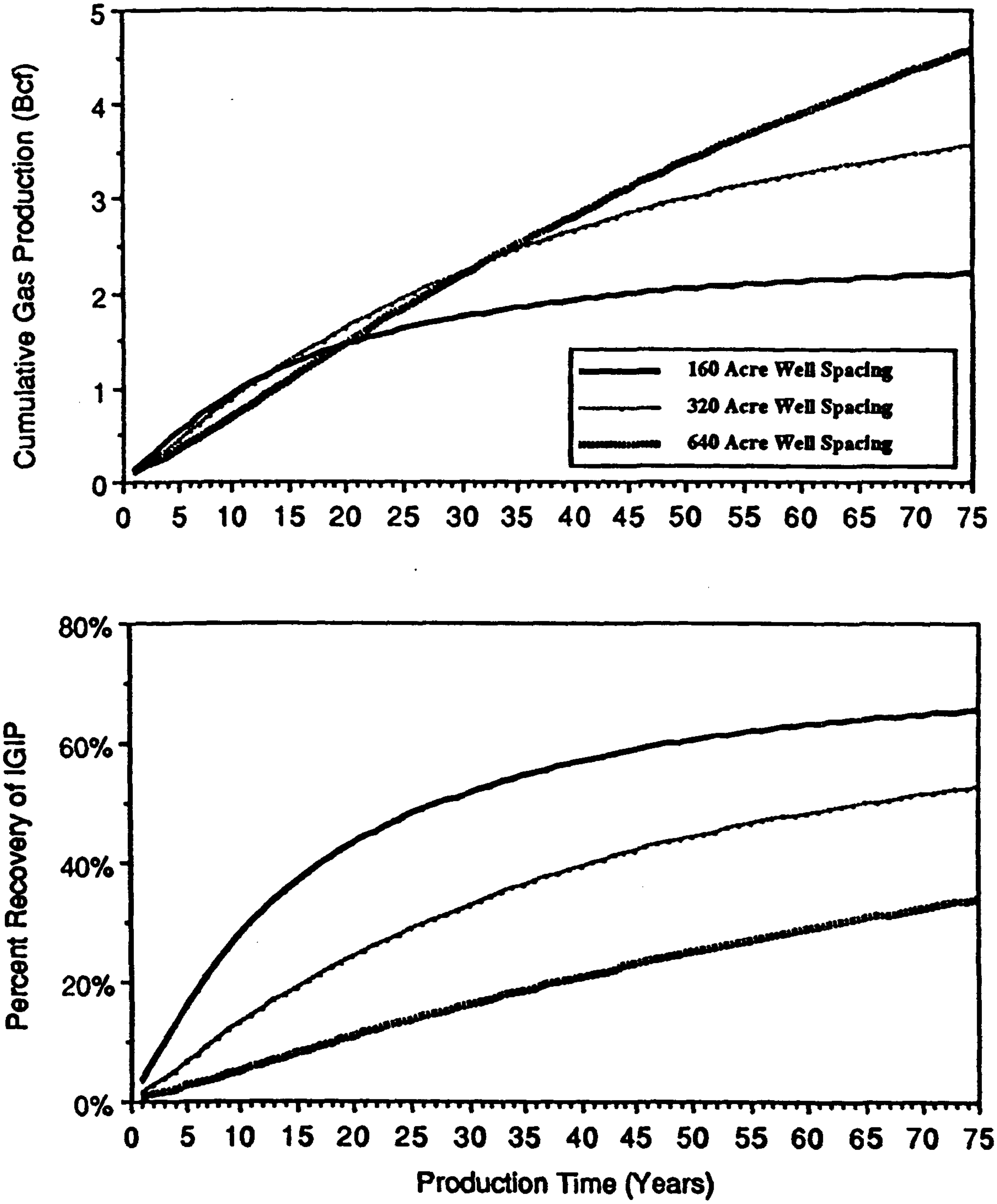
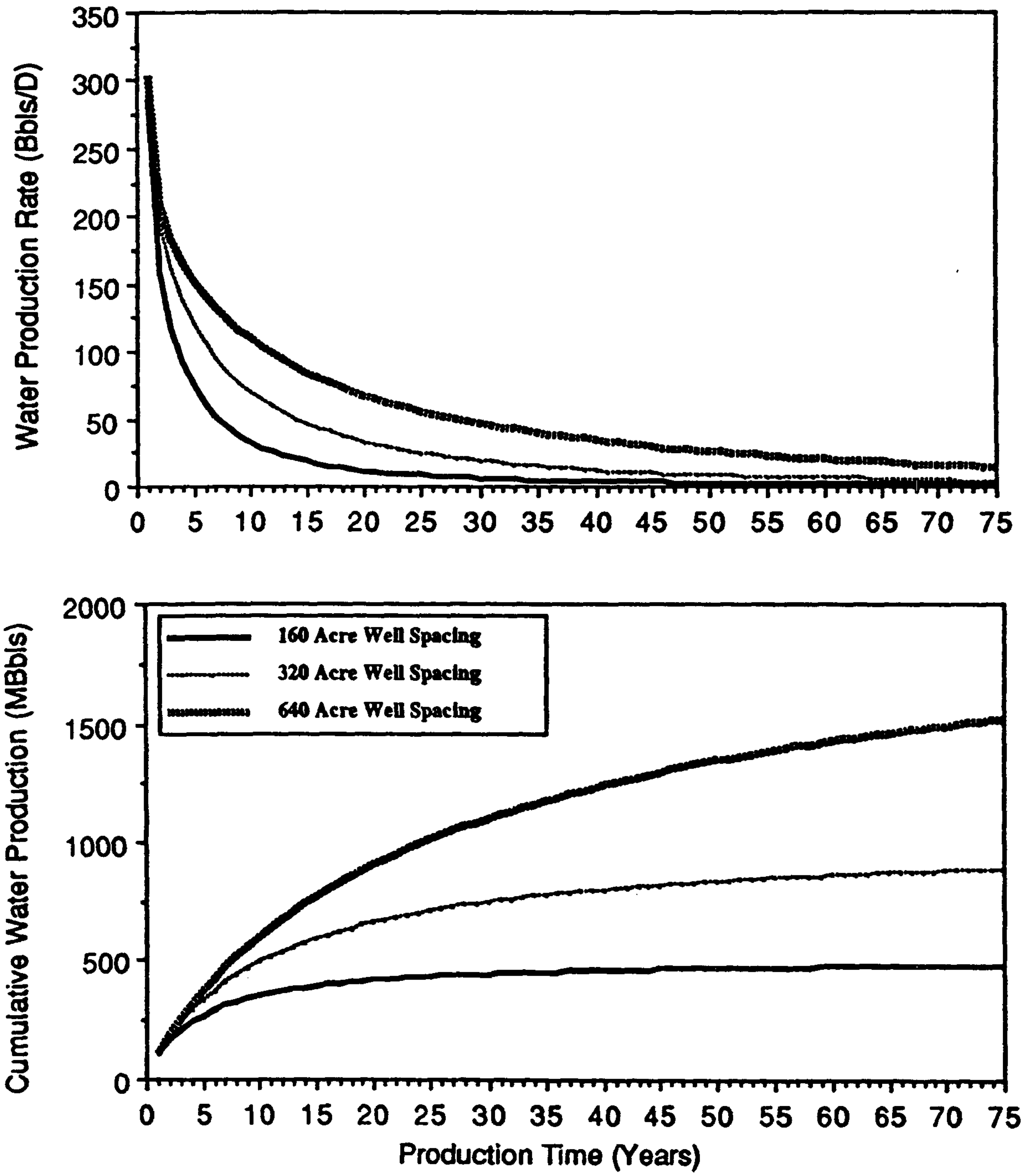


Figure 8

San Juan Basin Sensitivity Analysis

Area 1 Type Reservoir - Single Well Case

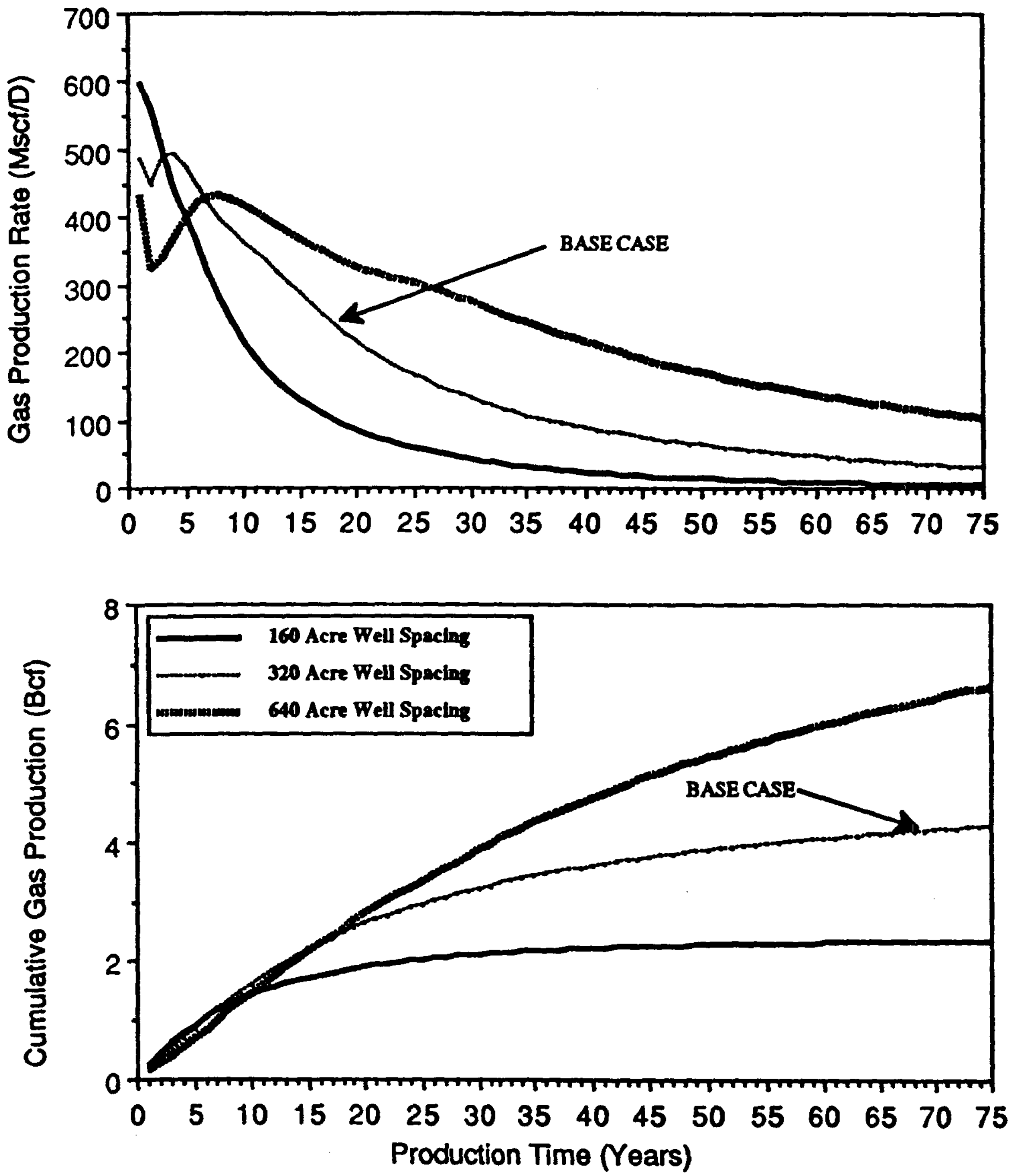
Permeability = 5md and Fracture Half Length = 300 Ft



Application of Richardson Operating Co.
Record on Appeal, 1585.

Figure 9

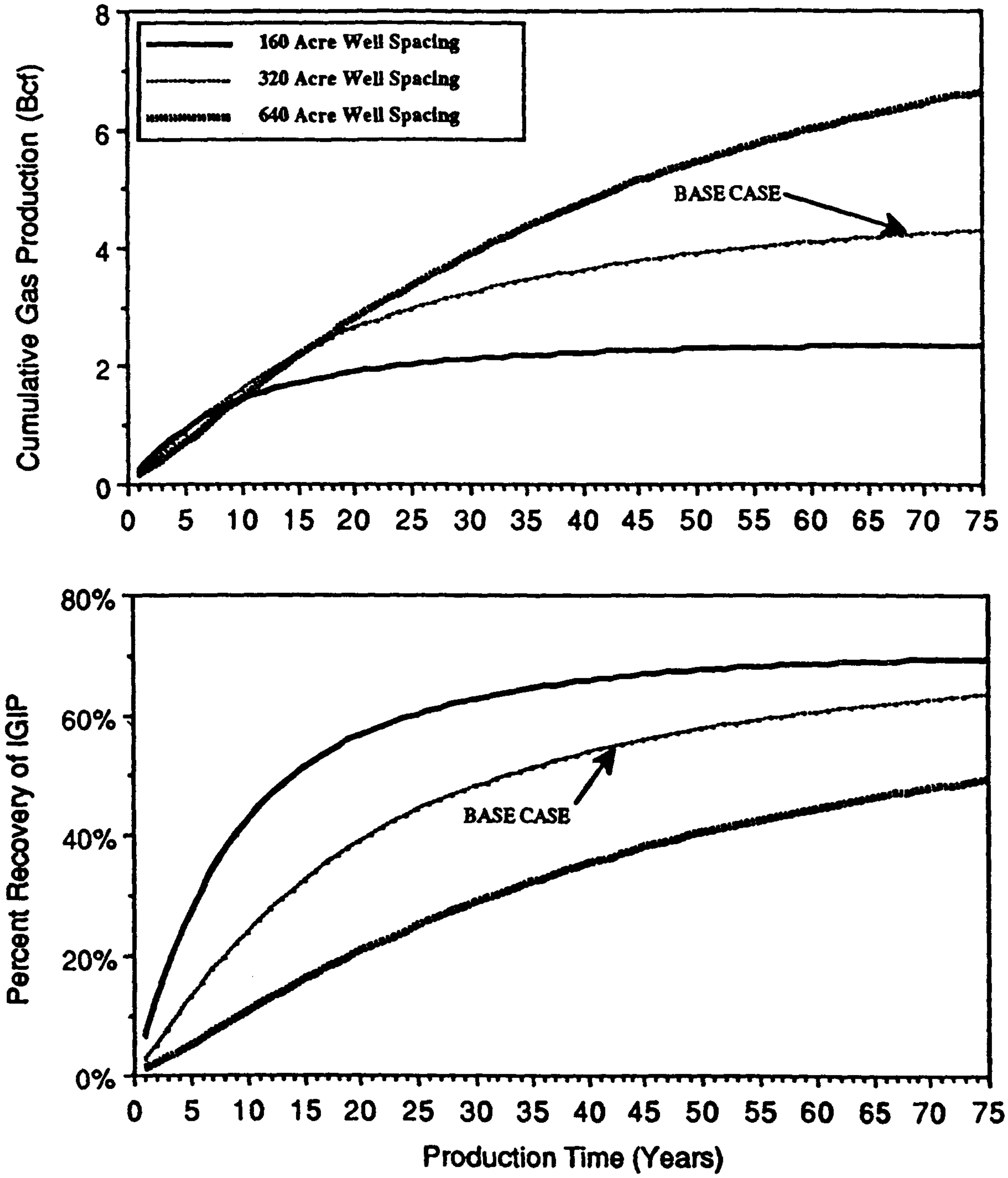
San Juan Basin Sensitivity Analysis
Area 1 Type Reservoir - Single Well Case
Permeability = 10md and Fracture Half Length = 300 Ft



Application of Richardson Operating Co.
Record on Appeal, 1586.

Figure 10

San Juan Basin Sensitivity Analysis
Area 1 Type Reservoir - Single Well Case
Permeability = 10md and Fracture Half Length = 300 Ft



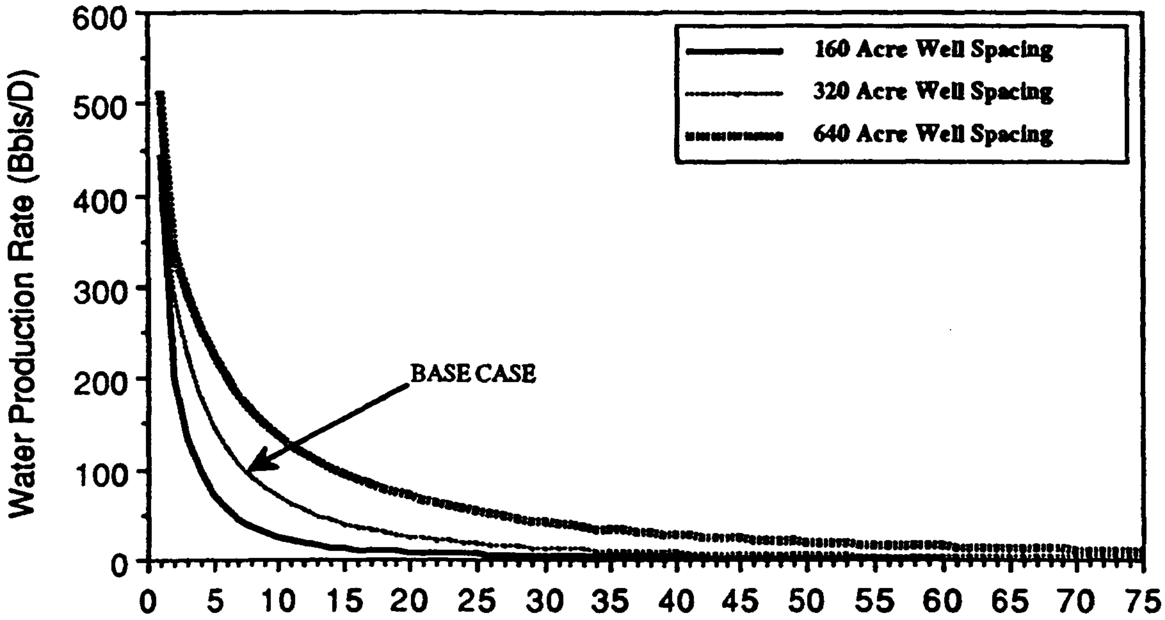
Application of Richardson Operating Co.
Record on Appeal, 1587.

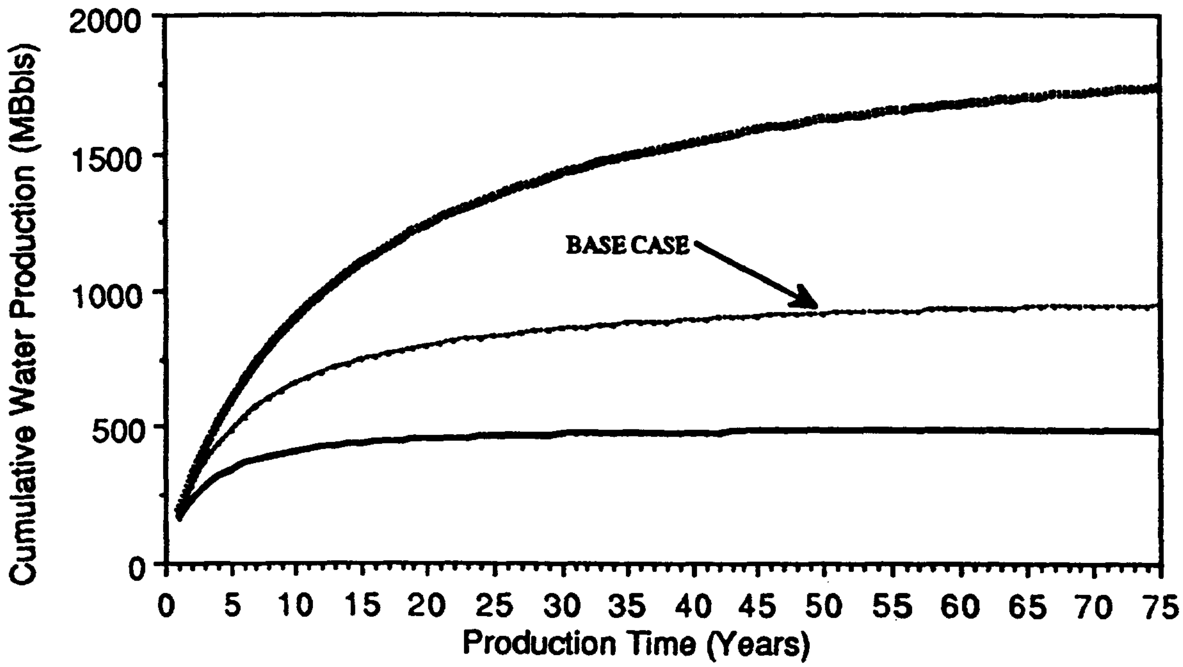
Figure 11

San Juan Basin Sensitivity Analysis

Area 1 Type Reservoir - Single Well Case

Permeability = 10md and Fracture Half Length = 300 Ft





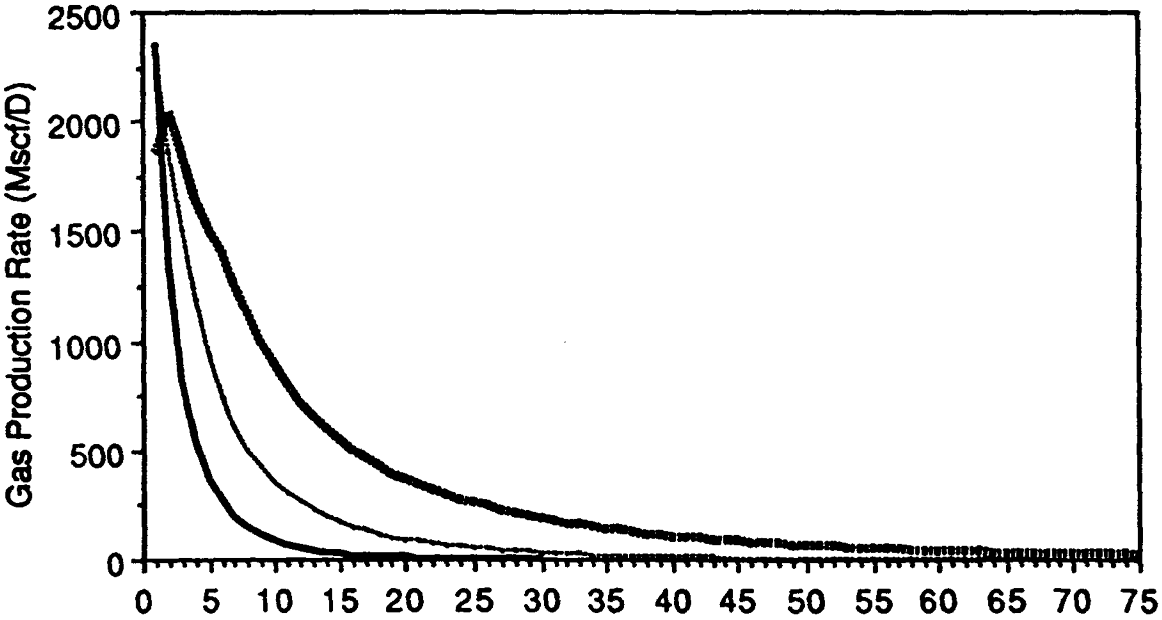
Application of Richardson Operating Co.
Record on Appeal, 1588.

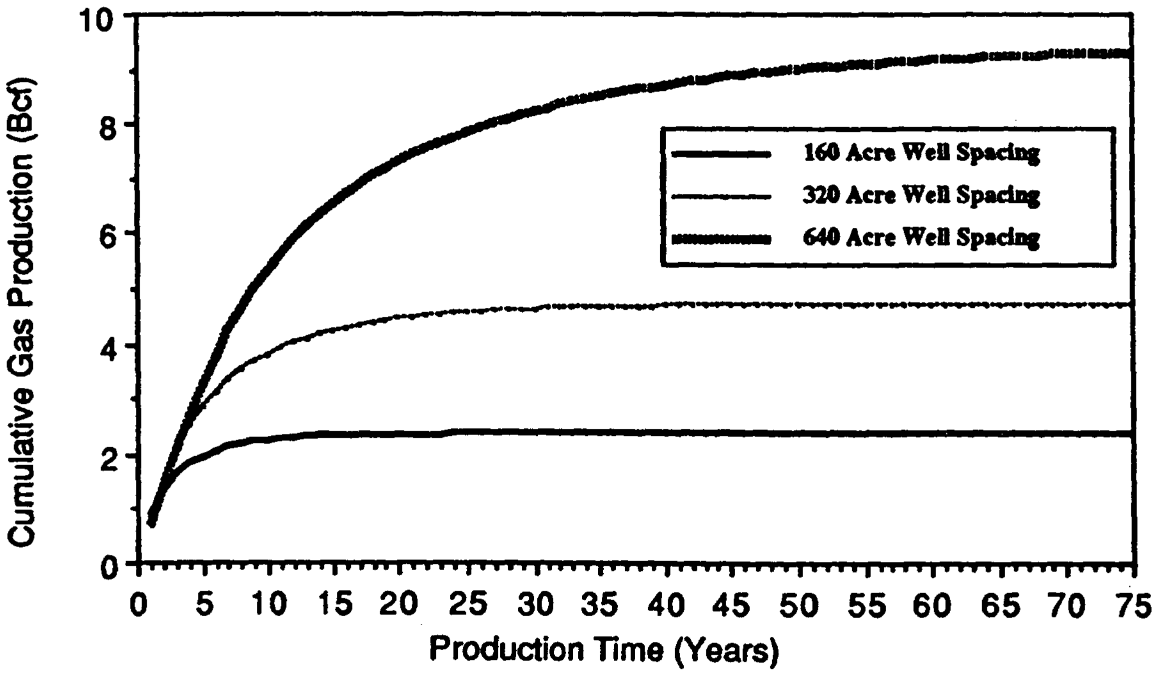
Figure 12

San Juan Basin Sensitivity Analysis

Area 1 Type Reservoir - Single Well Case

Permeability = 50md and Fracture Half Length = 300 Ft

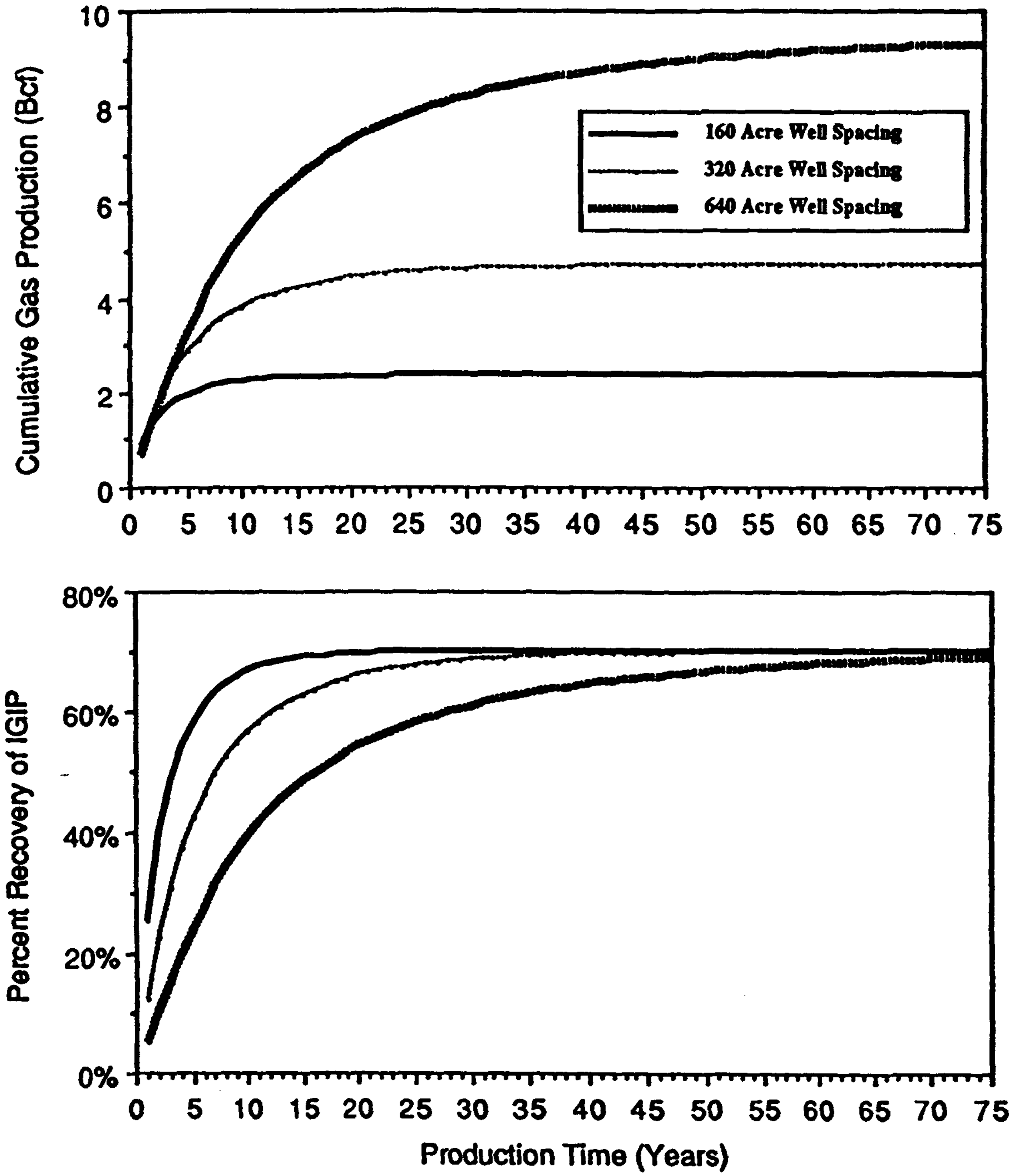




Application of Richardson Operating Co.
Record on Appeal, 1589.

Figure 13

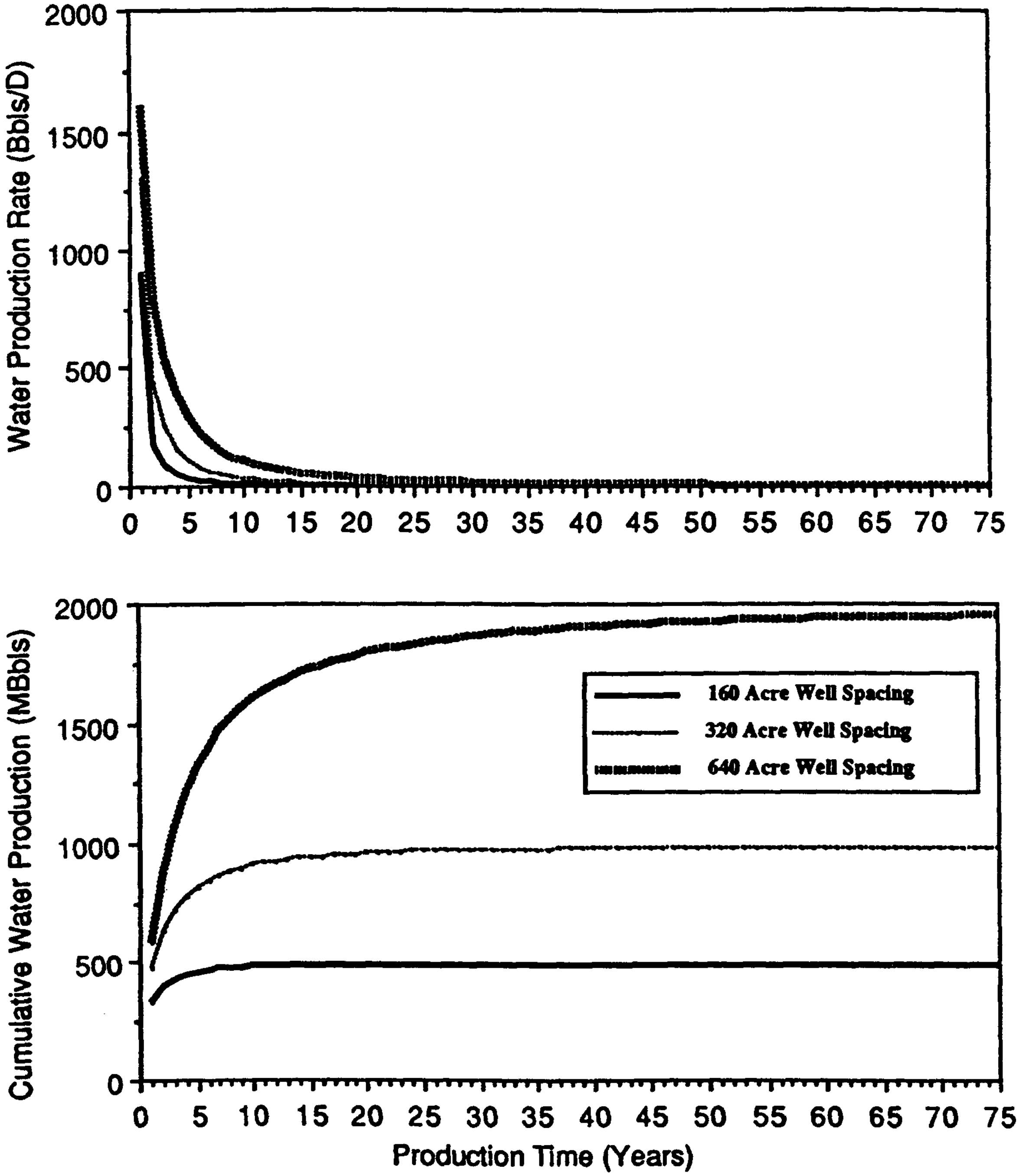
San Juan Basin Sensitivity Analysis
Area 1 Type Reservoir - Single Well Case
Permeability = 50md and Fracture Half Length = 300 Ft



Application of Richardson Operating Co.
Record on Appeal, 1590.

Figure 14

San Juan Basin Sensitivity Analysis
Area 1 Type Reservoir - Single Well Case
Permeability = 50md and Fracture Half Length = 300 Ft

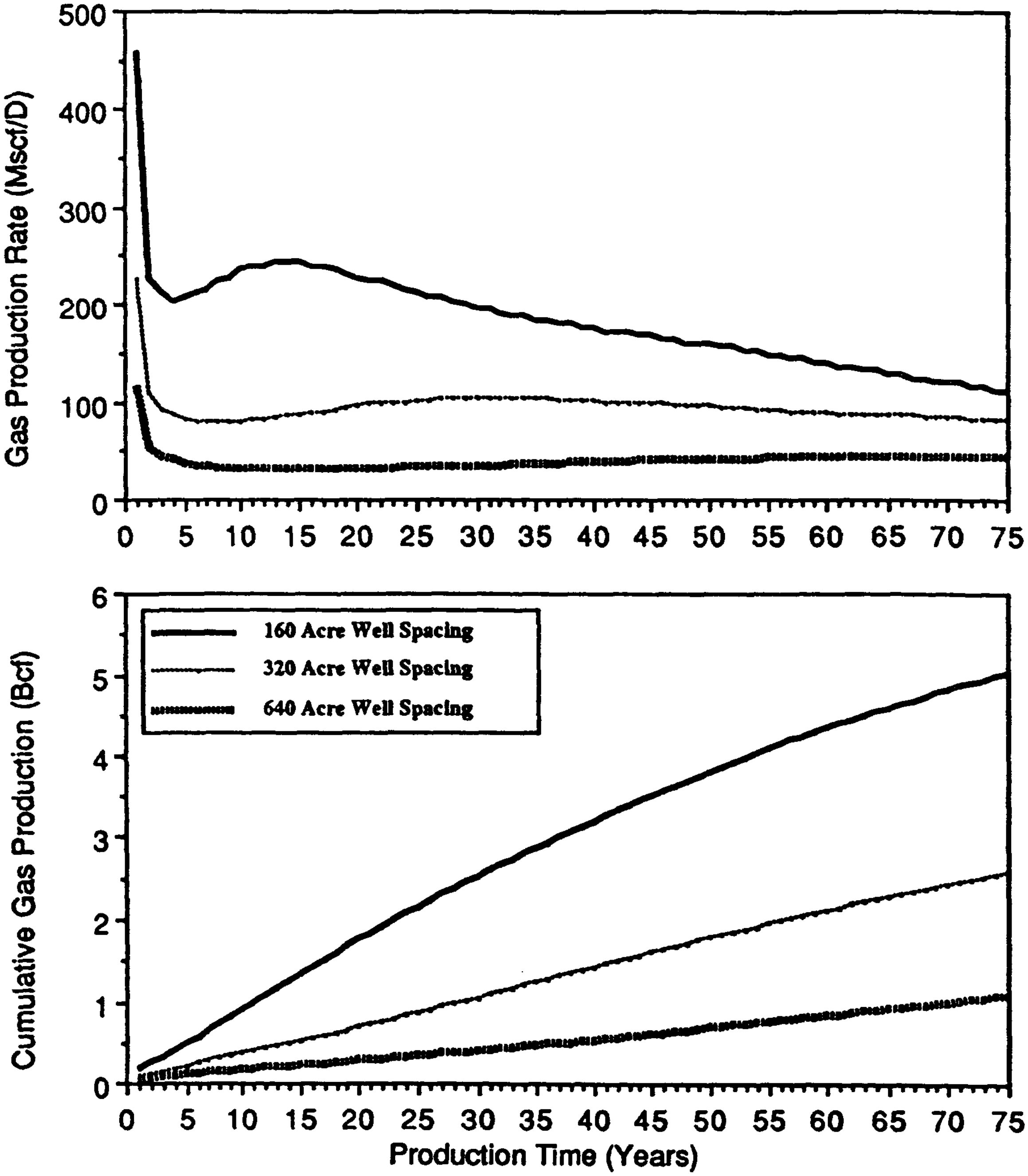


ICF Resources Incorporated

Application of Richardson Operating Co.
Record on Appeal, 1591.

Figure 15

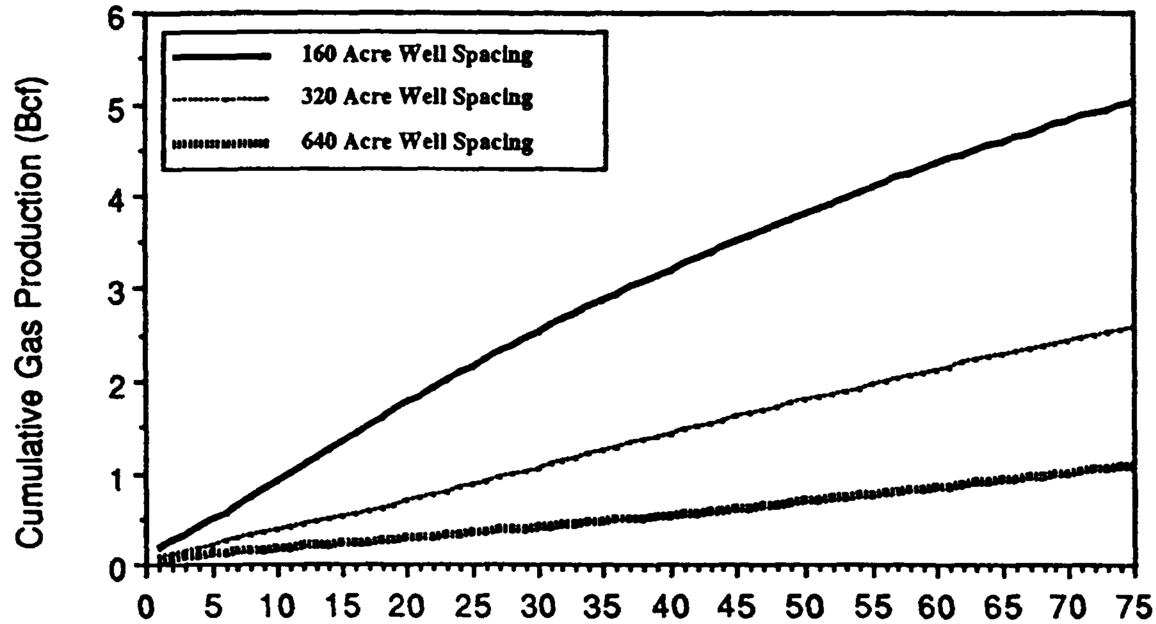
San Juan Basin Sensitivity Analysis
Area 1 Type Reservoir - Full Section Case
Permeability = 1md and Fracture Half Length = 300 Ft

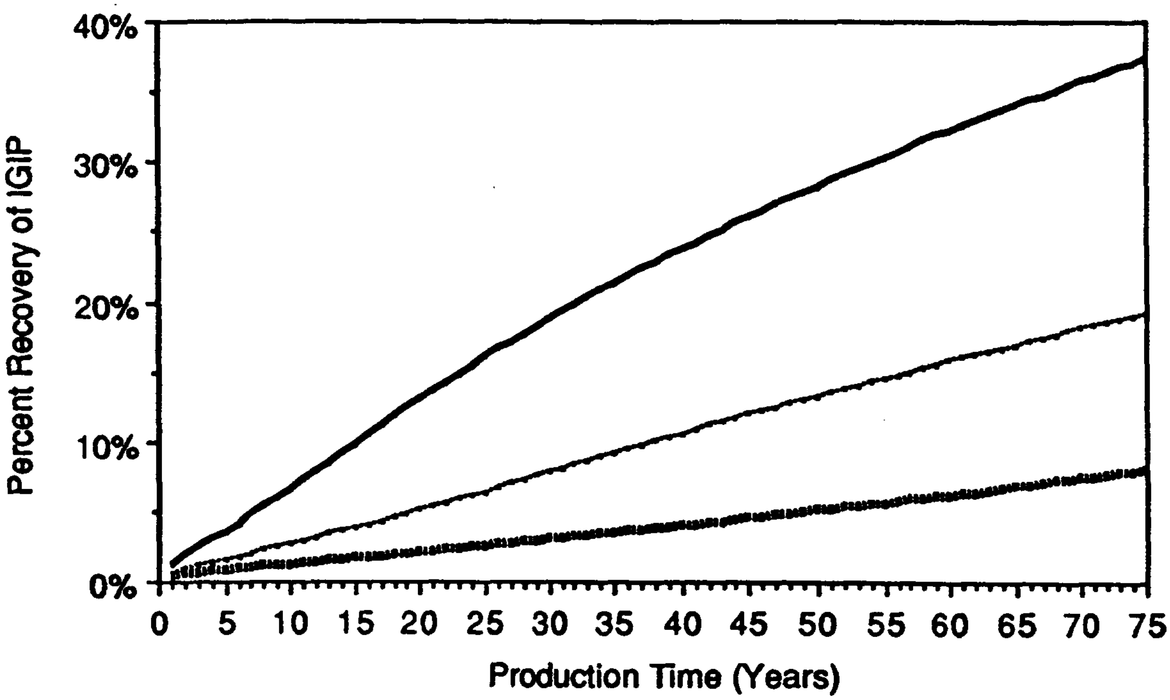


Application of Richardson Operating Co.
Record on Appeal, 1592.

