DOE/BETC/RI-80/8
80/8

MULTIPLE-WELL TESTING IN LOW PERMEABILITY GAS SANDS

By

Harold Bixel
Intercomp Resource Development and Engineering, Inc.

and

Herbert B. Carroll, Jr. and Alex Crawley
Bartlesville Energy Technology Center

Date Published—October 1980

Bartlesville Energy Technology Center
U.S. Department of Energy
Bartlesville, Oklahoma

ABSTRACT

The purpose of this work was to determine the effect of various reservoir and well parameters in order to design a multiple-well pressure transient test to be conducted in low permeability gas reservoirs. The parameters investigated were formation permeability, porosity, gas saturation, net pay thickness and well spacing. Long test times were found to be required for interference or pulse testing in low permeability gas reservoirs; however, the well spacing has been optimized. These calculations were made using two techniques: interference testing and pulse testing.

TABLE OF CONTENTS

	Page
Introduction	1
Theoretical considerations	3
Pressure response and time lag in low permeability gas reservoirs	8
Example calculation	9
Effect of reservoir properties upon pulse test response	14
Gas permeability	14
Porosity	14
Gas saturation	14
Well spacing	23
Pulse length	23
Conclusions	23
References	25

TABLES

1.	Base case	15
2.	Effect of permeability	16
3.	Effect of porosity	17
4.	Effect of gas saturation	18

ILLUSTRATIONS

Fig. No.		
1.	Active and observation wells in a multiple-well test	2
2.	Illustration of pulse test response at the observation well	4
3.	Pulse-testing: Relation between time lag and pulse cycle length	5
4.	Pulse-testing: Relation among pulse response amplitude, time lag and pulse cycle length	6
5.	Real gas deviation factor	10
6.	Gas viscosity	11
7.	Base case, r = 100 ft	13
8.	Base case, r = 400 ft	19
9.	Base case, r = 400 ft	20
10.	Effect of permeability	21
11.	Effect of porosity	22
12.	Effect of gas saturation	24

MULTIPLE-WELL TESTING IN LOW PERMEABILITY GAS SANDS

by

Harold Bixel[1/] and Herbert B. Carroll[2/]

INTRODUCTION

A multiple-well test involves a minimum of two wells as shown in figure 1. One well is active, that is, producing or injecting; and the other well (or wells) is used as a pressure observation point. The flow rate at the active well is varied, and the resulting pressure change in the reservoir is measured at the observation well. The observation well is generally shut-in several days before the test and remains shut-in during the test. From the pressure response at the observation well, we can estimate formation transmissibility, kh/μ, and formation storage, $\phi c_t h$.

There are two types of multiple-well tests. One is called an interference test. An interference test is conducted by changing the rate at the active well and measuring the resulting change in bottom hole pressure at the observation well. Prior to the test, the active well may have been producing or injecting. In this case, it is shut-in for the test. If the active well was shut-in prior to the test, it is put on production or injection at a constant rate for the test.

An interference test involves only one rate change at the active well. As a result, there is no unique characteristic to the pressure response at the observation well. This can be confusing if there is a general pressure trend in the reservoir due to the production or injection at other wells completed in the same reservoir. This disadvantage can be overcome by conducting a pulse test.

Pulse-testing is a specialized form of multiple-well testing first described by Johnson, Greenkorn and Woods (1,2,3)[3/]. The technique uses a series of flow-rate pulses at the active well. These pulses generally consist of alternate periods of production (or injection) and shut-in. The flow rate is the same during each flow period. The resulting pressure response is measured at the observation well.

1/ Harold Bixel, INTERCOMP, Denver, Colorado
2/ Herbert B. Carroll, Chief, Production Branch, BETC
3/ Underlined numbers in parentheses refer to references listed at the end of this report.

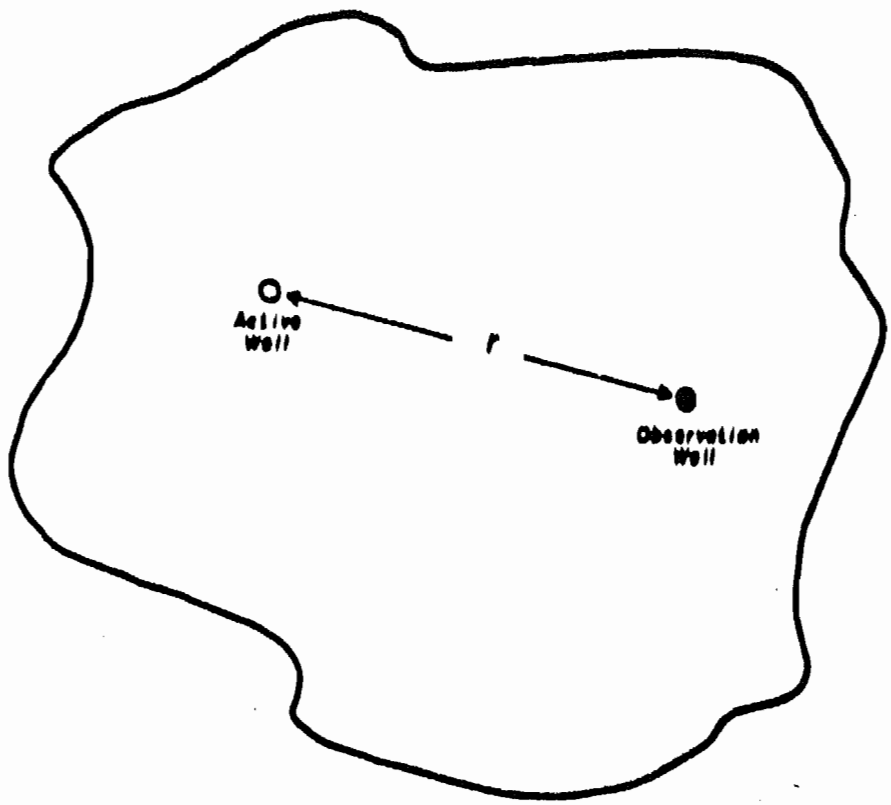

Figure 1 Active and Observation Wells in a Multiple-Well Test

The purpose of this work was to determine the effect of various reservoir and well parameters in order to design a multiple-well pressure transient test to be conducted in low permeability gas reservoirs. The parameters investigated were formation permeability, porosity, gas saturation, net pay thickness and well spacing.

THEORETICAL CONSIDERATIONS

Figure 2 is a schematic representation of the pressure response at the observation well during pulse testing of a two-well system. The active well was assumed to be shut-in prior to the beginning of the test. It was then put on production at a constant rate for Δt_p hours. Then it was shut-in for Δt_p hours, then produced at the same constant rate for Δt_p hours, followed by a shut-in, etc. This pulsing of the production rate at the active well is shown on the lower portion of figure 2.

Two values measured from the pressure response at the observation well are used in analyzing pulse-test data. These are the time lag, t_L, and the pressure response amplitude, Δp. The time lag is the elapsed time between the beginning of a rate pulse and the beginning of the pressure response at the observation well due to that pulse. Time lags for the first, second and sixth rate pulses are shown on figure 2. They are labeled t_{L1}, t_{L2} and t_{L6}. The pressure response amplitude for the same pulses are labeled Δp_1, Δp_2, and Δp_6.

The pressure response is obtained by drawing the tangent line between two successive valleys or peaks of the pressure response curve and drawing a parallel line tangent to the peak or valley associated with that particular response. The pressure response amplitude is the vertical distance between the two lines. This is illustrated on figure 2. Δp_1 is the pressure response due to the first production period or first pulse. Δp_2 is the pressure response for the second pulse or first shut-in period. A Δp for each successive pulse is obtained in the same manner.

