PULSE TESTING: A RESERVOIR DESCRIPTION METHOD

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ABSTRACT

Pulse testing is a pressure-transient method that can be used to calculate reservoir flow capacity and pore volume per unit area. This test was introduced in the late 1960's. Several publications that describe pulse test behavior in different reservoir systems appeared in the last few years.

This paper, a review paper, describes pulse testing and the information that can be learned by using it. A general overview of the relation between pulse testing and other pressure-transient tests (e.g., buildup tests) is presented. A method for pulse-test design and analysis of the data after running the test is described. The method of using pulse test data together with data from buildup and fall-off tests to select an appropriate reservoir model and obtain a reservoir description is presented. A field example is used to emphasize the use of the test.

INTRODUCTION

Obtaining an adequate reservoir description is the first step in predicting the reservoir performance under any recovery method. A recovery method may be a primary, a secondary, or a tertiary process. The effect of the reservoir description on the operation plans, and thus the oil ultimate and rate of recovery, is so significant that every possible method should be used to define this description. Single-well pressure transient tests have been used for a long time to determine such properties as the flow capacity around production and injection wells, the existence of fractures, the existence of nearby faults and boundaries and the wellbore conditions. These single-well tests tend to average the reservoir properties within the tested area and are therefore not sensitive to reservoir heterogeneity. Another type of pressure transient tests is multiple-well tests (interference and pulse tests). These tests are more sensitive to reservoir heterogeneity, and, thus, they can be used to help obtain an adequate reservoir description. This paper describes pulse testing, and the information that can be learned from such testing, as well as the advantages of using pulse tests over interference tests. A simple and accurate method for design and analysis of pulse tests is described to enable the practicing engineer to obtain the reservoir properties from this test using only a desk top calculator. The use of pulse tests to obtain more detailed description about the reservoir heterogeneity is also explained; however, if such detailed description is required, computer models will have to be used. A field example is used to emphasize the use of pulse tests.

Pulse tests in particular and pressure transient tests in general can be used to help obtain an adequate description for heterogeneous reservoirs, but they cannot be used alone to obtain this description. The reason is that pressure transient tests give the same behavior for several types of heterogeneity and, therefore, more than one reservoir description may be used to explain and match a given set of pressure transient results. Other reservoir description methods must be used in conjunction with pressure transient tests to solve this problem.

Description of Pulse Test

Pulse testing is a multiple-well pressure transient test. Usually the test is run using two wells. In this case, the value of the horizontal permeability between the two wells can be determined. The test can also be run between two sets of perforations in the same well after isolating the two perforations from each other in the wellbore. In this case, the formation vertical permeability can be determined. In this paper, the discussion will be limited to horizontal pulse tests. A series of flow changes are initiated at one well and pressure response due to these changes is measured at the other well. The flow changes at the pulsing well are generated by alternate periods of flow and shut-in (or injection and shut-in). At the responding well a sensitive differential pressure gauge records the pressure response.

Pulse Test Terminology

Several techniques can be used to analyze pulse-test data, though the tangent method is the most preferable one because it acts as a simple linear filter to remove the linear components of reservoir pressure trends.[1] This technique requires that two independent characteristics of each of the flow disturbance and the pressure response curve be known. For the flow disturbance, the two independent characteristics are the flow rate and timing. For the pressure response curve, the two independent characteristics are the response amplitude and the time lag. Figure 1 shows the pulse-test terminology as used in this paper. The response amplitude is the pressure increment between the tangent to two consecutive valleys and the parallel tangent at the peak between them, or it is the pressure increment between the tangent to two consecutive peaks and the parallel tangent at the valley between them. The elapsed time between the end of a certain period and the point of tangency is called the time lag.