Figure 16

San Juan Basin Sensitivity Analysis
Area 1 Type Reservoir - Full Section Case
Permeability = 1md and Fracture Half Length = 300 Ft

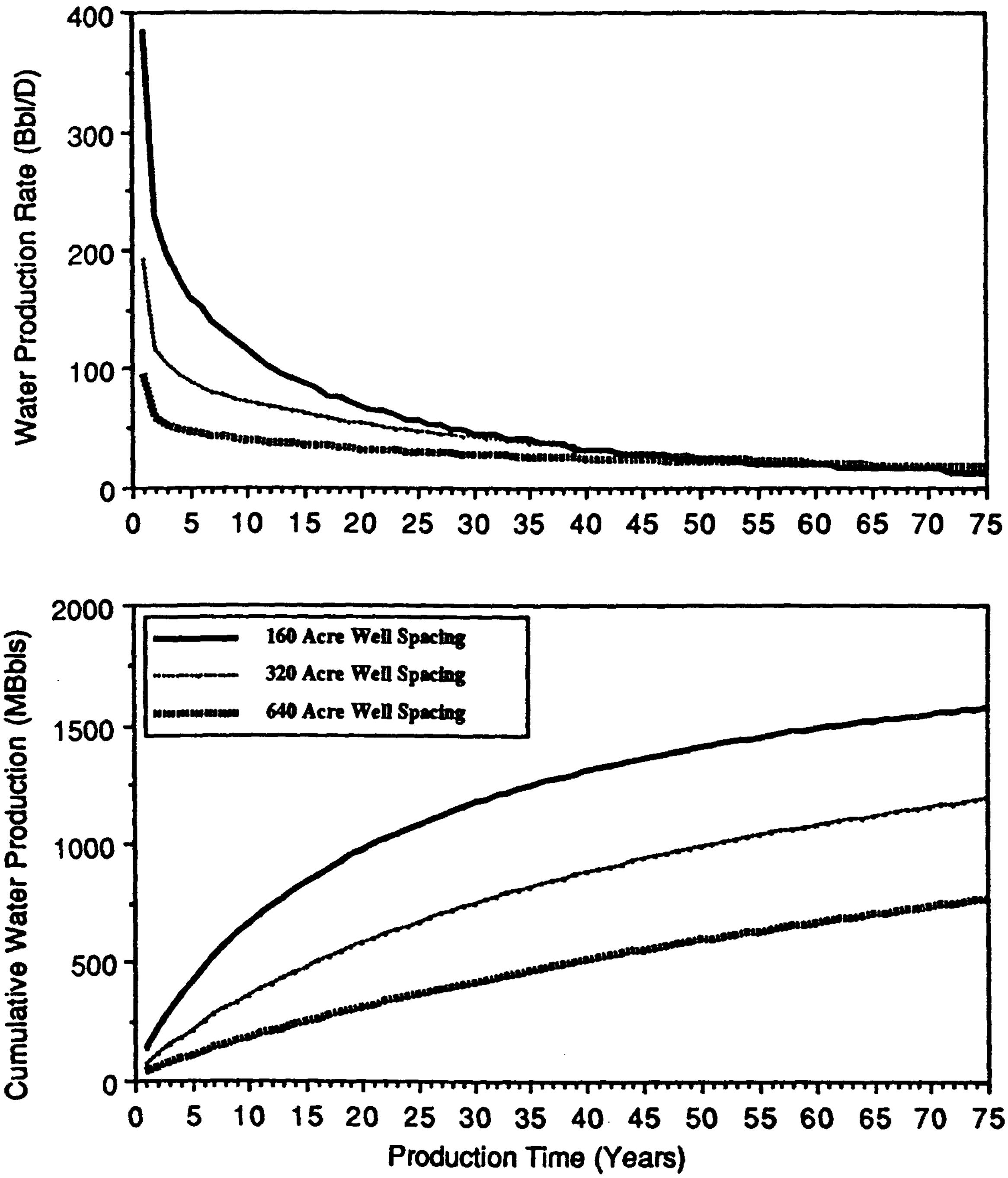




Application of Richardson Operating Co.
Record on Appeal, 1593.

Figure 17

San Juan Basin Sensitivity Analysis
Area 1 Type Reservoir - Full Section Case
Permeability = 1md and Fracture Half Length = 300 Ft



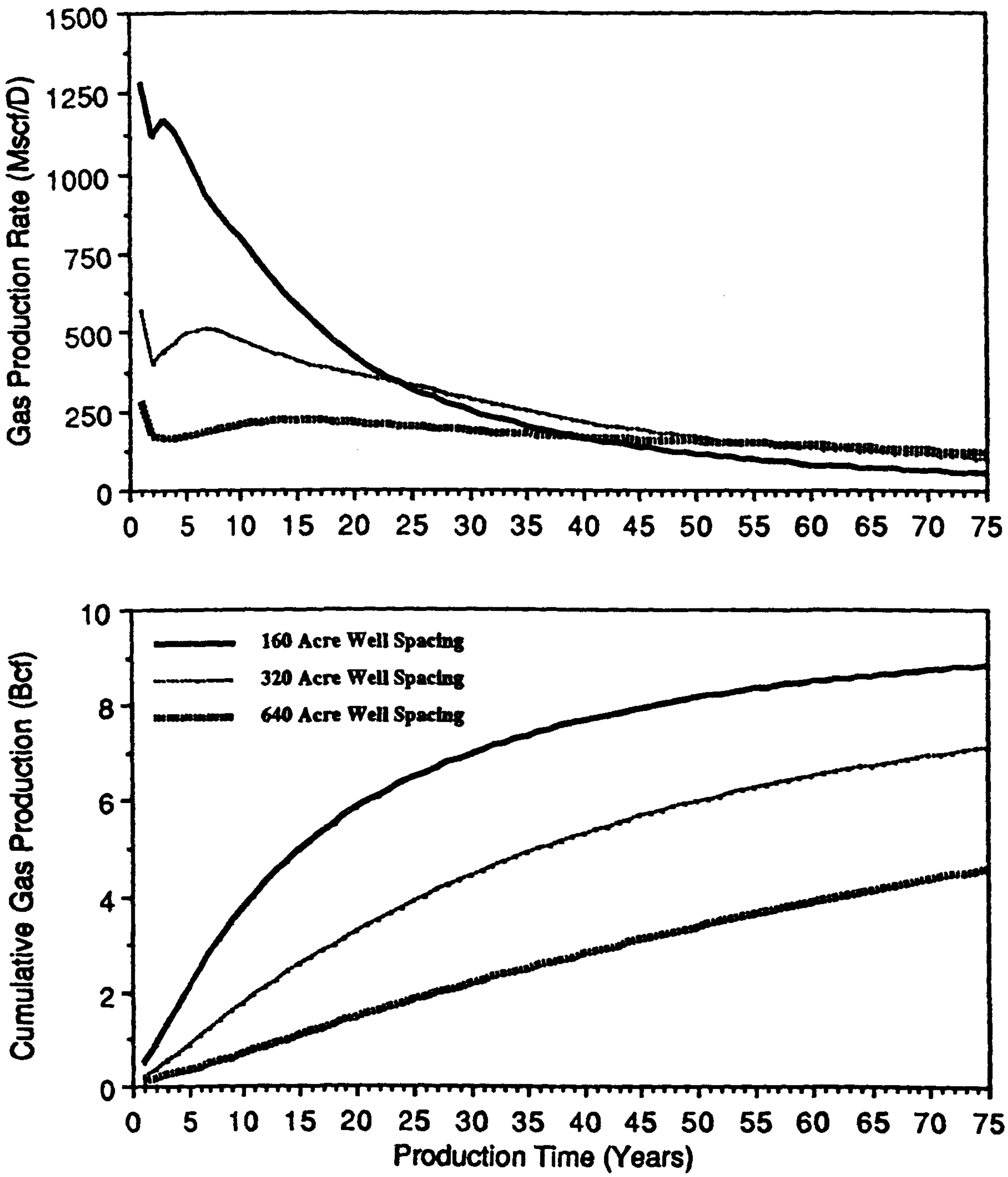
Application of Richardson Operating Co.
Record on Appeal, 1594.

Figure 18

San Juan Basin Sensitivity Analysis

Area 1 Type Reservoir - Full Section Case

Permeability = 5md and Fracture Half Length = 300 Ft



ICF Resources Incorporated

Application of Richardson Operating Co.
Record on Appeal, 1595.

Figure 19

San Juan Basin Sensitivity Analysis
Area 1 Type Reservoir - Full Section Case
Permeability = 5md and Fracture Half Length = 300 Ft

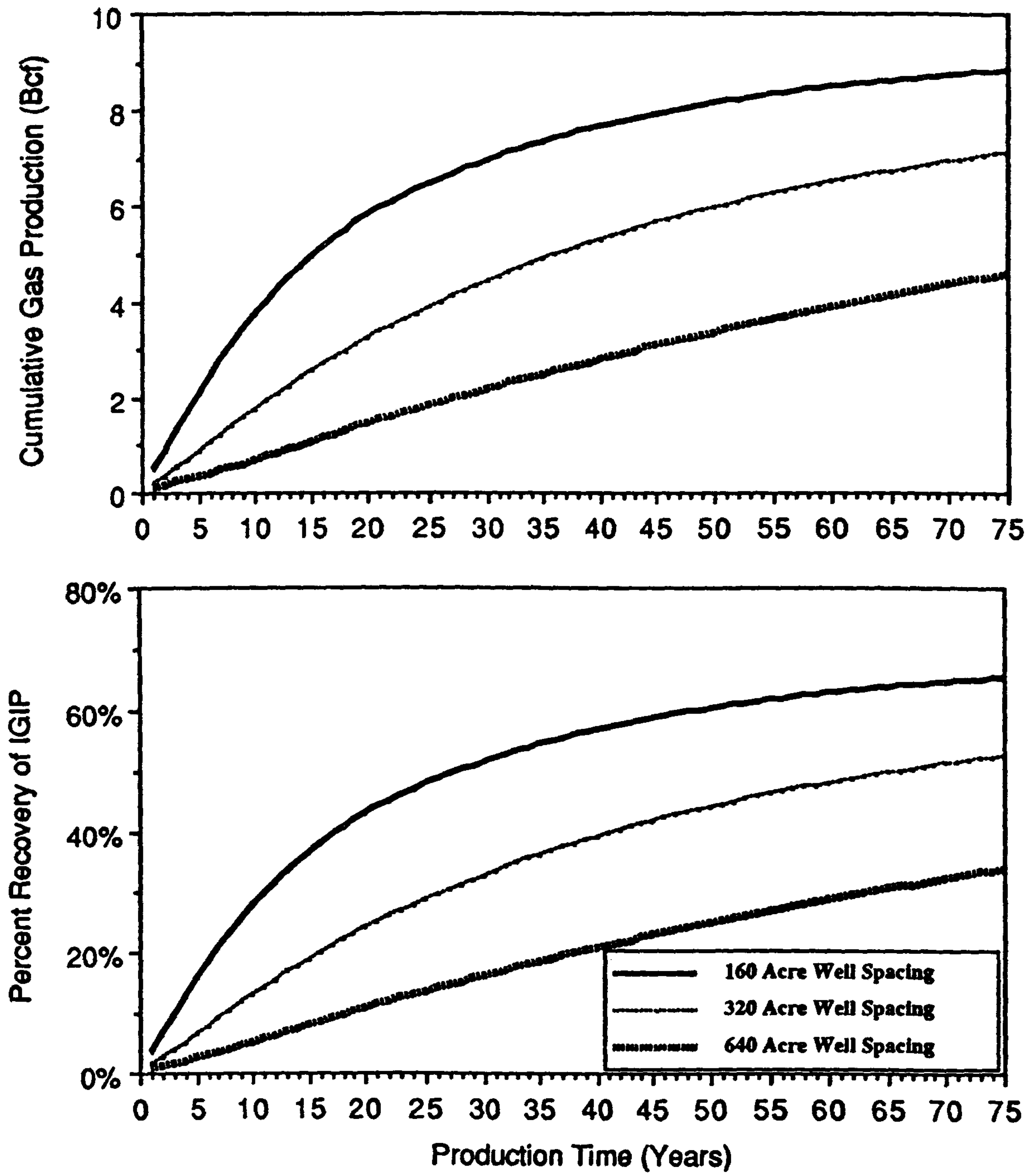


Figure 20

San Juan Basin Sensitivity Analysis

Area 1 Type Reservoir - Full Section Case

Permeability = 5md and Fracture Half Length = 300 Ft

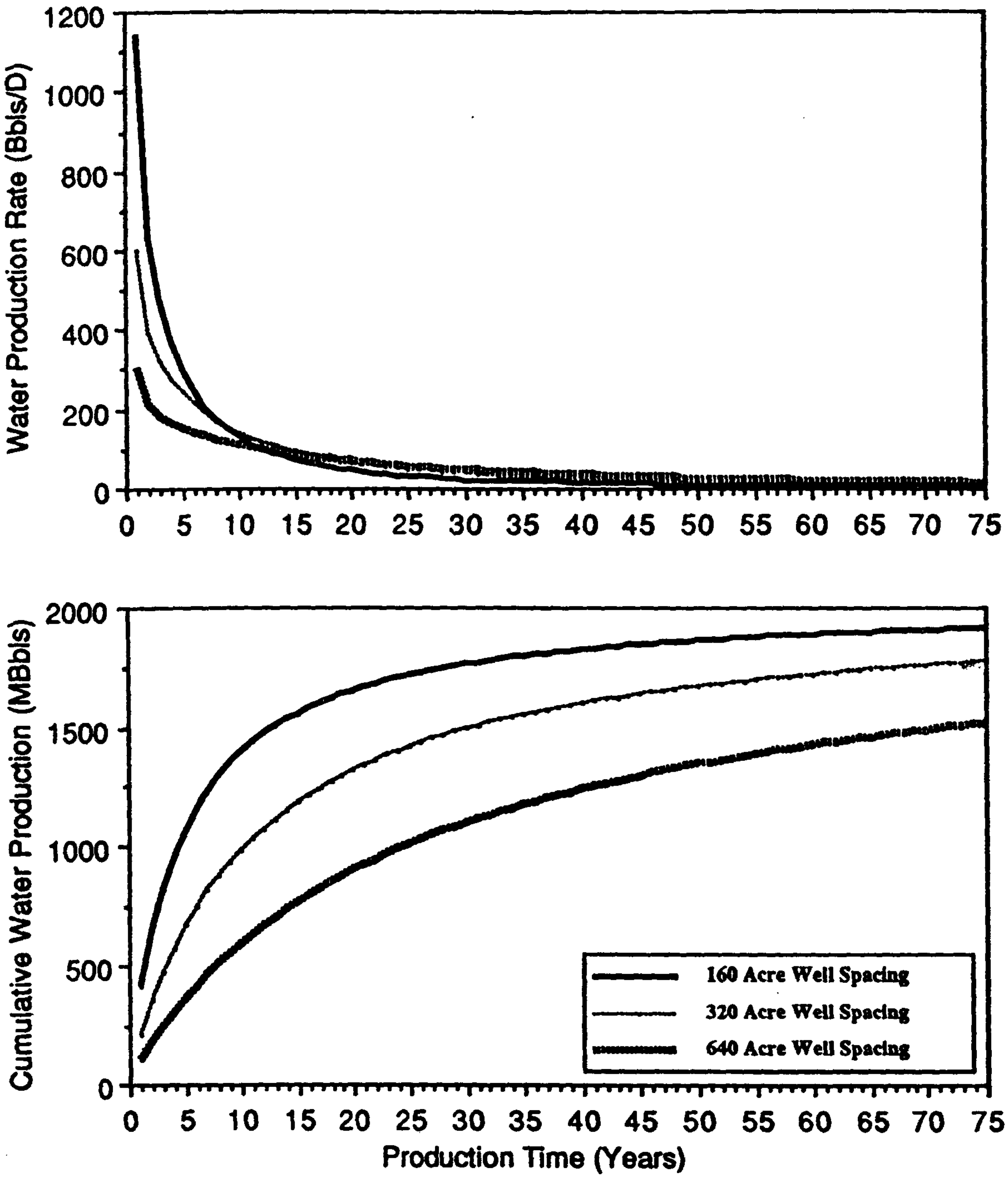
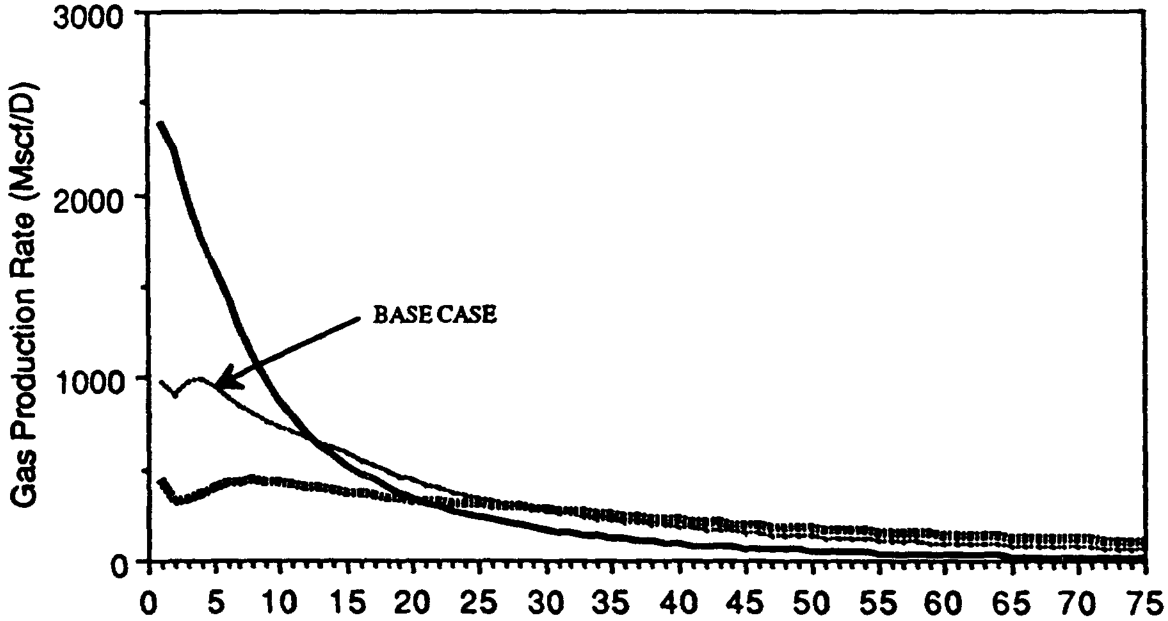
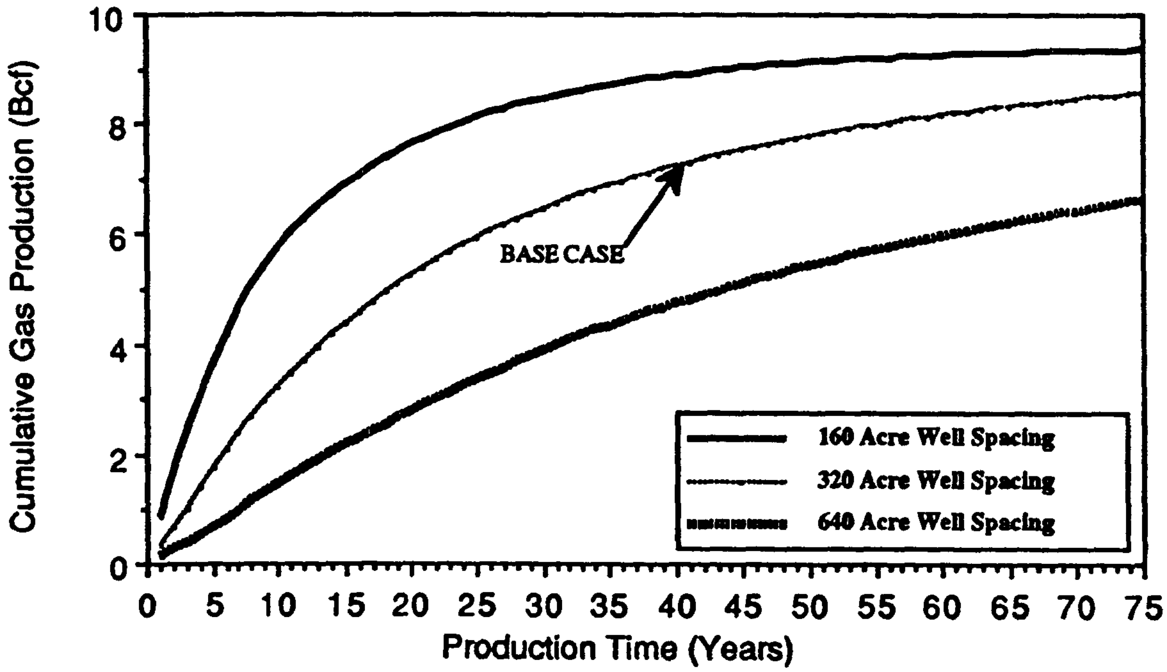


Figure 21

San Juan Basin Sensitivity Analysis
Area 1 Type Reservoir - Full Section Case
Permeability = 10md and Fracture Half Length = 300 Ft

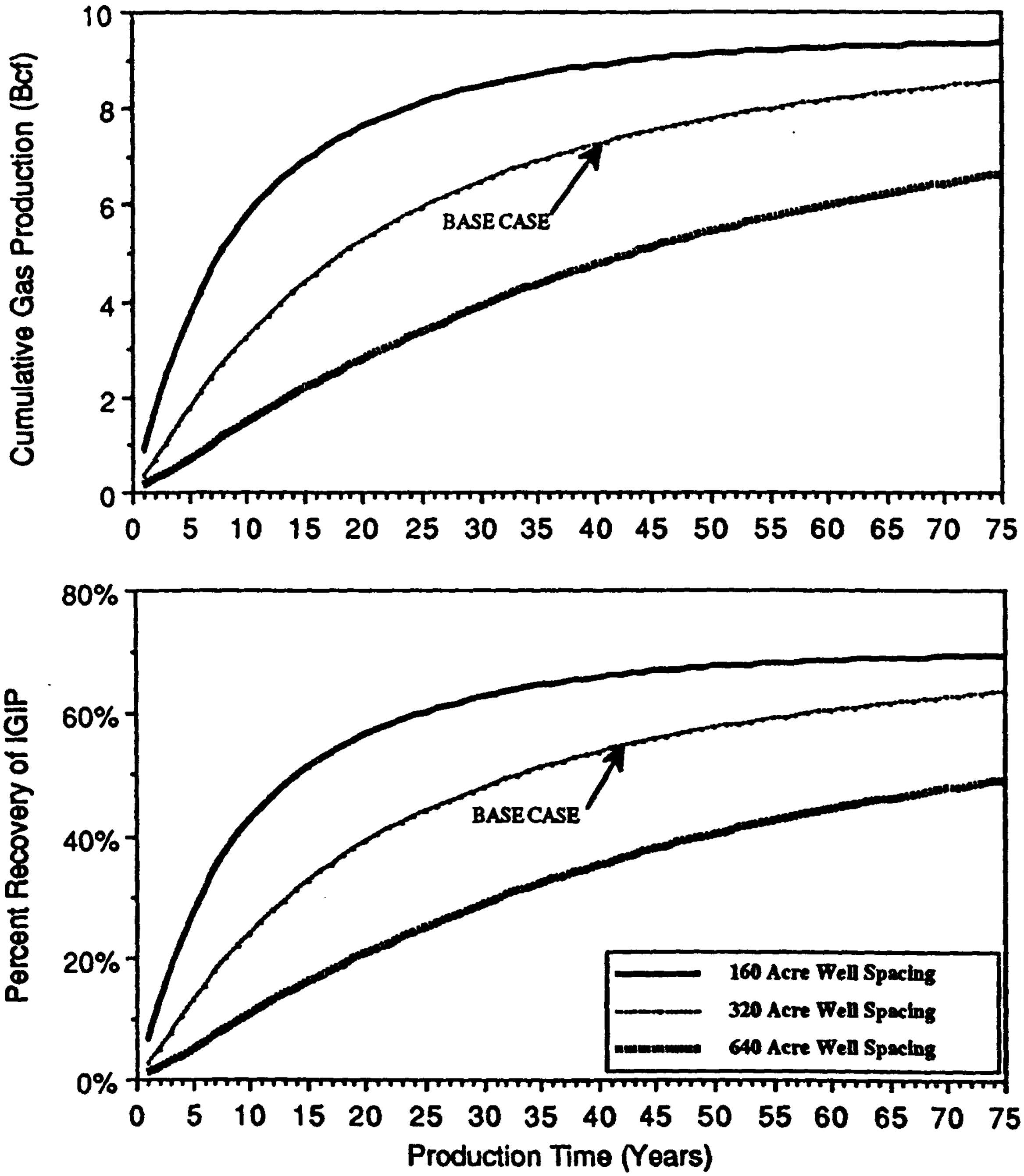




Application of Richardson Operating Co.
Record on Appeal, 1598.

Figure 22

San Juan Basin Sensitivity Analysis
Area 1 Type Reservoir - Full Section Case
Permeability = 10md and Fracture Half Length = 300 Ft



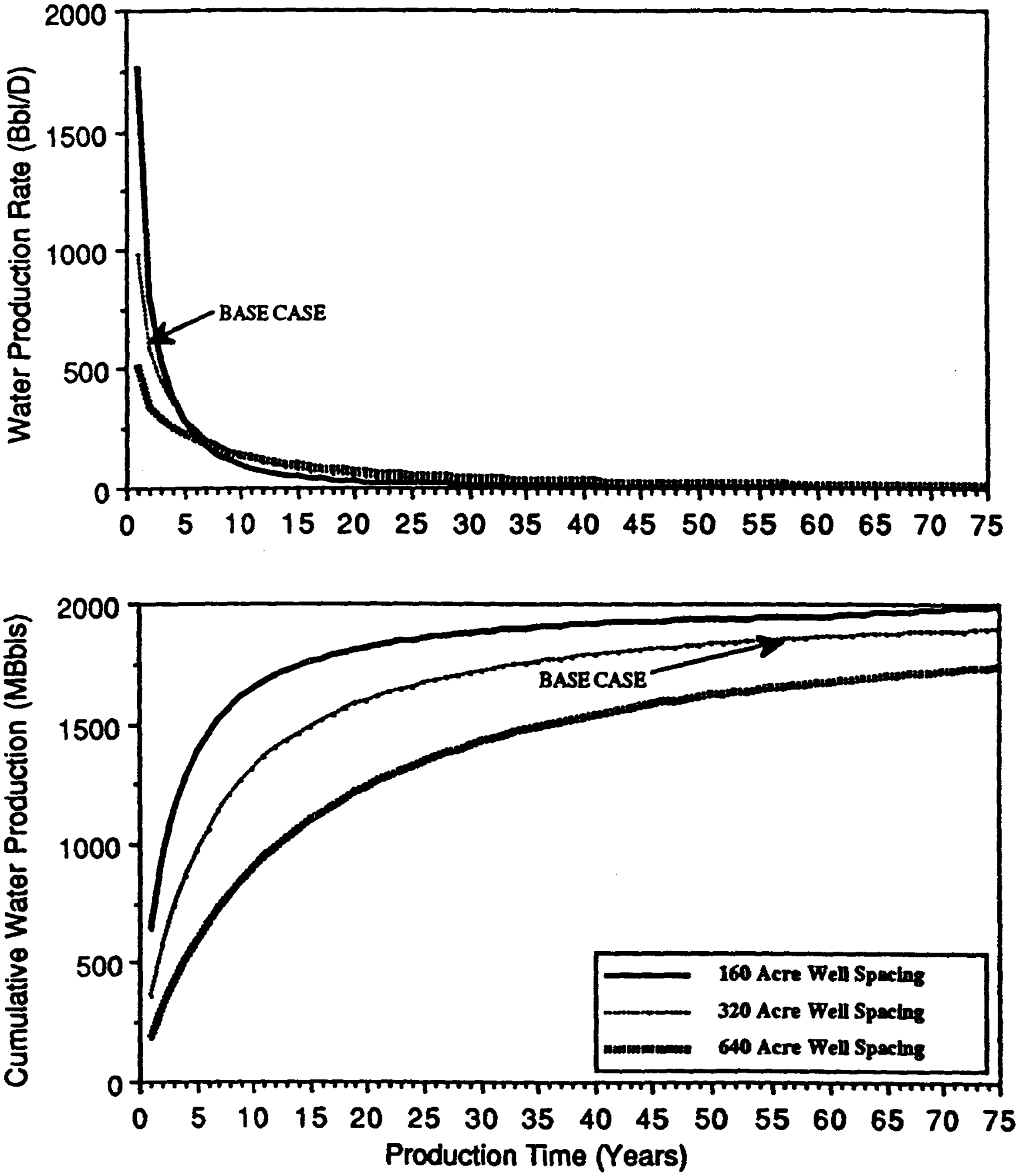
Application of Richardson Operating Co.
Record on Appeal, 1599.

Figure 23

San Juan Basin Sensitivity Analysis

Area 1 Type Reservoir - Full Section Case

Permeability = 10md and Fracture Half Length = 300 Ft



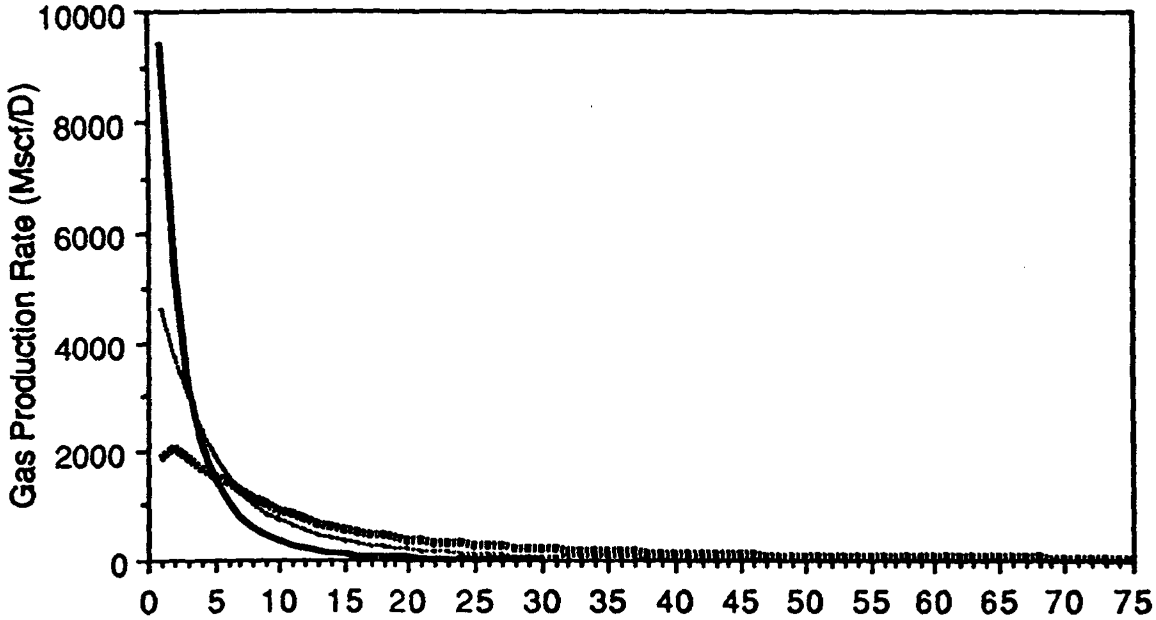
Application of Richardson Operating Co.
Record on Appeal, 1600.

Figure 24

San Juan Basin Sensitivity Analysis

Area 1 Type Reservoir - Full Section Case

Permeability = 50md and Fracture Half Length = 300 Ft



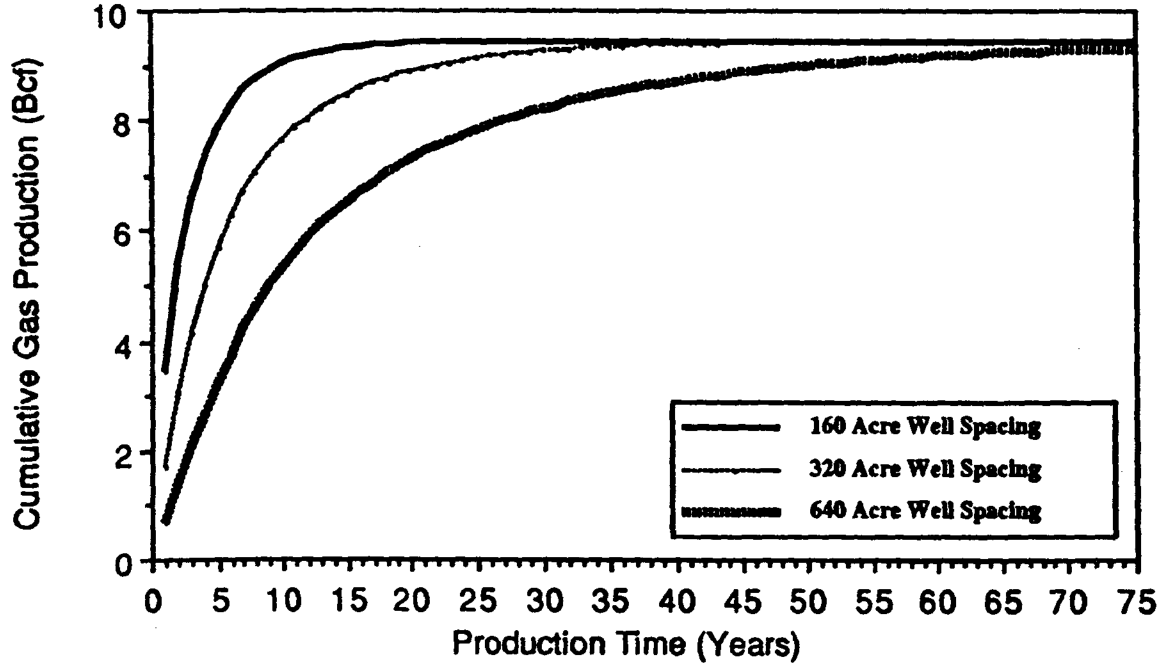
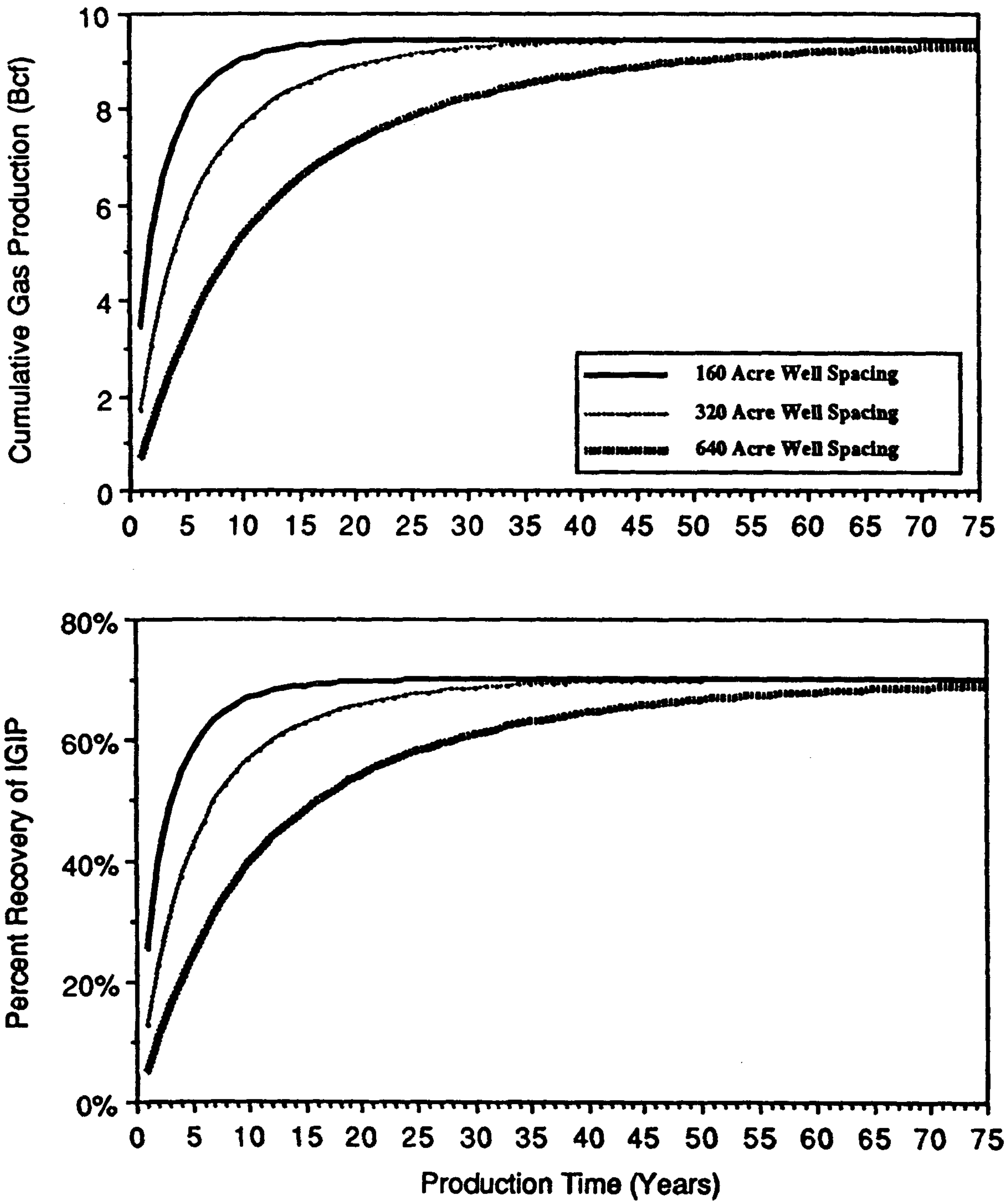


Figure 25

San Juan Basin Sensitivity Analysis

Area 1 Type Reservoir - Full Section Case

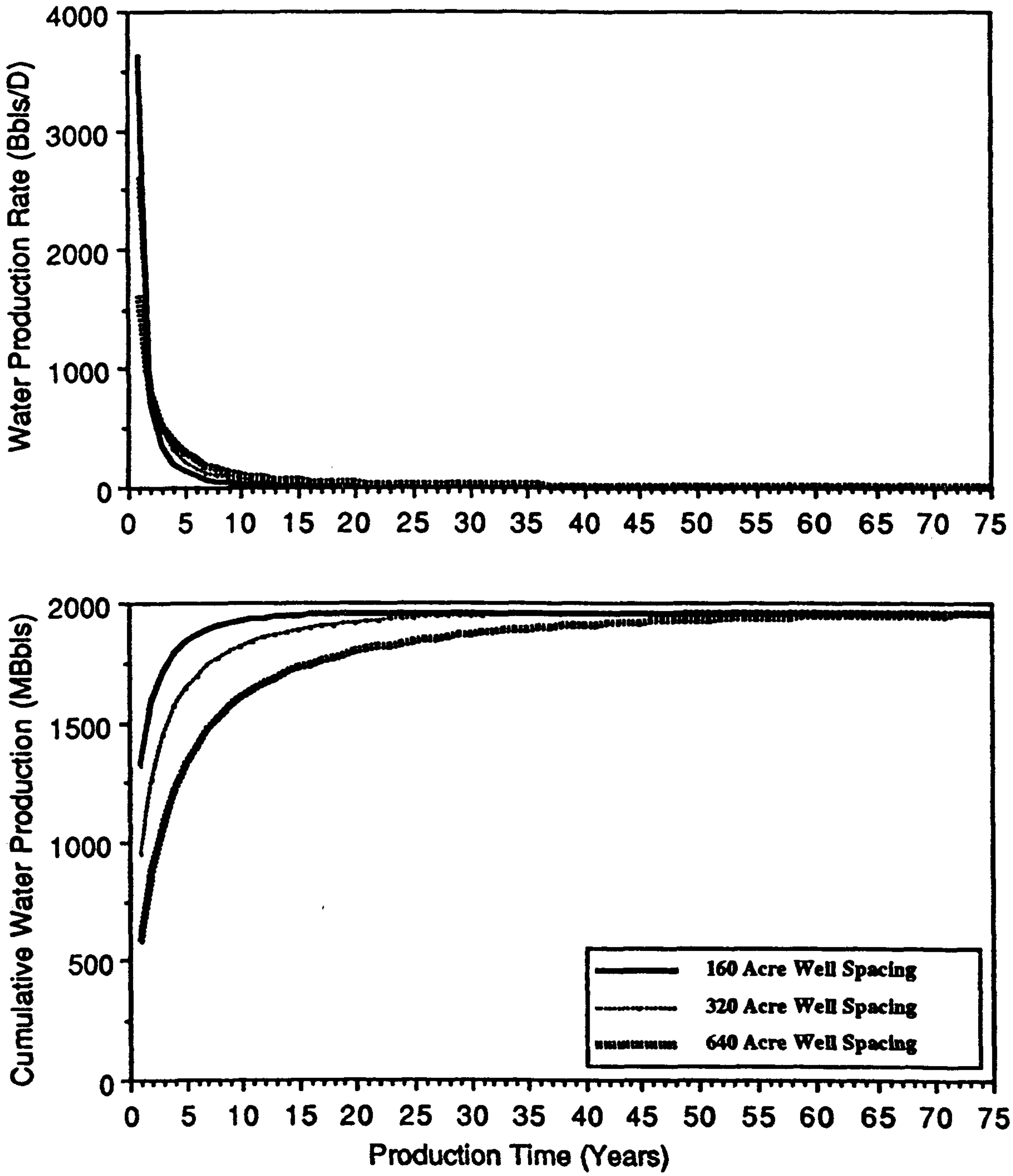
Permeability = 50md and Fracture Half Length = 300 Ft



Application of Richardson Operating Co.
Record on Appeal, 1602.