Bigham (4) gives a technique for analyzing the test data. The technique shown here assumes equal pulse length. He has also developed a technique for analyzing data from a test using unequal pulse lengths (5). His correlation for the equal pulse length case is given on figures 3 and 4. He correlated the ratio of time lag to pulse length, $t_L/\Delta t_p$ with the functions:

$$\left[(t_L)_D/r_D^2\right]_{\text{Fig. 3}}$$

and

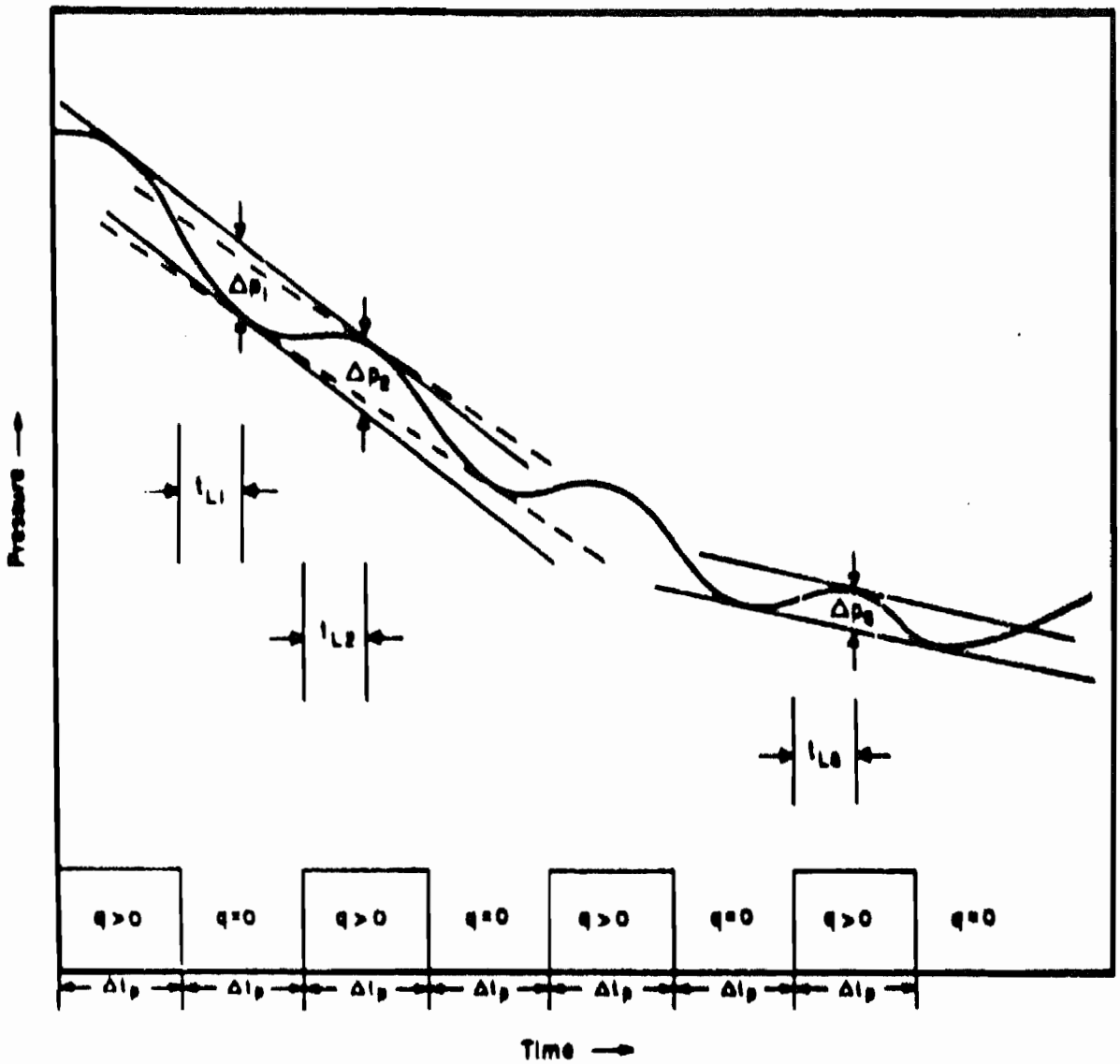

Figure 2 Illustration of Pulse Test Response at the Observation Well

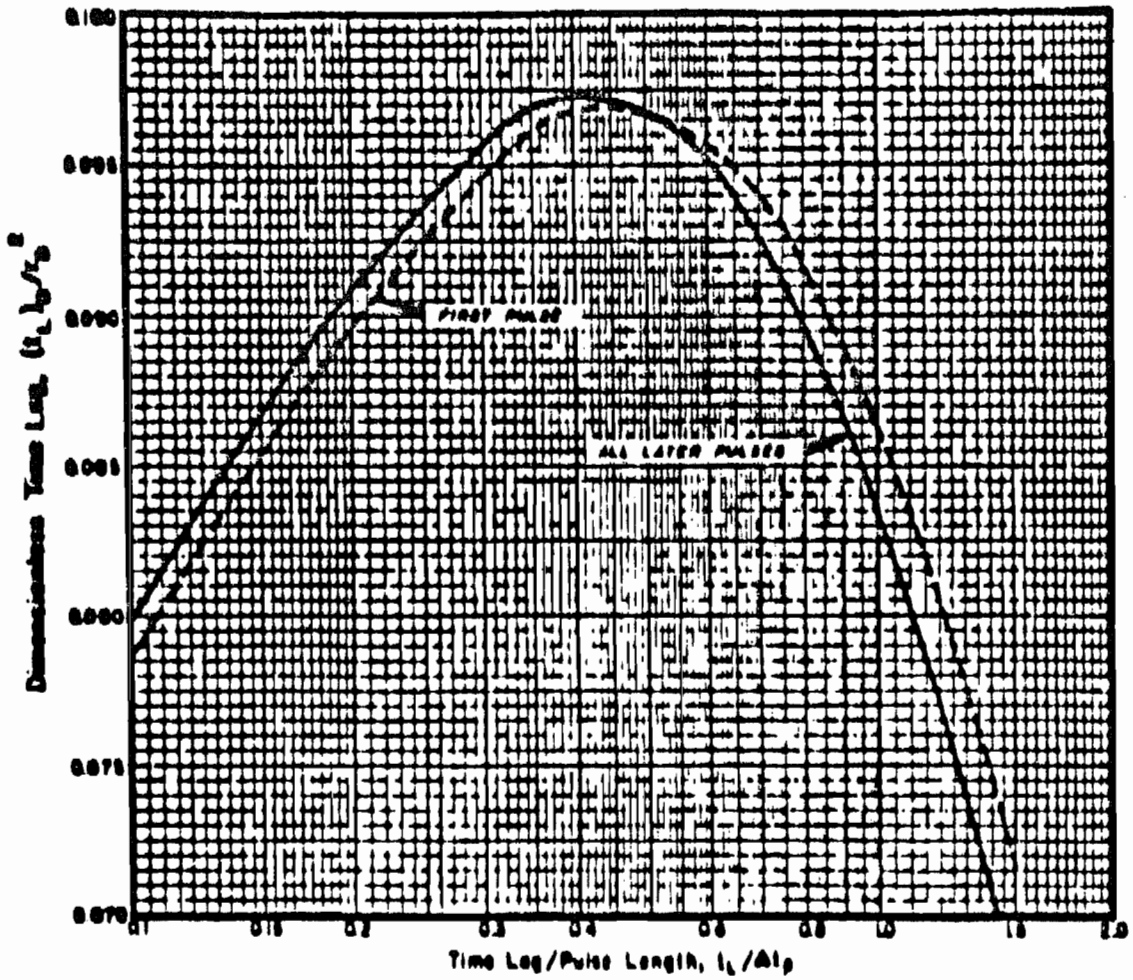

Figure 3 Pulse-Testing: Relation Between Time Lag and Pulse Cycle Length. Applies Only for Pulses of Equal Length. After Brigham (1).