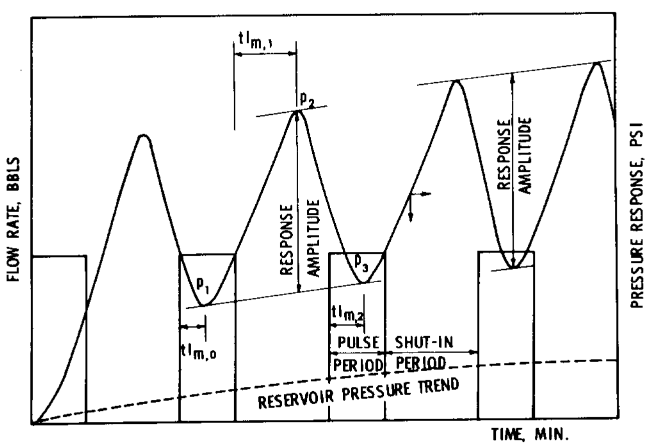

FIGURE 1—PULSE-TEST TERMINOLOGY

Theoretical Background

The advantages of pulse test over the conventional interference test are that the pressure response from a pulse test can be distinguished easily from other trends in the reservoir pressure and the pulse test values are more sensitive to the formation properties between the two wells used in the test.[1]

The effects of different factors on the response of pulse tests have been reported.[1,5-7] Studies have shown the response of pulse testing for a wide range of reservoir properties,[1,5] when areal heterogeneities exist,[6] and for a two-zone reservoir.[7] Some papers supply enough information for an engineer to design and analyze a pulse test.[2-3,8] Here we follow reference 8. To design and analyze any well test is simply to relate the test parameters to the reservoir and well properties. In the case of pulse testing, the test parameters are the pulse period, the shut-in period, the time lags, and the response amplitude. The reservoir properties are the formation permeability, porosity and thickness, the fluid viscosity, the total compressibility, and the distance between the pulsing and the responding wells.

The reservoir properties and the test parameters can be used to define the following dimensionless groups.

Pulse Ratio:

$$R' = \frac{\text{pulse period}}{\text{pulse period + shut-in period}}$$

$$= \frac{\Delta t}{\Delta t + R \cdot \Delta t} = \frac{1}{1 + R} \qquad (1)$$

The nomenclature is given at the end of the paper.

Dimensionless Cycle Period:

$$\Delta t_{cycD} = \frac{k\ \Delta t_{cyc}}{56{,}900\ \phi c_t\ \mu r_{bw}^2} \qquad (2)$$

Dimensionless Time Lag:

$$t\ell_D = \frac{t\ell}{\Delta t_{cyc}} = \frac{t\ell}{\Delta t\ (1 + R)} \qquad (3)$$

Dimensionless Response Amplitude:

$$\Delta p_D = \frac{kh\ \Delta p}{70.6\ B\ \mu q} \qquad (4)$$

The relations among the dimensionless time lag, the dimensionless cycle period, the dimensionless response amplitude, and the pulse ratio can be used to design and analyze pulse tests. The general mathematical equations relating the time lag, the cycle period, and the response amplitude for any pulse ratio were developed by using the unsteady-state flow model of the line source for an infinite, homogeneous reservoir containing a single-phase, slightly compressible fluid.[3]

Curves relating the dimensionless time lag to the dimensionless cycle period and the dimensionless response amplitude are presented in Figures 2 through 9.

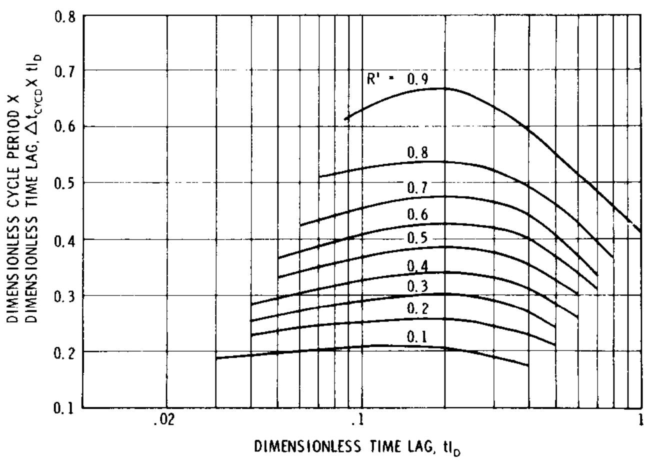

FIGURE 2 DIMENSIONLESS CYCLE PERIOD X DIMENSIONLESS TIME LAG VS DIMENSIONLESS TIME LAG FOR THE FIRST ODD PULSES.