Figure 26

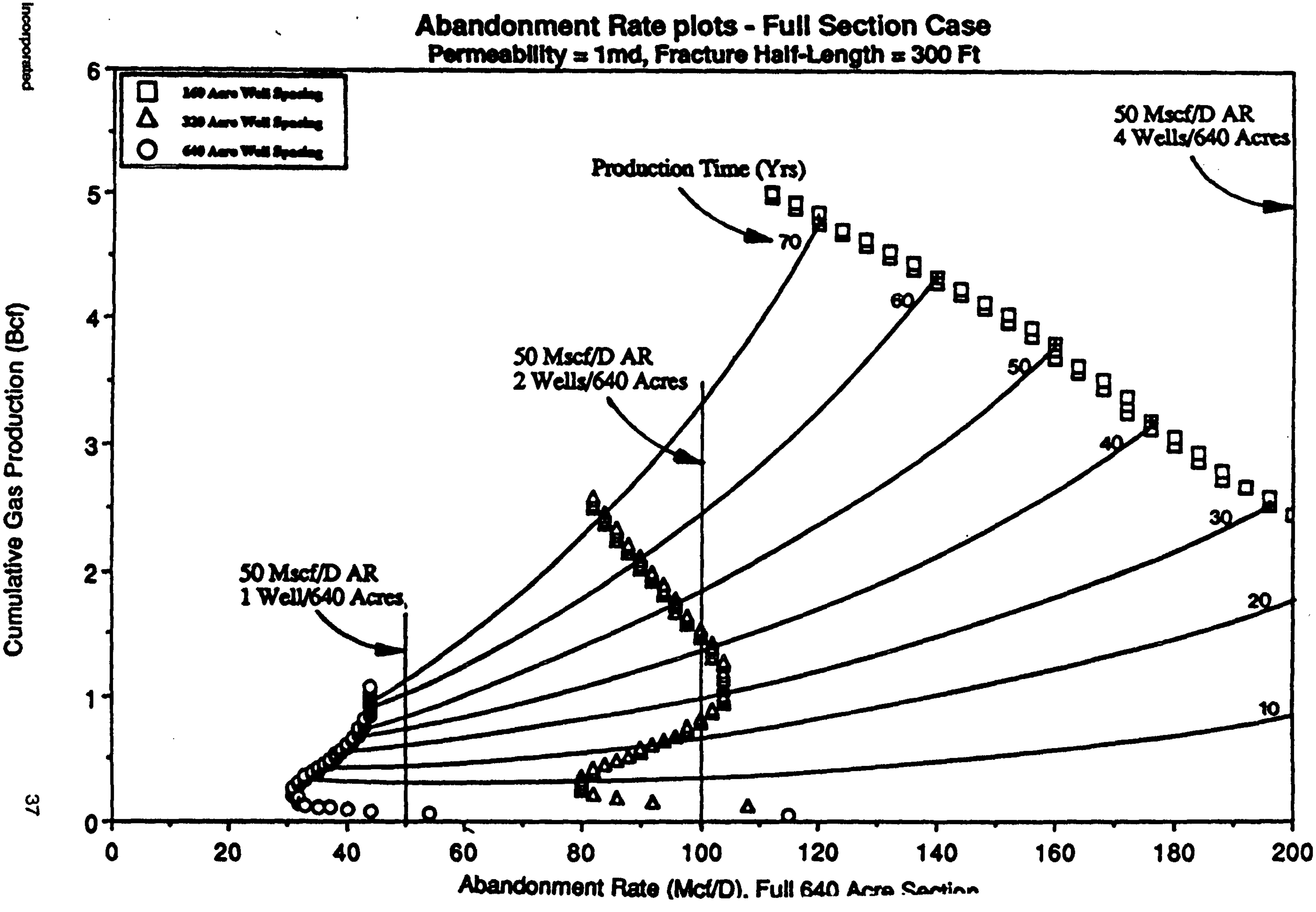
San Juan Basin Sensitivity Analysis
Area 1 Type Reservoir - Full Section Case
Permeability = 50md and Fracture Half Length = 300 Ft



Application of Richardson Operating Co.
Record on Appeal, 1604.

Figure 27 a

San Juan Basin Area 1



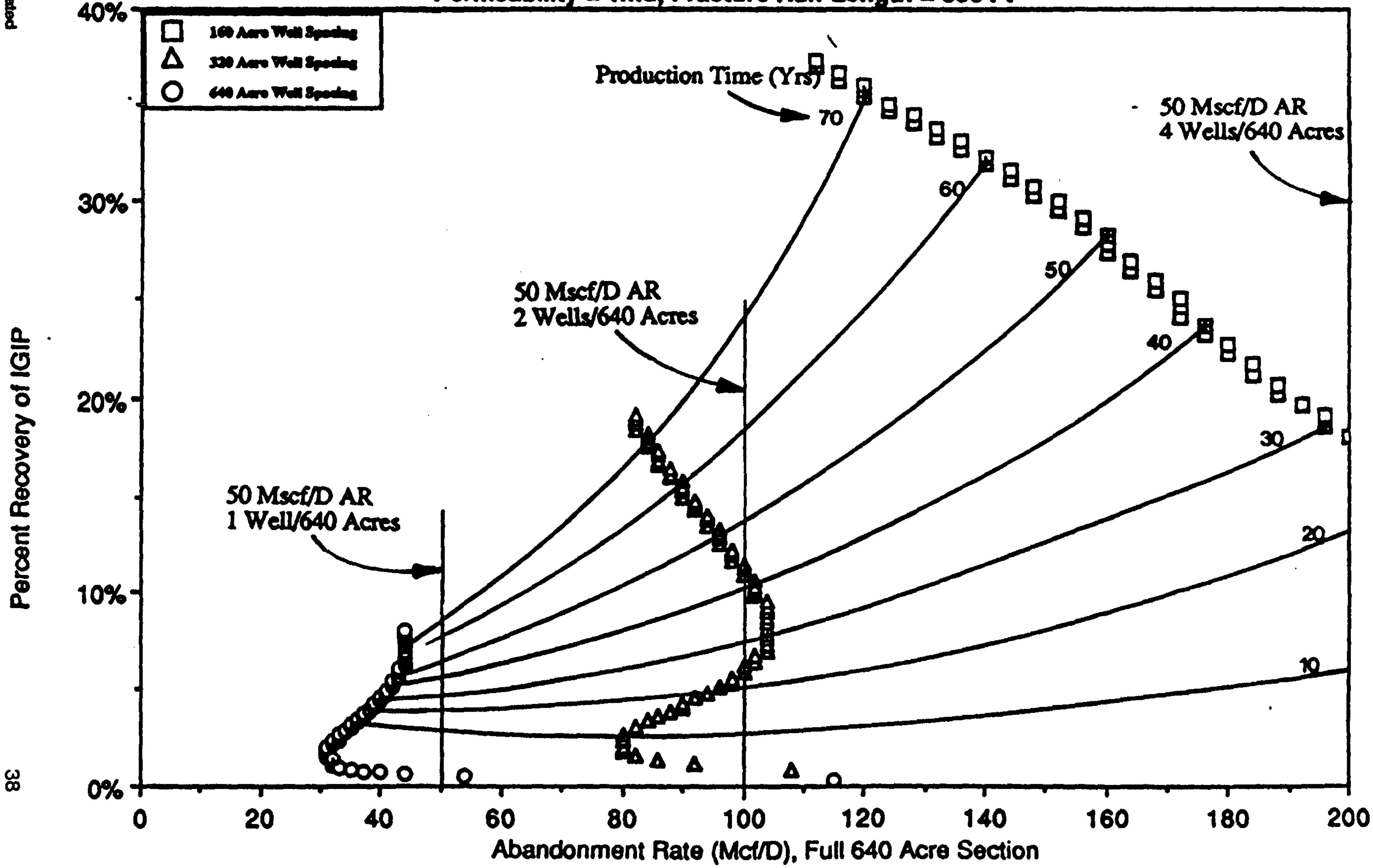
Application of Richardson Operating Co.
Record on Appeal, 1605.

Figure 27 b

San Juan Basin Area 1

Abandonment Rate plots - Full Section Case

Permeability = 1md, Fracture Half-Length = 300 Ft

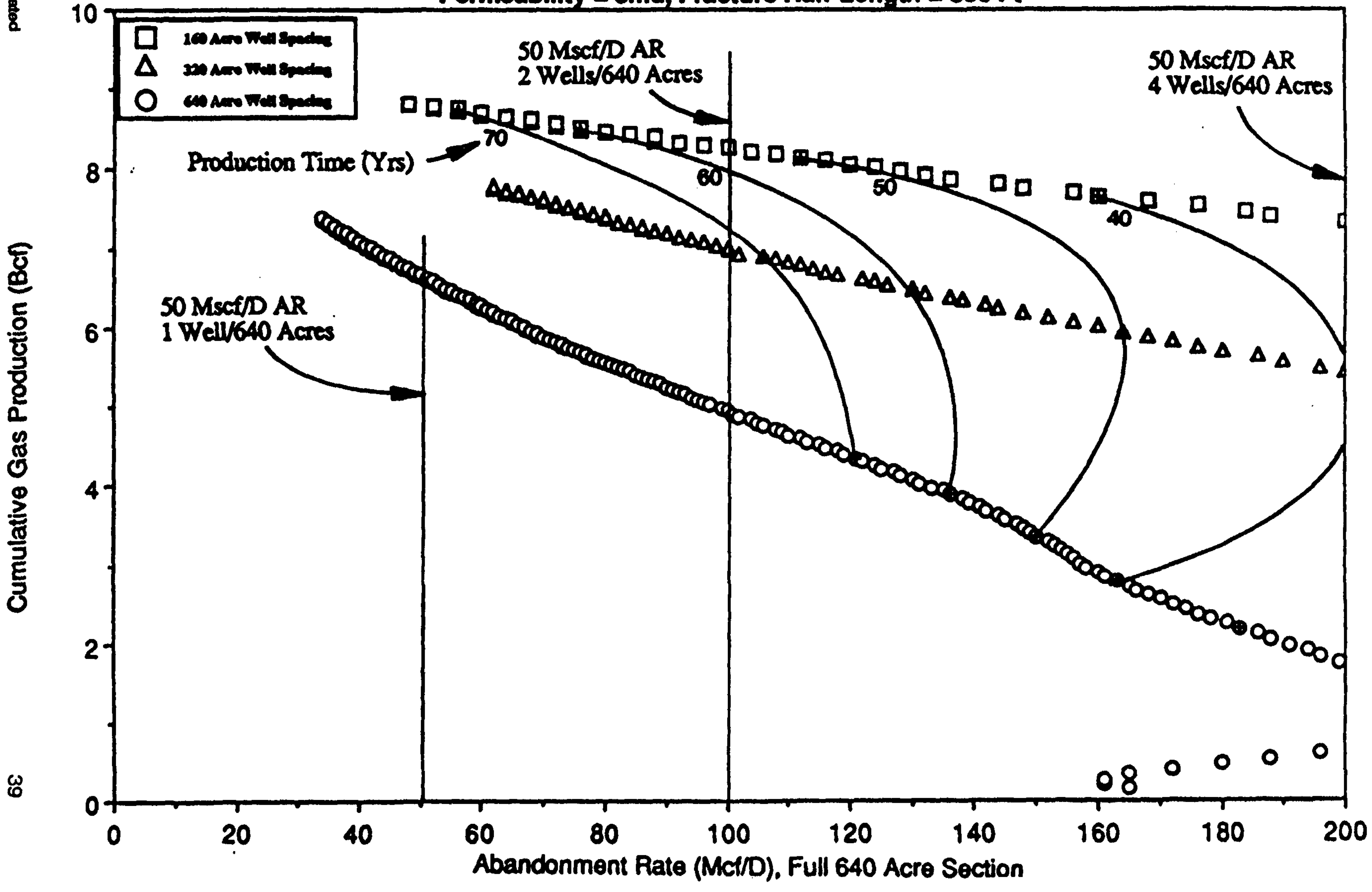


Application of Richardson Operating Co.
Record on Appeal, 1606.

Figure 28 a

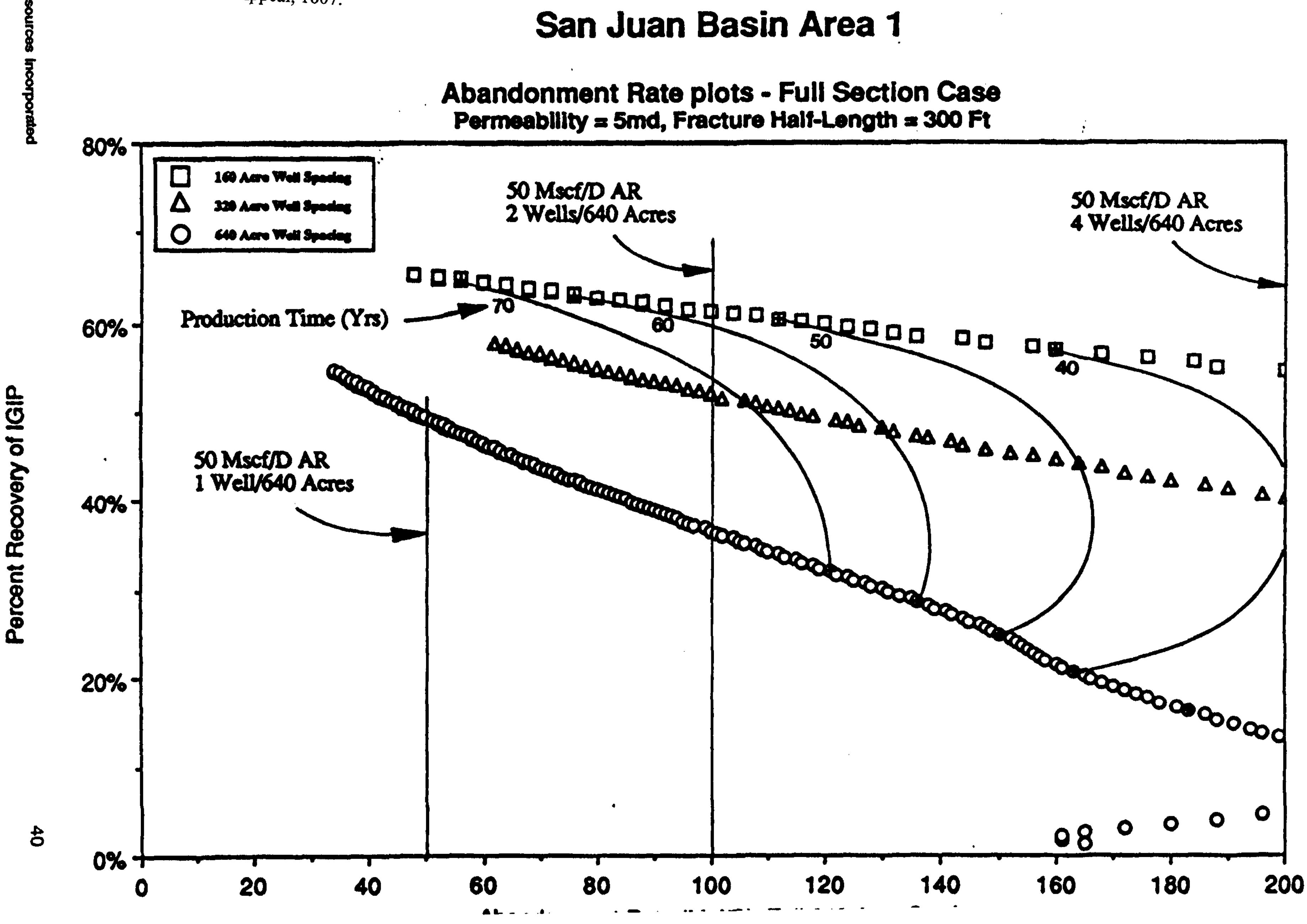
San Juan Basin Area 1

Abandonment Rate plots - Full Section Case
Permeability = 5md, Fracture Half-Length = 300 Ft



Application of Richardson Operating Co.
Record on Appeal, 1607.

Figure 28 b

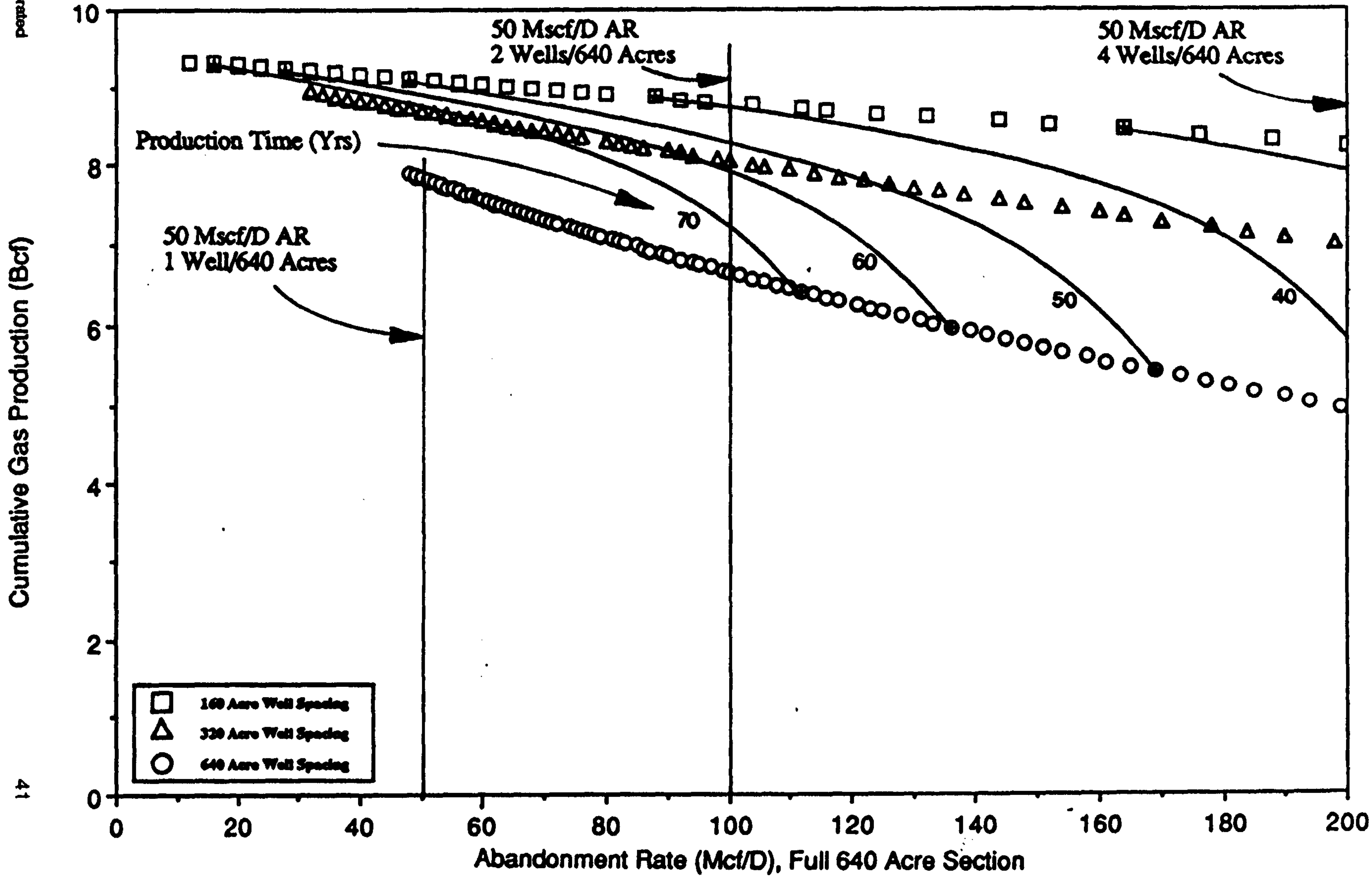


Application of Richardson Operating Co.
Record on Appeal, 1608.

Figure 29 a

San Juan Basin Area 1

Abandonment Rate plots - Full Section Case
Permeability = 10 md, Fracture Half-Length = 300 Ft



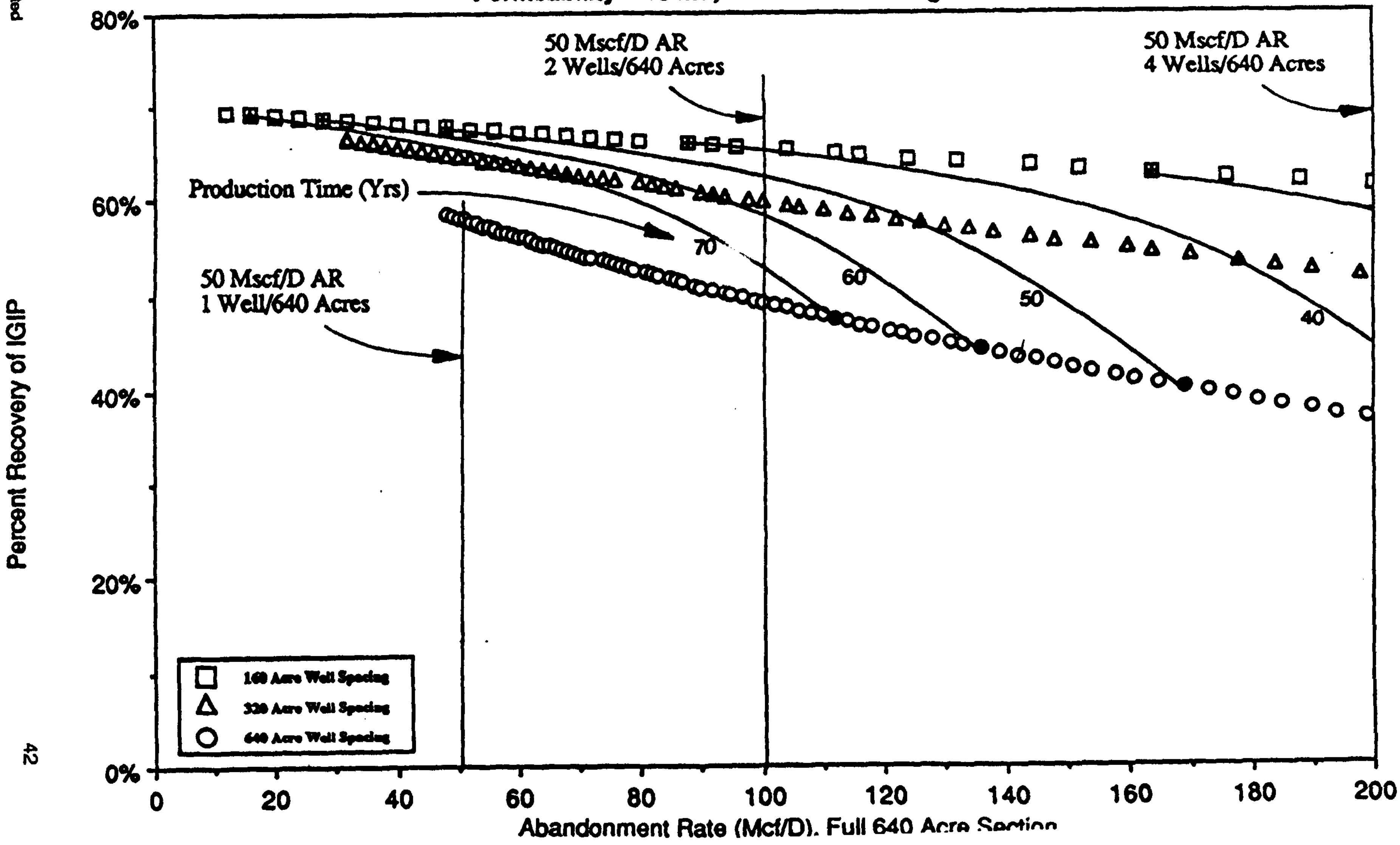
Application of Richardson Operating Co.
Record on Appeal, 1609.

Figure 29 b

San Juan Basin Area 1

Abandonment Rate plots - Full Section Case

Permeability = 10 md, Fracture Half-Length = 300 Ft



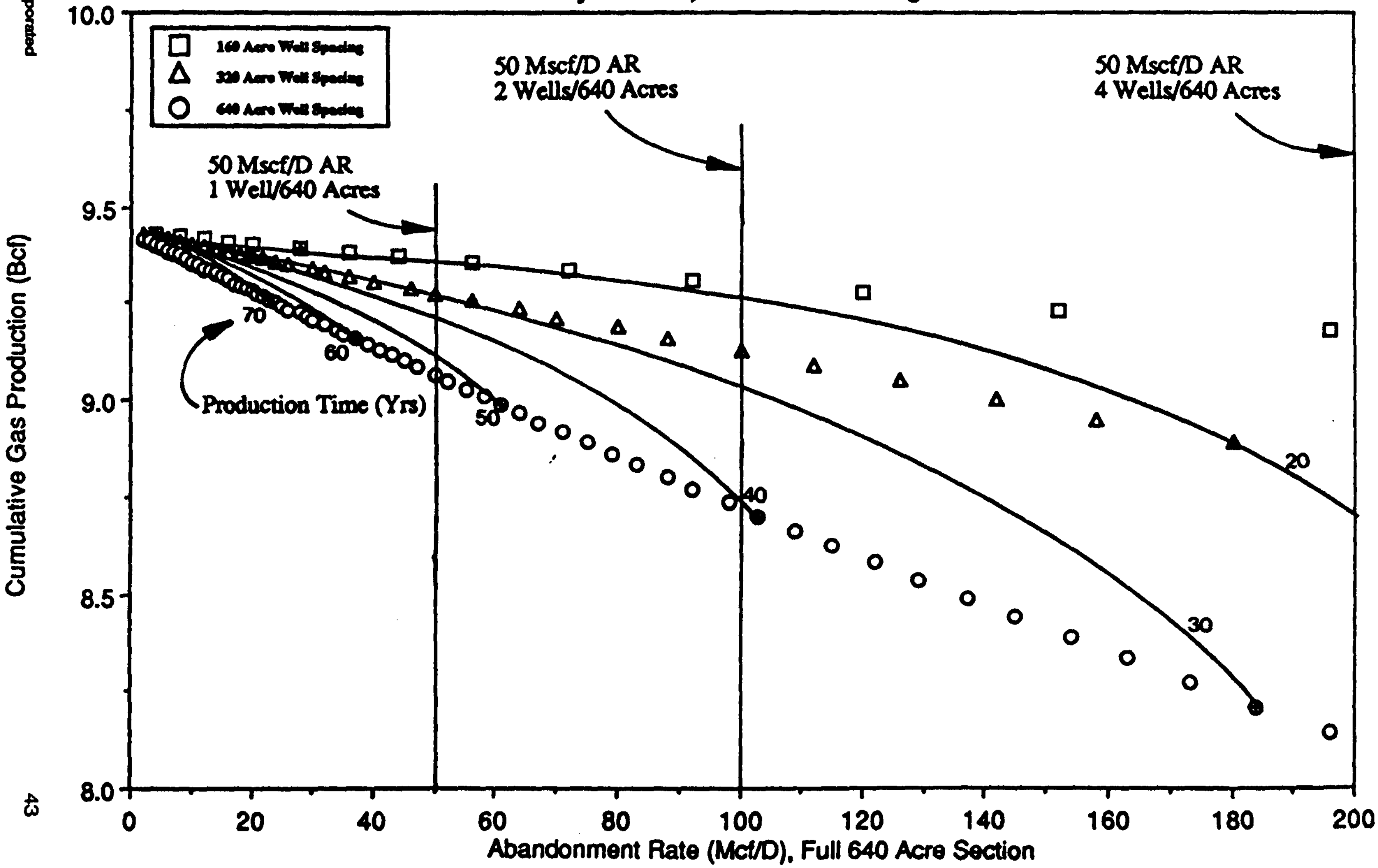
Application of Richardson Operating Co.
Record on Appeal, 1610.

Figure 30 a

San Juan Basin Area 1

Abandonment Rate plots - Full Section Case

Permeability = 50 md, Fracture Half-Length = 300 Ft



Application of Richardson Operating Co.
Record on Appeal, 1611.

Figure 30 b

San Juan Basin Area 1

Abandonment Rate plots - Full Section Case

Permeability = 50 md, Fracture Half-Length = 300 Ft

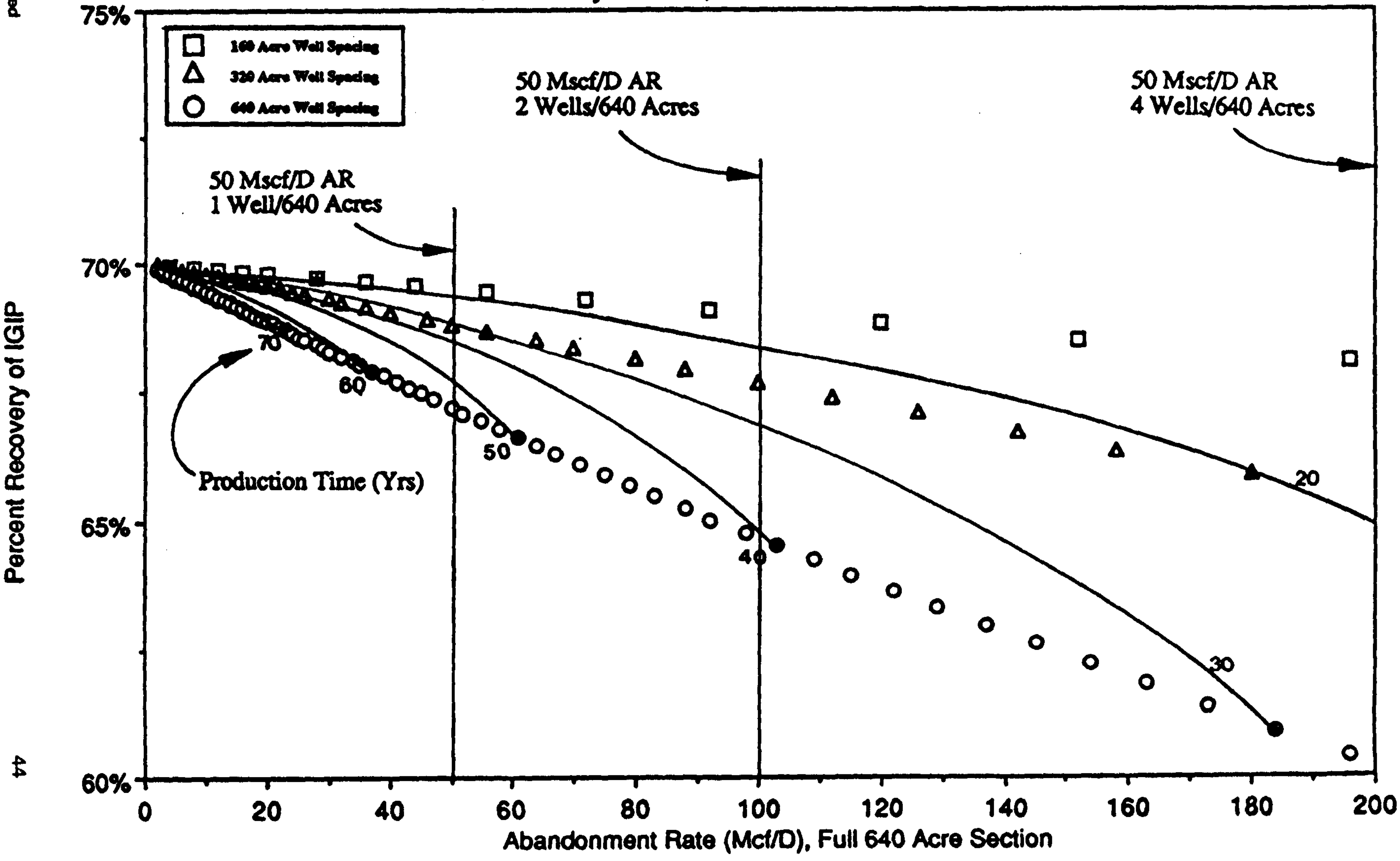
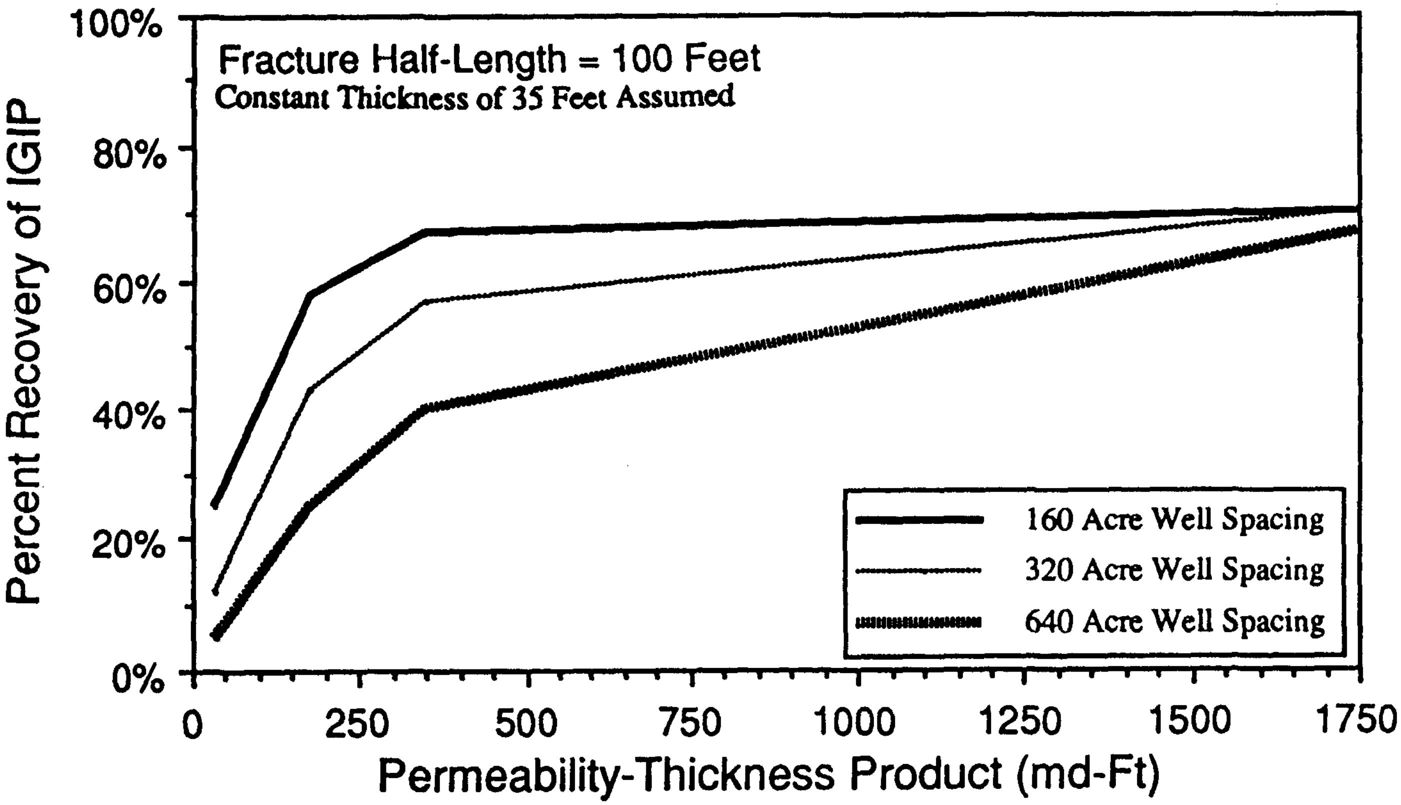


Figure 31

San Juan Basin Area 1 Gas Recovery vs kh

75 Year Simulation

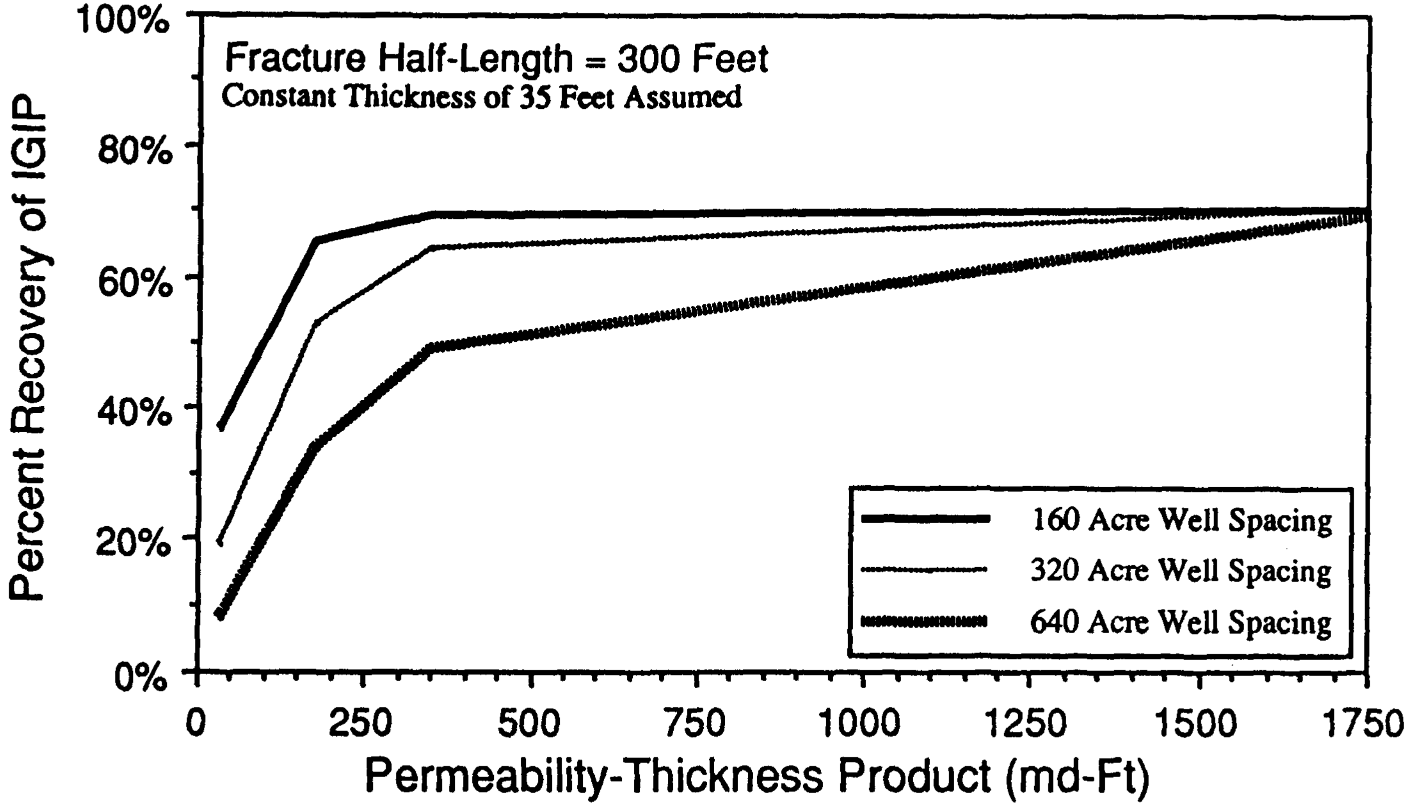


Application of Richardson Operating Co.
Record on Appeal, 1612.