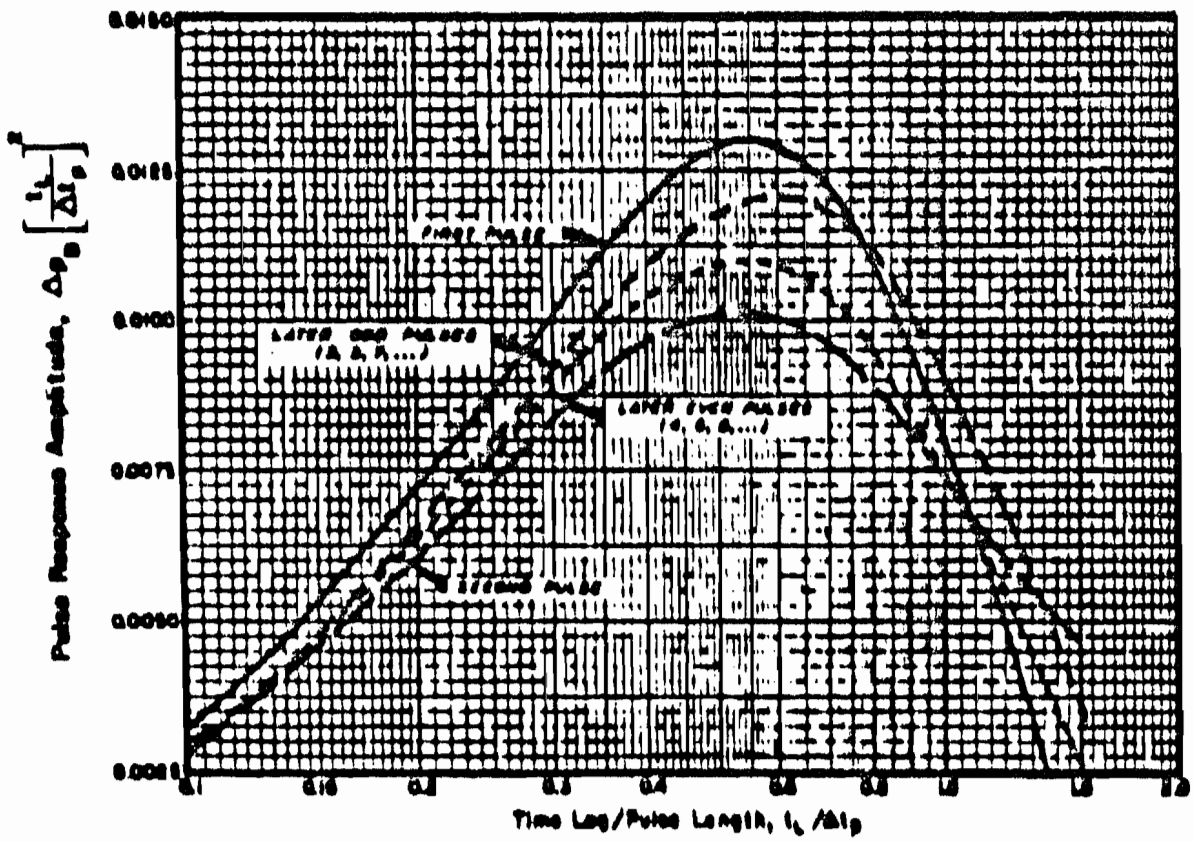

FIGURE 4. - Pulse-Testing: Relation Among Pulse Response Amplitude, Time Lag and Pulse Cycle Length. Applies Only for Pulses of Equal Length. After Brigham (4).

$$\left[\Delta p_D \left(\frac{t_L}{\Delta t_p}\right)^2\right]_{\text{Fig. 4}}$$

For a gas well, these functions are defined as:

$$\left[\frac{(t_L)_D}{r_D^2}\right]_{\text{Fig. 3}} = \frac{0.002637\ k_g t_L}{\phi(\mu c_t)_i\ r^2} \tag{1}$$

and

$$\left[\Delta p_D \left(\frac{t_L}{\Delta t_p}\right)^2\right]_{\text{Fig. 4}} = \frac{k_g h\ \Delta m(p) \left(\frac{t_L}{\Delta t_p}\right)^2}{1422 q T} \tag{2}$$

where

k_g	=	gas permeability, md
t_L	=	time lag, hours
Δt_p	=	pulse length, hours
ϕ	=	porosity, fraction
h	=	producing interval, ft
q	=	production rate, MSCF/D
r	=	distance between active and observation wells, ft
T	=	reservoir temperature, ^{o}R
$(\mu)_i$	=	gas viscosity at reservoir pressure and temperature, cp
$(c_t)_i$	=	total compressibility at reservoir pressure and temperature, psi^{-1}
$\Delta m(p)$	=	pressure response amplitude in terms of the real gas potential (6), $psia^2/cp$

For a gas reservoir, $(c_t)_i$ is defined by

$$(c_t)_i = S_g(c_g)_i + S_w c_w + c_f = S_g\left[(c_g)_i - c_w\right] + c_w + c_f \qquad (3)$$

where

S_g = gas saturation, fraction

S_w = water saturation, fraction

$(c_g)_i$ = gas compressibility measured at initial reservoir pressure and temperature, psi^{-1}

c_w = water compressibility, psi^{-1}

c_f = rock pore-volume compressibility, psi^{-1}

PRESSURE RESPONSE AND TIME LAG IN LOW PERMEABILITY GAS RESERVOIRS

Equations 1, 2 and 3 together with figures 3 and 4 can be used to estimate pulse-test performance. Solving equation 1 for t_L and equation 2 for $\Delta m(p)$ gives:

$$t_L = \frac{\phi(\mu c_t)_i\, r^2 \left[(t_L)_D/r_D^2\right]_{\text{Fig. 3}}}{0.0002637\, k_g} \qquad (4)$$

and

$$\Delta m(p) = \frac{1422qT\left[\Delta p_D(t_L/\Delta t_p)^2\right]_{\text{Fig. 4}}}{k_g h(t_L/\Delta t_p)^2} \qquad (5)$$

t_L and $\Delta m(p)$ are estimated from these equations for various values of $t_L/\Delta t_p$ using estimates of the necessary reservoir and fluid properties. Then knowing the relationship between pressure and $m(p)$, Δp can be calculated.

Example Calculation

Assume that

k_g = 0.1 md

ϕ = 0.1

S_g = 0.5

r = 100 ft

h = 50 ft

Gas gravity = 0.65

Reservoir Temperature = 180° F

Initital Reservoir Pressure, p_i = 3514.7 psia

Figure 6 is a plot of gas viscosity versus pressure for a gas gravity of 0.65 and temperature of 180° F. The viscosity at 3514.7 psia is:

μ = 0.0224 cp

Gas compressibility is estimated using figure 5 and

$$c_g = \frac{1}{p} - \frac{1}{z}\frac{\partial z}{\partial p}$$

or $(c_g)_i = 2.28 \times 10^{-4}$ psi^{-1} @ 3514.7 psia. Water and rock pore-volume compressibilities are estimated from figures D.16 and D.10 of reference 7.

$$c_w = 3 \times 10^{-6} \text{ psi}^{-1}$$

and $$c_f = 5 \times 10^{-6} \text{ psi}^{-1}$$

From equation 3,

$$(c_t)_i = 0.5(2.28 \times 10^{-4}) + 0.5(3 \times 10^{-6}) + 5 \times 10^{-6}$$

$$= 1.21 \times 10^{-4} \text{ psi}^{-1}$$

If we assume $t_L/\Delta t_p = 0.55$, we get for the first pulse:

$(t_L)_D/r_D^2 = 0.0963$ from figure 3 and

$\Delta p_D(t_L/\Delta t_p)^2 = 0.013$ from figure 4.

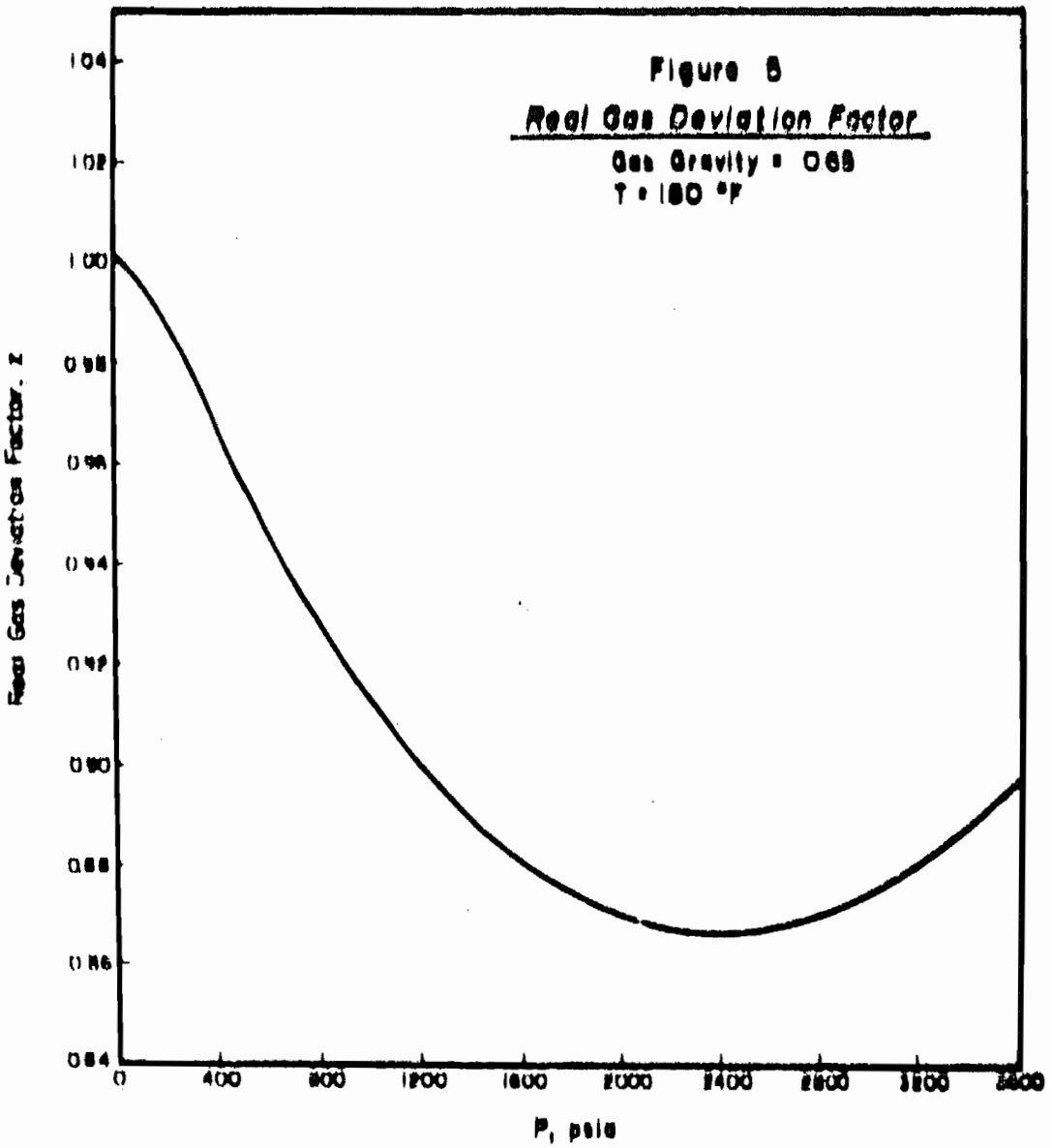
Figure 5
Real Gas Deviation Factor
Gas Gravity = 0.65
T = 180 °F
Real Gas Deviation Factor, z
1.04
1.02
1.00
0.98
0.96
0.94
0.92
0.90
0.88
0.86
0.84
0
400
800
1200
1600
2000
2400
2800
3200
3600
P, psia