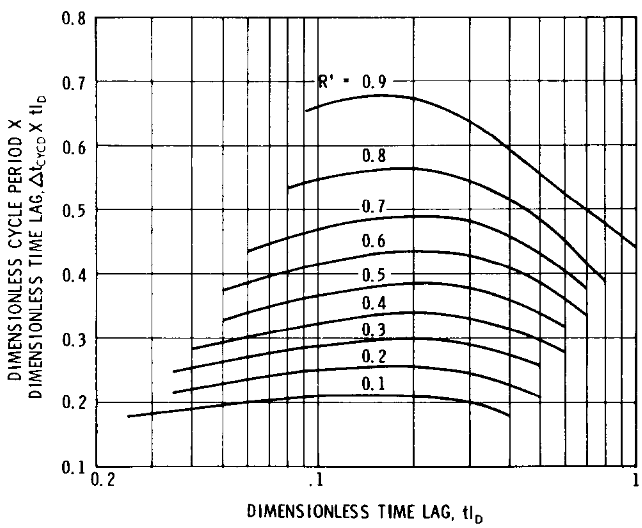

FIGURE 3 DIMENSIONLESS CYCLE PERIOD X DIMENSIONLESS TIME LAG VS DIMENSIONLESS TIME LAG FOR ALL BUT THE FIRST ODD PULSE.

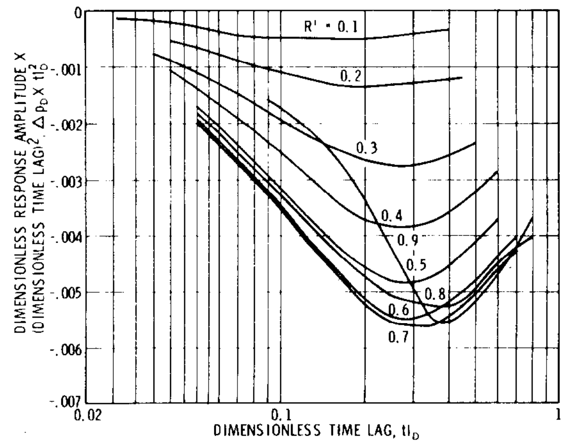

FIGURE 4—DIMENSIONLESS RESPONSE AMPLITUDE X (DIMENSIONLESS TIME LAG)^2 VS DIMENSIONLESS TIME LAG FOR THE FIRST ODD PULSES.

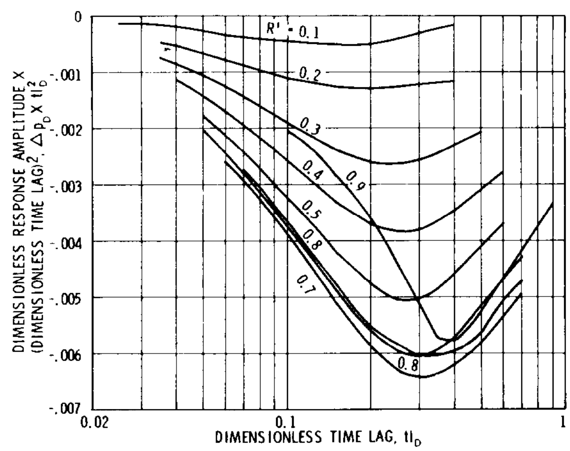

FIGURE 5—DIMENSIONLESS RESPONSE AMPLITUDE X (DIMENSIONLESS TIME LAG)^2 VS DIMENSIONLESS TIME LAG FOR ALL BUT THE FIRST ODD PULSE.