Figure 32

San Juan Basin Area 1
Gas Recovery vs kh

75 Year Simulation



Application of Richardson Operating Co.
Record on Appeal, 1613.

Figure 33

San Juan Basin Area 1
Gas Recovery vs kh

75 Year Simulation

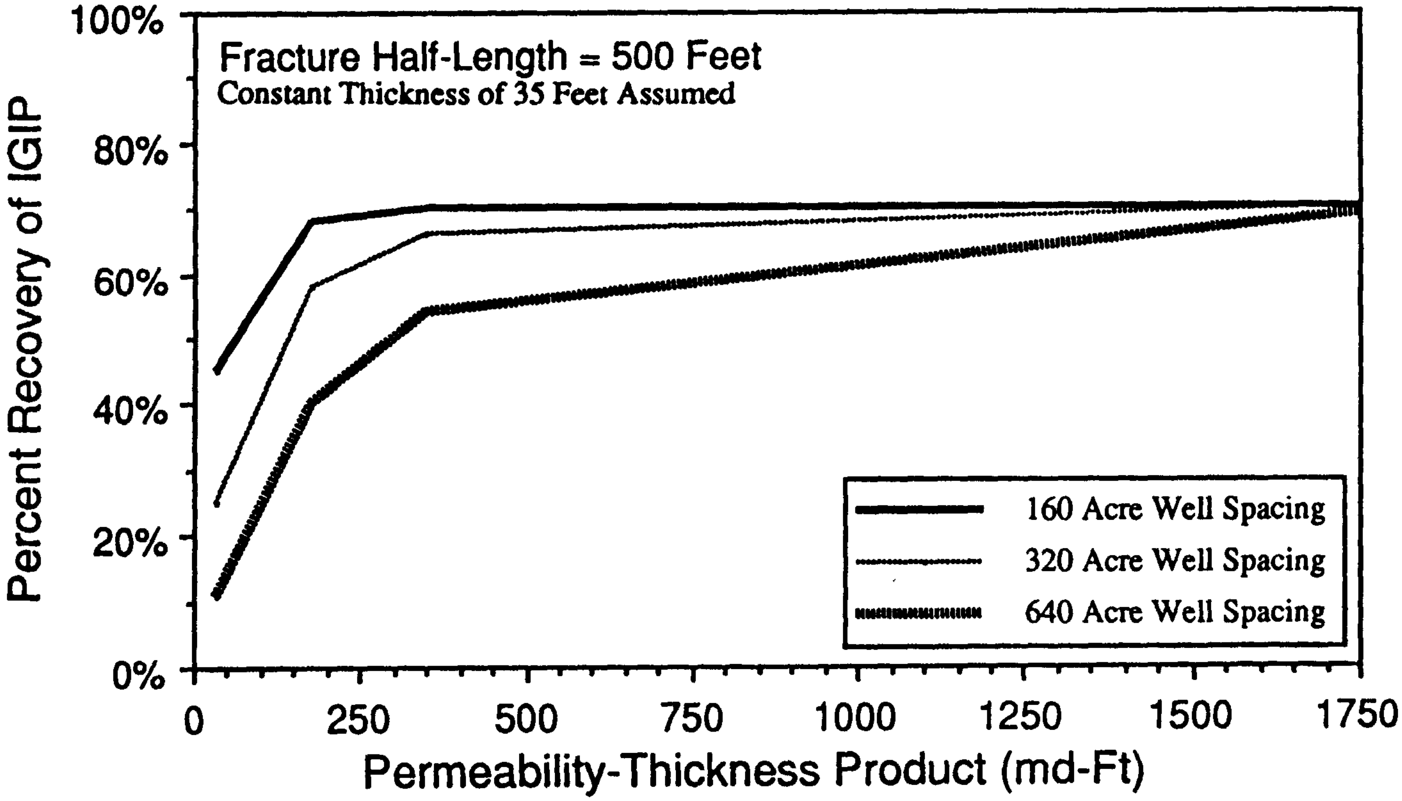
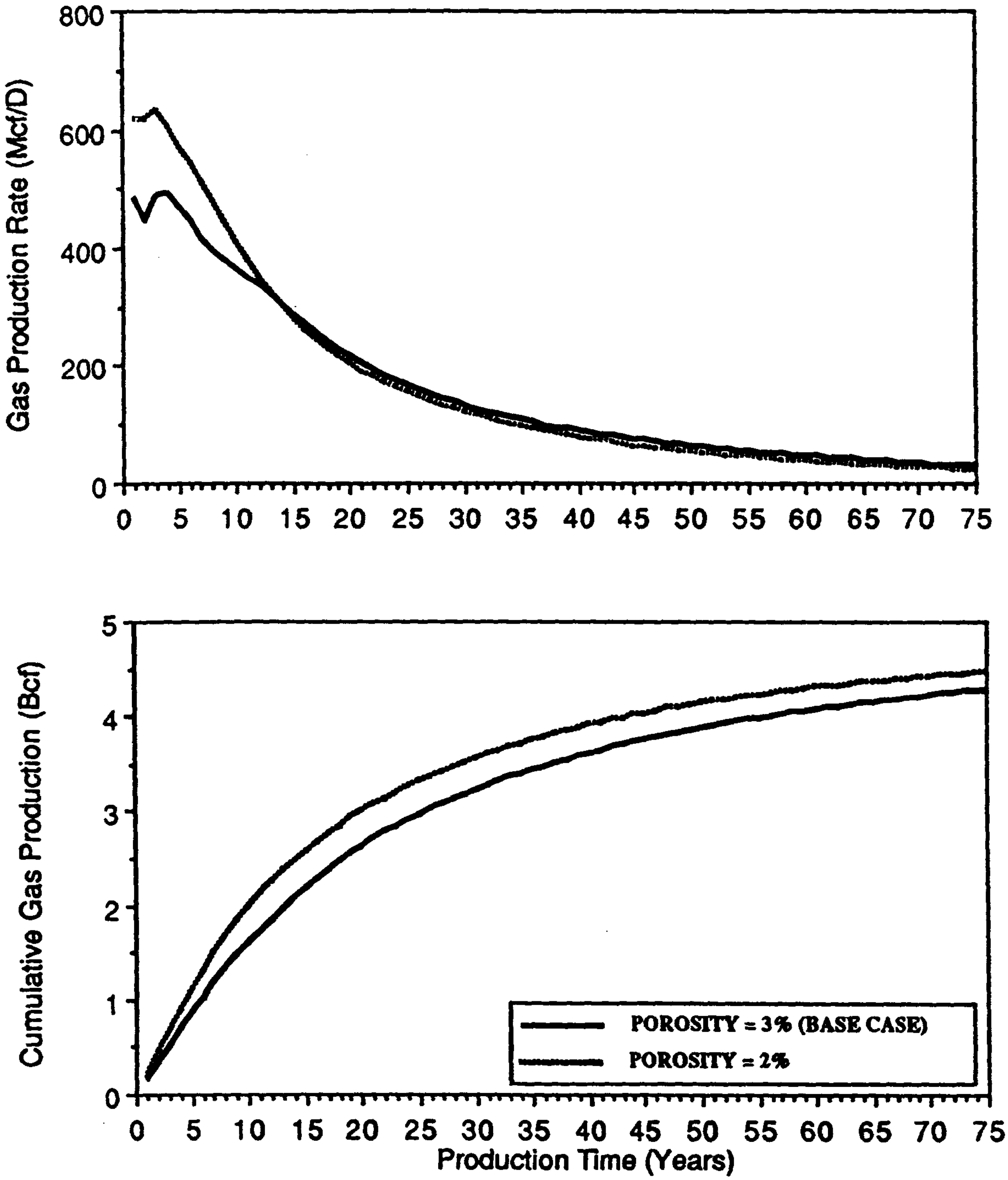


Figure 34

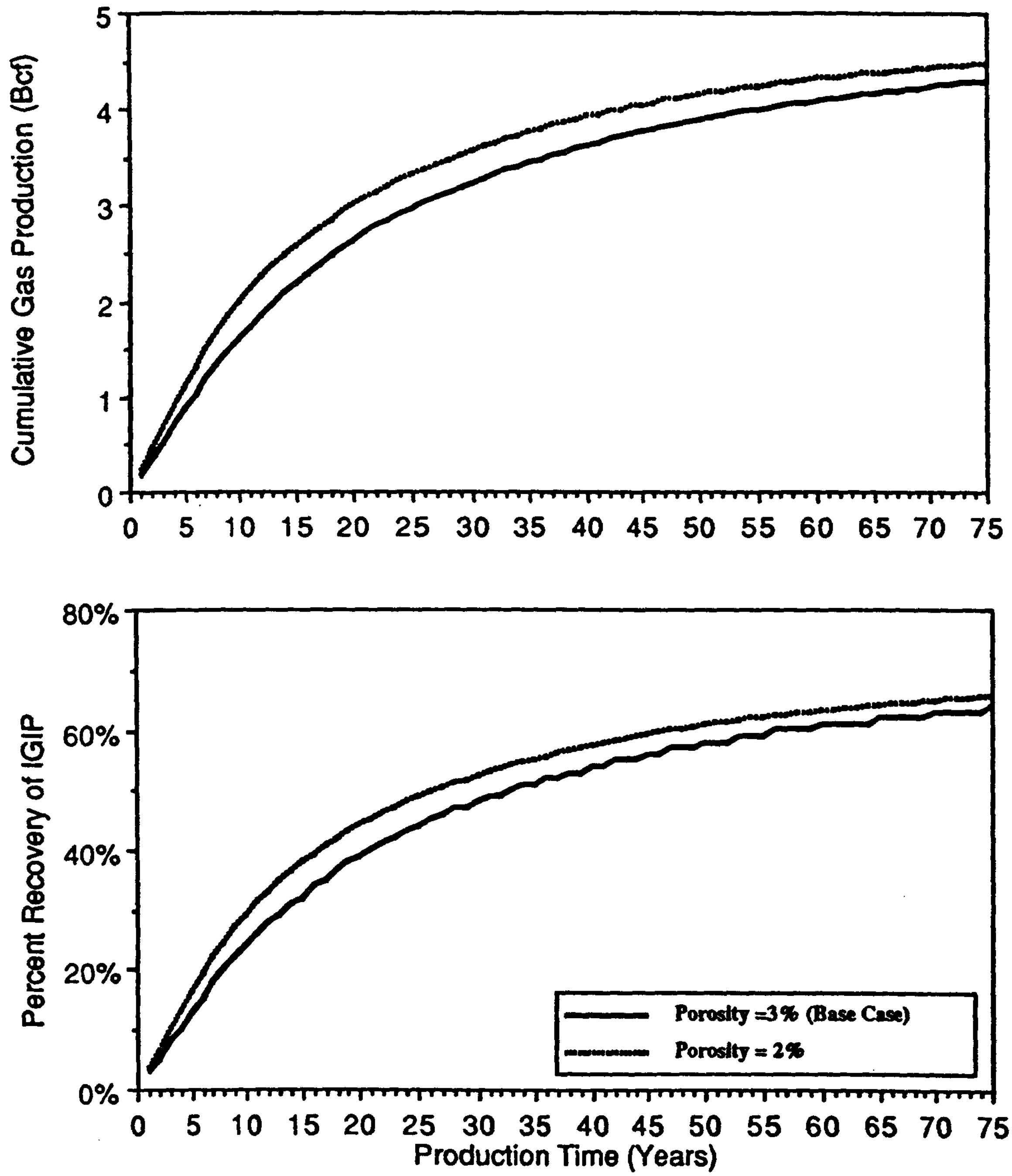
San Juan Basin Sensitivity Analysis
Area 1 Type Reservoir
Base Case Variation in Porosity



Application of Richardson Operating Co.
Record on Appeal, 1615.

Figure 35

San Juan Basin Sensitivity Analysis
Area 1 Type Reservoir
Base Case Variation in Porosity



Application of Richardson Operating Co.
Record on Appeal, 1616.

Figure 36

San Juan Basin Sensitivity Analysis
Area 1 Type Reservoir
Base Case Variation in Porosity

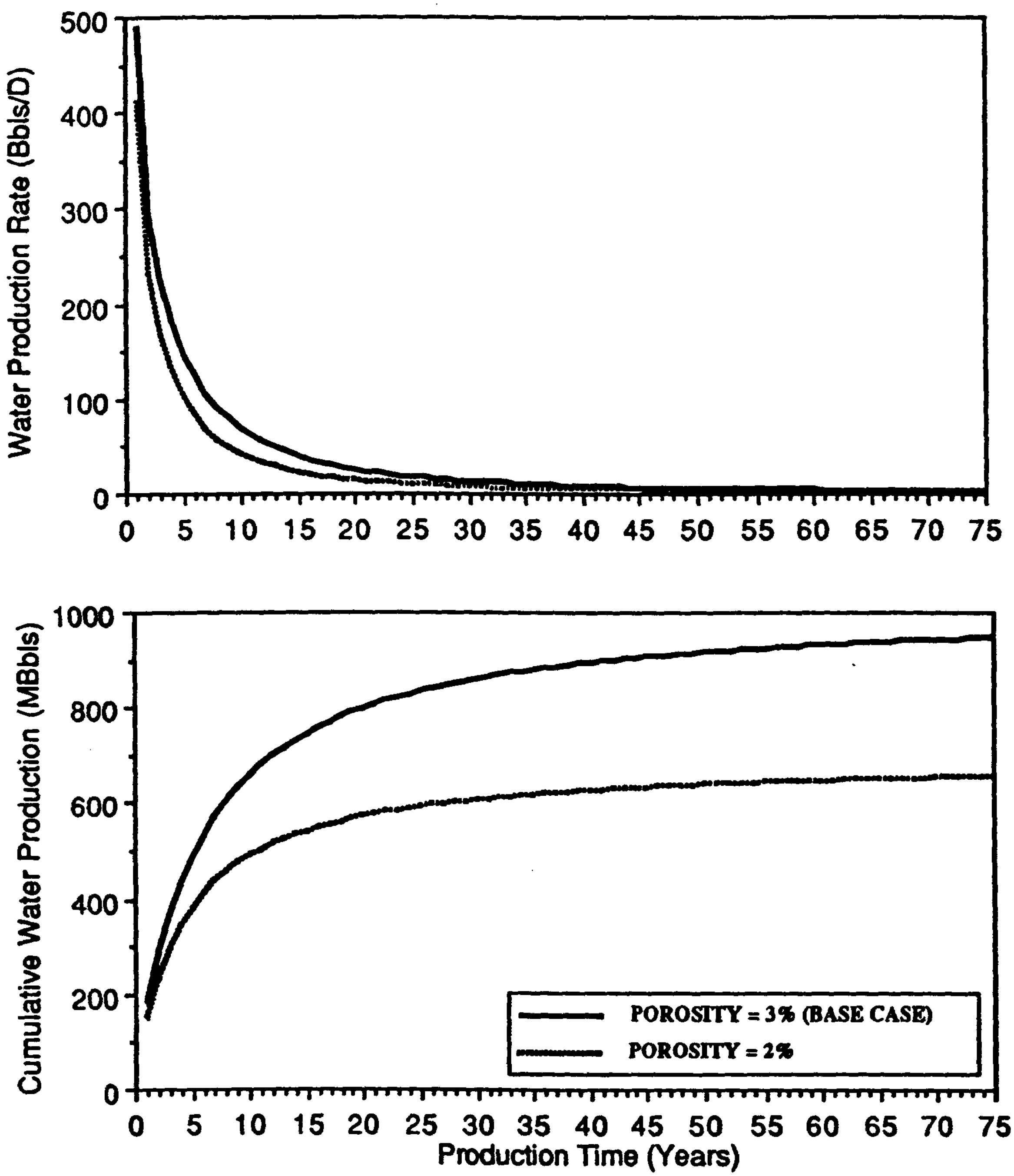
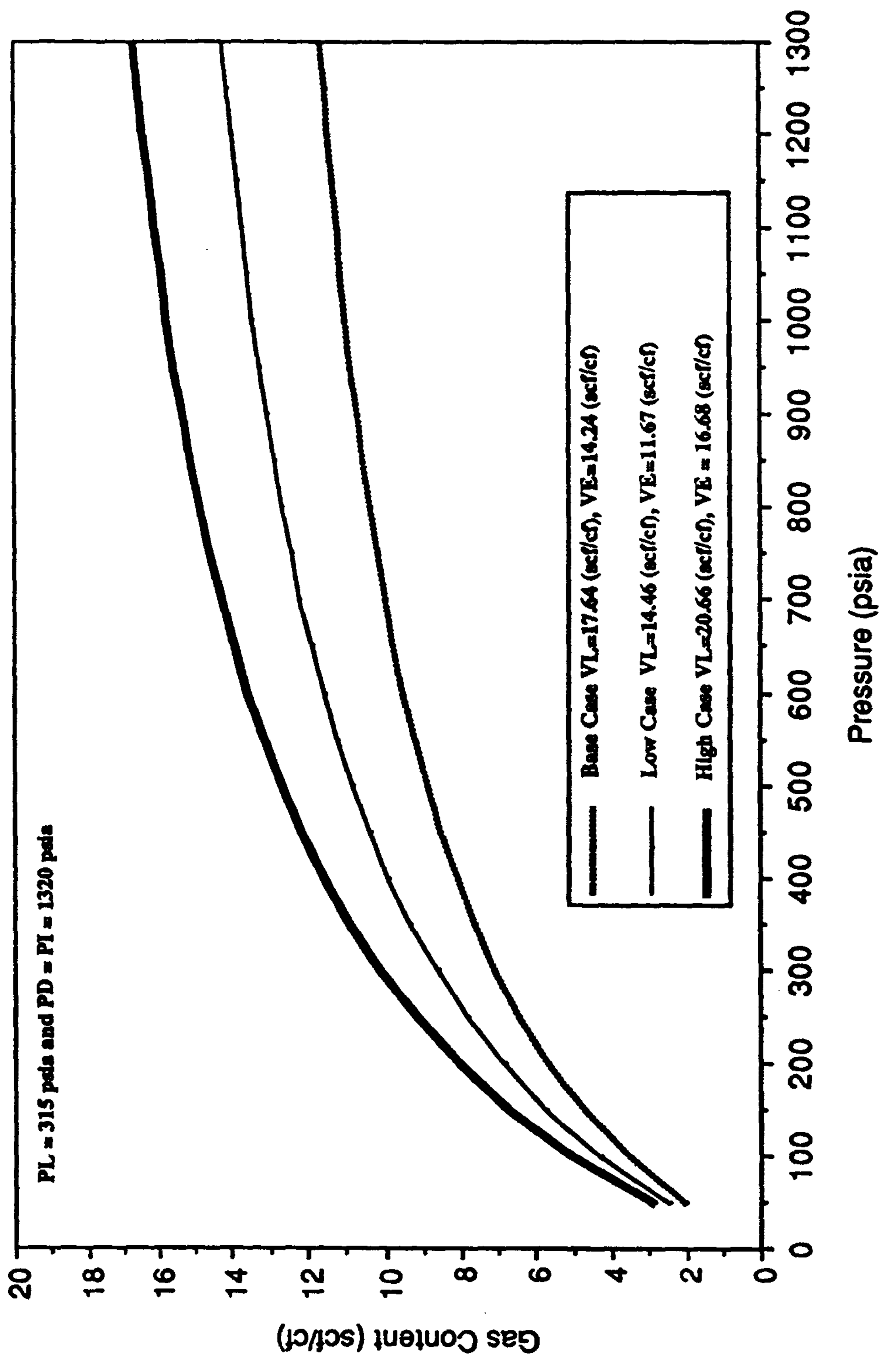


Figure 37

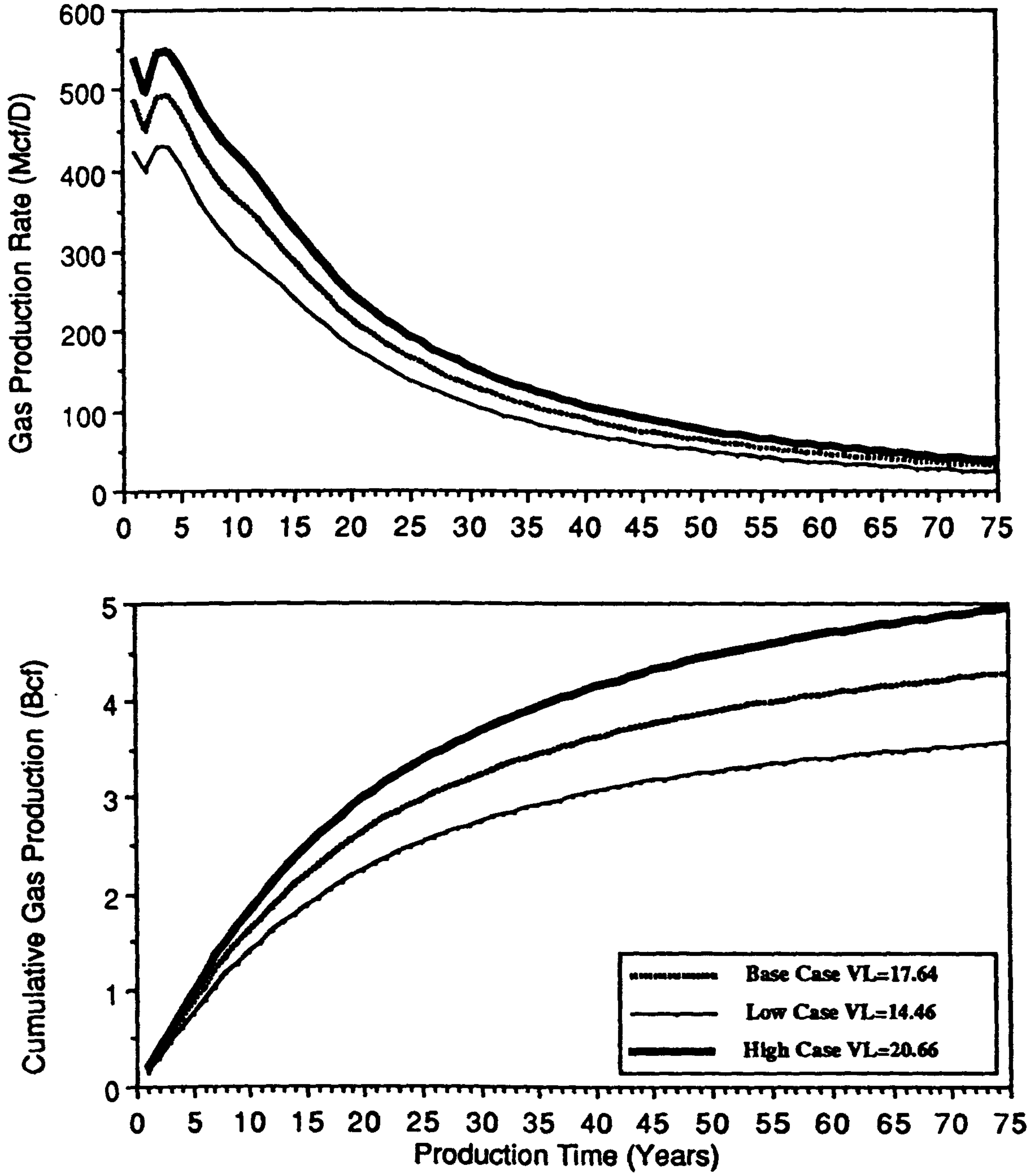
Sensitivity Analysis for San Juan Basin
Area 1 Type Reservoir
Variation in the Desorption Isotherm (VL)



Application of Richardson Operating Co.
Record on Appeal, 1618.

Figure 38

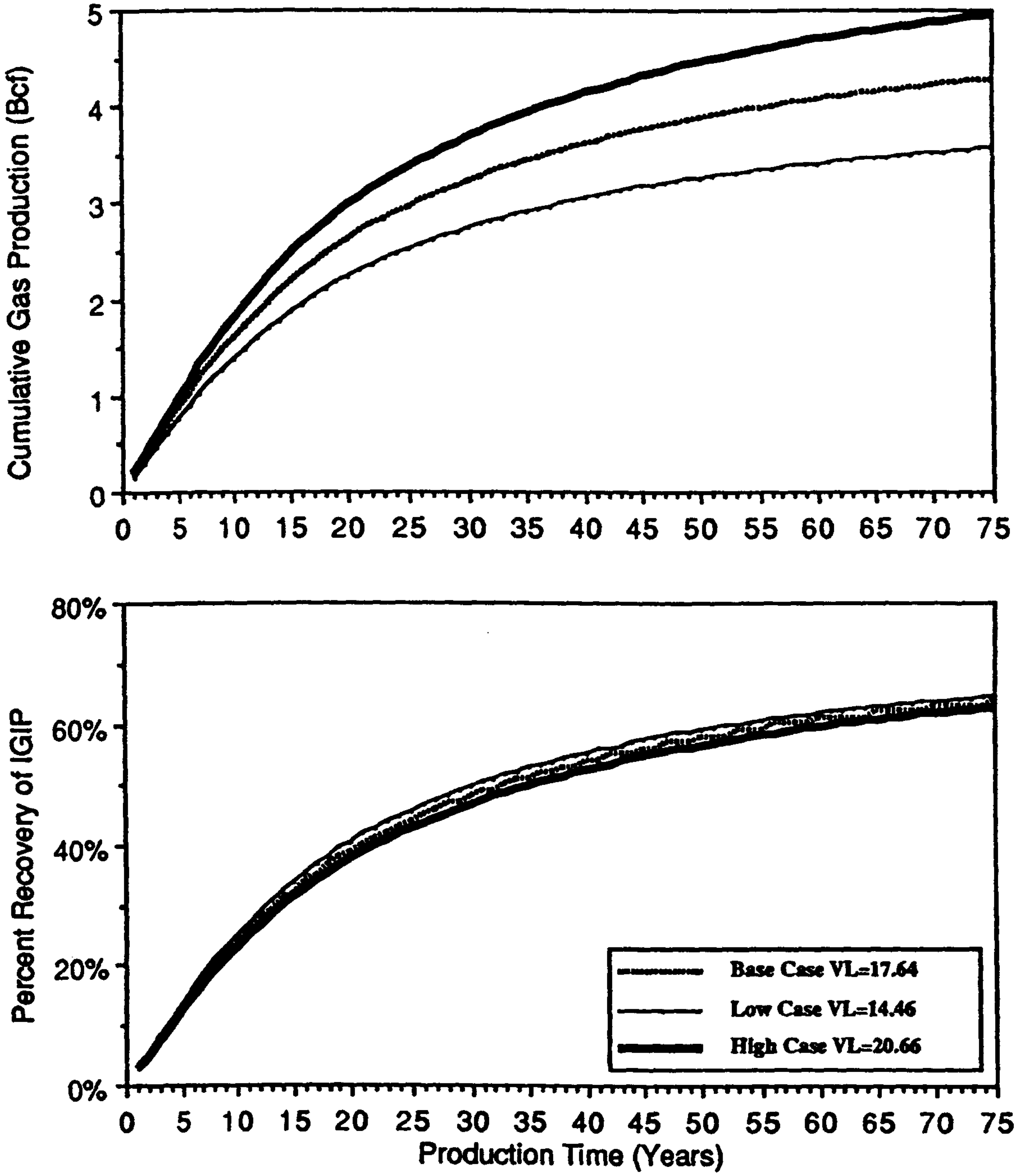
San Juan Basin Sensitivity Analysis
Area 1 Type Reservoir
Base Case Variation in Langmuir Volume



Application of Richardson Operating Co.
Record on Appeal, 1619.

Figure 39

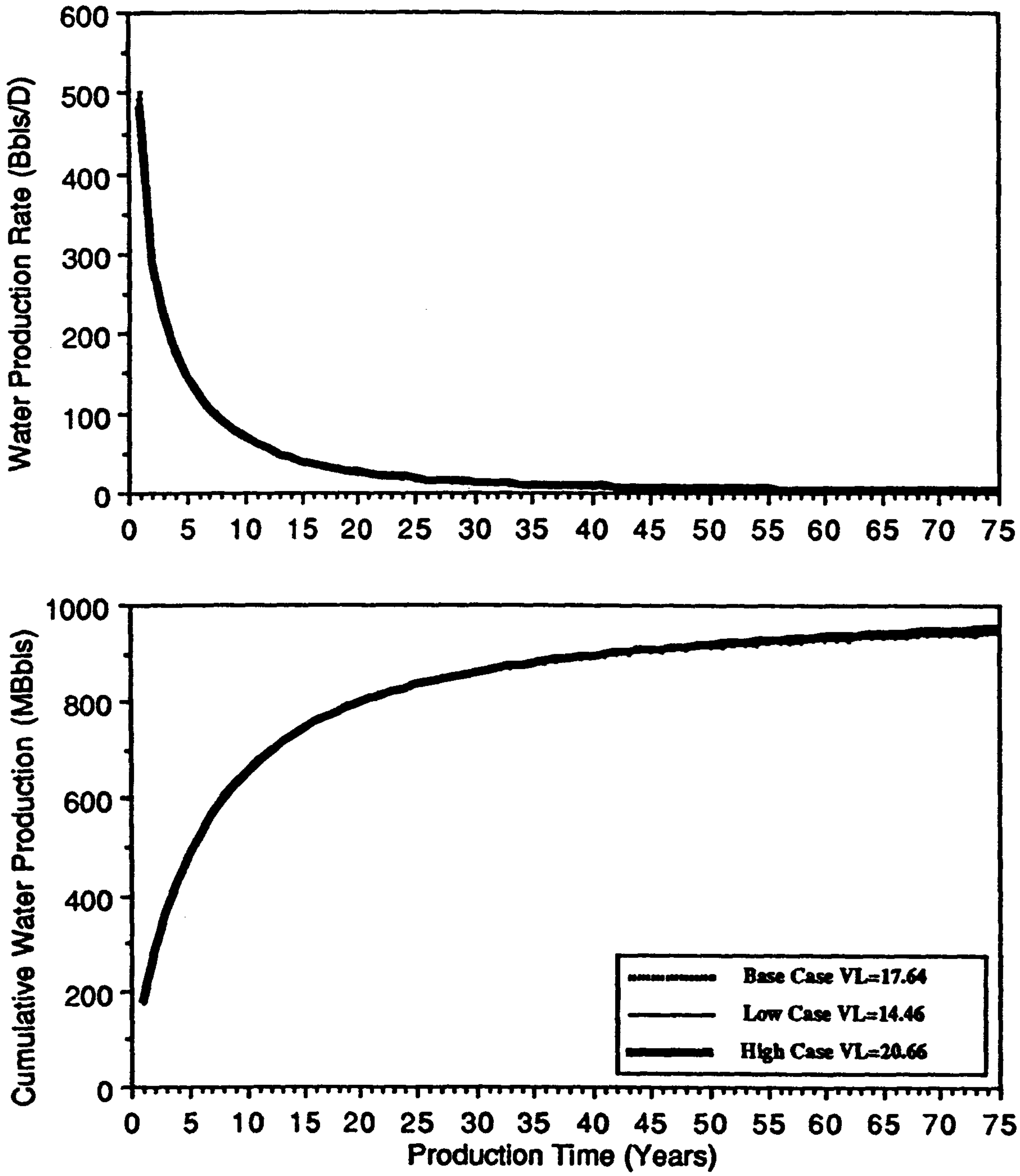
San Juan Basin Sensitivity Analysis
Area 1 Type Reservoir
Base Case Variation in Langmuir Volume



Application of Richardson Operating Co.
Record on Appeal, 1620.

Figure 40

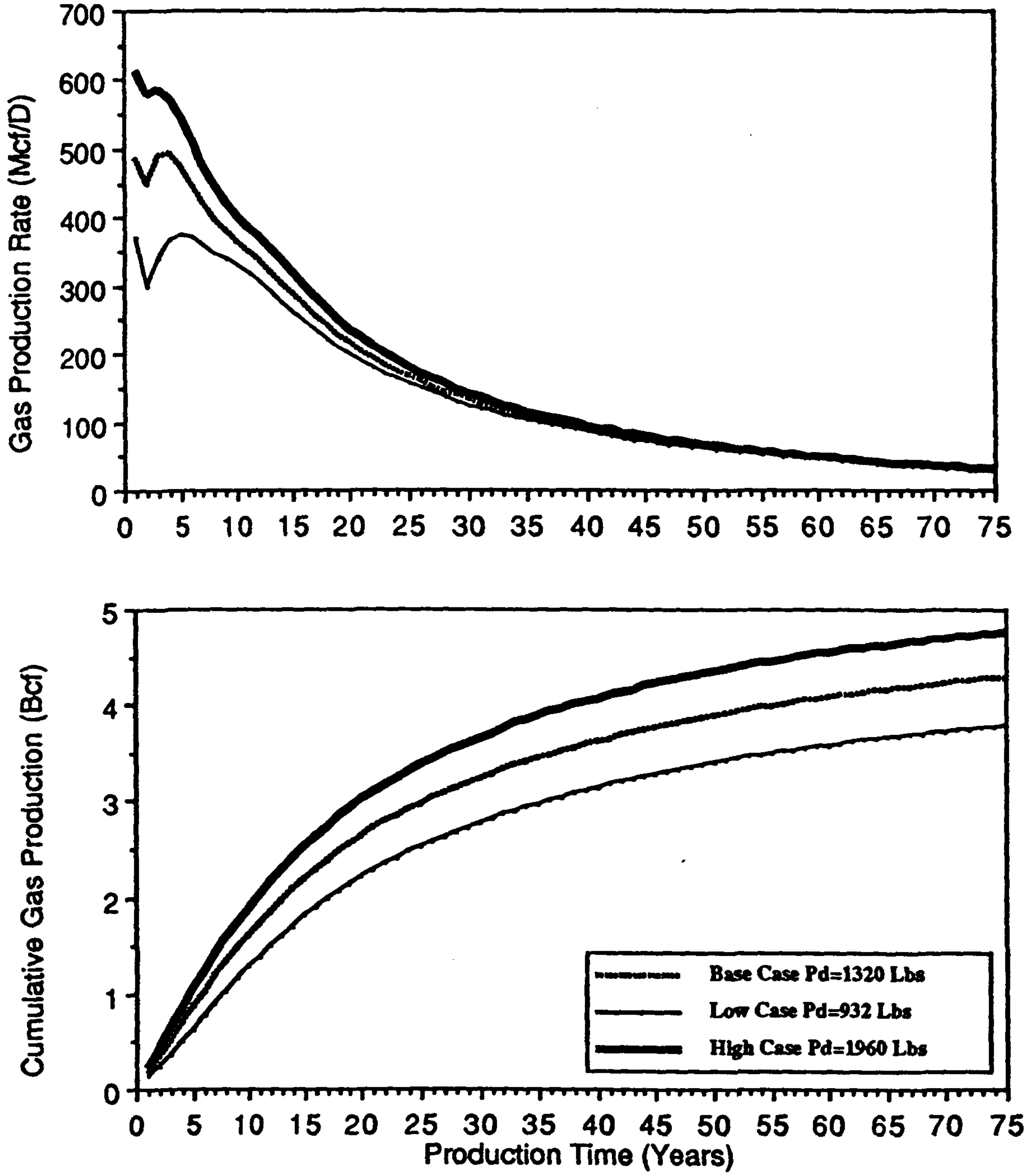
San Juan Basin Sensitivity Analysis
Area 1 Type Reservoir
Base Case Variation in Langmuir Volume



Appli· ·ation of Richardson Operating Co.
Reco·:d on Appeal, 1621.

Figure 41

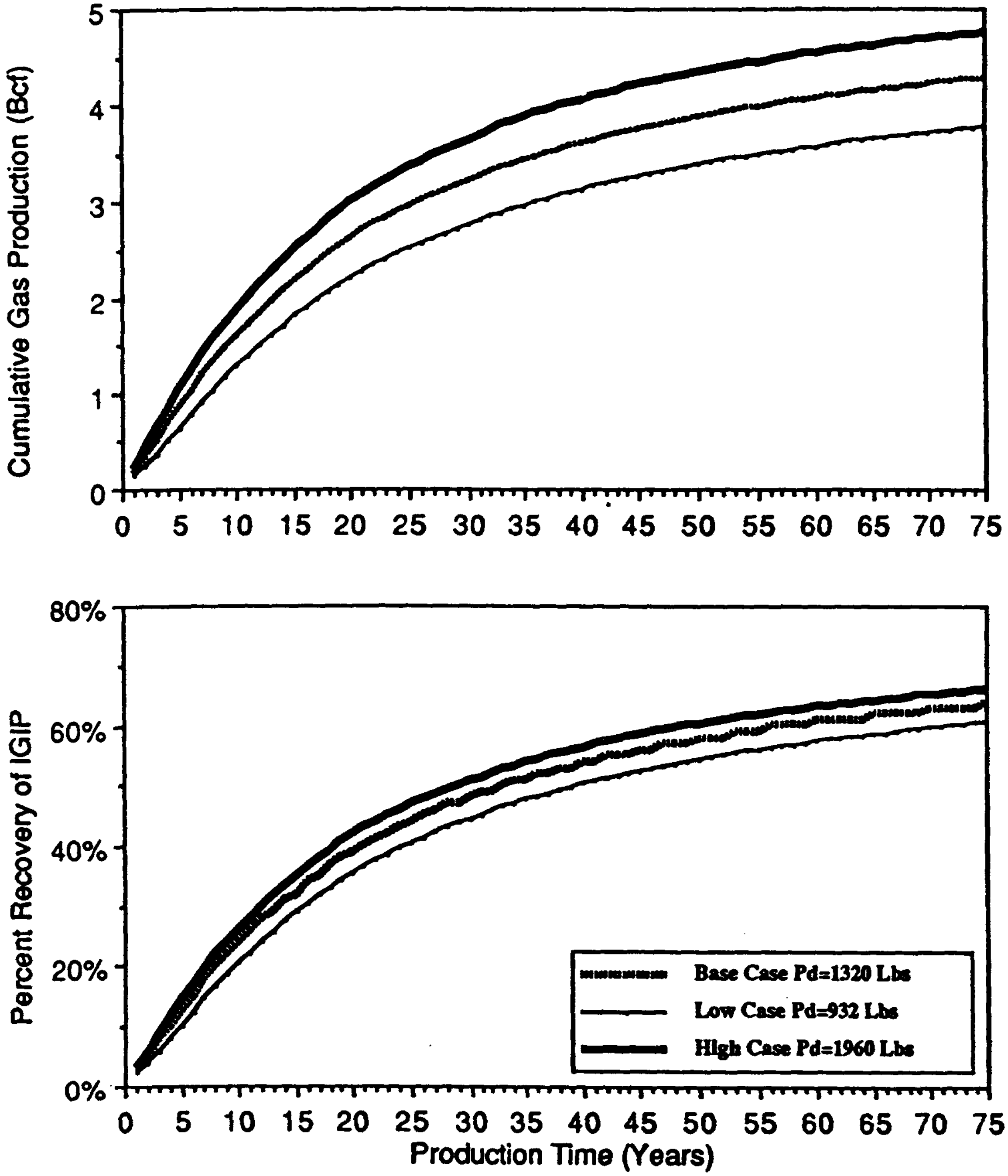
San Juan Basin Sensitivity Analysis
Area 1 Type Reservoir
Base Case Variation in Desorption Pressure



Application of Richardson Operating Co.
Record on Appeal, 1622.