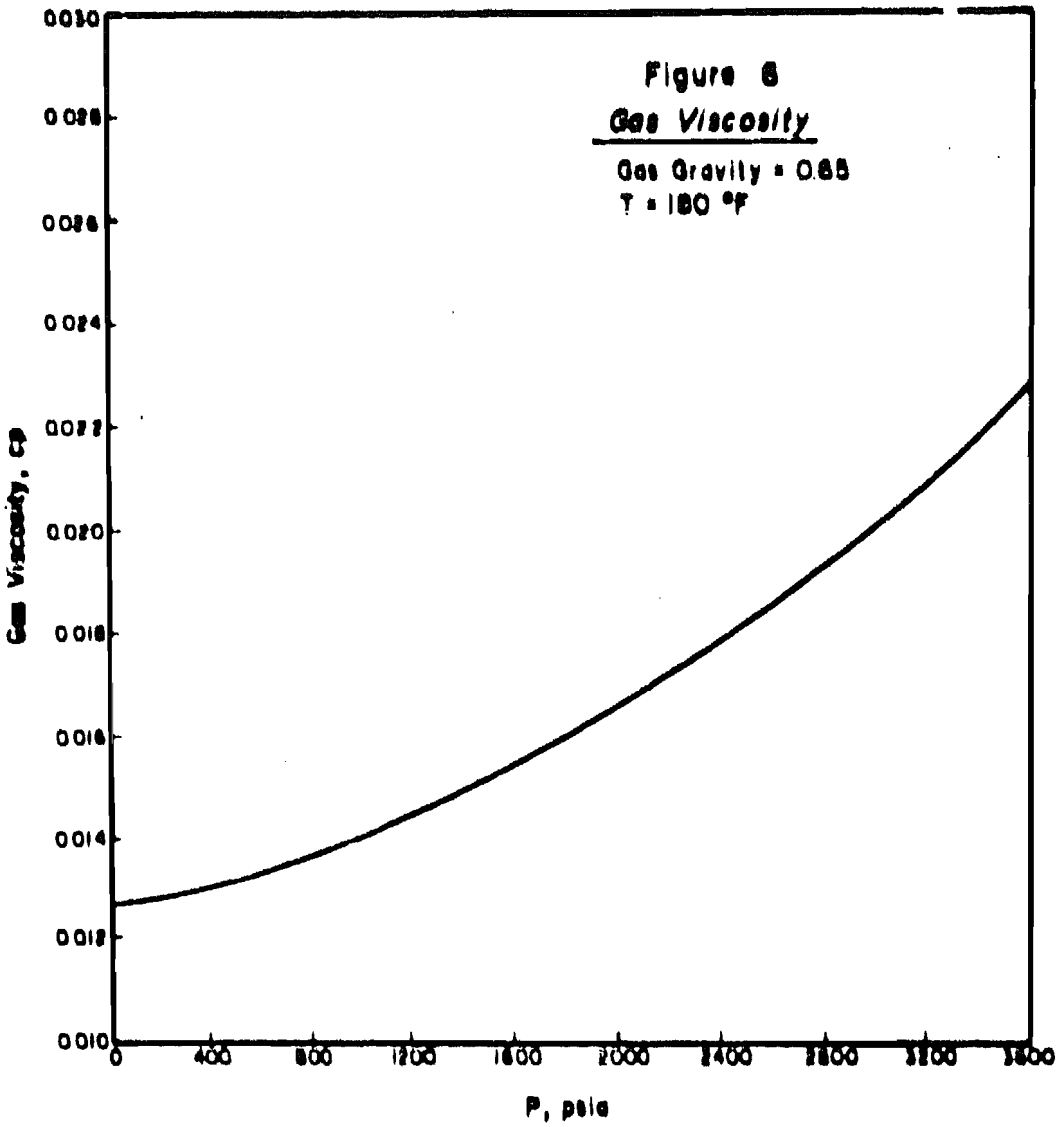
Figure 6
Gas Viscosity
Gas Gravity = 0.65
T = 180 °F
Gas Viscosity, cp
0.030
0.028
0.026
0.024
0.022
0.020
0.018
0.016
0.014
0.012
0.010
0
400
800
1200
1600
2000
2400
2800
3200
3600
P, psia

Substituting in equation 4 gives:

$$t_L = \frac{(0.1)(0.0224)(1.21 \times 10^{-4})(100)^2(0.0963)}{0.0002637(0.1)} = 9.9 \text{ hours}$$

and since $t_L/\Delta t_p = 0.55$,

$$\Delta t_p = 9.9/0.55 = 18 \text{ hours}$$

From equation 5,

$$\Delta m(p) = \frac{1422(640)(0.013)}{(0.1)(50)(0.55)^2} q = 7.822 \times 10^3 q$$

We estimate this well is capable of producing 550 MSCF/D at a flowing bottom hole pressure of 600 psia.

$$\Delta m(p) = 7.822 \times 10^3(550) = 4.302 \times 10^6 \text{ psia}^2/\text{cp}$$

From the data given on figures 5 and 6, we can calculate that:

$$\Delta p = 2.816 \times 10^{-6} \Delta m(p)$$

or $\Delta p = 12.1$ psi

These calculations show that if the well was alternately produced at 550 MSCF/D for 18 hours and shut-in for 18 hours, the amplitude of the first pressure pulse seen in an observation well located 100 ft from the producer would be 12.1 psi. The lag time for the pulse is 9.9 hours. The same procedure is followed if later pulses are to be considered.

The entire test was simulated using a computer model based on the superposition principle. The pressures measured at the observation well are plotted on figure 7. The computer simulation gives a lag time, t_L, of 9.5 hours and a Δp of 12.6 psi. This is good agreement with the values obtained using figures 3 and 4 together with equations 4 and 5.

The first 18 hours of the test of figure 7 is an interference test and can be analyzed using techniques described in reference 7. Pressure interference at the observation well is measurable approximately 4 hours after the active well is put on production. The total drawdown at the observation well is 15.7 psi at the end of the first 18-hour flow period.