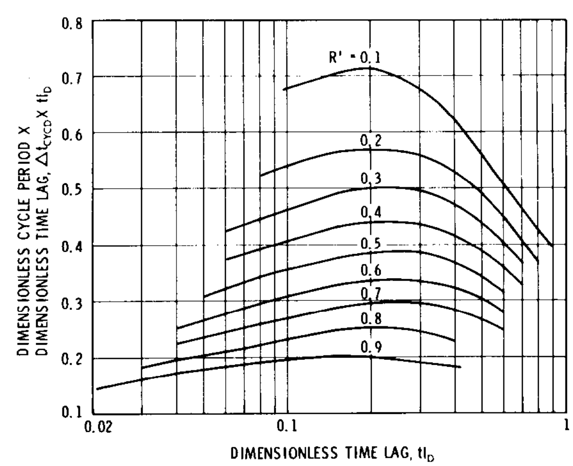

FIGURE 6—DIMENSIONLESS CYCLE PERIOD X DIMENSIONLESS TIME LAG VS DIMENSIONLESS TIME LAG FOR THE FIRST EVEN PULSE.

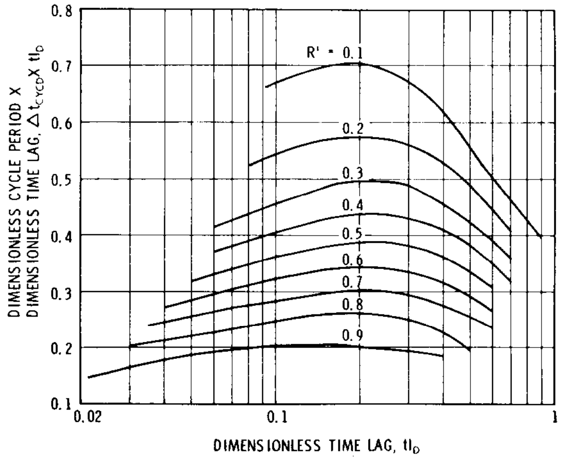

FIGURE 7—DIMENSIONLESS CYCLE PERIOD X DIMENSIONLESS TIME LAG VS DIMENSIONLESS TIME LAG FOR ALL BUT THE FIRST EVEN PULSE.

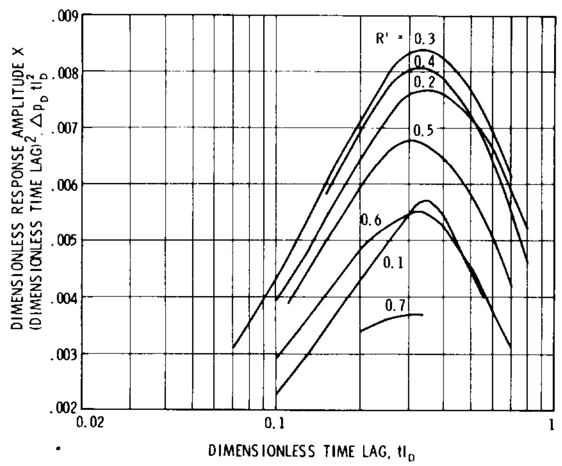

FIGURE 8—DIMENSIONLESS RESPONSE AMPLITUDE X (DIMENSIONLESS TIME LAG)^2 VS DIMENSIONLESS TIME LAG FOR THE FIRST EVEN PULSES.

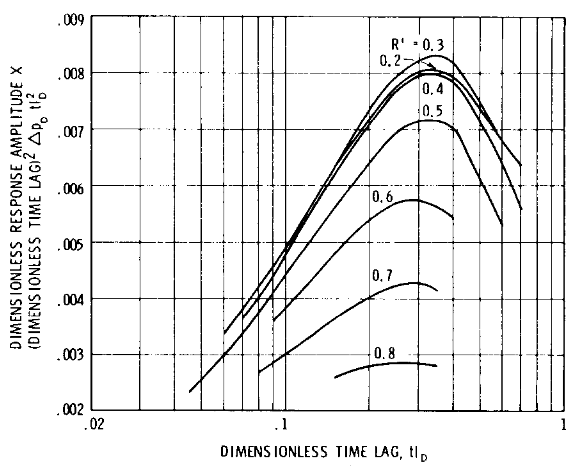

FIGURE 9—DIMENSIONLESS RESPONSE AMPLITUDE X (DIMENSIONLESS TIME LAG)^2 VS DIMENSIONLESS TIME LAG FOR ALL BUT THE FIRST EVEN PULSE.