Figure 42

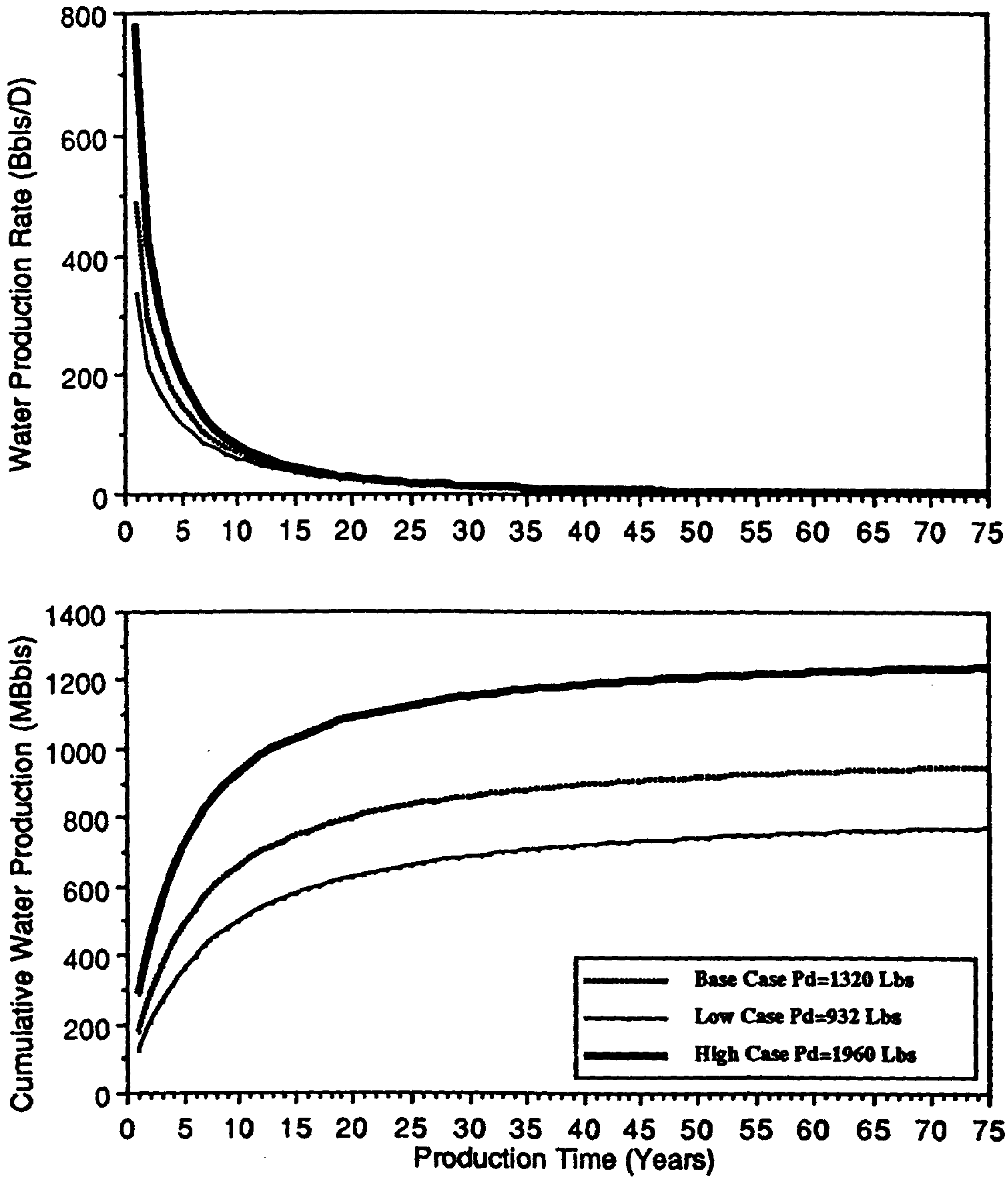
San Juan Basin Sensitivity Analysis
Area 1 Type Reservoir
Base Case Variation in Desorption Pressure



Application of Richardson Operating Co.
Record on Appeal, 1623.

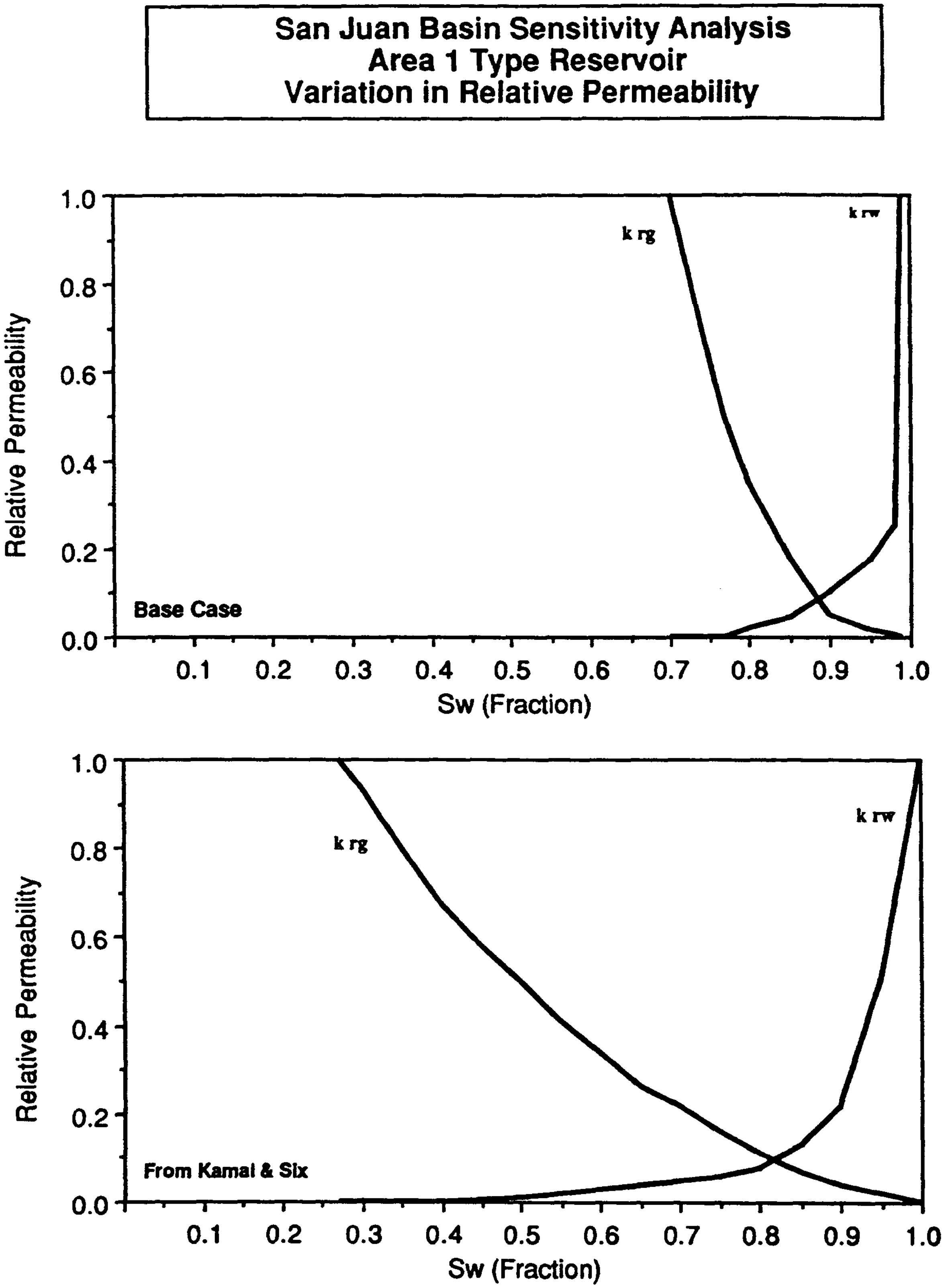
Figure 43

San Juan Basin Sensitivity Analysis
Area 1 Type Reservoir
Base Case Variation in Desorption Pressure



Application of Richardson Operating Co.
Record on Appeal, 1624.

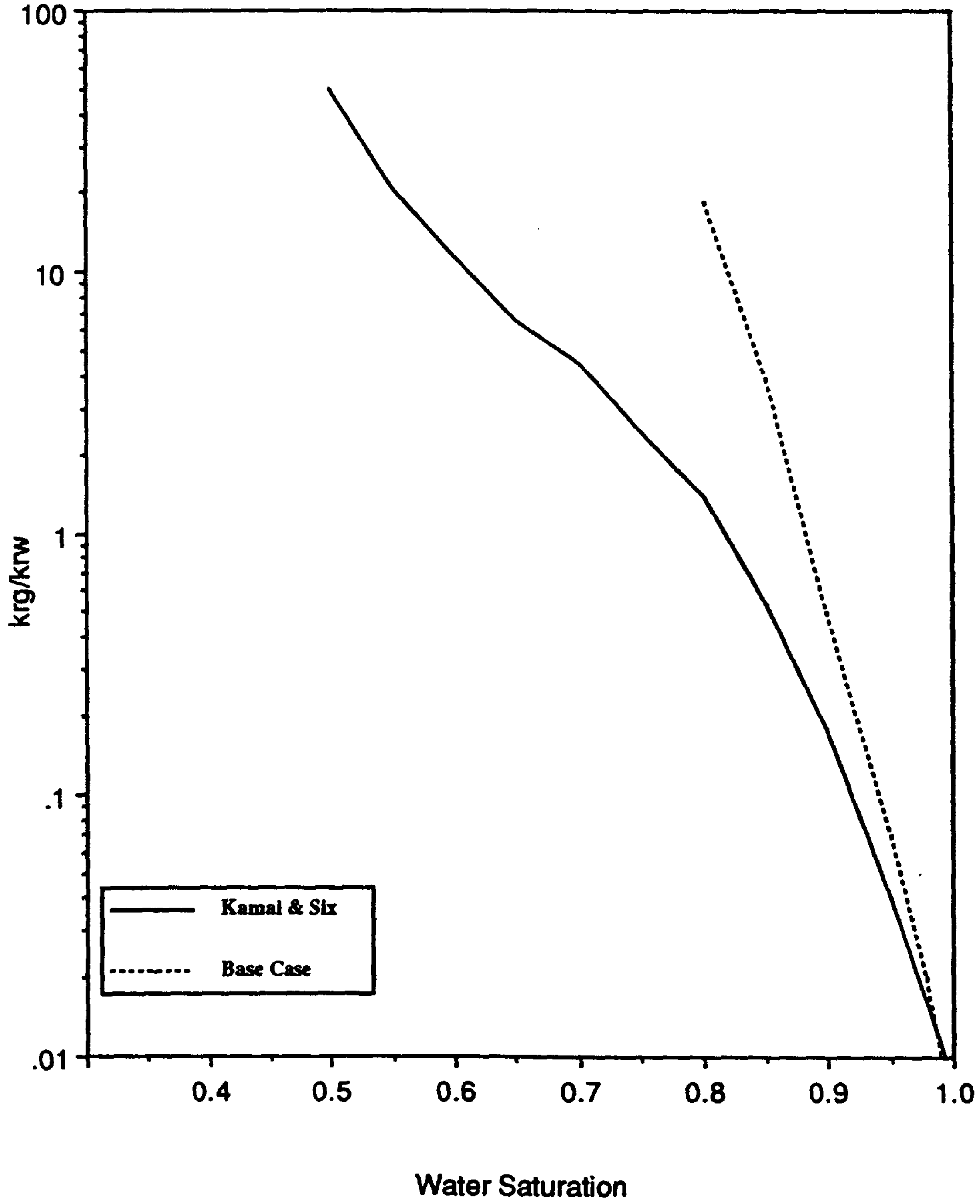
Figure 44



Application of Richardson Operating Co.
Record on Appeal, 1625.

Figure 45

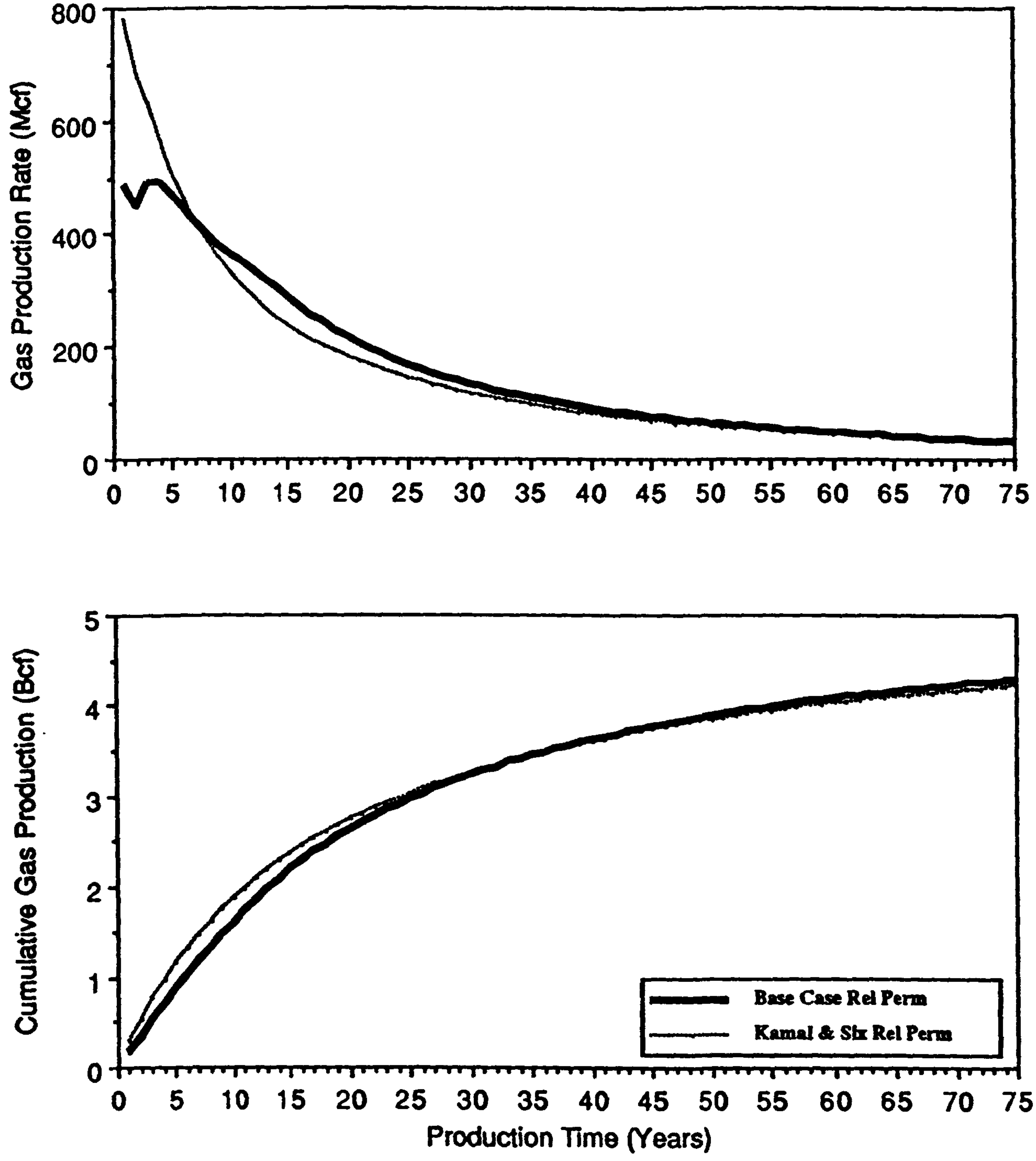
San Juan Basin Sensitivity Analysis
Area 1 Type Reservoir
Variations in krg/krw Ratio



Application of Richardson Operating Co.
Record on Appeal, 1626.

Figure 46

San Juan Basin Sensitivity Analysis
Area 1 Type Reservoir
Base Case Variation in Relative Permeability



Application of Richardson Operating Co.
Record on Appeal, 1627.

Figure 47

San Juan Basin Sensitivity Analysis
Area 1 Type Reservoir
Base Case Variation in Relative Permeability

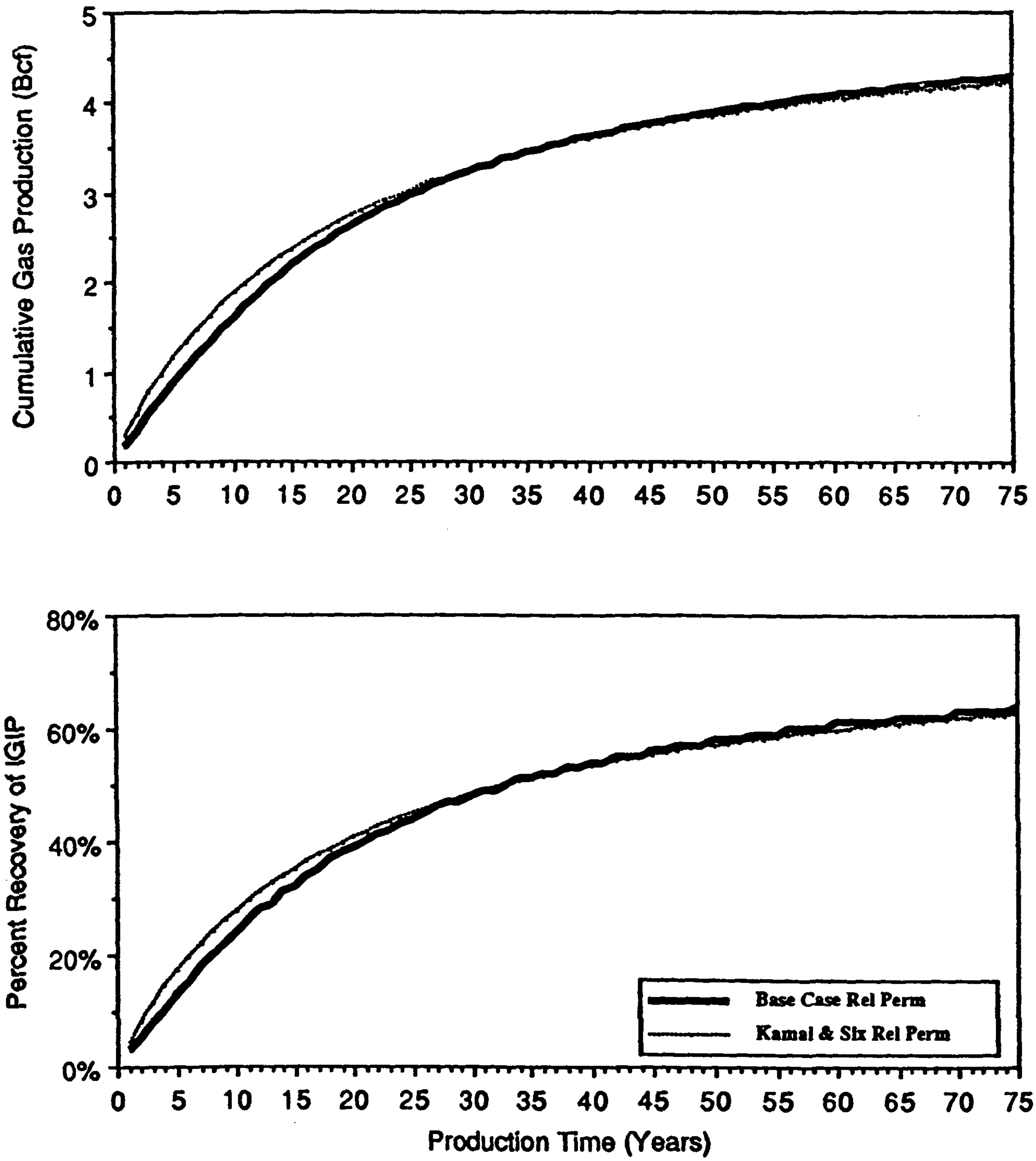
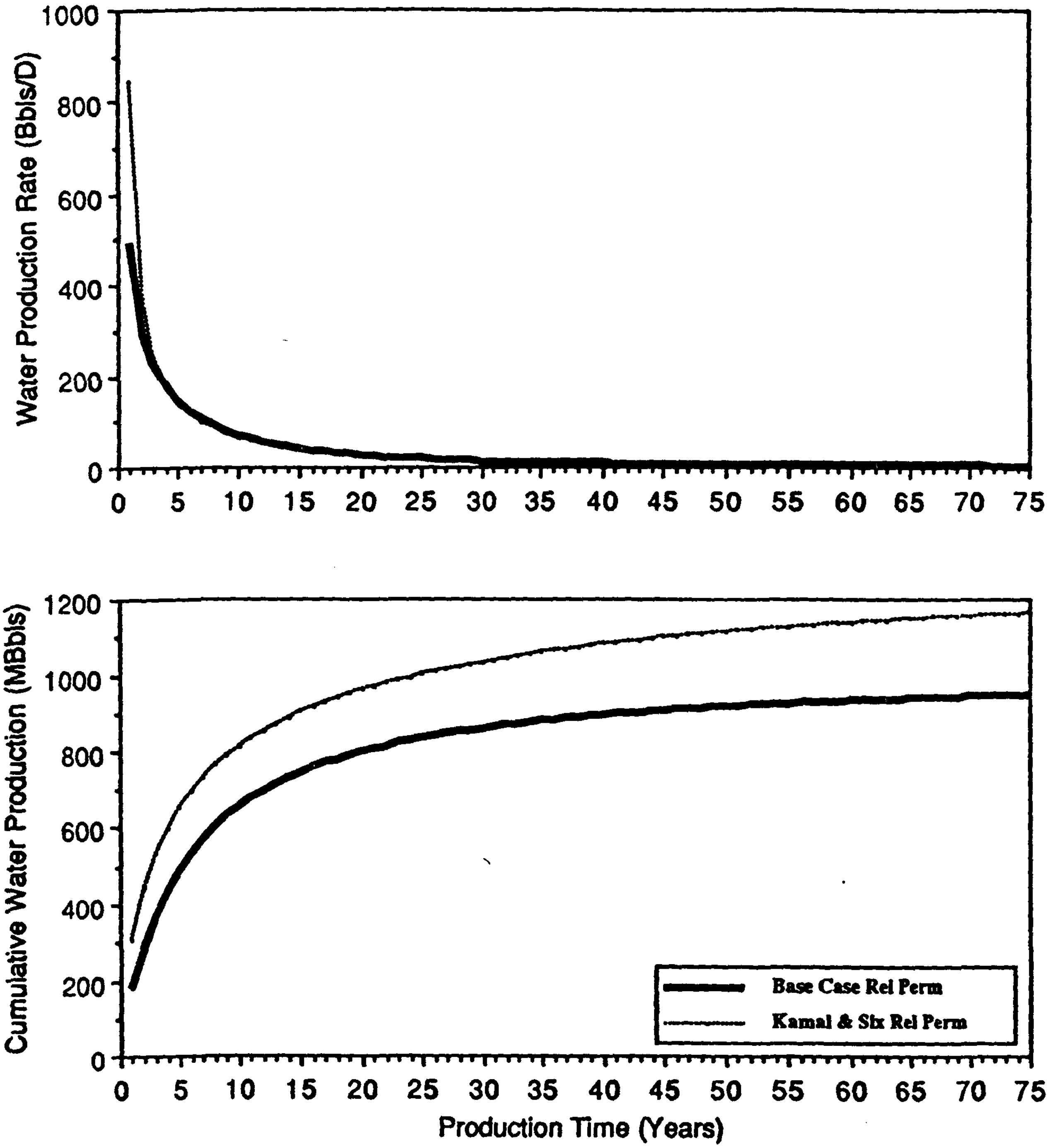


Figure 48

San Juan Basin Sensitivity Analysis
Area 1 Type Reservoir
Base Case Variation in Relative Permeability



Application of Richardson Operating Co.
Record on Appeal, 1629.

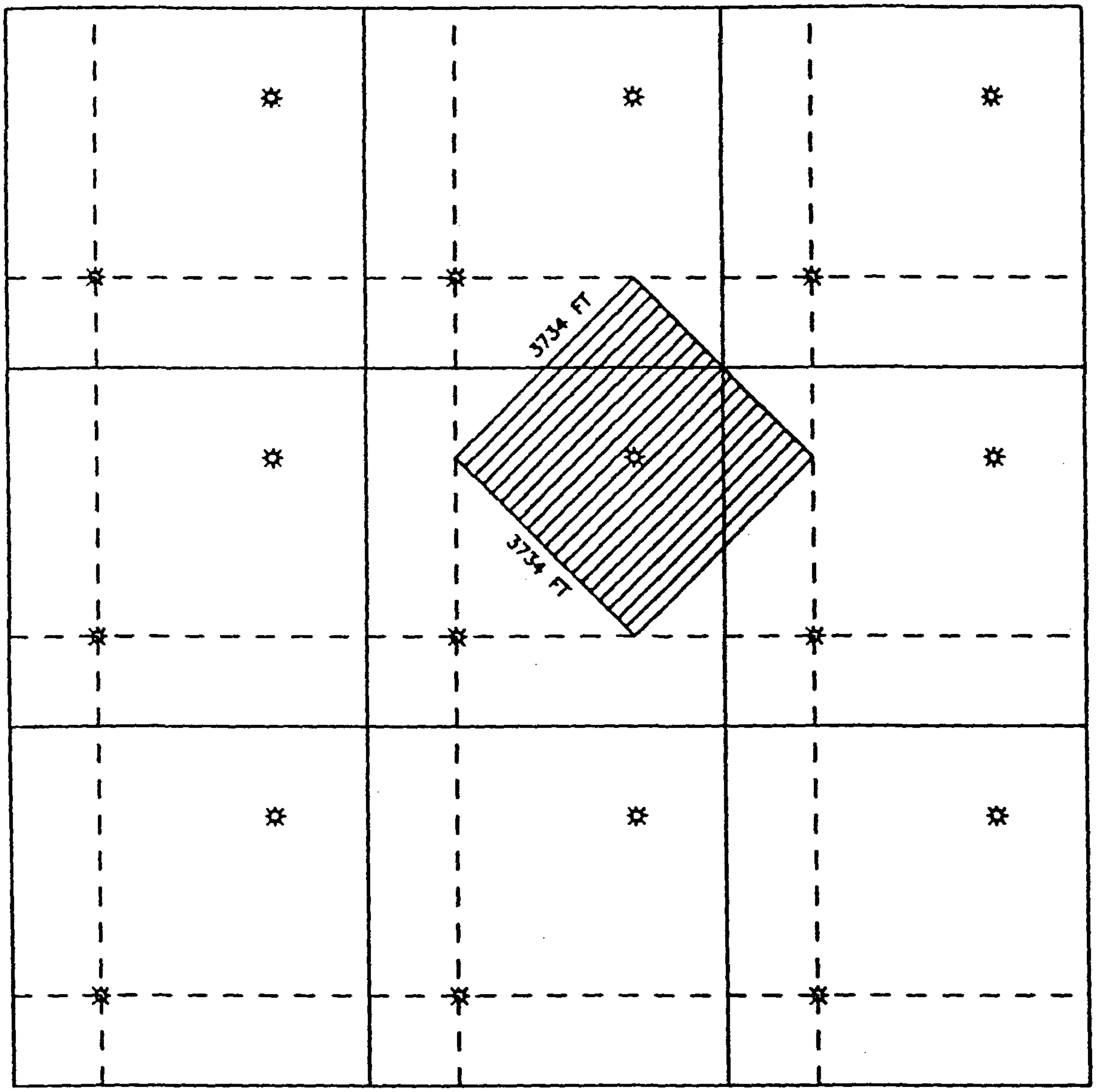
APPENDIX A: EFFECTS OF SIMULATOR GRID GEOMETRY

To demonstrate that all three of the well spacings under consideration could be accurately simulated as one-quarter of a single well's drainage area, the "Base Case" was simulated as both a 320 acre square with one well in the center, and as a 640 acre five-spot pattern with a total of two wells (i.e., one full well in the center and four one-quarter wells in each corner), as shown in Figure A-1. The COMETPC 3-D simulation results are compared in Figure A-2, and show that no loss in accuracy occurs from using one-quarter of a well to represent multi-well interference effects, for the homogeneous and isotropic system as was assumed here.

The manner in which the various fracture half-lengths were gridded so that differences in production reflected changes in the magnitude of the half-lengths also had to be determined. Various fracture tip geometries were tested, as well as variations in the number of grid blocks used to represent the total fracture half-length. As shown in Figure A-3, Cases 1 and 3 used grids with a square fracture tip, whereas Case 2 utilized a rectangular fracture tip. In addition, only three grid blocks were used in Cases 1 and 2 to represent the total fracture half-length of 300 feet, while five grid blocks were used in Case 3. These comparison simulations were run with the "Base Case" conditions. Figure A-4 clearly indicates that no appreciable differences in gas production will result from the way in which the various fracture half-lengths are gridded, so long as some minimum number of blocks is employed.

Figure A-1

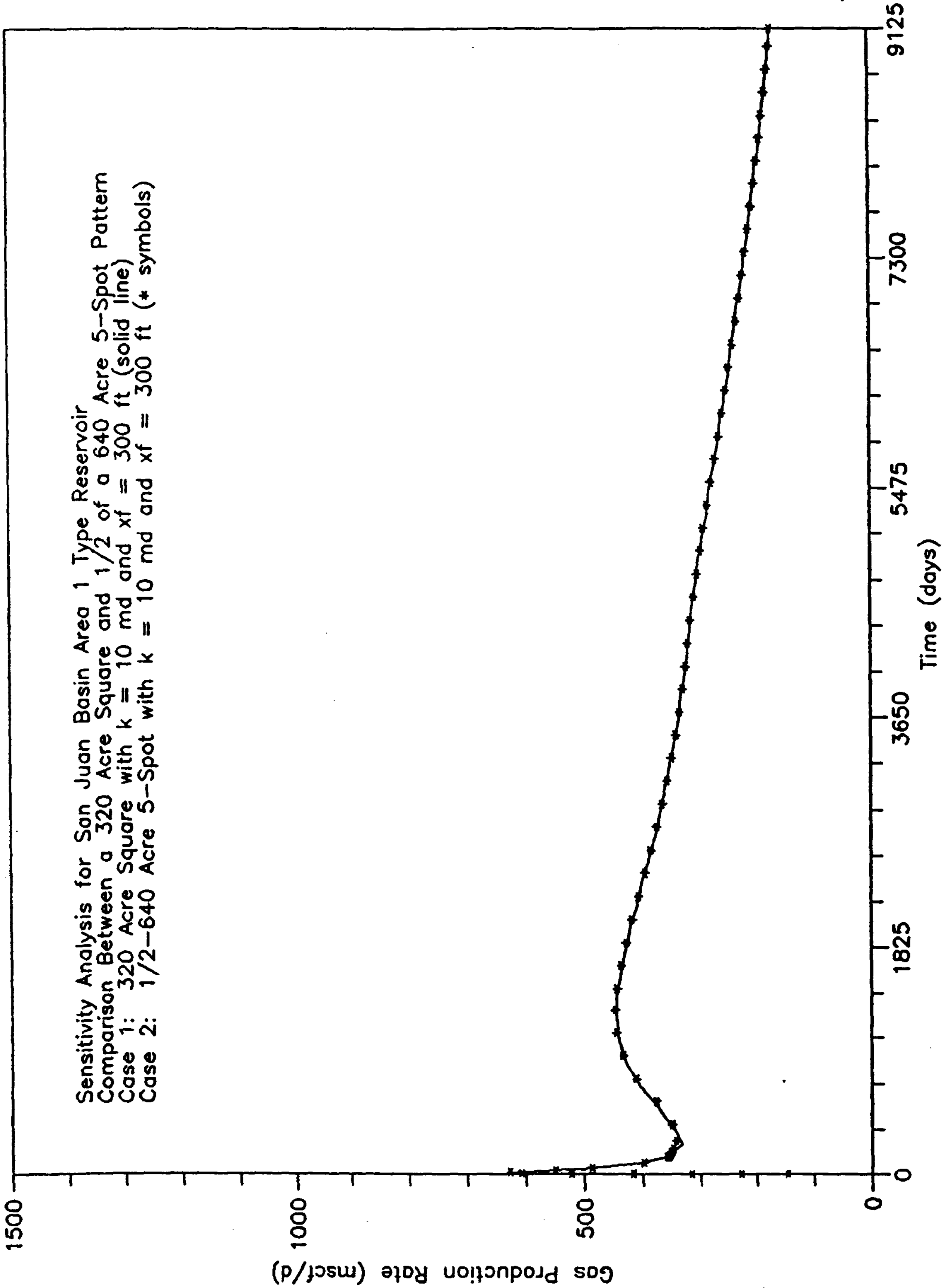
RELATIONSHIP BETWEEN
320 ACRE SQUARES AND 640 ACRE 5-SPOT PATTERNS



Gas Well Location
Section Line
640 Acre 5-Spot Patterns
320 Acre Symmetry Element for COMET 3-D Simulation

Application of Richardson Operating Co.
Record on Appeal, 1631.

Figure A-2

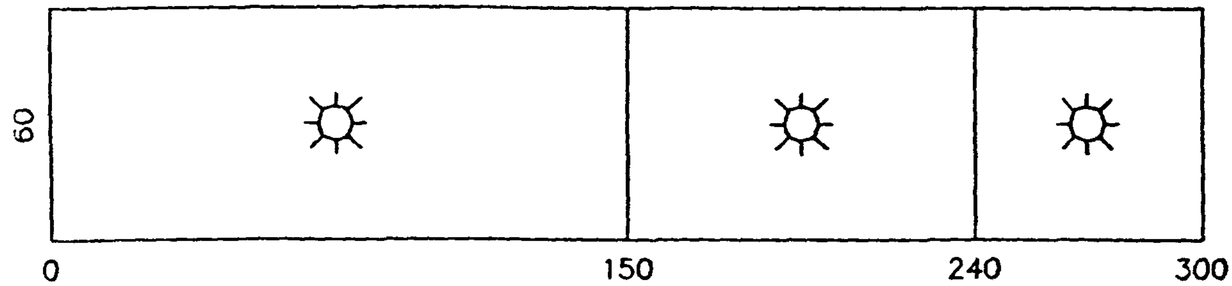


Sensitivity Analysis for San Juan Basin Area 1 Type Reservoir
Comparison Between a 320 Acre Square and 1/2 of a 640 Acre 5–Spot Pattern
Case 1: 320 Acre Square with k = 10 md and xf = 300 ft (solid line)
Case 2: 1/2–640 Acre 5–Spot with k = 10 md and xf = 300 ft (* symbols)
Gas Production Rate (mscf/d)
1500
1000
500
0
Time (days)
1825
3650
5475
7300
9125

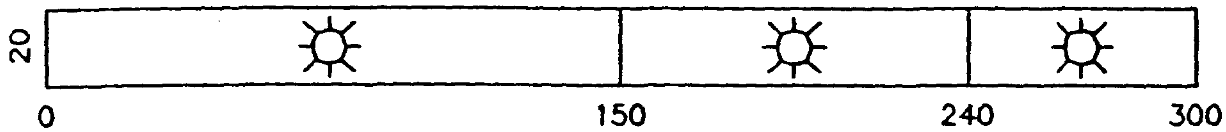
Figure A-3

RELATIONSHIP BETWEEN FRACTURE TIP GEOMETRIES

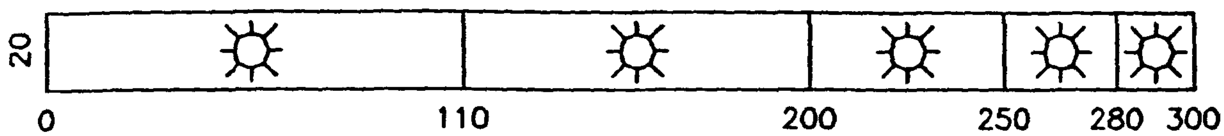
Case 1: 60 x 60 ft Tip and xf = 3 Grid Blocks



Case 2: 60 x 20 ft Tip and xf = 3 Grid Blocks

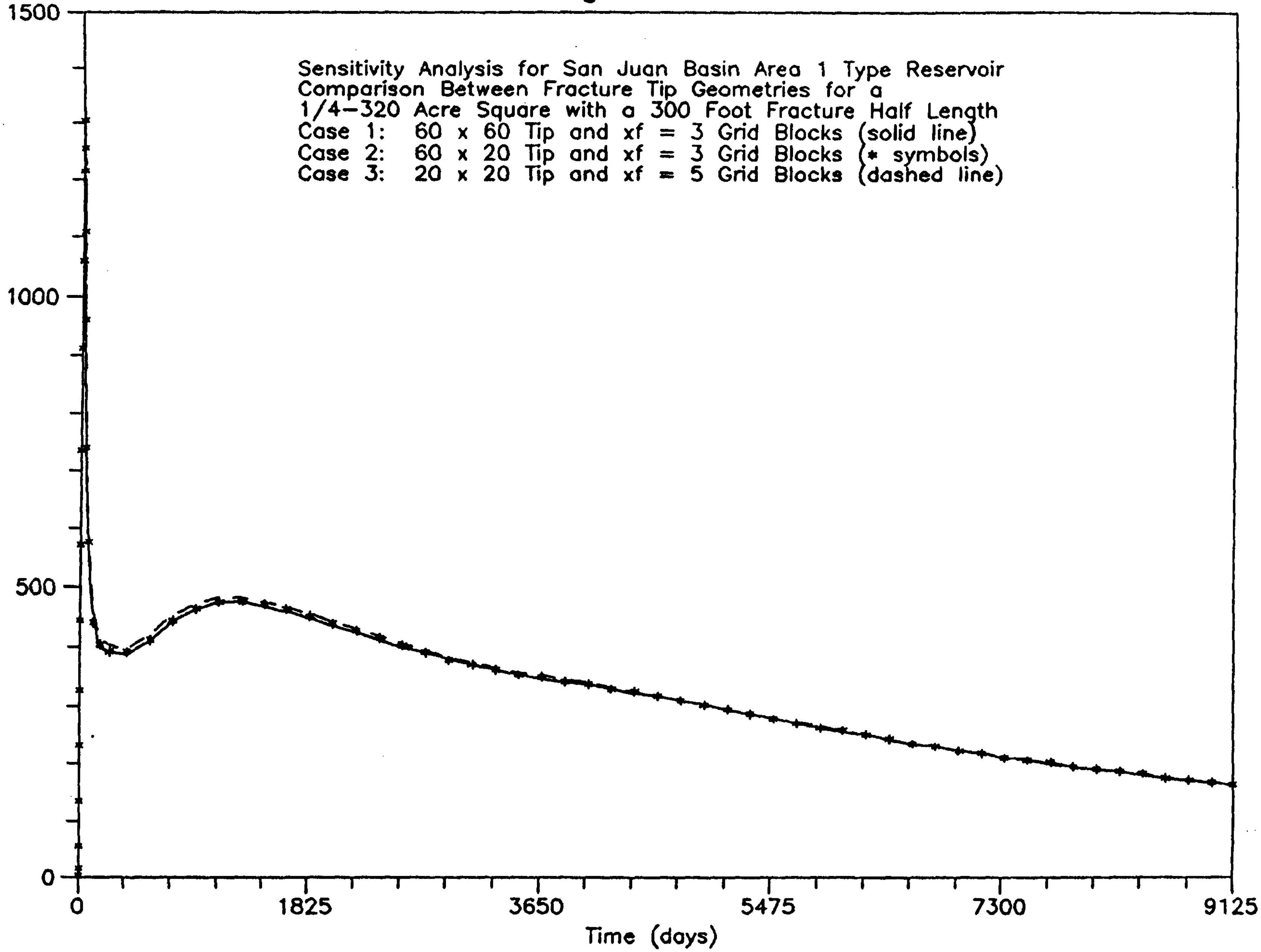


Case 3: 20 x 20 ft Tip and xf = 5 Grid Blocks



Application of Richardson Operating Co.
Record on Appeal, 1633.