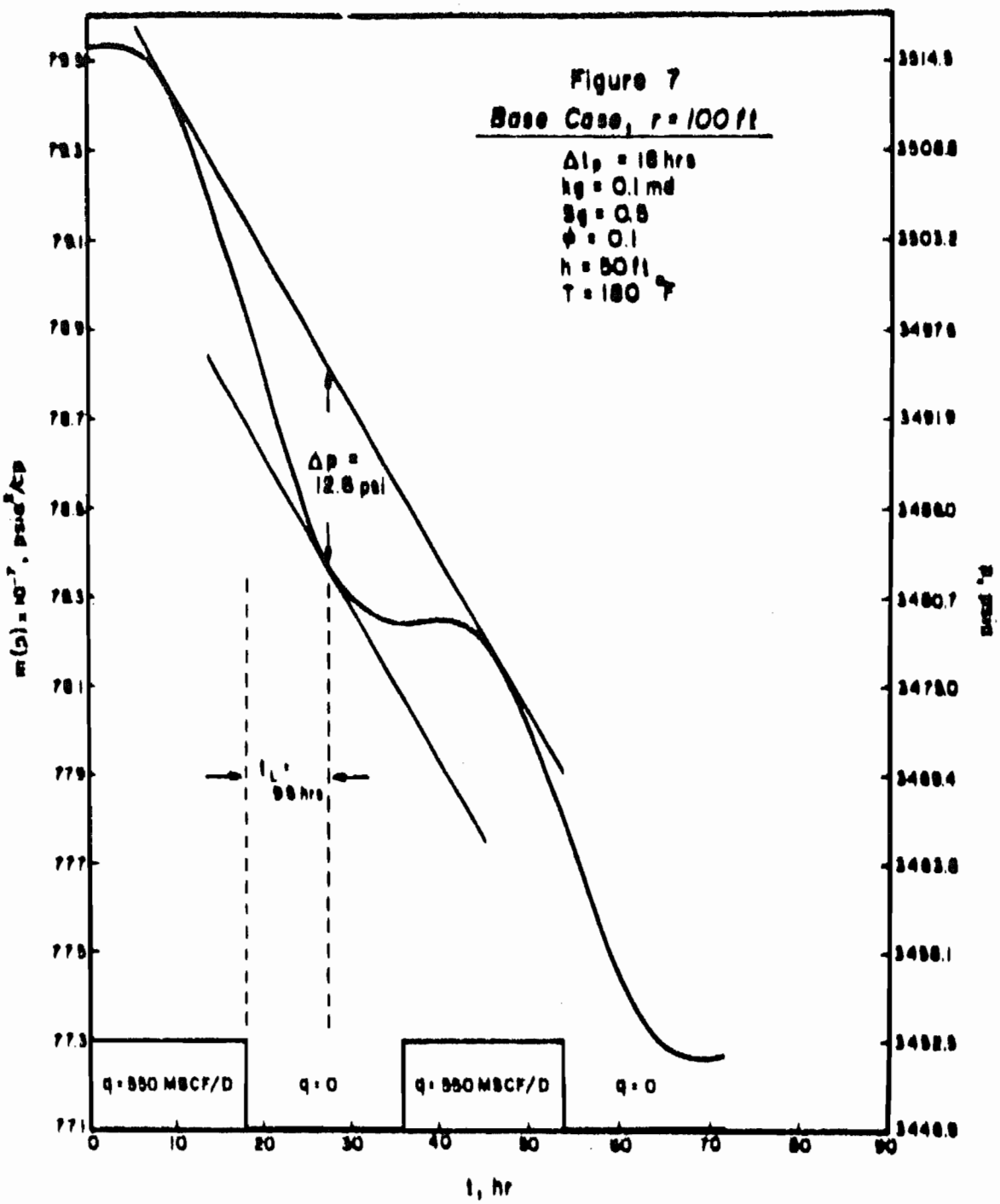
Figure 7
Base Case, r = 100 ft
Δt_p = 18 hrs
k_g = 0.1 md
S_g = 0.5
φ = 0.1
h = 50 ft
T = 180 °F
Δp = 12.6 psi
t_L = 9.9 hrs
q = 550 MSCF/D
q = 0
q = 550 MSCF/D
q = 0
t, hr

EFFECT OF RESERVOIR PROPERTIES UPON PULSE TEST RESPONSE

Equations 4 and 5 together with figures 1 and 4 were used to calculate the effect various reservoir parameters have upon pulse test response. The results are given in tables 1 through 4. These results are based on an initial reservoir pressure of 3,500 psig.

Table 1 is the base case against which the results shown in the other tables are compared. The reservoir variable used in preparing table 1 are for the most optimistic case. The tables give lag time, pulse time and response amplitude for several values of $t_L/\Delta t_p$ and well spacings of 100, 200 and 400 ft. Figures 7, 8 and 9 show simulator results for well spacing of 100 and 400 ft and different pulse lengths.

Gas Permeability

Table 2 shows the effect of changing permeability from 0.1 md to 0.01 md. The other reservoir parameters were held constant. We assumed the well's production rate was proportional to kh in preparing table 2.

Permeability to gas appears in the denominator of both equations 4 and 5. This means lag time is inversely proportional to k_g. Reducing k_g from 0.1 md to 0.01 md causes t_L and Δt_p to be 10 times the values shown in table 1.

$\Delta m(p)$ is also inversely proportional to k_g, but we assumed q was proportional to kh. The causes the ratio $q/k_g h$ to remain constant, and the values of Δp in table 2 are the same as those in table 1.

Figure 10 shows the simulator results for $t_L/\Delta t_p$ of 0.55 and r of 100 ft. The results are similar to figure 7. The time scale has been expanded by a factor of 10.

Porosity

Porosity appears only in the numerator of equation 4. This means that time lag is directly proportional to ϕ. The results of changing porosity from 0.1 to 0.05 are given in table 3. The values for t_L and Δt_p in table 1 are reduced by a factor of 2 in table 3.

The results of a simulated pulse test with ϕ equal to 0.05 are shown on figure 11.

Gas Saturation

The effect of gas saturation is reflected in the total compressibility, $(c_t)_i$, in equation 4. An increase in $(c_t)_i$ causes t_L and Δt_p to increase, and a decrease in $(c_t)_i$ causes a corresponding decrease in these two terms.

TABLE 1

BASE CASE

k_g = 0.1 md

ϕ = 0.1

S_g = 0.50

h = 50 ft.

T = 180°F.

q = 550 MSCF/D

p_i = 3500 psig

Gas gravity = 0.65

	r=100 ft			r=200 ft			r=400 ft		
$t_L/\Delta t_p$	t_L, hr	Δt_p, hr	Δp, psi	t_L, hr	Δt_p, hr	Δp, psi	t_L, hr	Δt_p, hr	Δp, psi
0.20	9.1	45.5	50.7	36.4	182.0	50.7	145.6	728.0	50.7
0.40	10.0	25.0	21.1	40.0	100.0	21.1	160.0	400.0	21.1
0.55	9.9	18.0	12.1	39.6	72.0	12.1	158.4	288.0	12.1
0.60	9.8	16.3	10.1	39.2	65.2	10.1	156.8	260.8	10.1
0.80	9.4	11.8	4.8	37.6	47.2	4.8	150.4	188.0	4.8
1.00	8.8	8.8	2.3	35.2	35.2	2.3	140.8	140.8	2.3
1.35	7.4	5.5	0.4	29.6	22.0	0.4	118.4	87.7	0.4

TABLE 2

EFFECT OF PERMEABILITY

k_g = 0.01 md

ϕ = 0.1

S_g = 0.50

h = 50 ft

T = 190°F

q = 55 MSCF/D

p_i = 3500 psig

Gas gravity = 0.65

	r=100 ft			r=200 ft			r=400 ft		
$t_L/\Delta t_p$	t_L, hr	Δt_p, hr	Δp, psi	t_L, hr	Δt_p, hr	Δp, psi	t_L, hr	Δt_p, hr	Δp, psi
0.20	91.1	455.5	50.7	364.4	1822.0	50.7	1457.6	7288.0	50.7
0.40	100.0	250.0	21.1	400.0	1000.0	21.1	1600.0	4000.0	21.1
0.55	99.0	180.0	12.1	396.0	720.0	12.1	1584.0	2880.0	12.1
0.60	98.4	164.0	10.1	393.6	656.0	10.1	1574.4	2624.0	10.1
0.80	94.2	117.8	4.8	376.8	471.0	4.8	1884.0	2355.0	4.8
1.00	88.5	88.5	2.3	354.0	354.0	2.3	1416.0	1416.0	2.3
1.35	73.0	54.7	0.4	295.6	219.0	0.4	1182.4	875.9	0.4

TABLE 3

EFFECT OF POROSITY

k_g = 0.1 md

ϕ = 0.05

S_g = 0.50

h = 50 ft.