HOMOGENEOUS ISOTROPIC SYSTEMS

In this system the porosity and thickness are the same everywhere in the reservoir. The permeability is the same everywhere and in all directions.

Designing Pulse Tests

Designing a pulse test requires determining two criteria: the pulse times and the expected pressure response.

The proper pulse time should be used so that the test falls around the midpoint of the range of effectiveness.[2] The dimensionless time lag determined by the following empirical equations assures that the test will fall in the effective range.

$$t\ell_D = 0.09 + 0.3R' \text{ (odd pulses)} \quad (5)$$

$$t\ell_D = 0.09 \times 0.3\,(1 - R') \text{ (even pulses)} \quad (6)$$

Knowledge of the expected pressure response is important so that the range and sensitivity of the pressure gauge and the length of time needed for the test can be predetermined.

1. The first step in designing a pulse test is to select the pulse ratio. If a specific pulse ratio is more convenient for oilfield operations, this ratio should be used. Otherwise, a pulse ratio near 0.7 or 0.3 is recommended, depending on whether the odd pulses or the even pulses will be used to analyze the results of the test. In no case should the ratio be below 0.2 or above 0.8.
2. Calculate the dimensionless time lag using Equations 5 or 6.
3. Determine the dimensionless cycle period using the dimensionless time lag and the appropriate curve in Figures 2, 3, 6, or 7.
4. Determine the dimensionless response amplitude using the dimensionless time lag and the appropriate curve in Figures 3, 5, 8, or 9.
5. Using "approximate" known values of the formation permeability, porosity, and thickness, the viscosity of the oil, and the total compressibility, together with the dimensionless cycle period, the dimensionless response amplitude, and Equations 2 and 4, calculate the cycle period and the response amplitude.
6. Using the pulse ratio and the cycle period, calculate the pulsing period and the shut-in period.

Analyzing Pulse Tests

After running the test, drawing the slopes, and measuring the time lags and the response amplitudes, use the following method to determine the values of (kh/μ) and $(\phi c_t h)$.

1. Calculate the dimensionless time lag using Equations 3.
2. Determine the dimensionless cycle period using the dimensionless time lag and the appropriate curve in Figures 2, 3, 6, or 7.
3. Determine the dimensionless response amplitude using the dimensionless time lag and the appropriate curve in Figures 4, 5, 8, or 9.
4. Calculate the value of (kh/μ) from Equation 4 and the value of $(\phi c_t h)$ from Equation 2.

HOMOGENEOUS ANISOTROPIC SYSTEMS

The porosity and thickness in this case are uniform throughout the reservoir. The permeability is the same everywhere, but it varies with direction.

Pulse Testing in Homogeneos Anisotropic Systems

Papadopulos[9] presented analysis techniques for multiple-well tests in anisotropic reservoirs. Ramey[10] adapted the Papadopulos solution to the petroleum literature. The same analysis technique for homogeneous isotropic formations is used here, except that the equations for calculating the reservoir properties are different.

$$\sqrt{\frac{k_{xx}\,k_{yy} - k_{xy}^2\,h}{\mu}} = 70.6\,q\,B\,\frac{(\Delta p_D)}{\Delta p} \quad (7)$$

$$\phi c_t h = \left[\frac{k_{xx}k_{yy} - k_{xy}^2}{k_{xx}\,y^2 + k_{yy}\,x^2 - 2k_{xy}\,xy}\right]\frac{h}{\mu}\cdot$$

$$\cdot\ \frac{1}{56{,}900}\ \frac{\Delta t_{cyc}}{\Delta t_{cycD}}\ . \quad (8)$$

$$k_{xx} = \frac{1}{2}\left\{(k_{xx} + k_{yy})\right.$$

$$\left. + \left[(k_{xx} - k_{yy})^2 + 4k_{xy}^2\right]^{1/2}\right\} \quad (9)$$