Figure A-4

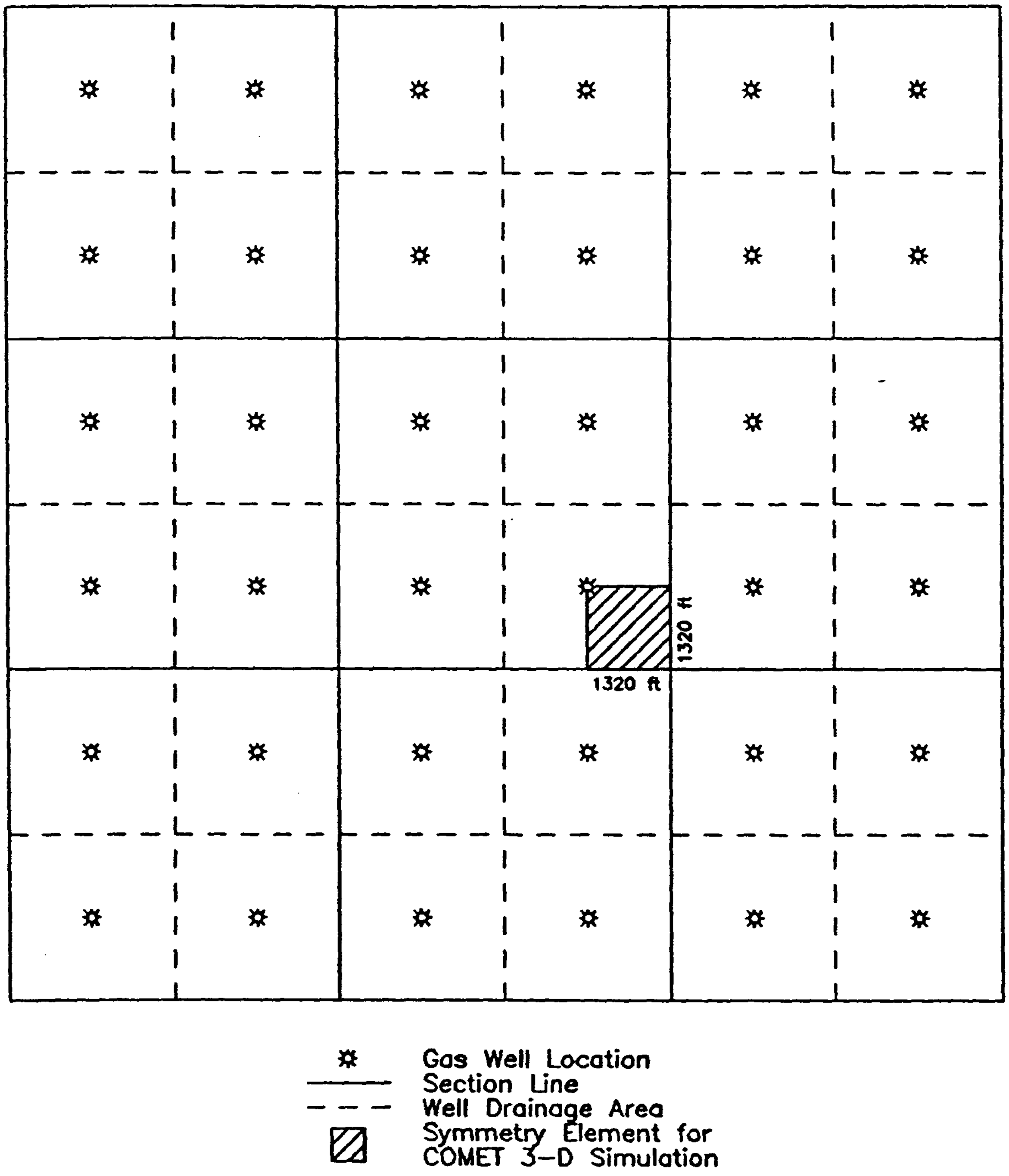

Sensitivity Analysis for San Juan Basin Area 1 Type Reservoir
Comparison Between Fracture Tip Geometries for a
1/4−320 Acre Square with a 300 Foot Fracture Half Length
Case 1: 60 x 60 Tip and xf = 3 Grid Blocks (solid line)
Case 2: 60 x 20 Tip and xf = 3 Grid Blocks (* symbols)
Case 3: 20 x 20 Tip and xf = 5 Grid Blocks (dashed line)
1500
1000
500
0
ɹduction Rate (mscf/d)
0
1825
3650
5475
7300
9125
Time (days)

APPENDIX B: GRID CONFIGURATIONS FOR COMETPC 3-D SIMULATION

Grid configurations for the various well spacings were designed for use in COMETPC 3-D as shown in Figures B-1 through B-3. For each of the well spacings, both the full well drainage areas and the one-quarter elements of symmetry (which were utilized in the simulations) are shown. For each of the well spacings evaluated, three different fracture half-lengths were simulated (100, 300 and 500 feet). Each of these different fracture half-lengths required the design of a new grid for each of the respective well spacings, resulting in nine different grid schematics for the simulations (Figures B-4 through B-12).

Figure B-1

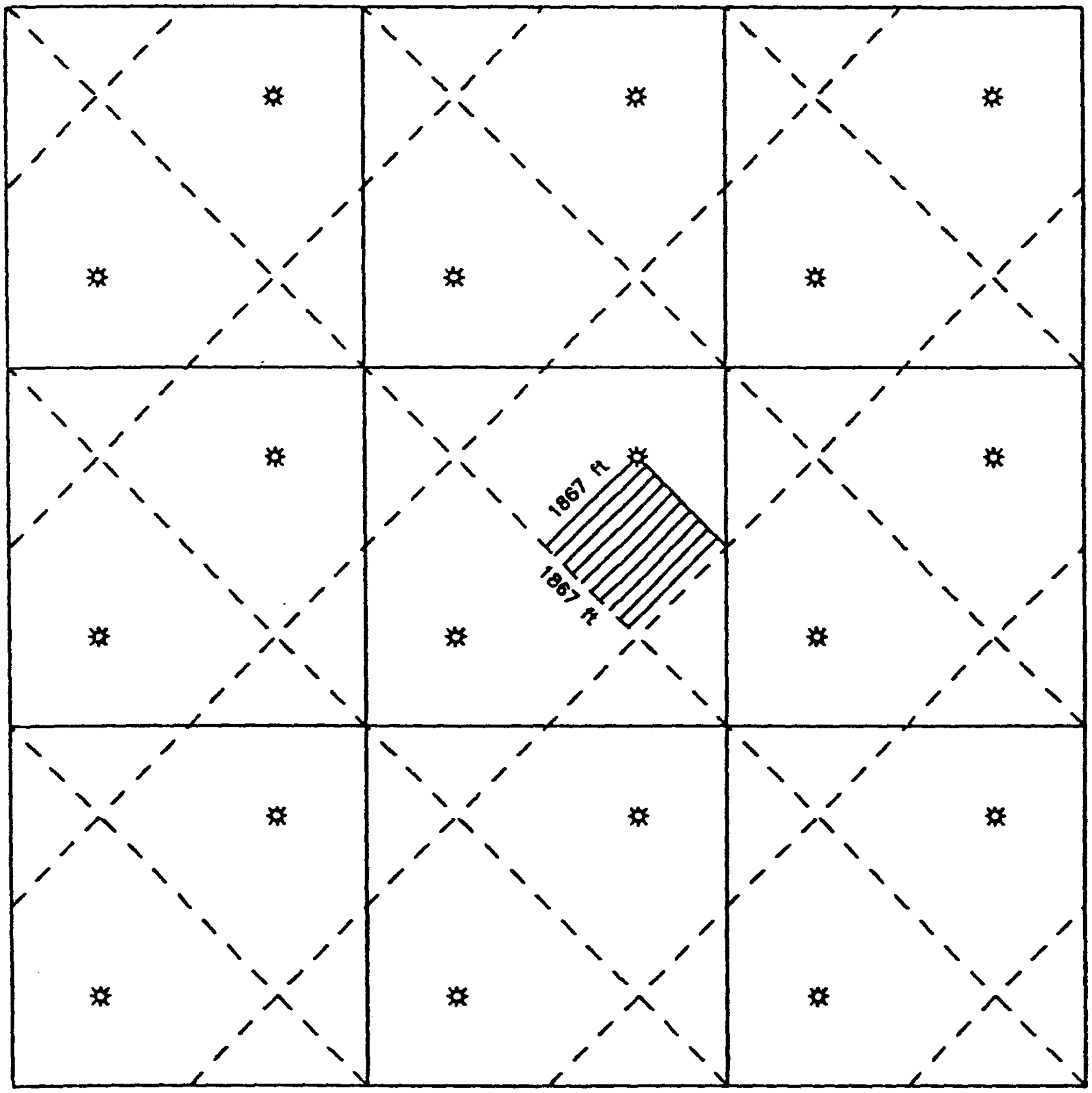
ELEMENTS OF SYMMETRY
FOR
160 ACRE WELL SPACING



Application of Richardson Operating Co.
Record on Appeal, 1636.

Figure B-2

ELEMENTS OF SYMMETRY
FOR
320 ACRE WELL SPACING

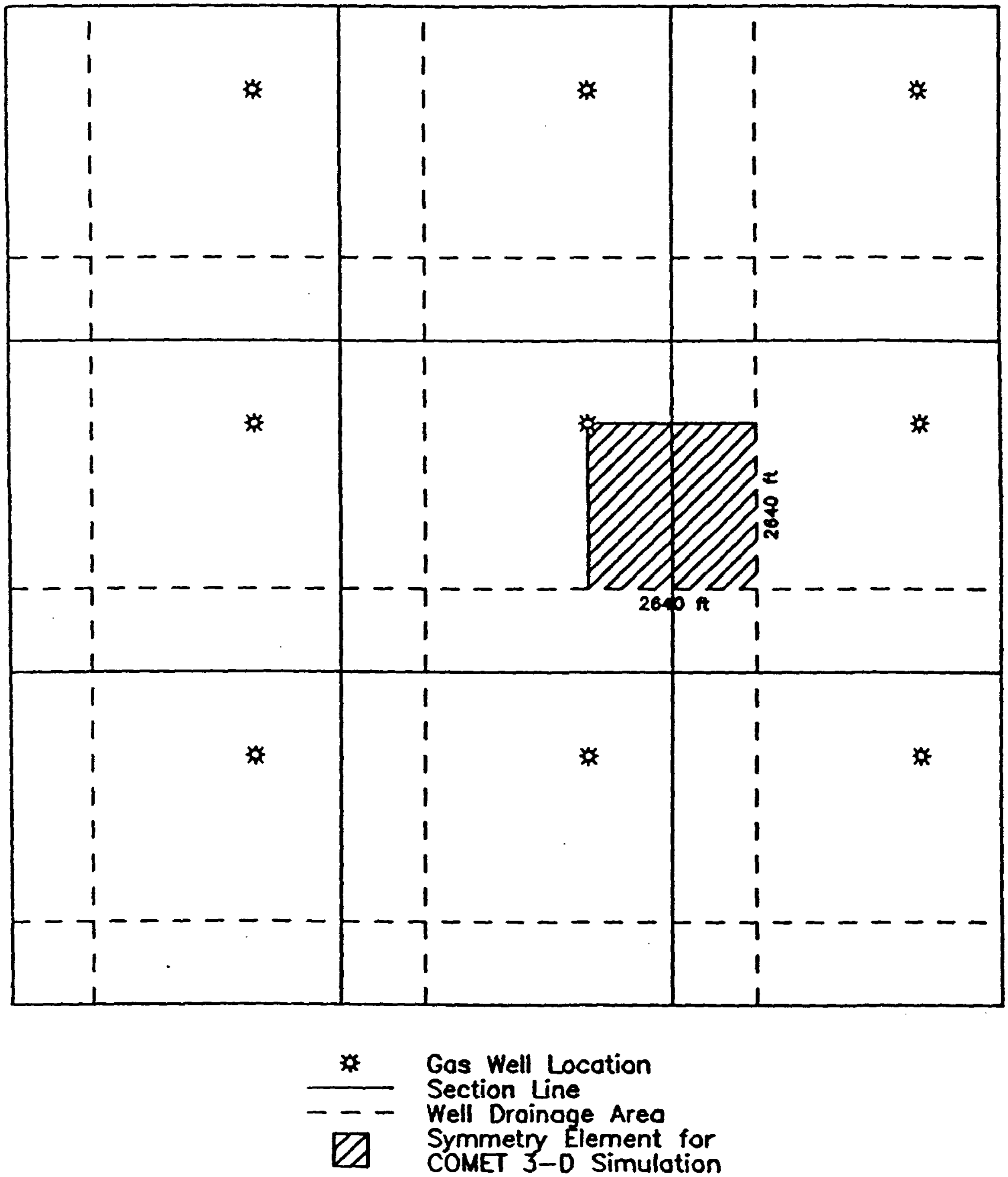


Gas Well Location
Section Line
Well Drainage Area
Symmetry Element for COMET 3-D Simulation

Application of Richardson Operating Co.
Record on Appeal, 1637.

Figure B-3

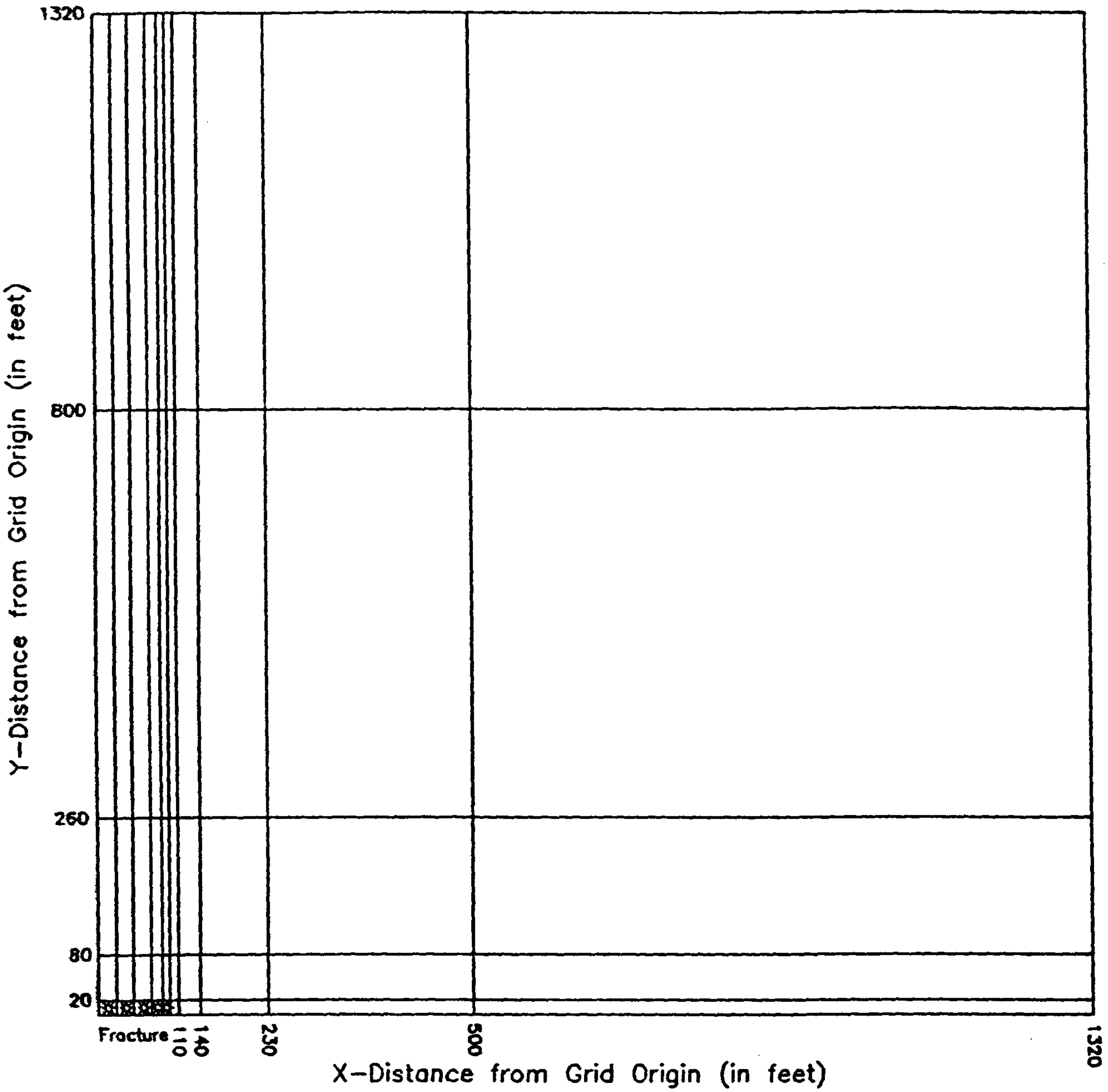
ELEMENTS OF SYMMETRY
FOR
640 ACRE WELL SPACING

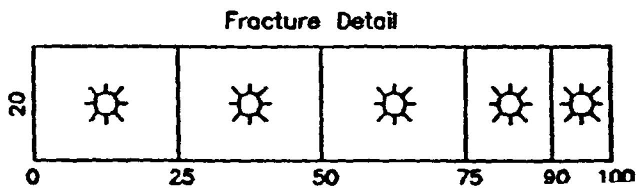


Application of Richardson Operating Co.
Record on Appeal, 1638.

Figure B-4

GRID SCHEMATIC FOR A
160 ACRE WELL SPACING AND 100 FOOT FRACTURE HALF LENGTH

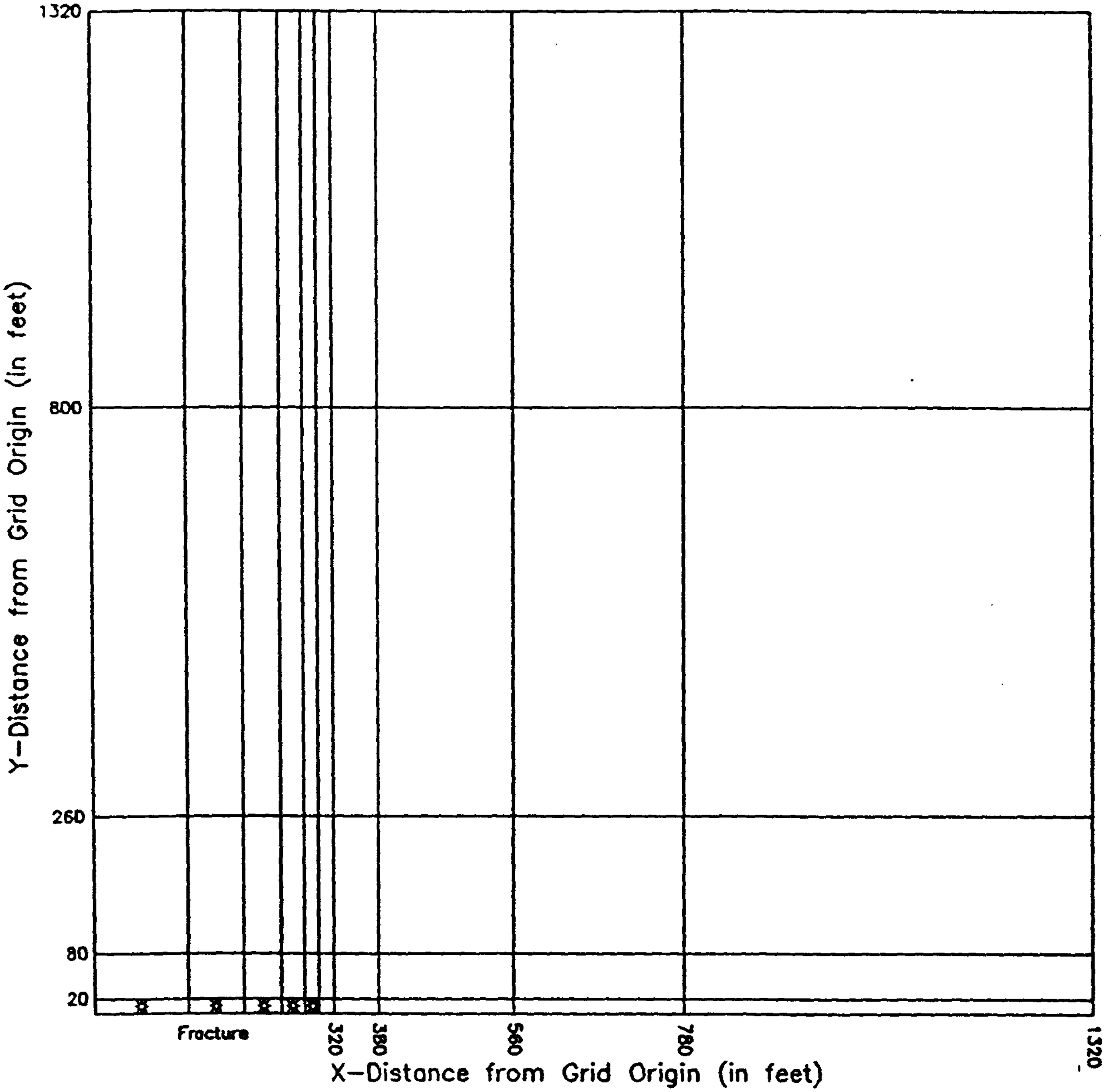


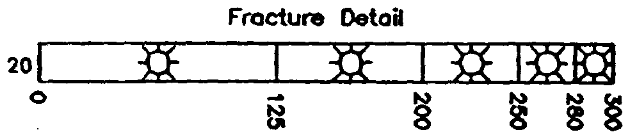


Application of Richardson Operating Co.
Record on Appeal, 1639.

Figure B-5

GRID SCHEMATIC FOR A
160 ACRE WELL SPACING AND 300 FOOT FRACTURE HALF LENGTH

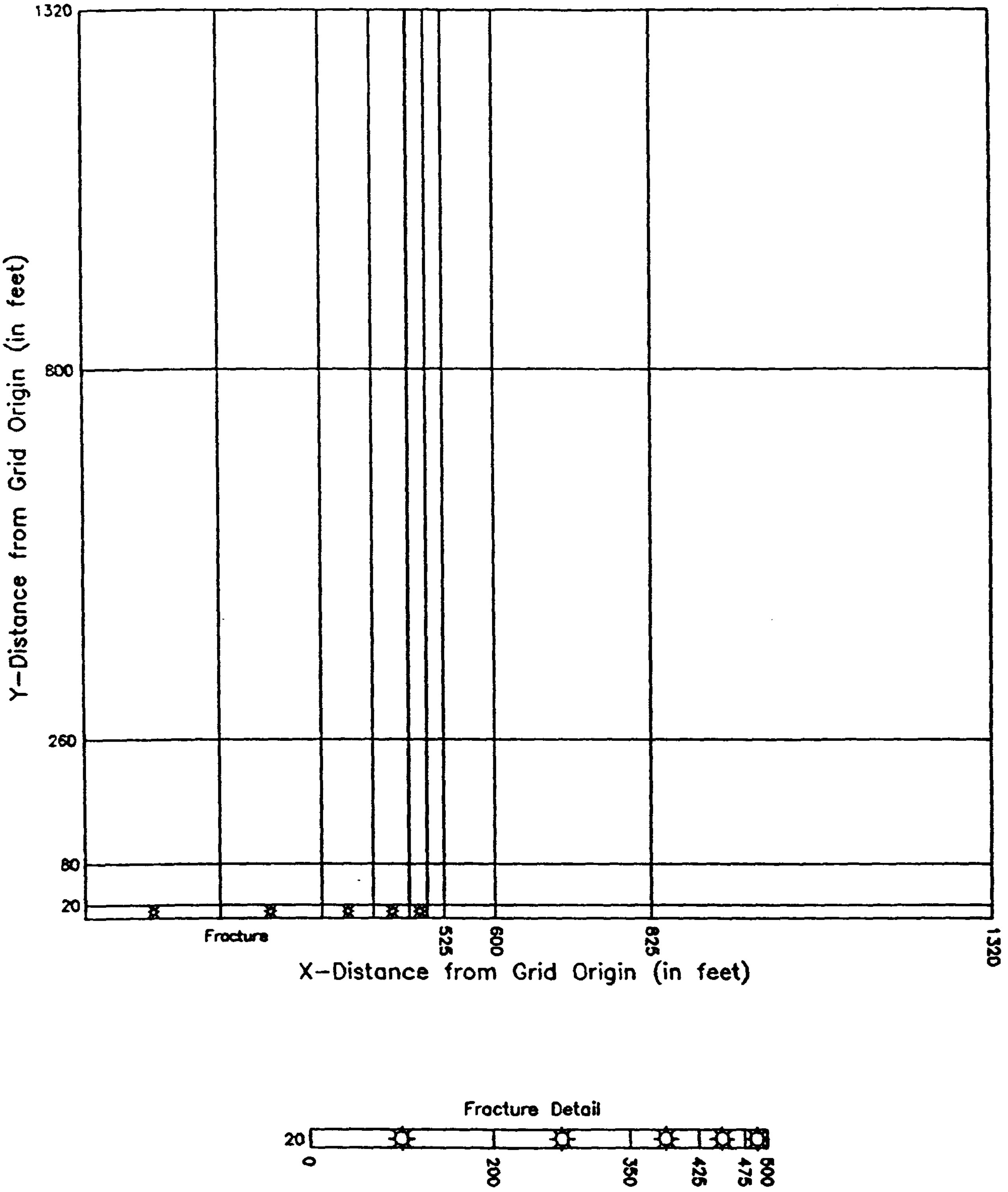




Application of Richardson Operating Co.
Record on Appeal, 1640.

Figure B-6

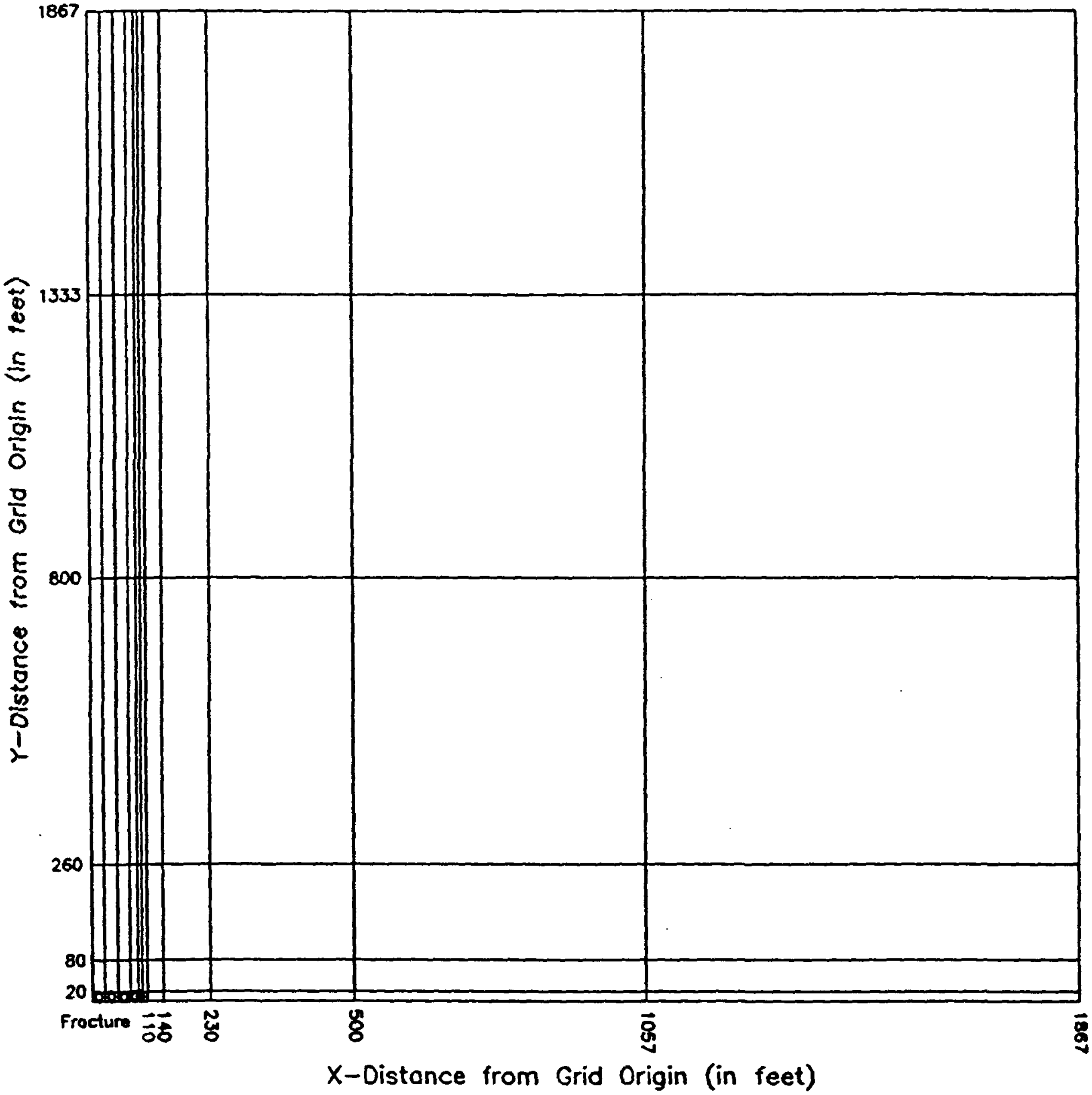
GRID SCHEMATIC FOR A
160 ACRE WELL SPACING AND 500 FOOT FRACTURE HALF LENGTH

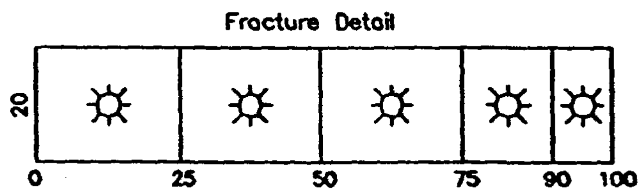


Application of Richardson Operating Co.
Record on Appeal, 1641.

Figure B-7

GRID SCHEMATIC FOR A
320 ACRE WELL SPACING AND 100 FOOT FRACTURE HALF LENGTH

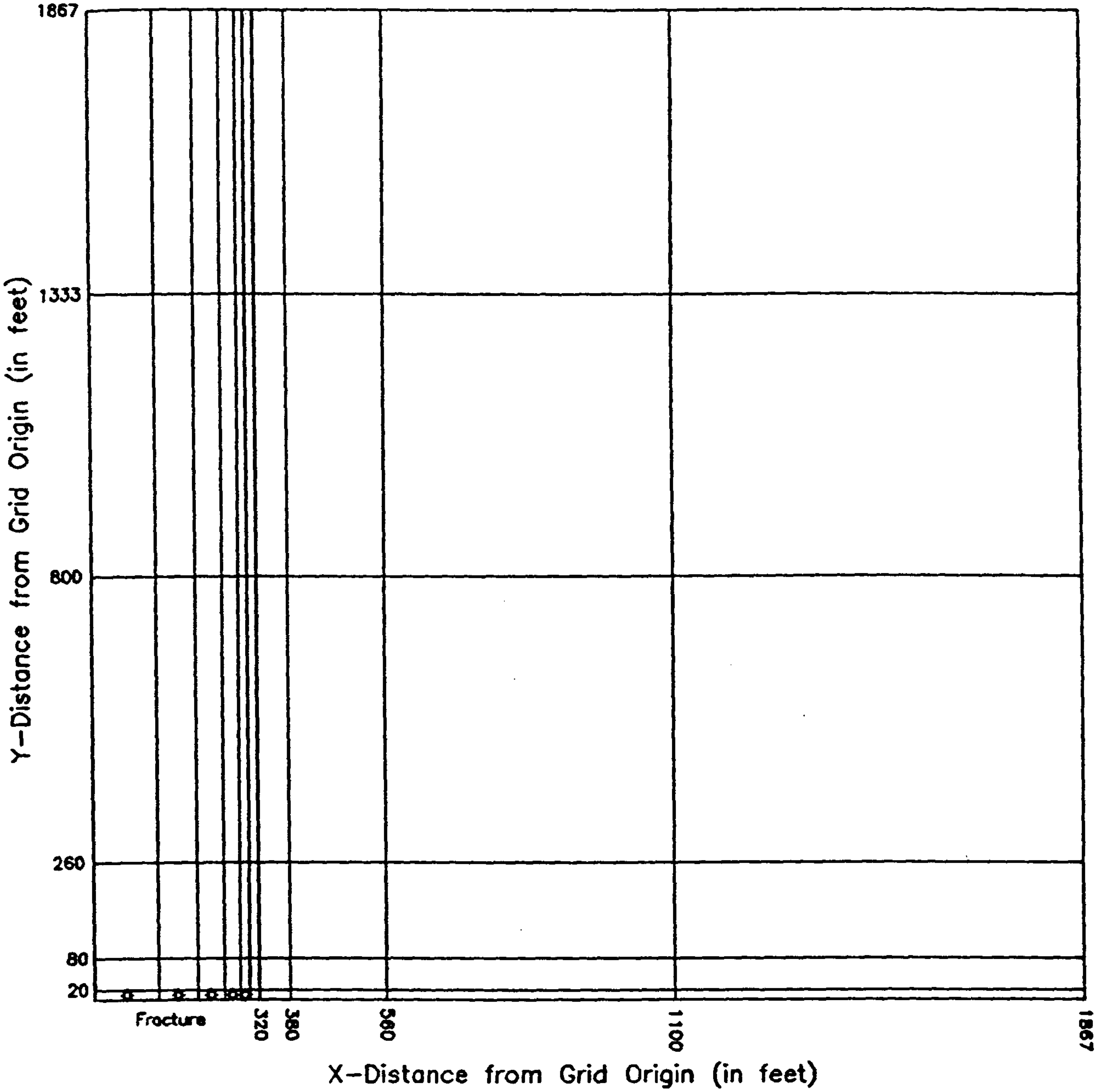




Application of Richardson Operating Co.
Record on Appeal, 1642.

Figure B-8

GRID SCHEMATIC FOR A
320 ACRE WELL SPACING AND 300 FOOT FRACTURE HALF LENGTH



Fracture Detail

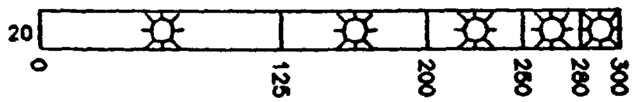
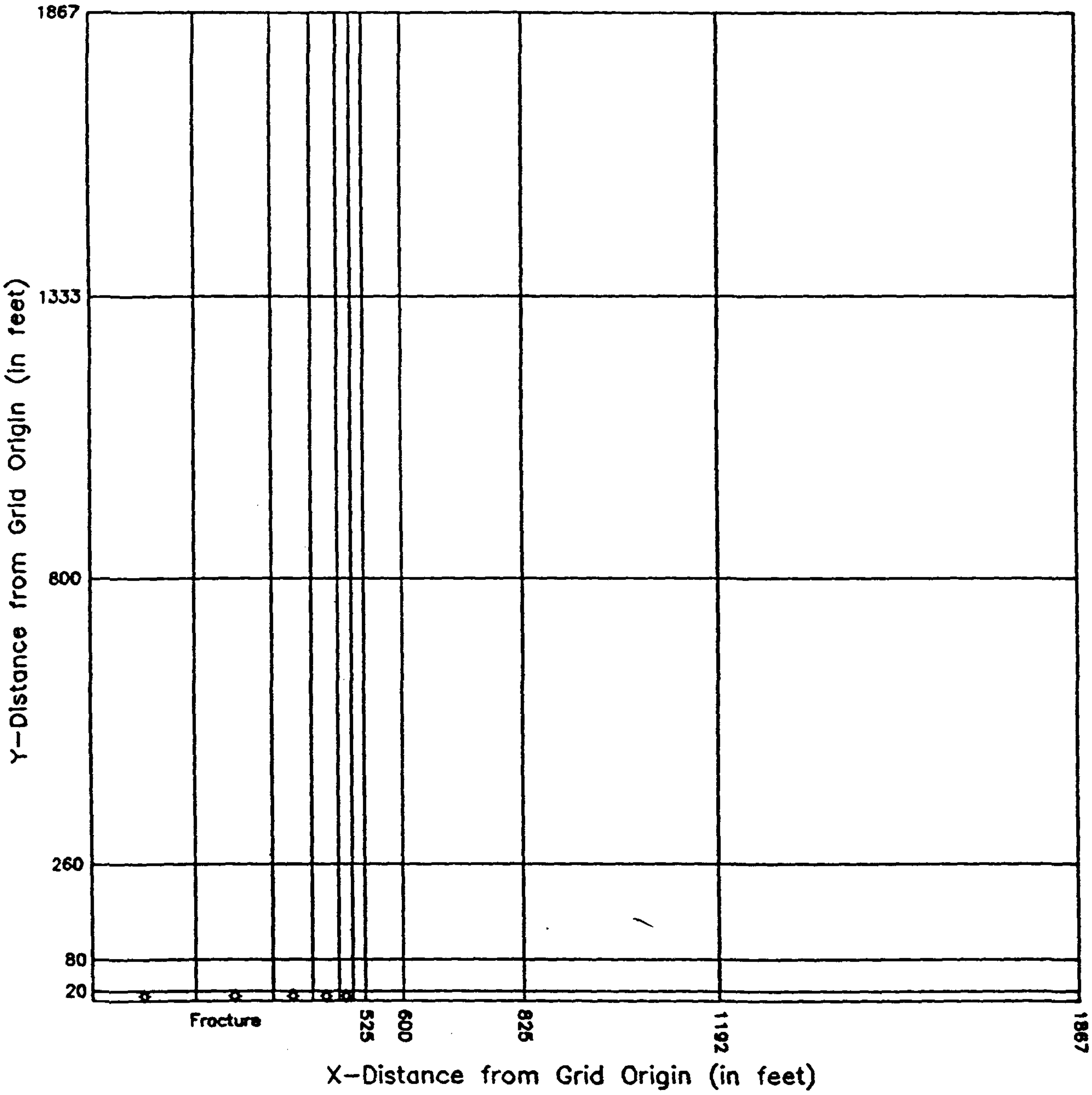
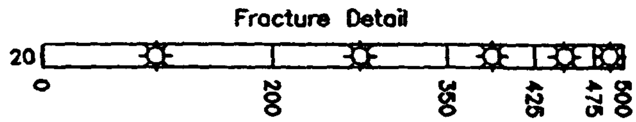


Figure B-9

GRID SCHEMATIC FOR A
320 ACRE WELL SPACING AND 500 FOOT FRACTURE HALF LENGTH

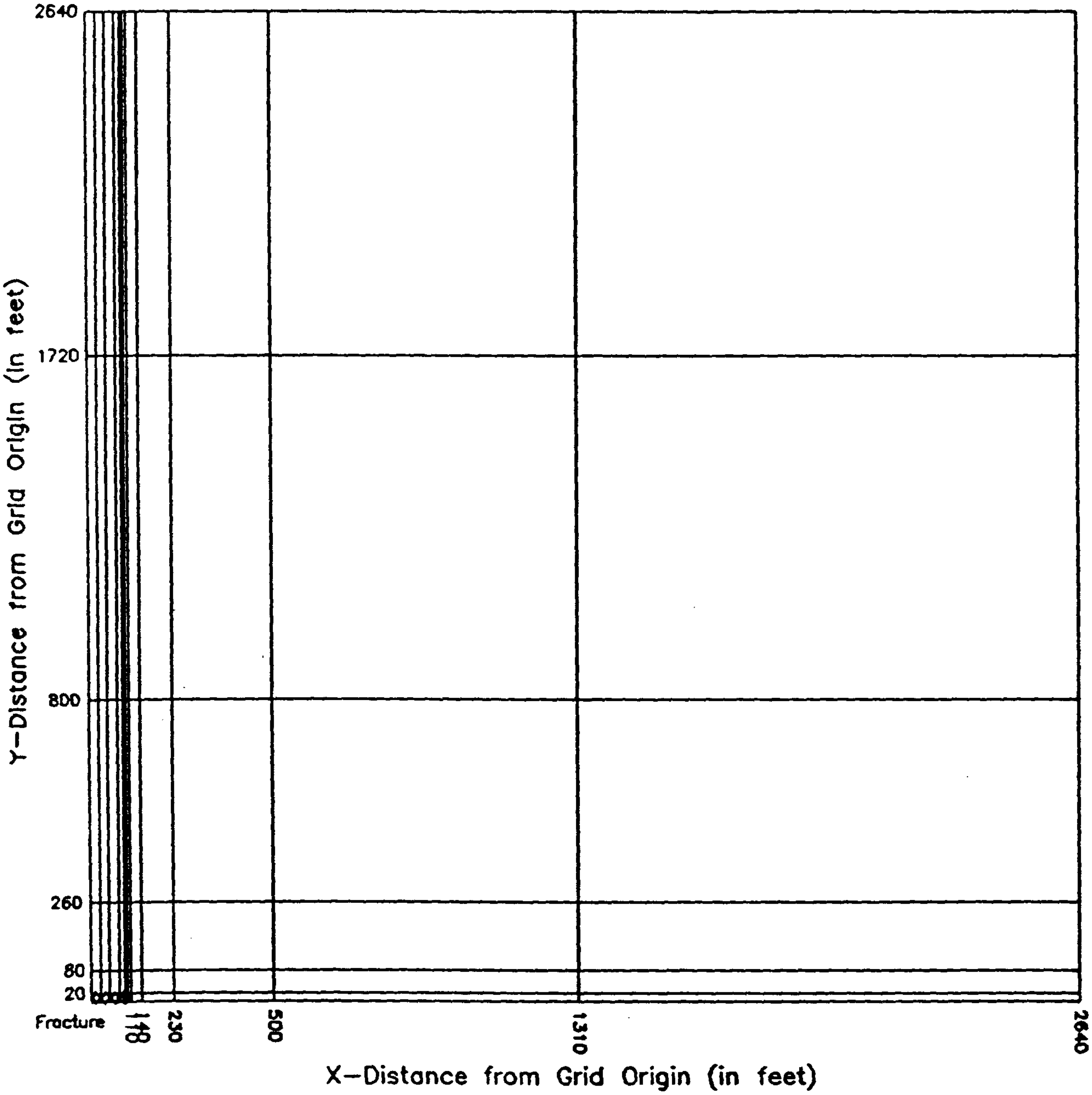




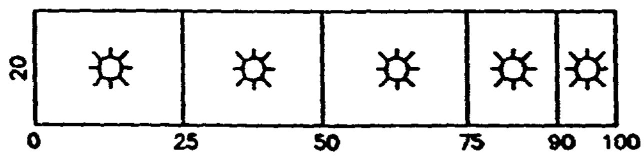
Application of Richardson Operating Co.
Record on Appeal, 1644.