T = 180°F.

q = 550 MSCF/D

p_i = 3500 psia

Gas gravity = 0.65

	r=100 ft			r=200 ft			r=400 ft		
$t_L/\Delta t_p$	t_L, hr	Δt_p, hr	Δp, psi	t_L, hr	Δt_p, hr	Δp, psi	t_L, hr	Δt_p, hr	Δp, psi
0.20	4.6	23.0	50.7	18.4	92.0	50.7	73.6	368.0	50.7
0.40	5.0	12.5	21.1	20.0	50.0	21.1	80.0	200.0	21.1
0.55	4.9	8.9	12.1	19.6	35.6	12.1	78.4	142.5	12.1
0.60	4.9	8.2	10.1	19.6	32.7	10.1	78.4	130.7	10.1
0.80	4.7	5.9	4.8	18.8	23.5	4.8	75.2	94.0	4.8
1.00	4.4	4.4	2.3	17.6	17.6	2.3	70.4	70.4	2.3
1.35	3.7	2.7	0.4	14.8	11.0	0.4	44.0	32.6	0.4

TABLE 4

EFFECT OF GAS SATURATION

k_g = 0.1

ϕ = 0.1

S_g = 0.25

h = 50 ft

T = 180°F.

q = 550 MSCF/D

p_i = 3500 psig

Gas gravity = 0.65

	r=100 ft			r=200 ft			r=400 ft		
$t_L/\Delta t_p$	t_L, hr	Δt_p, hr	Δp, psi	t_L, hr	Δt_p, hr	Δp, psi	t_L, hr	Δt_p, hr	Δp, psi
0.20	4.8	24.0	50.7	19.2	96.0	50.7	76.8	384.0	50.7
0.40	5.3	13.2	21.1	21.2	53.0	21.1	84.8	212.0	21.1
0.55	5.3	9.6	12.1	21.2	38.5	12.1	84.8	154.2	12.1
0.60	5.2	8.7	10.1	20.8	34.7	10.1	83.2	138.7	10.1
0.80	5.0	6.3	4.8	20.0	25.0	4.8	80.0	100.0	4.8
1.00	4.7	4.7	2.3	18.8	18.8	2.3	75.2	75.2	2.3
1.35	3.9	2.9	0.4	15.6	11.6	0.4	62.4	46.2	0.4

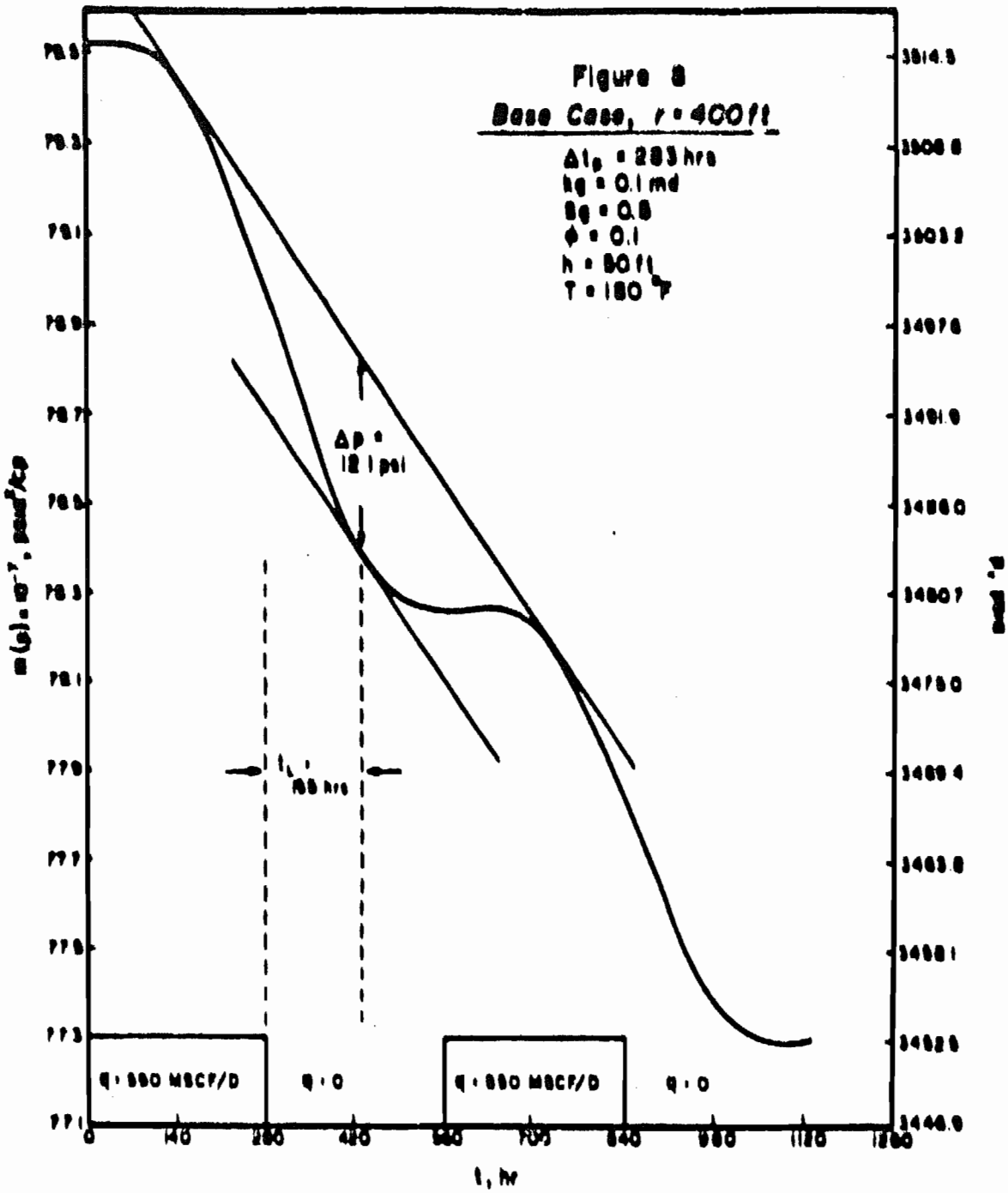
Figure 8
Base Case, r = 400 ft
Δt_p = 283 hrs
kg = 0.1 md
Sg = 0.8
φ = 0.1
h = 50 ft
T = 180 °F
Δp = 12.1 psi
t_L = 165 hrs
q = 550 MSCF/D
q = 0
q = 550 MSCF/D
q = 0
t, hr

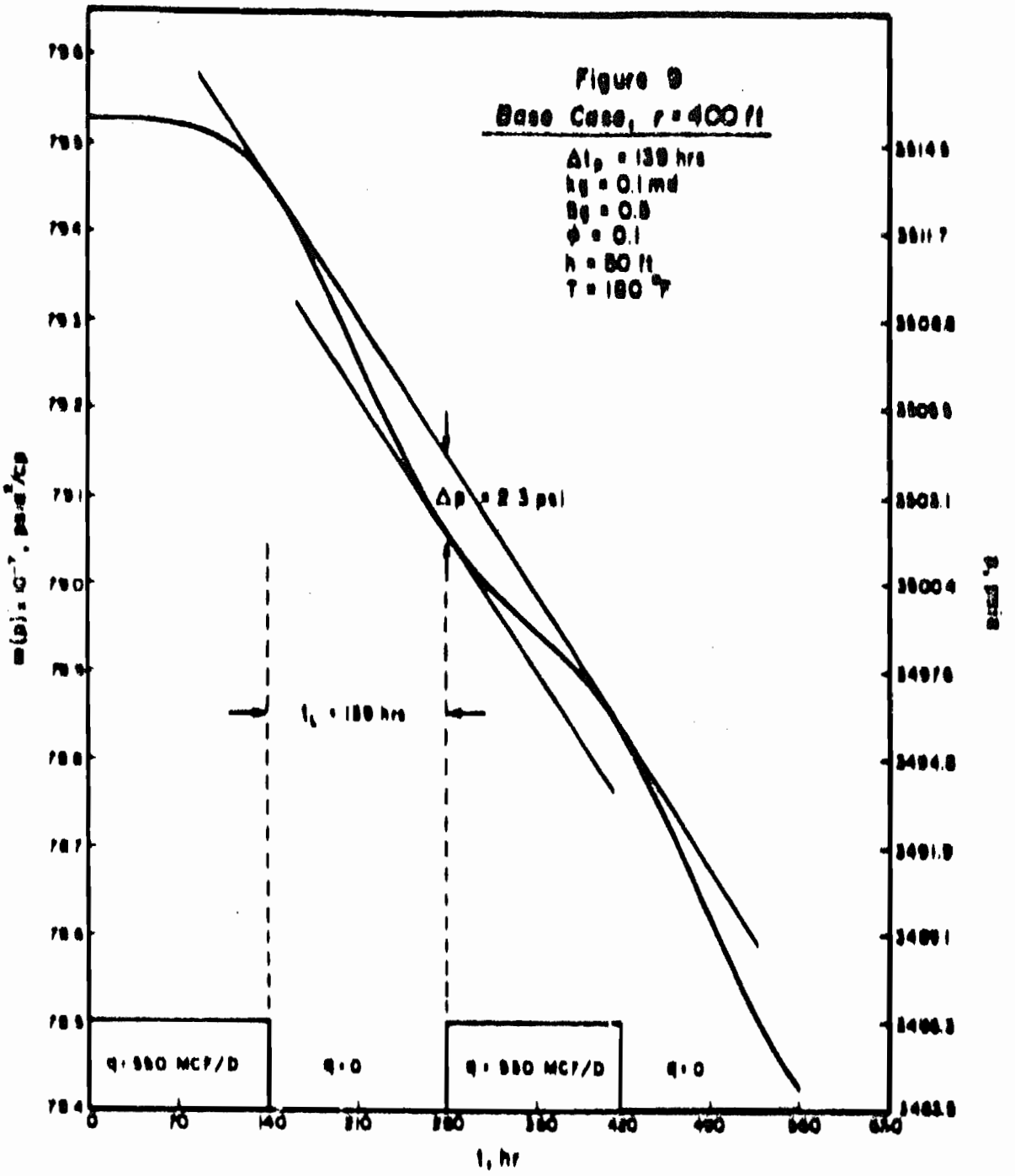
Figure 9
Base Case, r = 400 ft
Δt_p = 139 hrs
kg = 0.1 md
Sg = 0.5
φ = 0.1
h = 50 ft
T = 180 °F
Δp = 2.3 psi
t_s = 139 hrs
q = 550 MCF/D
q = 0
q = 550 MCF/D
q = 0
t, hr