$$k_{YY} = \frac{1}{2}\left\{(k_{xx} + k_{yy})\right.$$

$$\left. - \left[(k_{xx} - k_{yy})^2 + 4k_{xy}^2\right]^{1/2}\right\} \quad (10)$$

$$\theta = \arctan\left[\frac{k_{XX} - k_{xx}}{k_{xy}}\right] \quad (11)$$

Inspection of Equations 7-11 provides information about the behavior of homogeneous anisotropic systems. Equation 7 shows that the permeability function which affects the pressure match is independent of the direction of the line connecting the test wells, whereas the time match (Equation 8) depends on such direction. Analysis of more than one pulse test in the same area should, therefore, provide information on the feasibility of using homogeneous anisotropic models. If the match of pressure is the same in different tests, the model is applicable. If not, heterogeneous system analysis should be considered. In homogeneous anisotropic systems, the thickness is the same everywhere while in the heterogeneous reservoirs, the thickness is a space function. Variations of the thickness also causes differences among the pressure matches of different tests as can be seen from Equation 7. Therefore, whether it is because a permeability change or a thickness change, different pressure matches point to the need of using heterogeneous models in the analysis. Another test that may be applied is to compare the permeability calculated from single-well tests to the permeability function calculated from the pressure match. For homogeneous anisotropic systems they should be identical.

It should be noted that in analysis of homogeneous anisotropic systems, three permeability-related variables need to be determined (k_{XX}, k_{YY}, and θ) instead of only one variable in the case of homogeneous isotropic system. Therefore, three tests are needed to obtain this information. The three tests should be in three different directions.

HETEROGENEOUS SYSTEMS

If the data from multiple-well tests fail to meet the homogeneous model tests, for both isotropic and anisotropic cases, heterogeneous models should be used. This leads to the use of numerical solutions and computers. Heterogeneity may be areal, vertical, or both areal and vertical. To determine the reservoir parameters in this case, a computer model is needed to predict the pressure behavior at the responding well(s) as a result of the rate changes at the pulsing well(s). Initial values of the porosity, thickness, and permeability of the formation are assumed as space functions and the pressure behavior is predicted using the computer model. If a good match is obtained between the model and field data, the properties used in the model are adequate to describe the reservoir. If a good match is not obtained, the reservoir properties should be changed and another run should be made until an adequate match is obtained.

A pressure transient test yields two pieces of information, but since the number of tests is usually less than half the number of parameters to be estimated in case of heterogeneous reservoirs, nonunicity becomes a problem. Therefore, all available information about the total permeability-thickness around wells obtained from single-well tests, information about nearby boundaries, existence of fractures or layering, and use of other information (e.g., ϕ-k correlations, geological layers) is needed to achieve an acceptable reservoir description. The more information used, the better is the description.

Table 1 presents a summary of the different steps that should be used for analysis of the results of multiple-well tests to obtain a reservoir description together with the criteria to be used in determining the validity of each model.[11]

TABLE 1—DIFFERENT MODELS AND STEPS USED IN ANALYSIS OF PRESSURE TRANSIENT TESTS.

STEP NO.	MODEL	CRITERIA FOR VALIDITY OF MODEL. IF CRITERIA IS NOT MET, GO TO NEXT STEP
1	HOMOGENEOUS ISOTROPIC	1 - RESERVOIR PARAMETERS ARE ABOUT THE SAME FROM DIFFERENT TESTS. 2 - RESERVOIR PARAMETERS AGREE WITH VALUES OBTAINED FROM SINGLE-WELL TESTS
2	HOMOGENEOUS ANISOTROPIC	1- PRESSURE MATCH IS THE SAME FOR DIFFERENT TESTS 2- PERMEABILITY FUNCTION FROM MULTIPLE-WELL TESTS AGREES WITH PERMEABILITY CALCULATED FROM SINGLE-WELL TESTS
3	HETEROGENEOUS 2-D	1- REASONABLE AGREEMENT BETWEEN CALCULATED AND OBSERVED PRESSURES
4	HETEROGENEOUS 2-D LAYERED OR 3-D	1- REASONABLE AGREEMENT BETWEEN CALCULATED AND OBSERVED PRESSURES

Field Example

A field example that describes the use of pressure transient data in general and pulse test in particular in obtaining a reservoir description is presented in detail in reference 11. Here, we present a summary of this example.