Figure B-10

GRID SCHEMATIC FOR A
640 ACRE WELL SPACING AND 100 FOOT FRACTURE HALF LENGTH



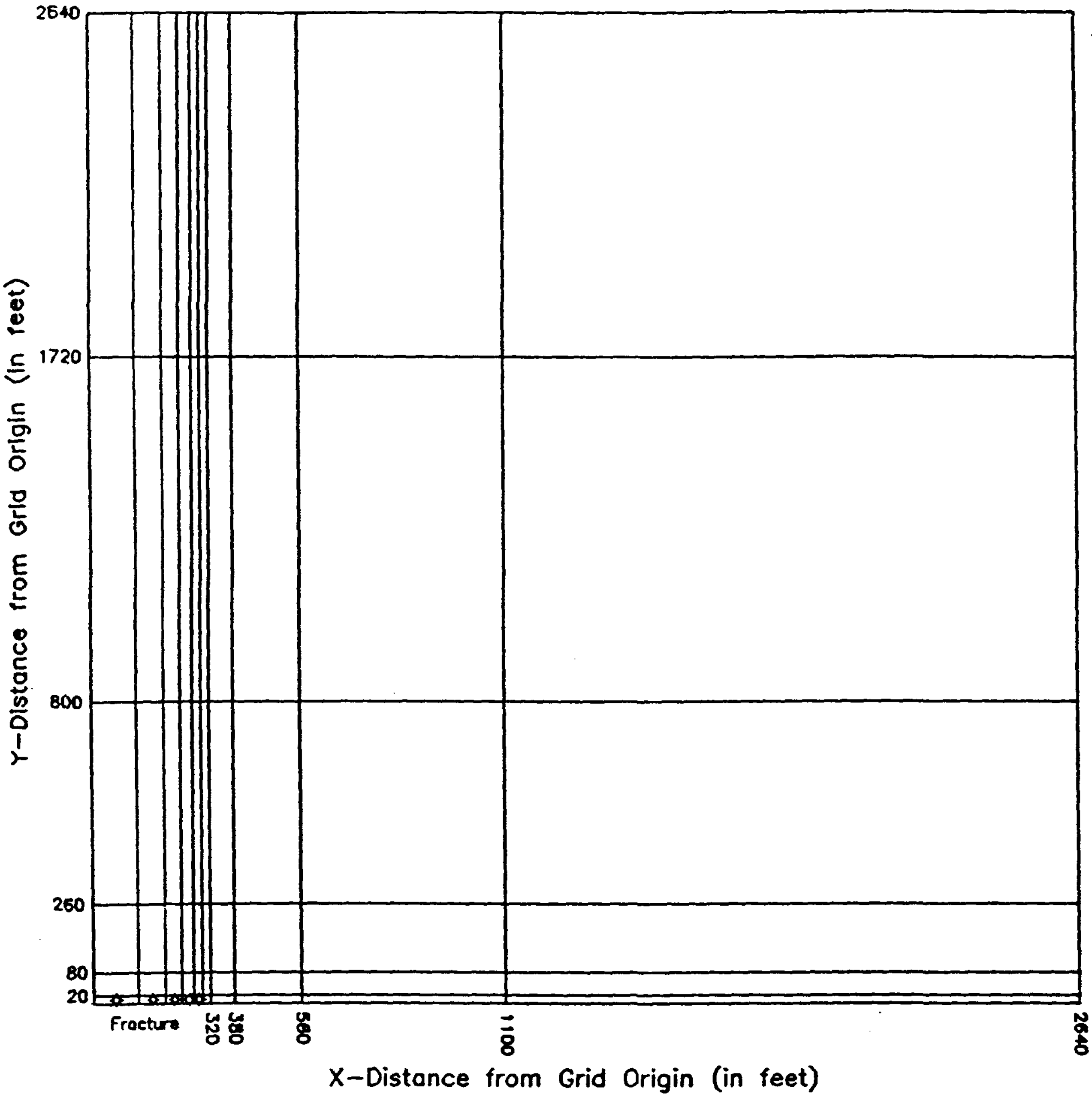
Fracture Detail

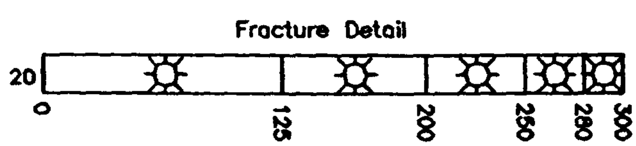


Application of Richardson Operating Co.
Record on Appeal, 1645.

Figure B-11

GRID SCHEMATIC FOR A
640 ACRE WELL SPACING AND 300 FOOT FRACTURE HALF LENGTH

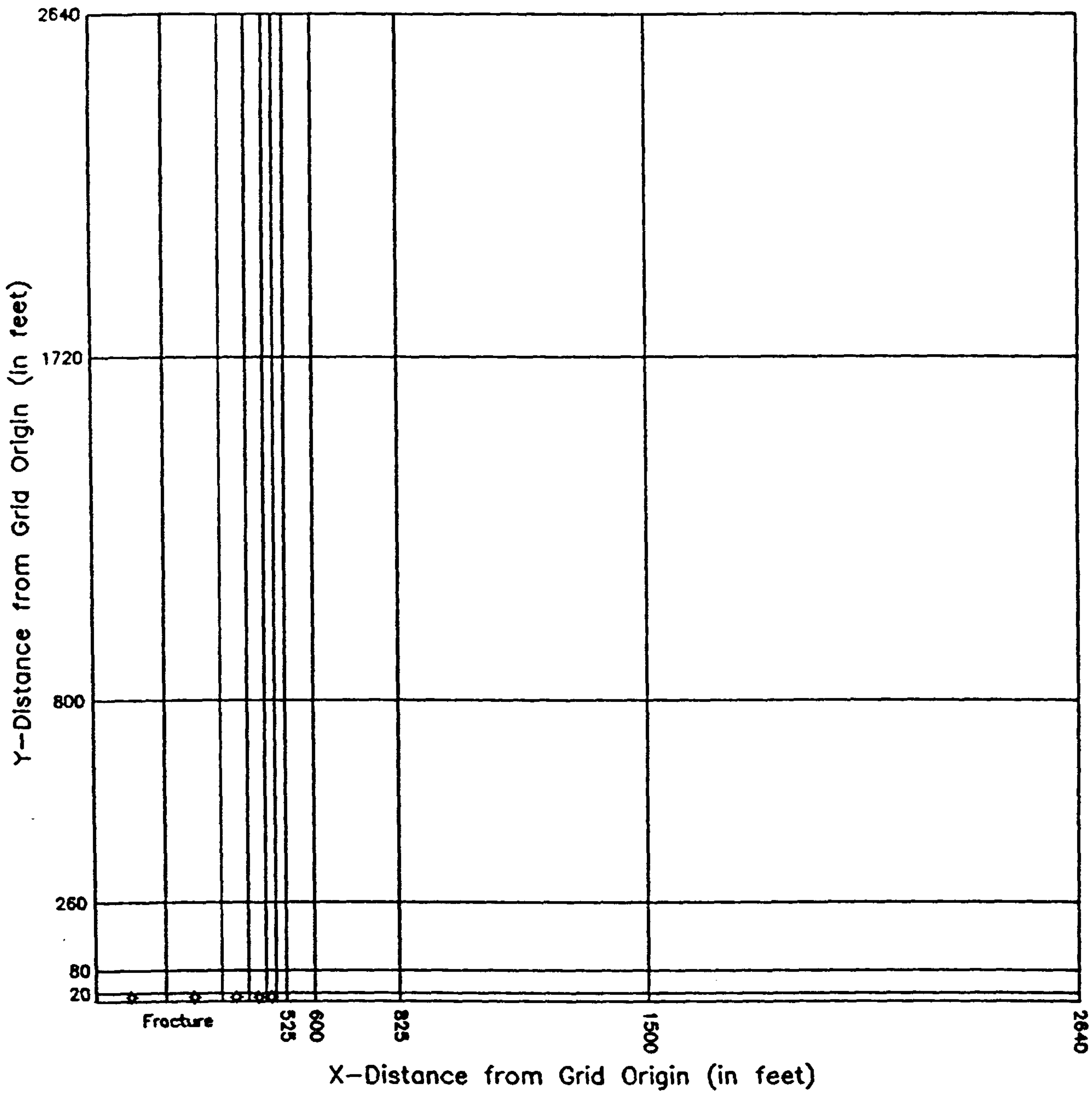


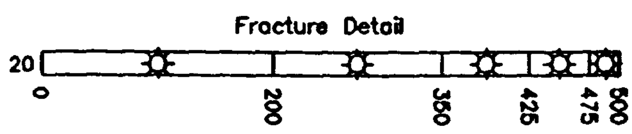


Application of Richardson Operating Co.
Record on Appeal, 1646.

Figure B-12

GRID SCHEMATIC FOR A
640 ACRE WELL SPACING AND 500 FOOT FRACTURE HALF LENGTH





Application of Richardson Operating Co.
Record on Appeal, 1647.

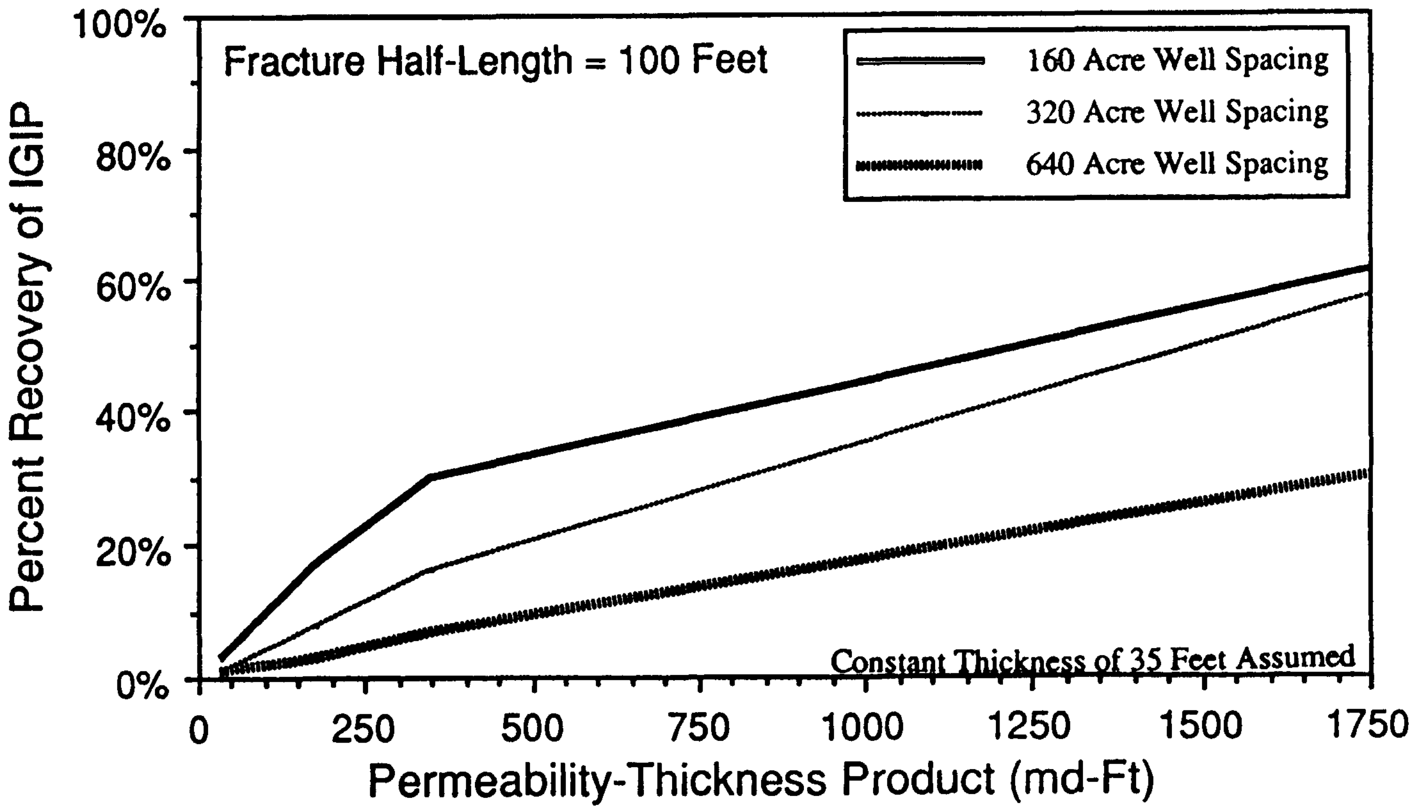
APPENDIX C

GAS RECOVERY VS. RESERVOIR kh FOR 10, 20, 30, 40, AND 50 YEAR SIMULATIONS

Figure C-1

San Juan Basin Area 1
Gas Recovery vs kh

10 Year Simulation

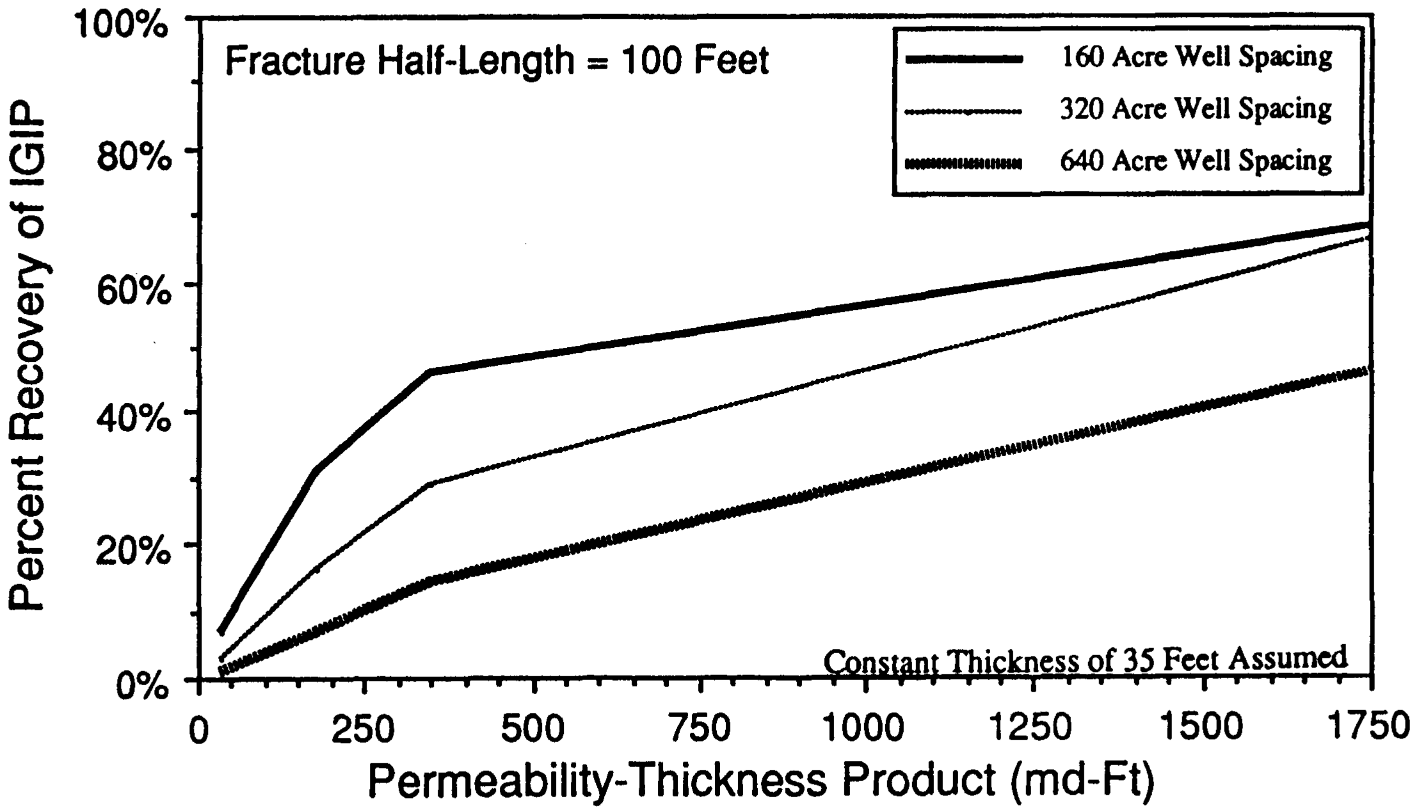


Application of Richardson Operating Co.
Record on Appeal, 1649.

Figure C-2

San Juan Basin Area 1
Gas Recovery vs kh

20 Year Simulation

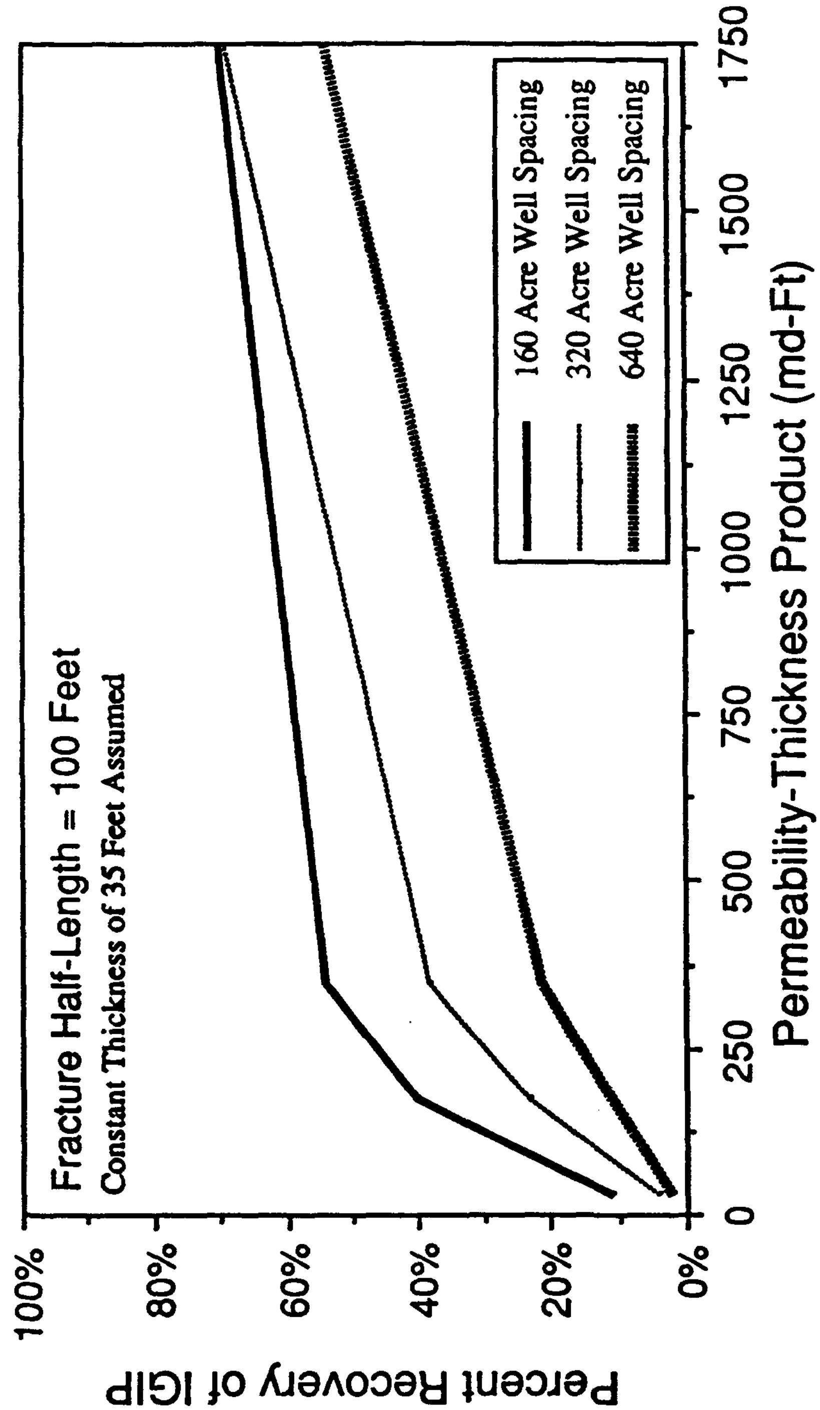


Application of Richardson Operating Co.
Record on Appeal, 1650.

Figure C-3

San Juan Basin Area 1
Gas Recovery vs kh

30 Year Simulation

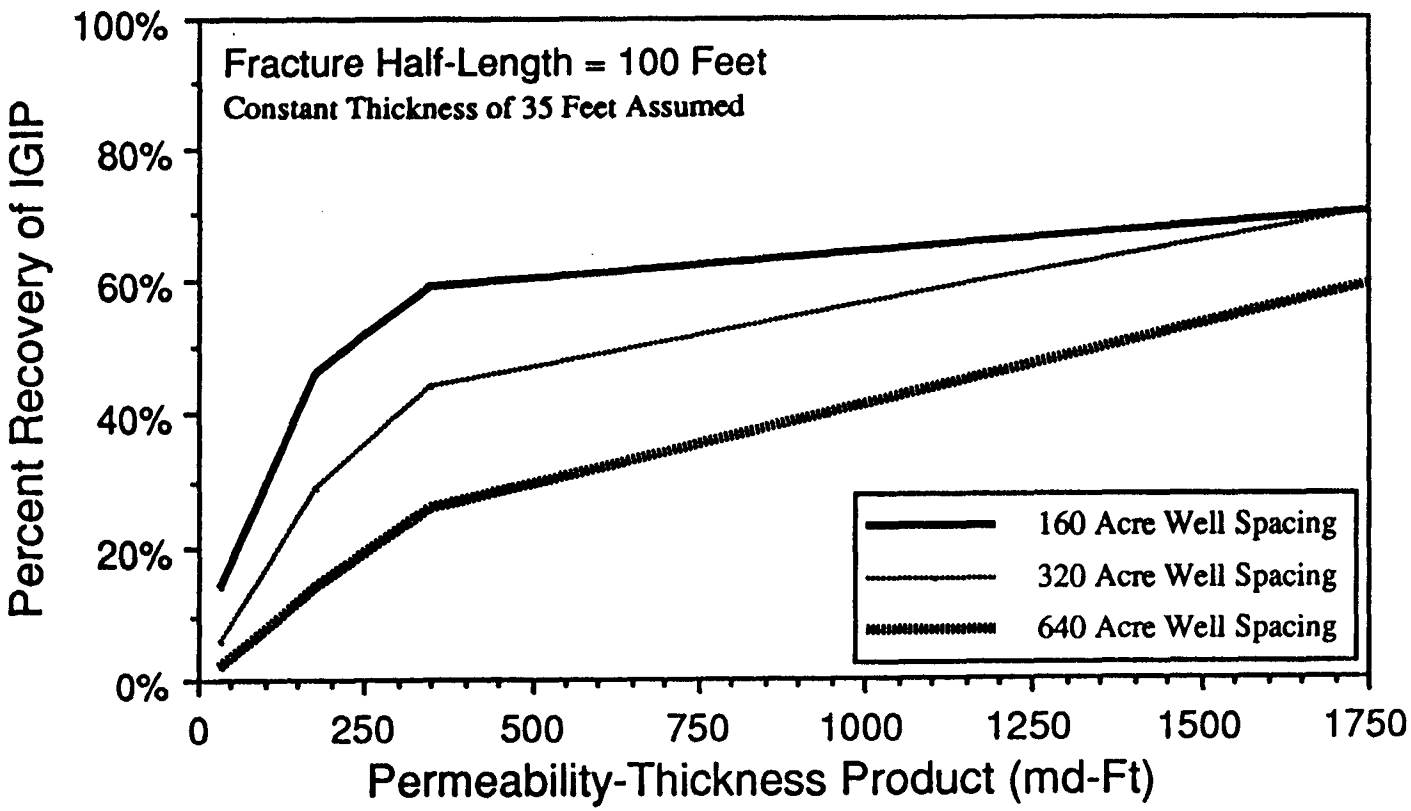


Application of Richardson Operating Co.
Record on Appeal, 1651.

Figure C-4

San Juan Basin Area 1
Gas Recovery vs kh

40 Year Simulation

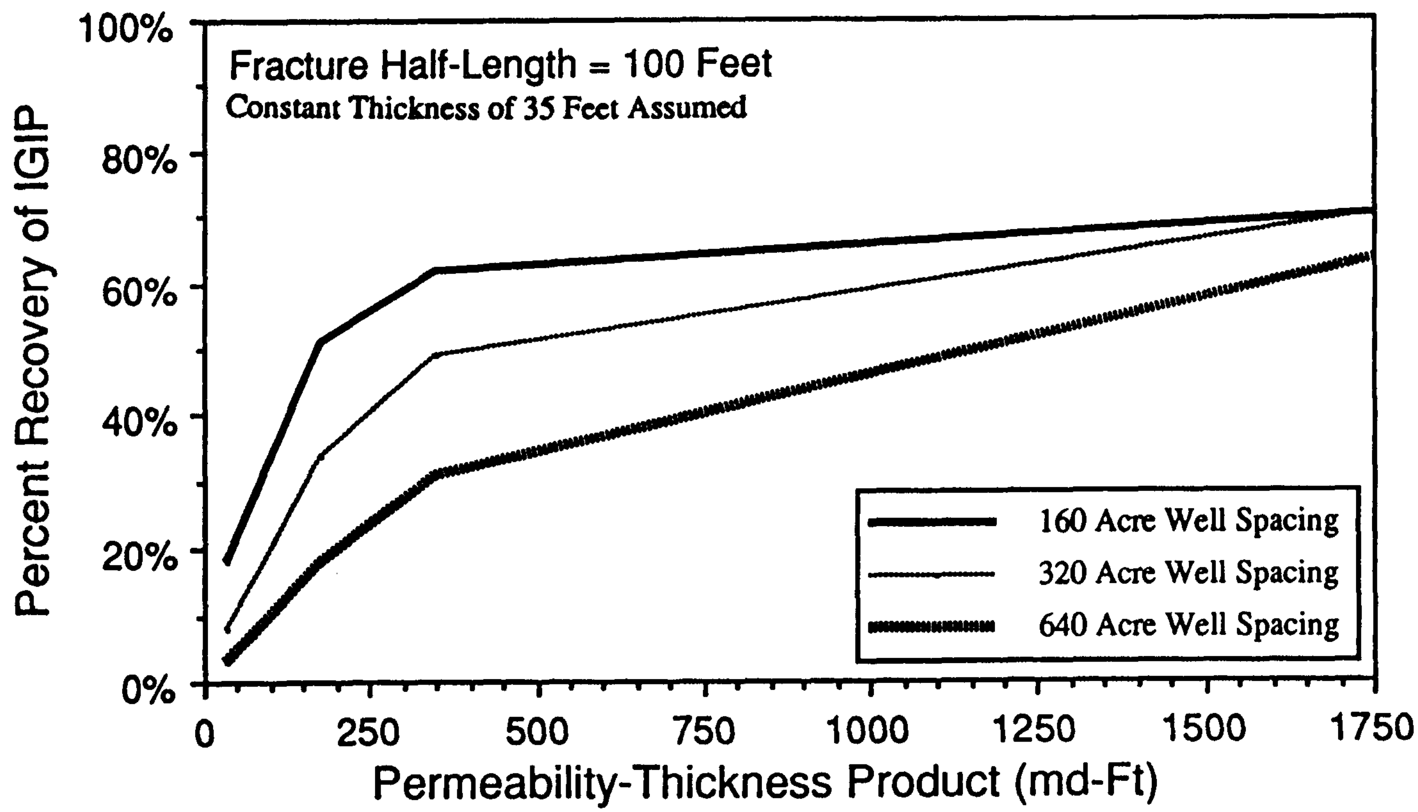


Application of Richardson Operating Co.
Record on Appeal, 1652.

Figure C-5

San Juan Basin Area 1
Gas Recovery vs kh

50 Year Simulation

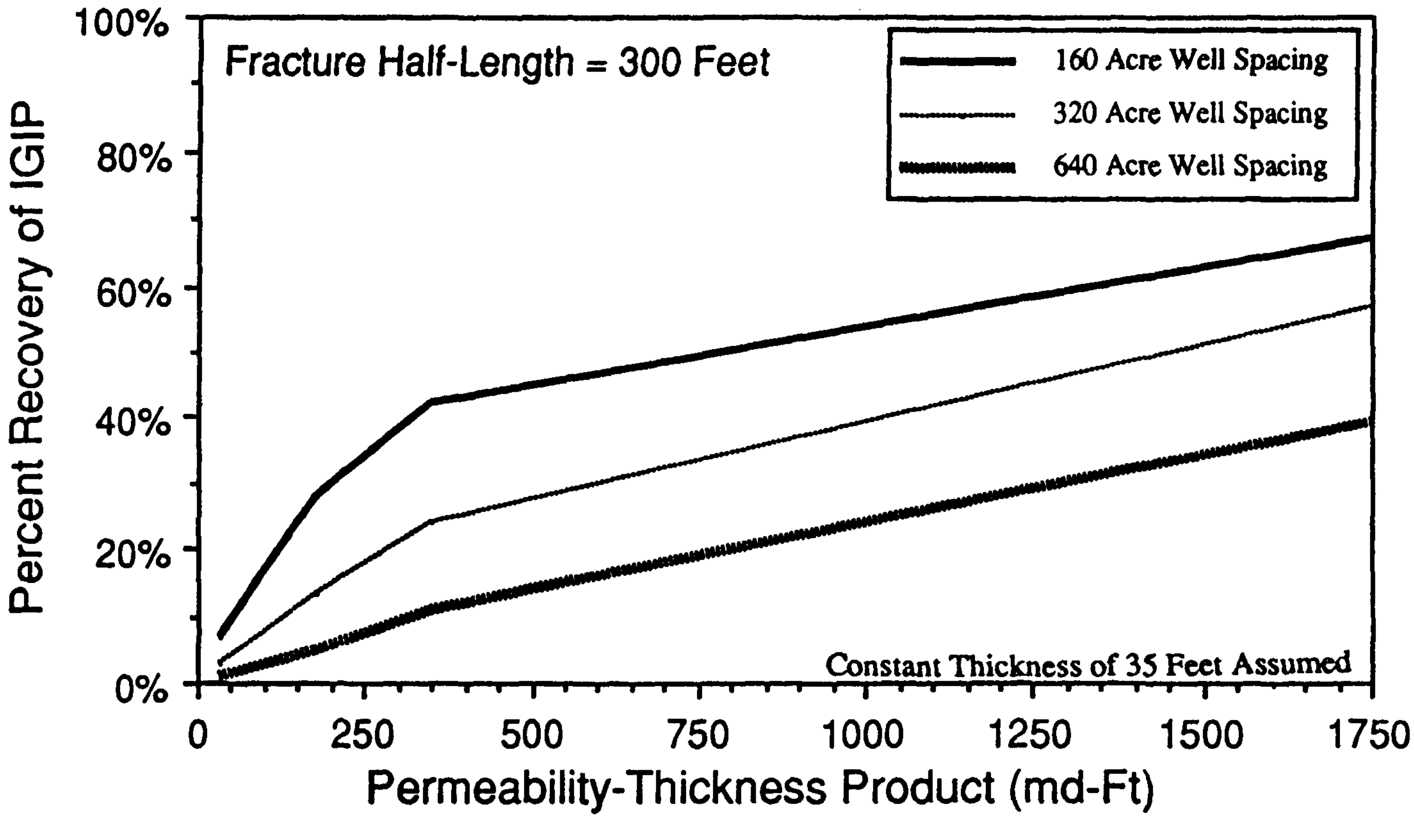


Application of Richardson Operating Co.
Record on Appeal, 1653.

Figure C-6

San Juan Basin Area 1
Gas Recovery vs kh

10 Year Simulation

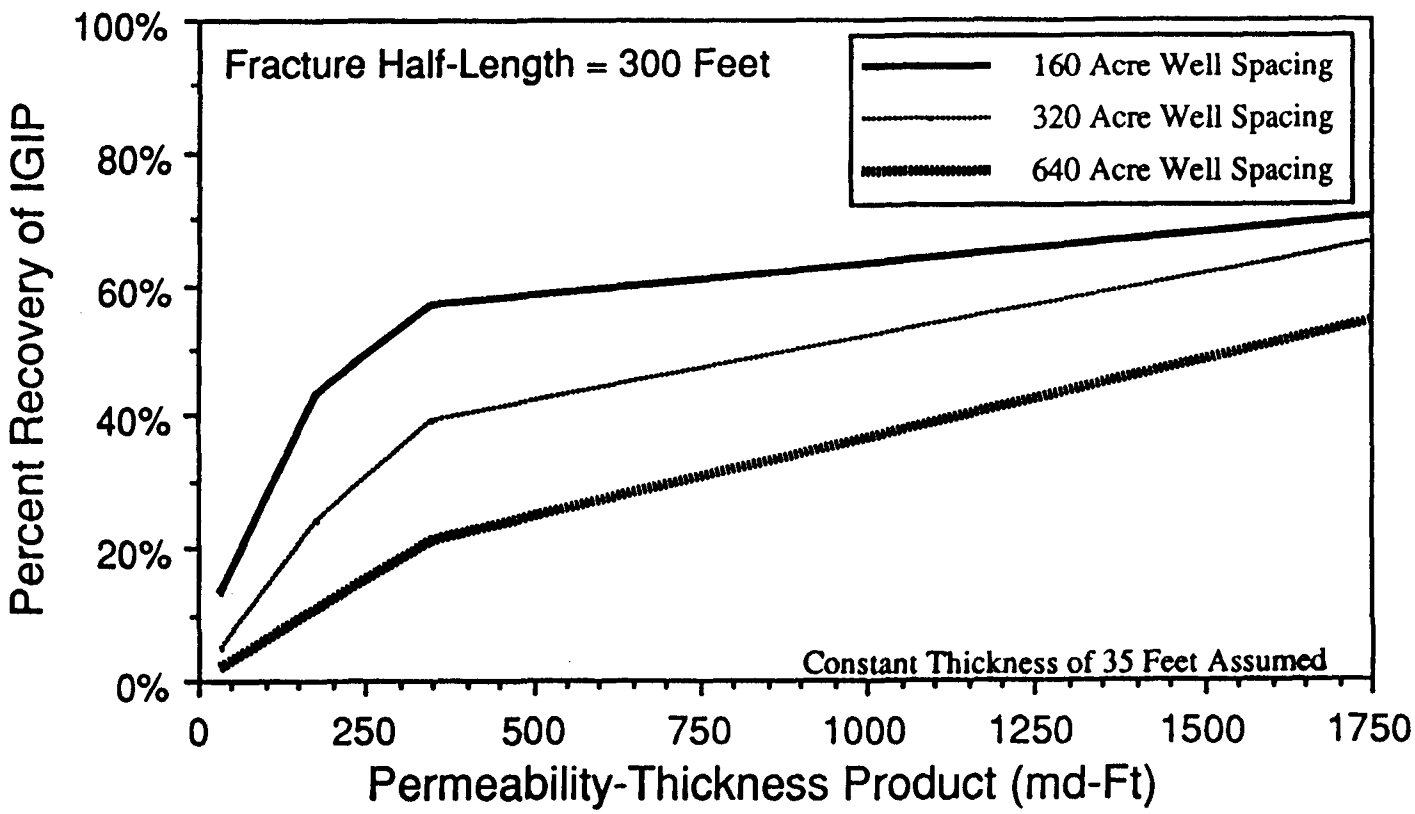


Application of Richardson Operating Co.
Record on Appeal, 1654.