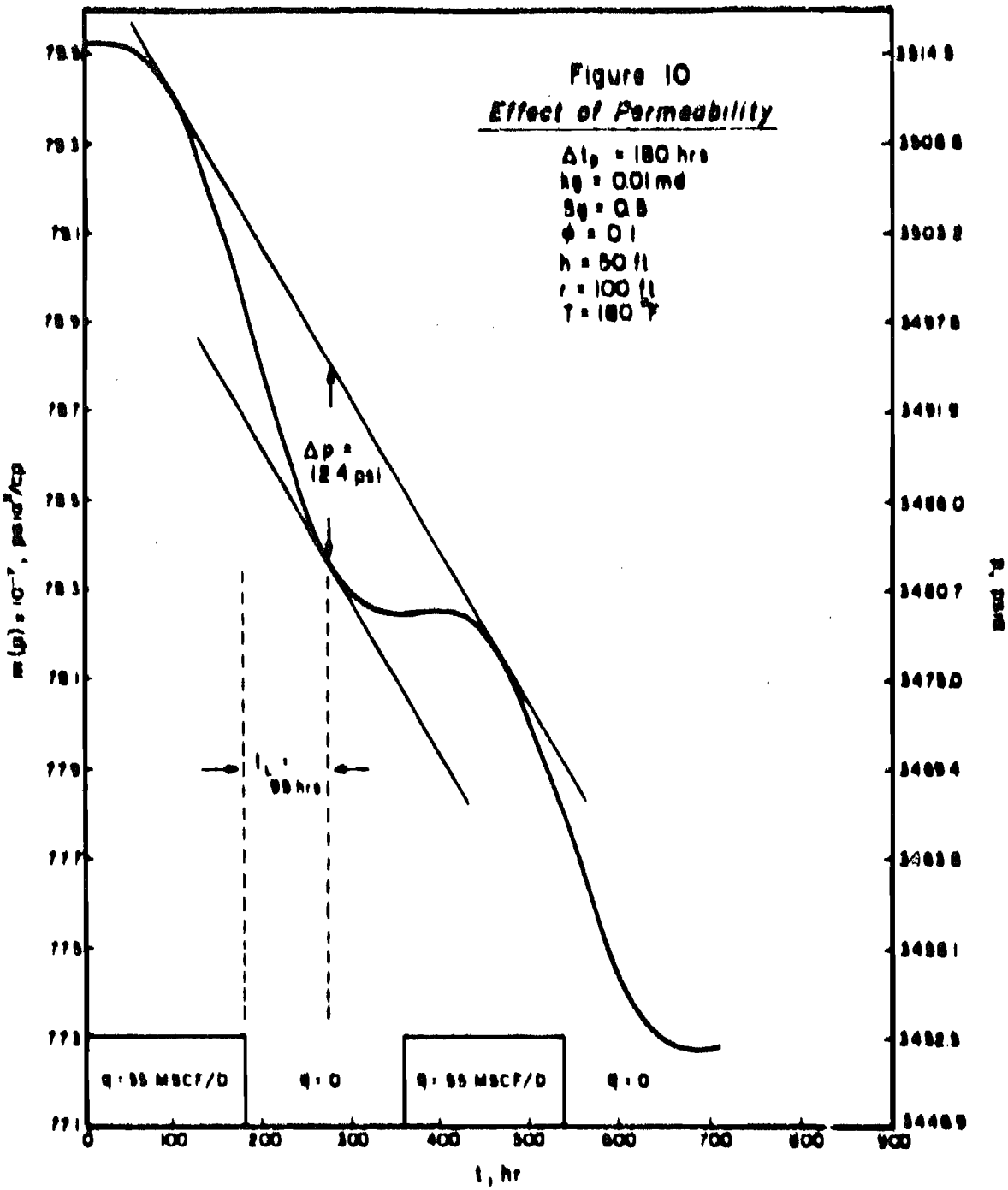
Figure 10
Effect of Permeability
Δt_p = 180 hrs
k_g = 0.01 md
S_g = 0.5
φ = 0.1
h = 50 ft
r = 100 ft
T = 180 °F
Δp = 12.4 psi
t_L = 95 hrs
q = 95 MSCF/D
q = 0
q = 95 MSCF/D
q = 0
t, hr
0
100
200
300
400
500
600
700
800
900

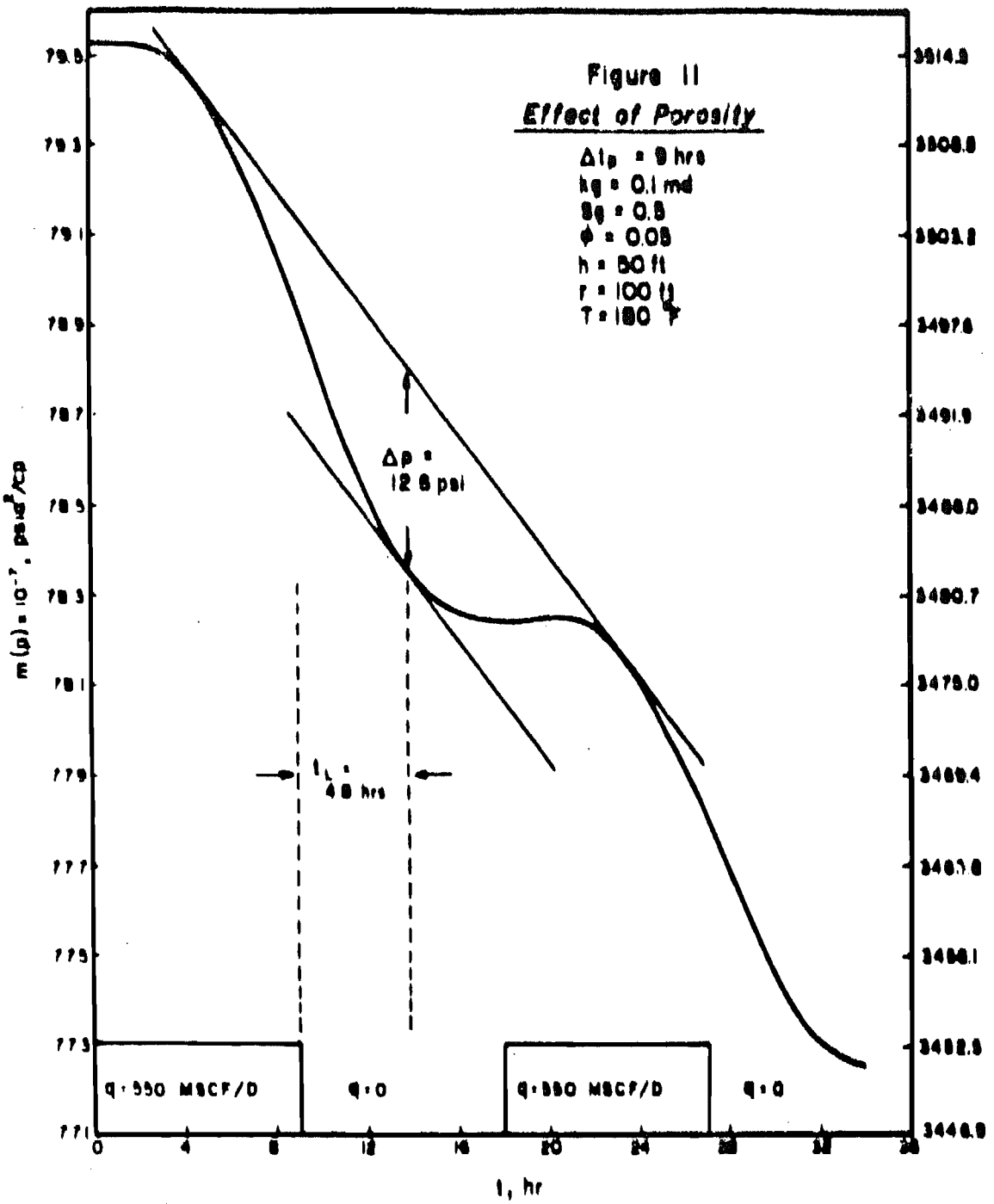
Figure 11
Effect of Porosity
Δt_p = 9 hrs
k_g = 0.1 md
S_g = 0.5
φ = 0.05
h = 50 ft
r = 100 ft
T = 180 °F
Δp = 12.8 psi
t_L = 4.8 hrs
q = 550 MSCF/D
q = 0
q = 550 MSCF/D
q = 0
m(p) = 10^-7, psia²/cp
t, hr