The Sloss Field

The Sloss Field in Kimball County, Nebraska, produces from the Muddy "J" sandstone. The Muddy "J" sand was considered as a good representative of homogeneous systems. Recovery of tertiary oil is sought in the watered-out reservoir. Single-well and multiple-well tests were conducted in the 9-acre micellar-polymer pilot area of the field. Figure 10 shows the wells locations in this pilot. Standard analysis of the single-well tests provided an average kh value of 204 md-ft. The individual kh values for the five pilot wells are shown in Table 2.

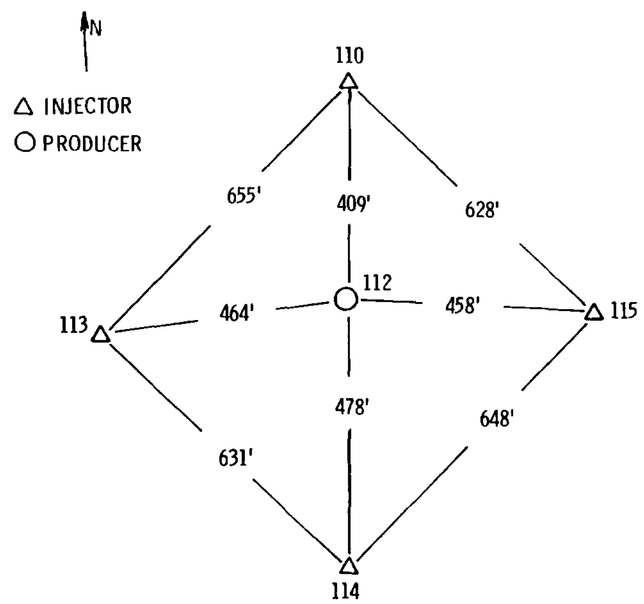

FIGURE 10 SLOSS MICELLAR PILOT.

TABLE 2—PERMEABILITY-THICKNESS VALUES AT PILOT WELLS FROM SINGLE-WELL TESTS.

WELL NO.	KH MD-FT
110	256.4
112	200.8
113	239
114	220
115	300

Pulse tests were conducted among the pilot wells. The data were first analyzed using the homogeneous isotropic method but unrealistic values of the reservoir parameters were obtained. Table 3 contains the results of these analyses. These results indicate that the homogeneous isotropic model is inadequate for describing this field. The next step was to use the homogeneous anisotropic model.

TABLE 3 ANALYSIS OF THE SLOSS FIELD PULSE TESTS USING HOMOGENEOUS ISOTROPIC MODEL.

WELL PAIR	k/ϕ MD	kh/q MD FT/RB/D	k ASSUME ϕ = 0.18 MD	h ASSUME ϕ = 0.18 AND MAX. q FT	q ASSUME ϕ = 0.18 AND h = 12 RB/D
110-112	433	.731	82	4.2	432
113-112	183	8.25	33	87	48
114-112	556	9.65	100	33.2	124
115-112	430	.78	77	3.6	360
110-113	NO RESPONSE				
110-115	404	1.5	73	8.4	348
114-113	474	3.01	92	13	332
114-115	238	3.088	43	24.7	175
113-115	199	4.823	36	49.3	90
114-110	210	1.866	38	18.9	244

As was pointed out above, if this is a reasonable model, the pressure match should be the same in all cases. It is clear from the wide variation in the kh/q values that this is not the case. An example of homogeneous anisotropic analysis is shown in Figure 11 where a *negative* value for the permeability was obtained in the southeast direction. Therefore, it was concluded that a heterogeneous model should be used for this area.