Figure C-7

San Juan Basin Area 1
Gas Recovery vs kh

20 Year Simulation

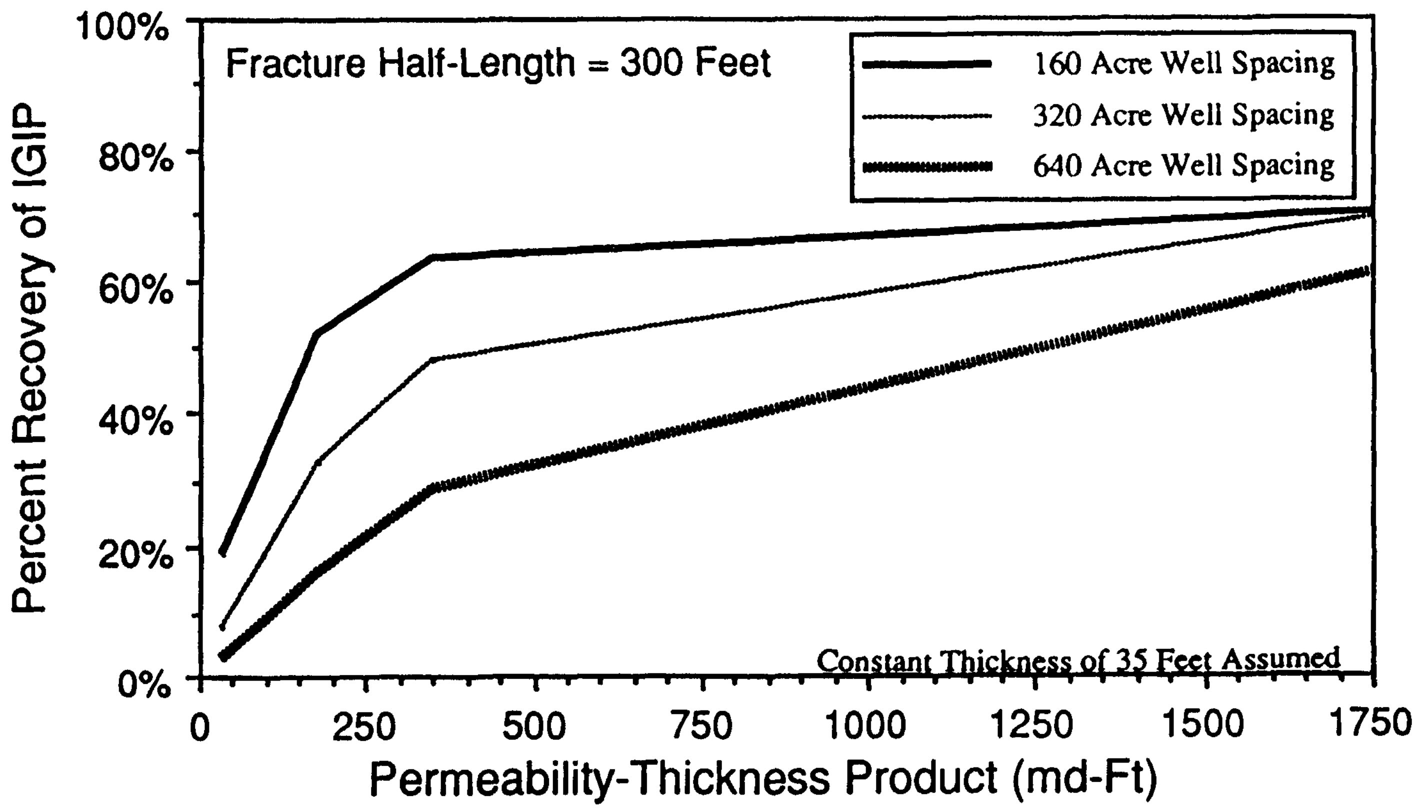


Application of Richardson Operating Co.
Record on Appeal, 1655.

Figure C-8

San Juan Basin Area 1
Gas Recovery vs kh

30 Year Simulation

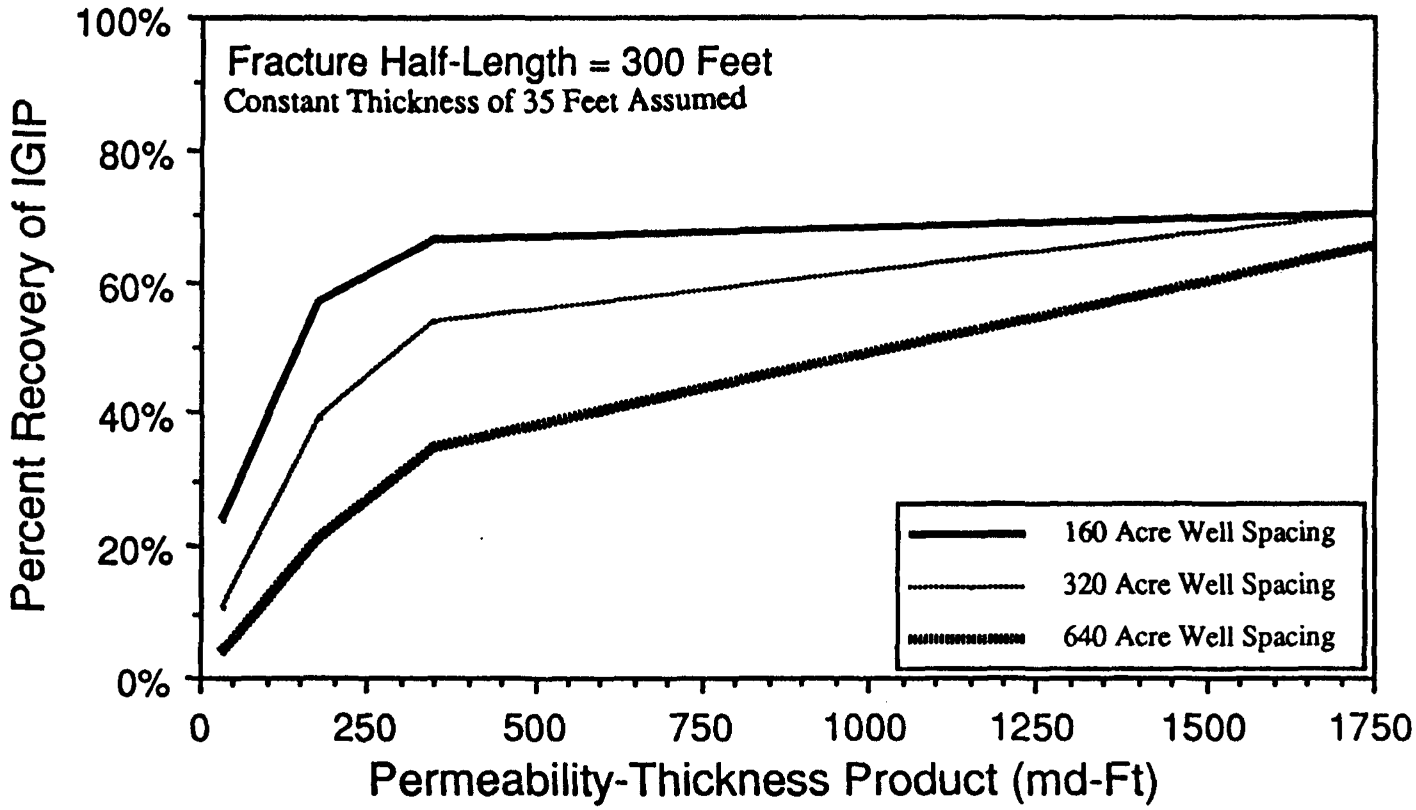


Application of Richardson Operating Co.
Record on Appeal, 1656.

Figure C-9

San Juan Basin Area 1
Gas Recovery vs kh

40 Year Simulation

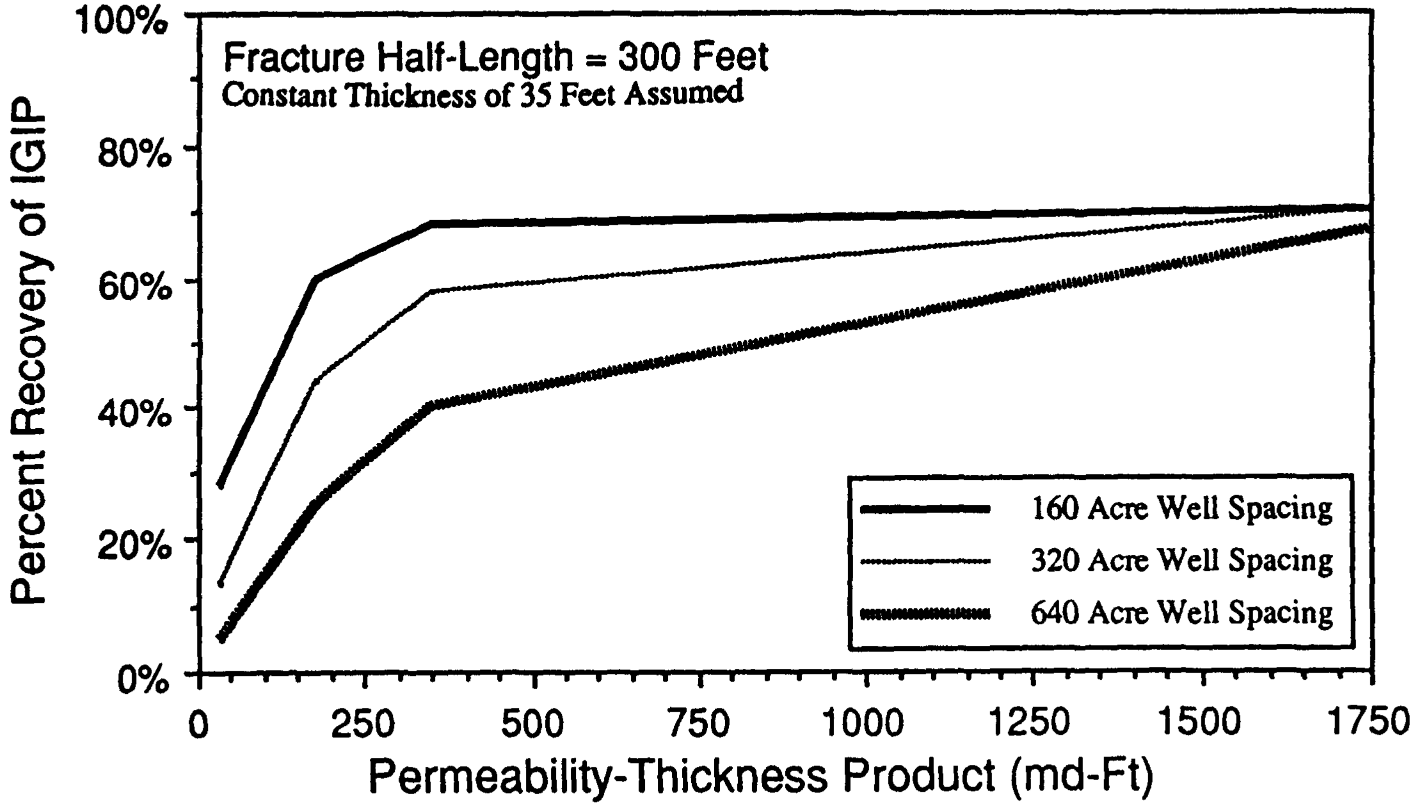


Application of Richardson Operating Co.
Record on Appeal, 1657.

Figure C-10

San Juan Basin Area 1
Gas Recovery vs kh

50 Year Simulation

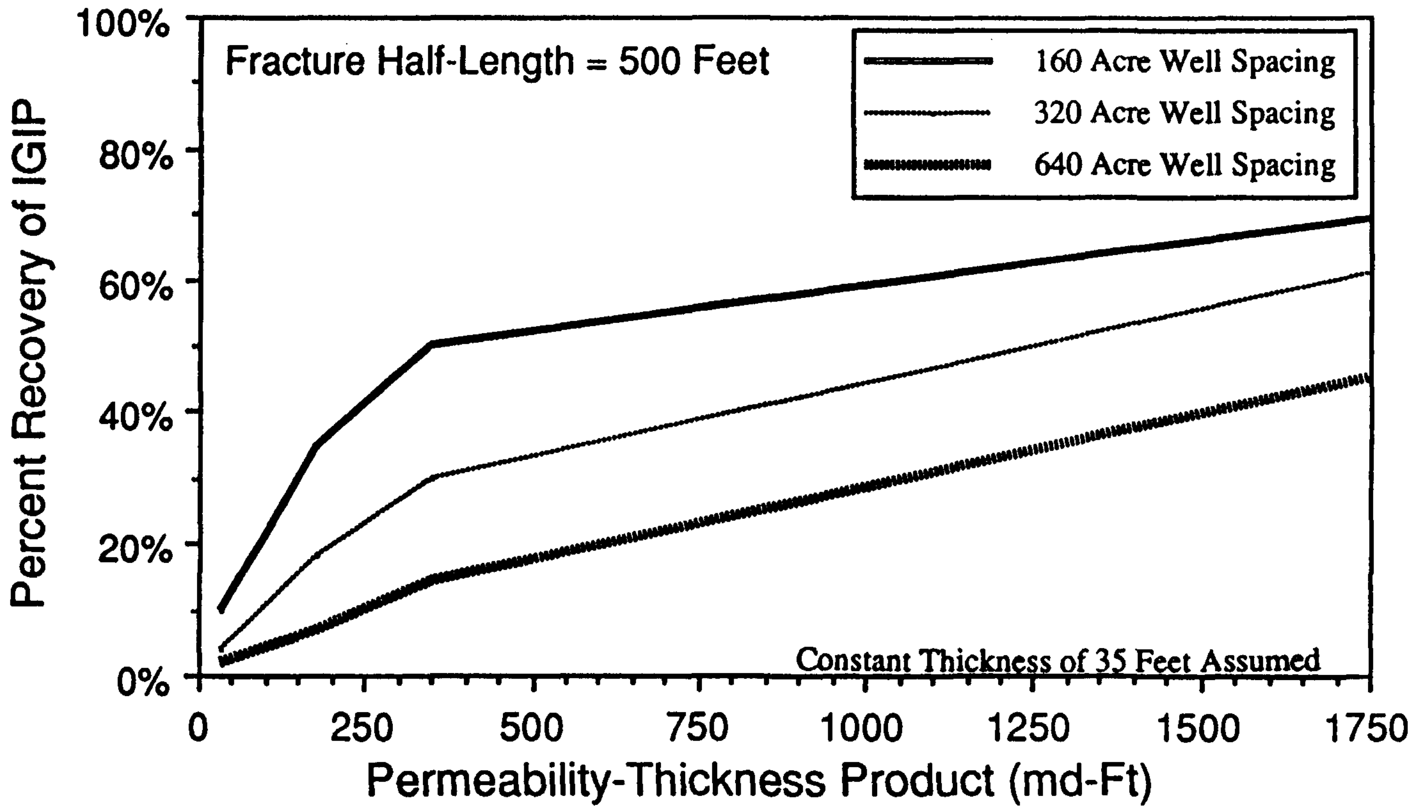


Application of Richardson Operating Co.
Record on Appeal, 1658.

Figure C-11

San Juan Basin Area 1
Gas Recovery vs kh

10 Year Simulation

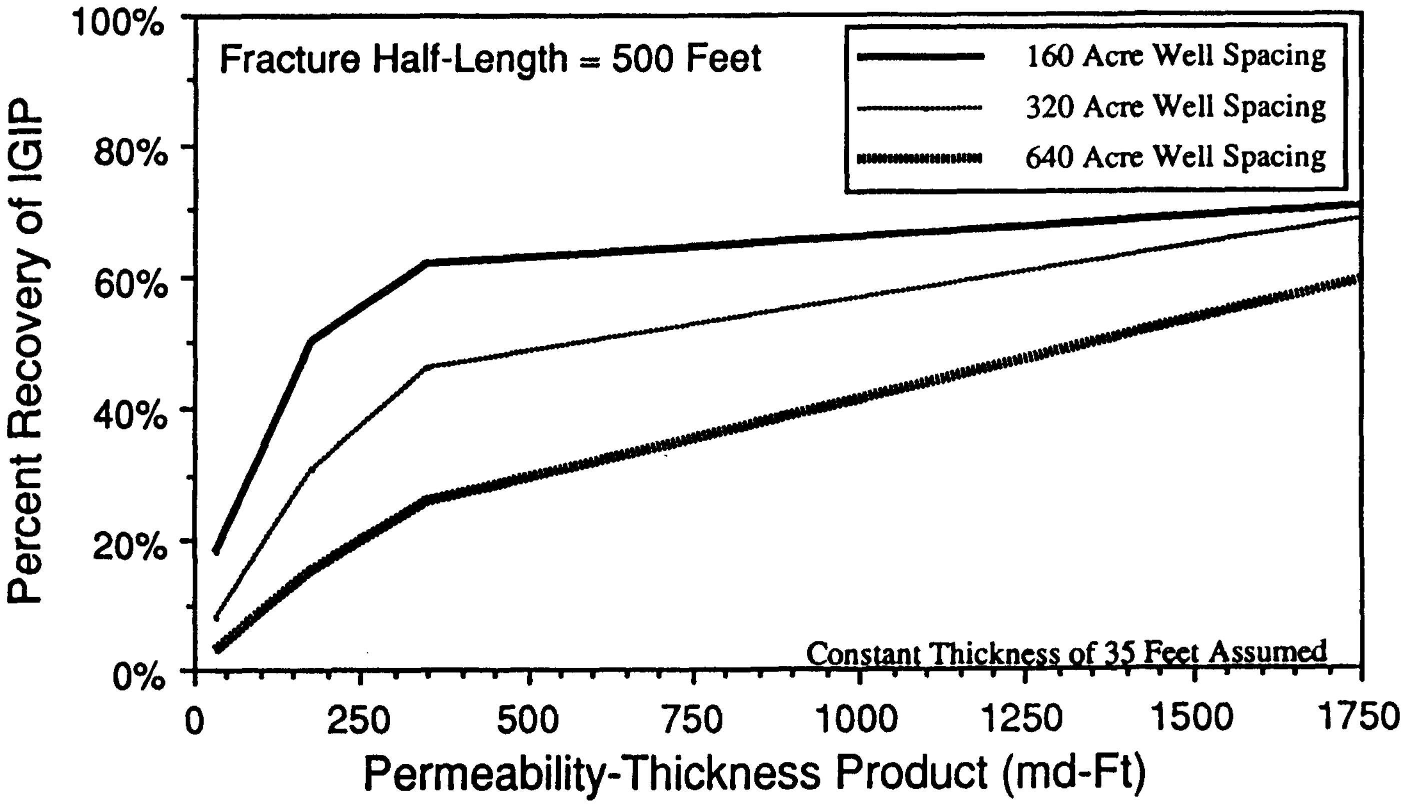


Application of Richardson Operating Co.
Record on Appeal, 1659.

Figure C-12

San Juan Basin Area 1
Gas Recovery vs kh

20 Year Simulation



Application of Richardson Operating Co.
Record on Appeal, 1660.

Figure C-13

San Juan Basin Area 1
Gas Recovery vs kh

30 Year Simulation

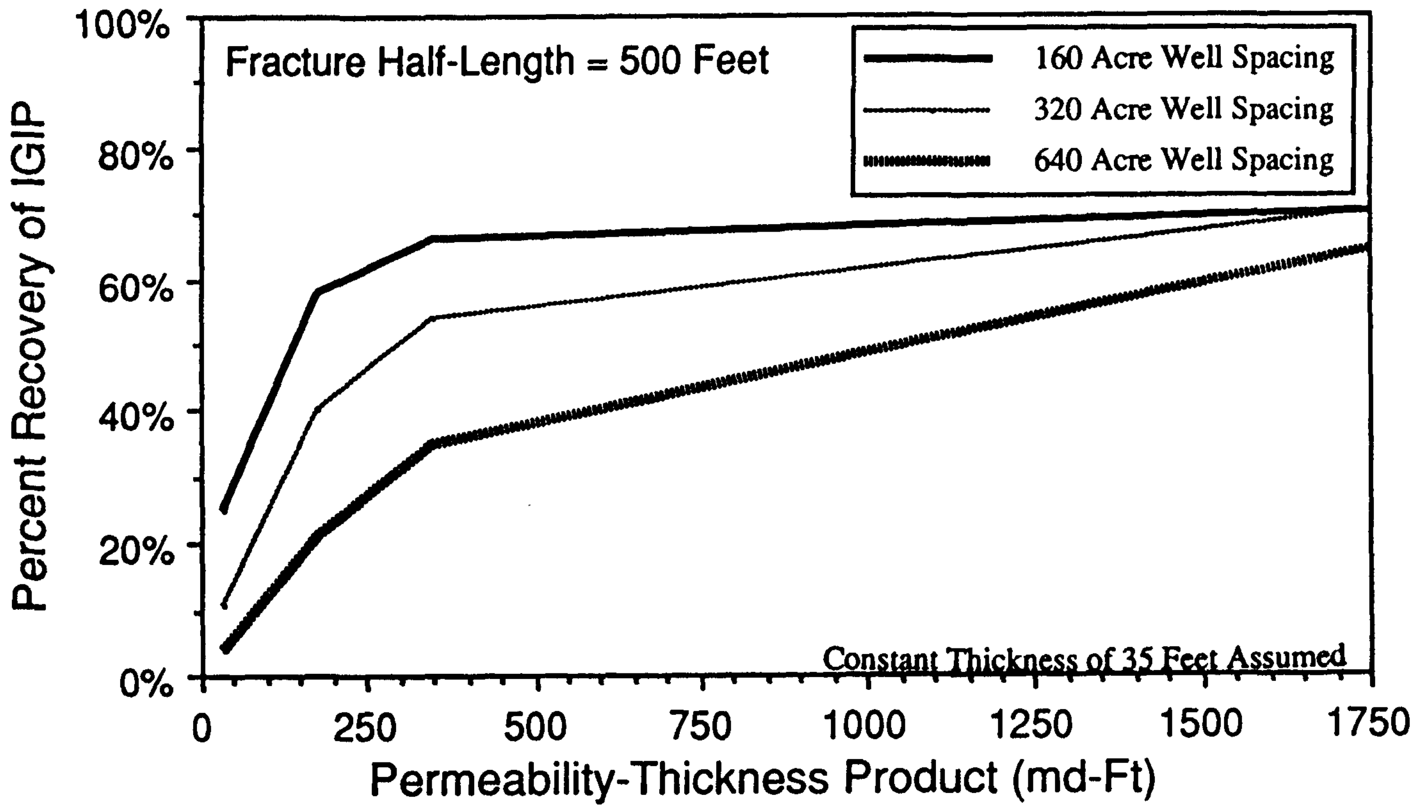
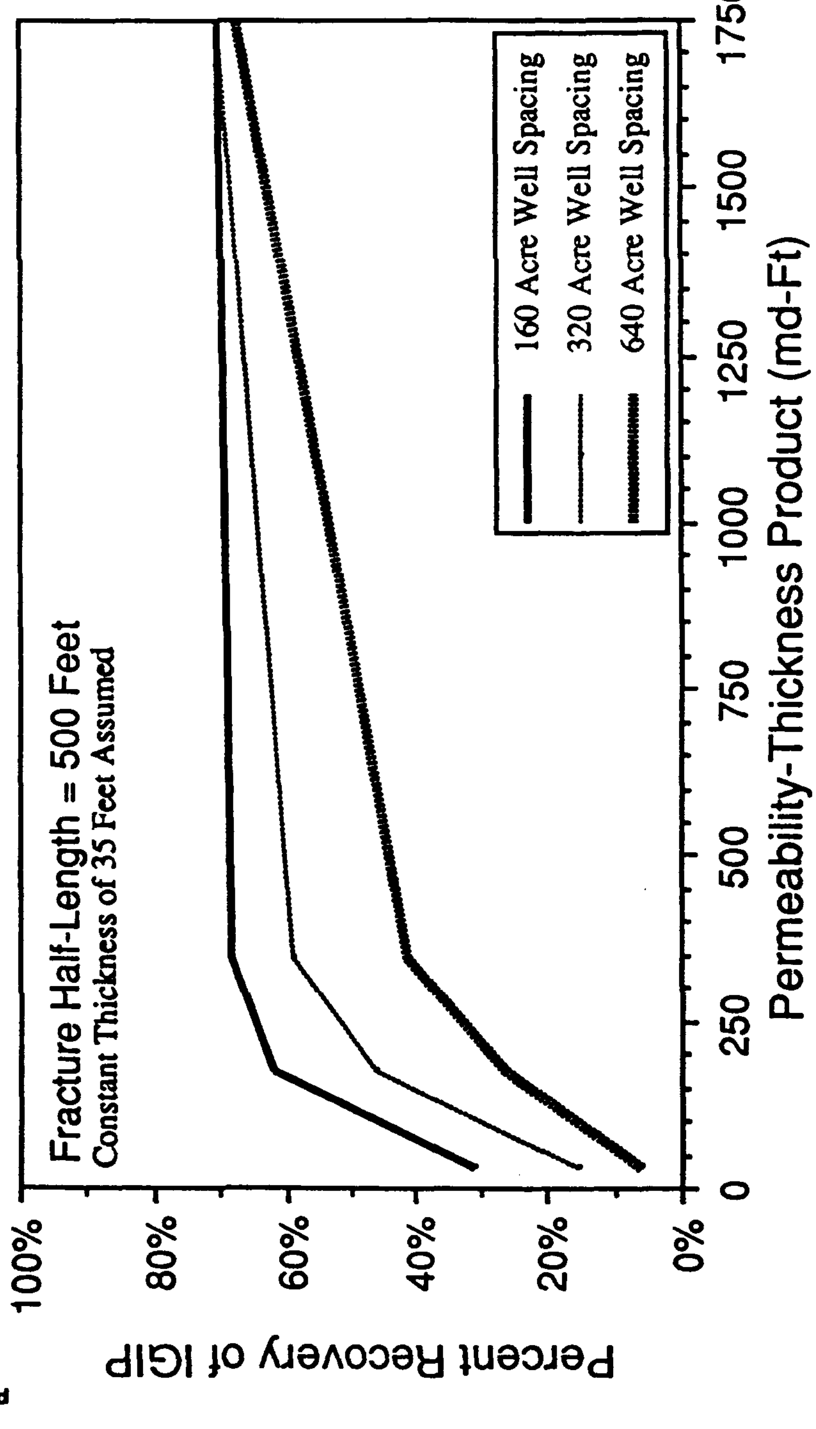


Figure C-14

San Juan Basin Area 1 Gas Recovery vs kh

40 Year Simulation

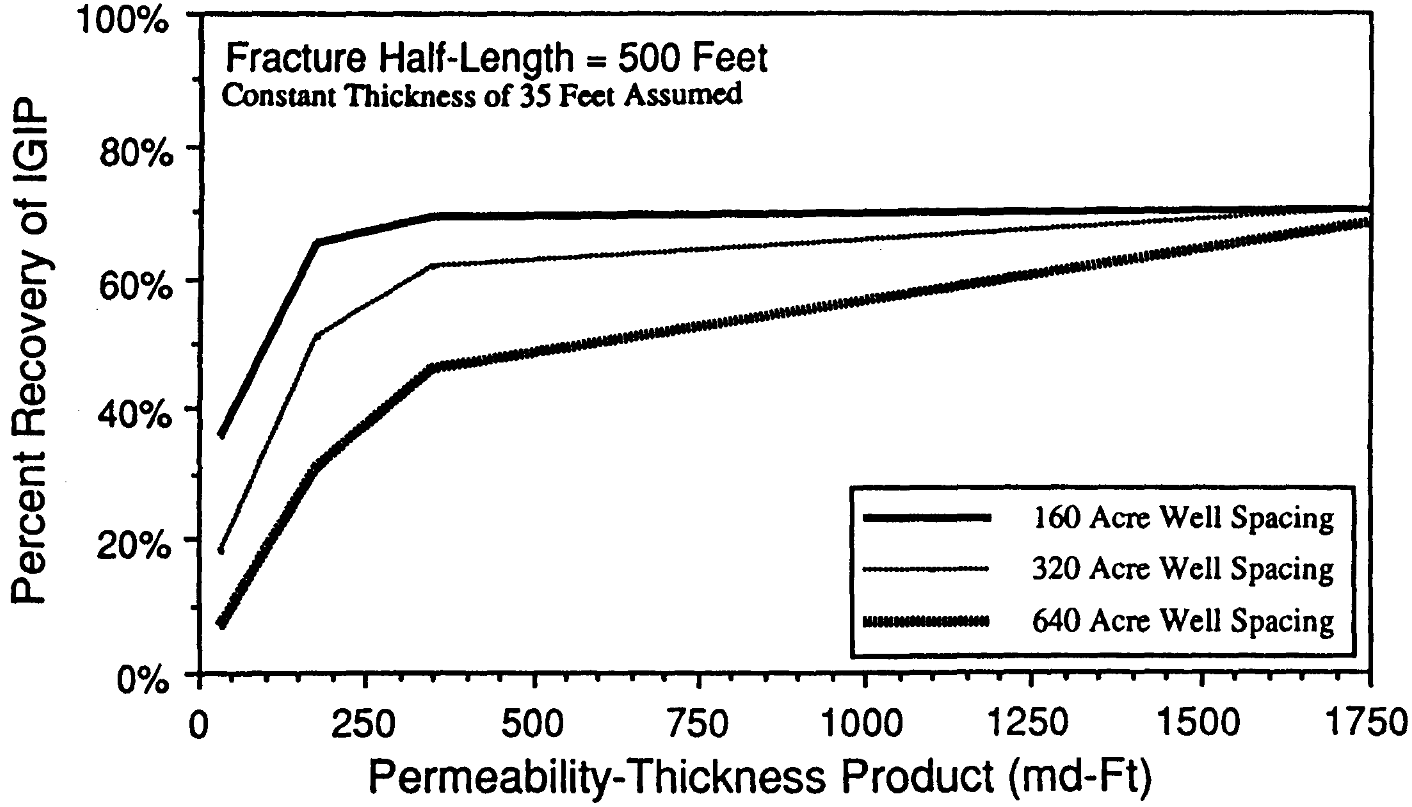


Application of Richardson Operating Co.
Record on Appeal, 1662.

Figure C-15

San Juan Basin Area 1 Gas Recovery vs kh

50 Year Simulation



Application of Richardson Operating Co.
Record on Appeal, 1663.

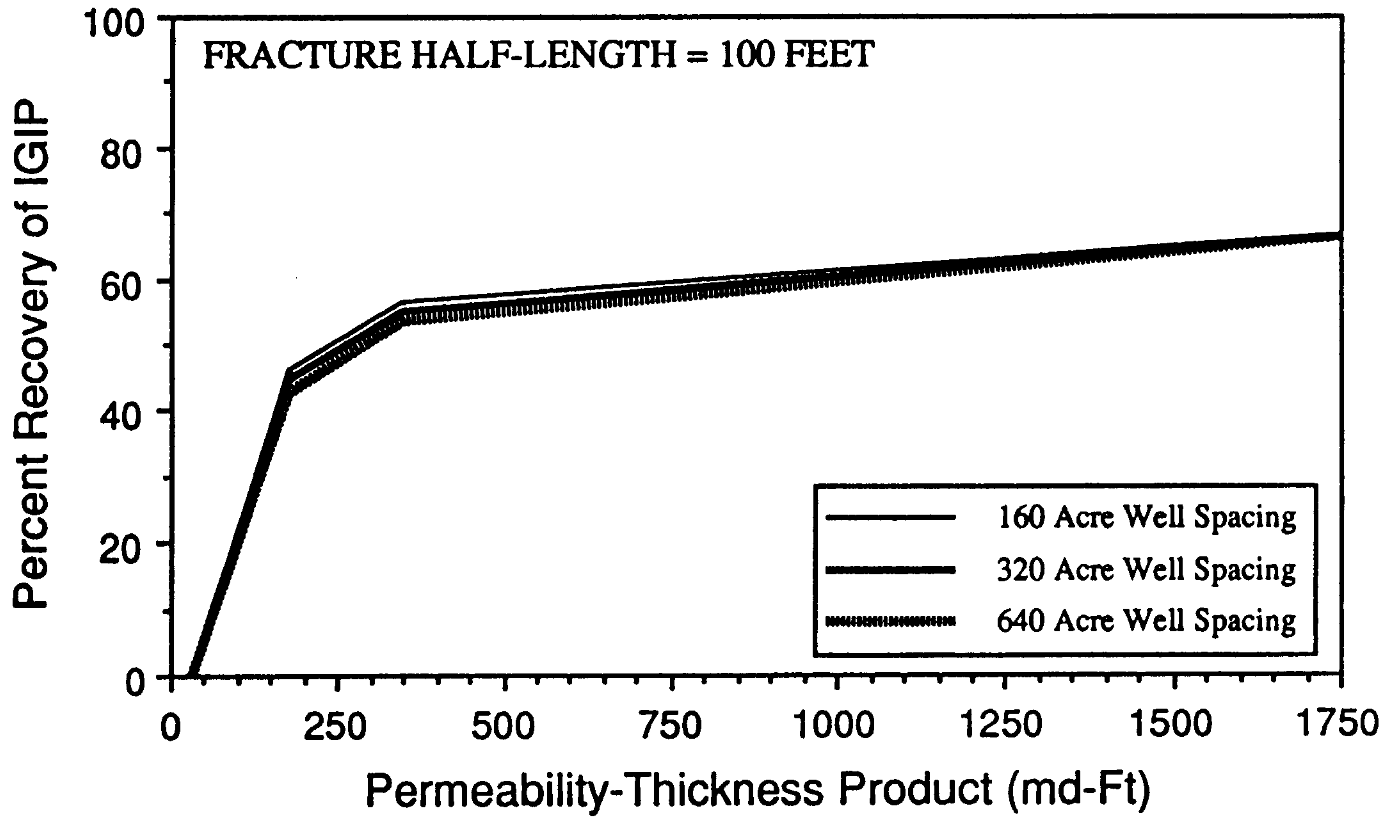
APPENDIX D

GAS RECOVERY VS. RESERVOIR kh FOR 50 MSCF/D ABANDONMENT RATE

Figure D-1

San Juan Basin Area 1
Gas Recovery vs kh

50 Mscf/d Abandonment Rate

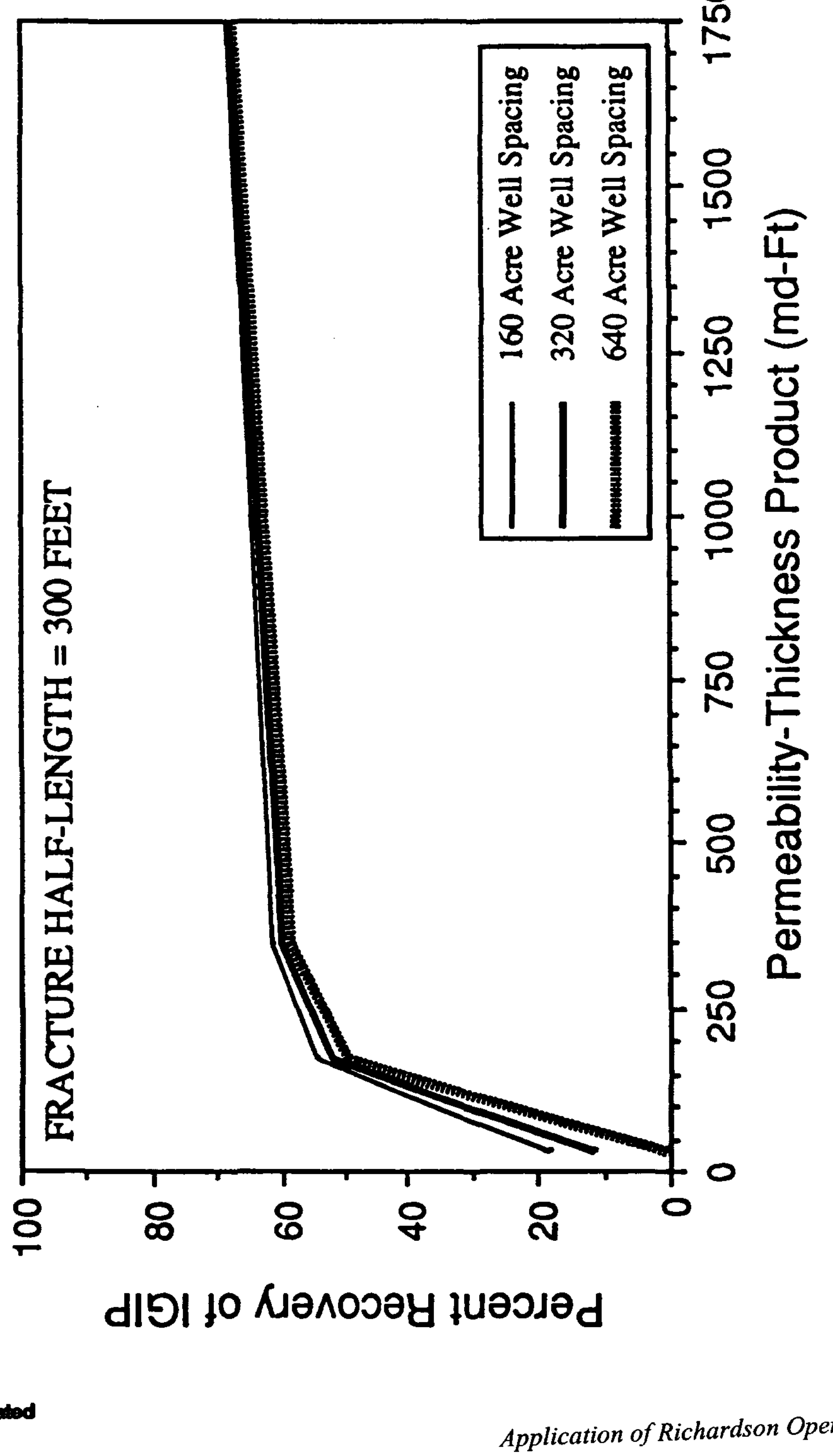


Application of Richardson Operating Co.
Record on Appeal, 1665.

Figure D-2

San Juan Basin Area 1
Gas Recovery vs kh

50 Mscf/d Abandonment Rate

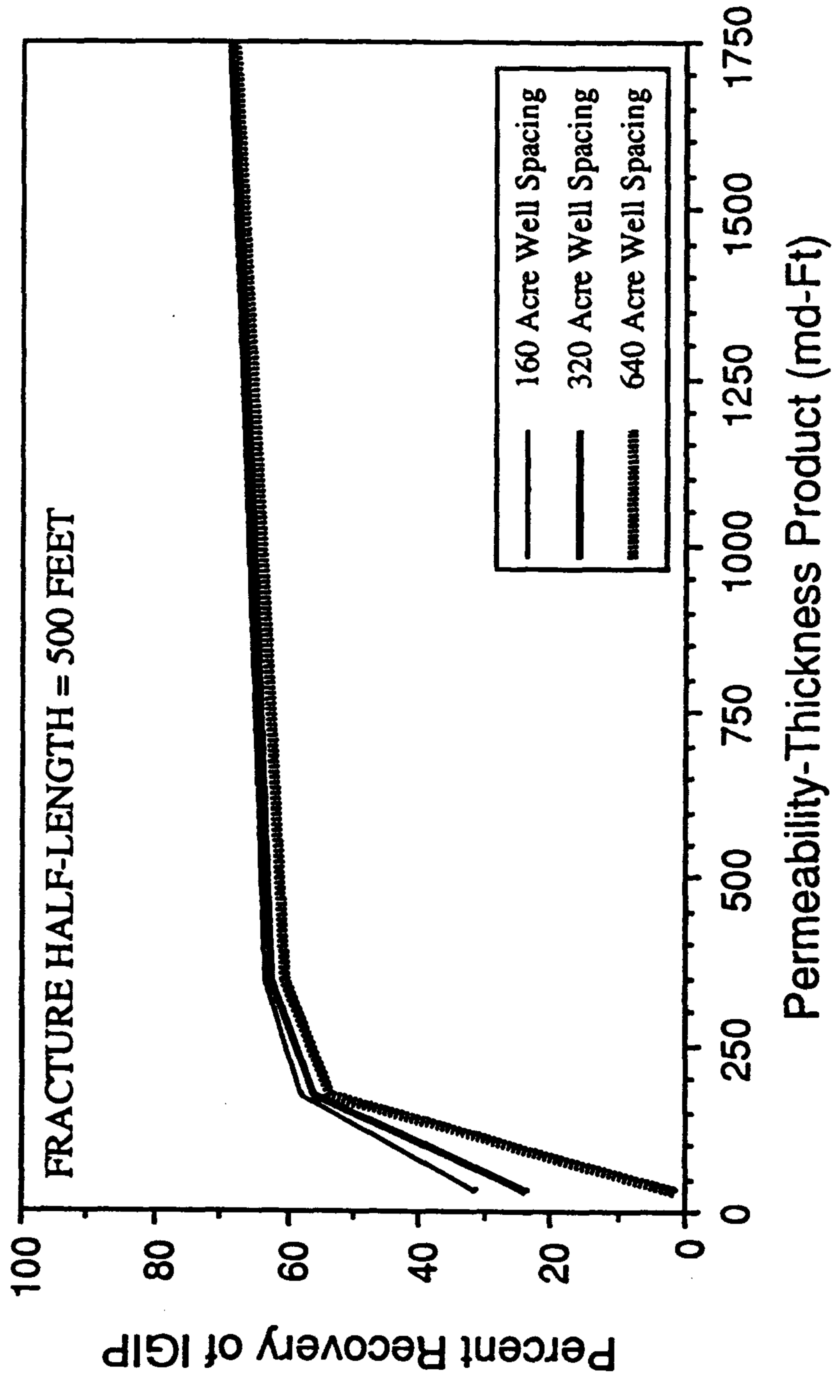


Application of Richardson Operating Co.
Record on Appeal, 1666.

Figure D-3

San Juan Basin Area 1
Gas Recovery vs kh

50 Mscf/d Abandonment Rate



Application of Richardson Operating Co.
Record on Appeal, 1667.