The value used for $(c_t)_i$ is calculated using equation 3. This shows that decreasing S_g causes a reduction in $(c_t)_i$. This causes a reduction in t_L and t_p. This is shown in table 4 for a gas saturation of 0.25.

The simulated response for one of the cases in table 4 is shown on figure 12.

Well Spacing

Equation 4 shows t_L to be directly proportional to the square of the distance between the active well and the observation well. Increasing the well spacing from 100 ft to 400 ft causes t_L and t_p to increase by a factor of 16. This is shown in the tables and on figure 8.

Pulse Length

The size of the pressure response is strongly influenced by the pulse length, t_p. This can be seen from the tables. Small pulse length means a small t_p. For this reason, the type of pressure recording device used in the observation well sets the pulse length. A highly sensitive pressure gauge will allow short pulse lengths.

CONCLUSIONS

1. Long test times are required for interference or pulse testing in low permeability gas reservoirs.

2. Test time is inversely proportional to reservoir permeability. For the same pressure response, it takes 10 times as long to test an 0.01 md reservoir as it does to test one of 0.1 md.

3. Test time is directly proportional to the square of the well spacing. It takes 16 times longer to test on 400-ft well spacing than it does on 100-ft spacing.

4. Test time is directly proportional to porosity. Reducing porosity from 0.1 to 0.05 cuts the testing time in half.

5. Test time is independent of formation thickness. Net pay thickness affects the magnitude of the pressure response at the observation well.

6. Low gas saturation reduces testing time.

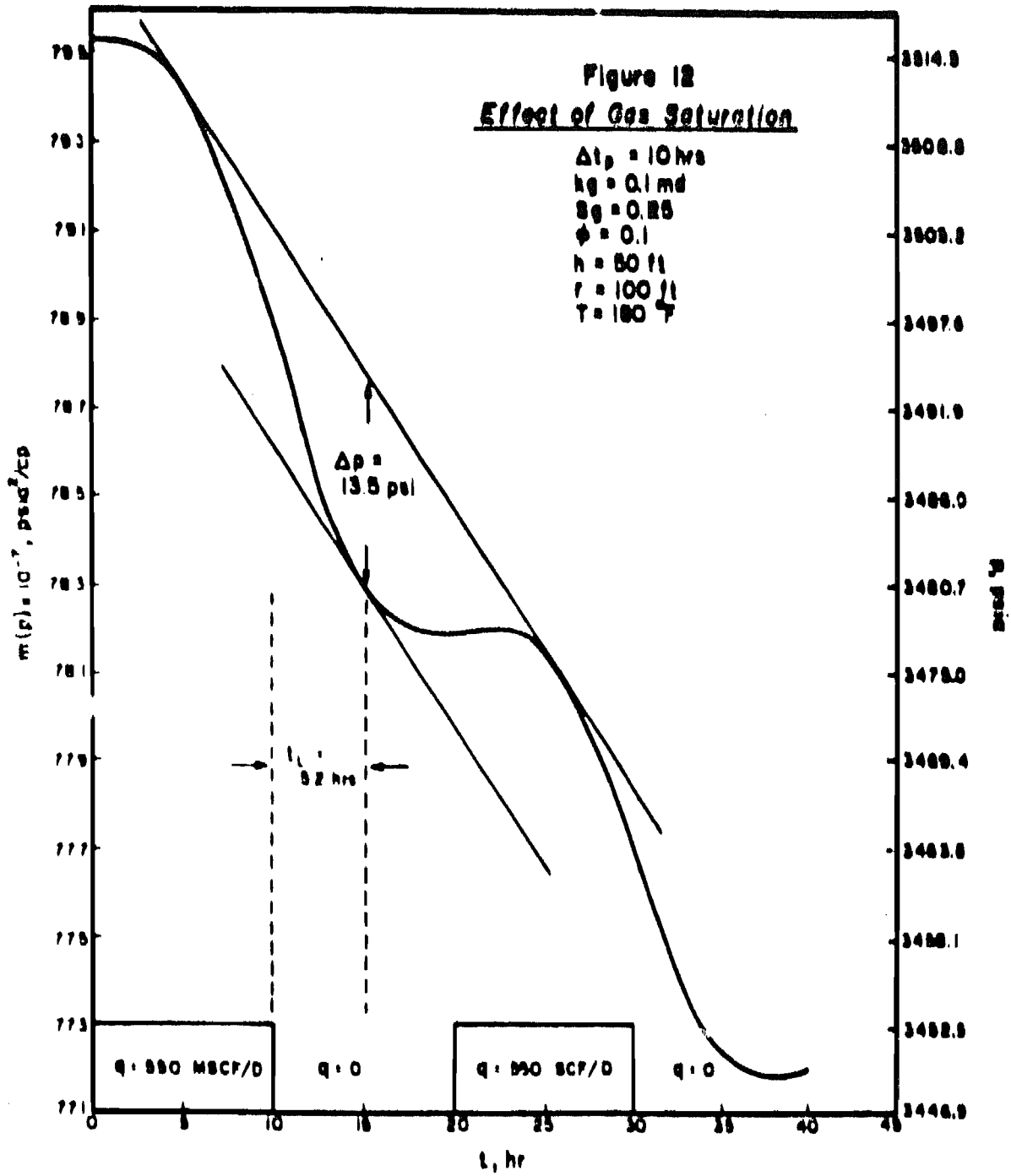
Figure 12
Effect of Gas Saturation
Δt_p = 10 hrs
kg = 0.1 md
Sg = 0.25
φ = 0.1
h = 50 ft
r = 100 ft
T = 180 °F
Δp = 13.5 psi
t_L = 5.2 hrs
q = 550 MSCF/D
q = 0
q = 550 SCF/D
q = 0
m(p) = 10^-7, psia²/cp
t, hr

REFERENCES

1. Johnson, C. R., R. A. Greenkorn, and E. G. Woods. Pulse-Testing: A New Method for Describing Reservoir Flow Properties Between Wells, J. Pet. Tech., Dec. 1966, pp. 1599-1604.

2. Greenkorn, R. A. and C. R. Johnson. Method for Defining Reservoir Heterogeneities, U. S. Patent No. 3,285,064, Nov. 15, 1966.

3. Johnson, C. R. Portable "Radar" for Testing Reservoirs Developed by Esso Production Research, Oil and Gas J., Nov. 20, 1967, pp. 162-164.

4. Brigham, W. E. Planning and Analysis of Pulse Tests, J. Pet. Tech., May, 1970, pp. 618-624; Trans., AIME, p. 249.

5. Kamal, Medhat and William E. Brigham. Pulse-Testing Response for Unequal Pulse and Shut-in Periods, Soc. Pet. Eng. J., Oct. 1975, pp. 399-410; Trans., AIME, p. 259.

6. Al-Hussainy, R., H. R. Ramey, Jr. and P. B. Crawford. The Flow of Real Gas Through Porous Media, J. Pet. Tech., May, 1966, pp. 624-636.

7. Earlougher, R. C. Jr. Advances in Well Test Analysis, Monograph Series, Soc. Pet. Eng., Dallas, TX, 1977.

☆ U.S. GOVERNMENT PRINTING OFFICE 1980-671-118/66