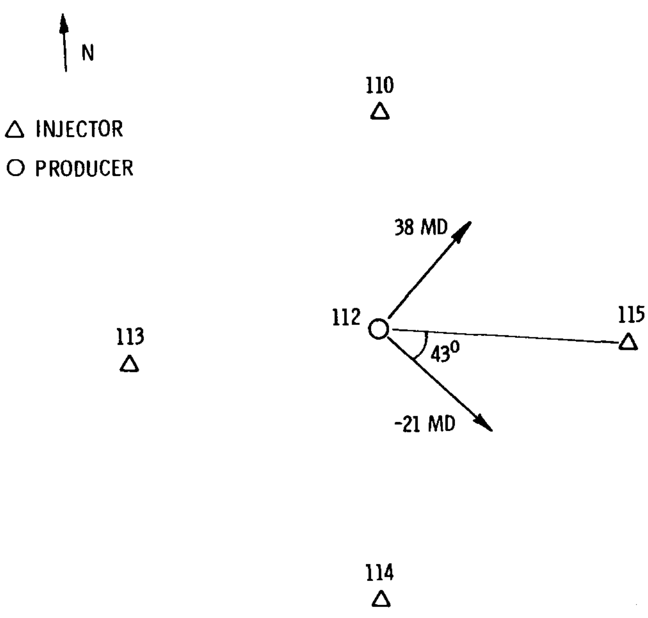

FIGURE 11 AN EXAMPLE OF HOMOGENEOUS ANISOTROPIC ANALYSIS.

Although the results of single-well tests conducted in the different pilot wells are in reasonable agreement, the reservoir is not homogeneous.

Several trail-and-error methods can be used with a computer model to obtain the match for the heterogeneous system. The two-dimensional model of Carter et al.[12] was used. Several zonations and starting parameter values were used but the final match was not satisfactory. Figure 12 shows the final match for the test between Wells 110 and 112 which is typical of all the obtained matches. Note that the observed response is generally higher than the calculated response. This behavior is an indication that a vertically heterogeneous system should be used rather than a single layer.

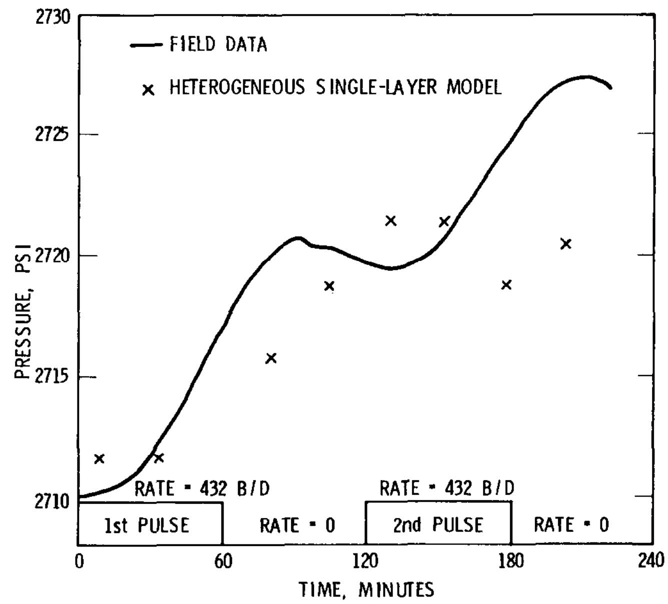

FIGURE 12 –HETEROGENEOUS SINGLE LAYER ANALYSIS WELLS 110-112.

A study of the core permeability for the pilot wells showed a significant contrast among the top, middle, and bottom parts of the formation. Therefore, a stratified three-layer model was used with no cross flow among the layers except at the wellbore. In this model the porosity, thickness, and permeability of the three layers were varied areally. The kh values obtained from single-well tests were used as a constraint on the total kh at the wells. The permeability-porosity correlations available from core data were used as a constraint on the relation between the values of these two parameters everywhere. A good match was obtained using this model. Figures 13 and 14 show as examples the match for Wells 110-112 and 113-112. The reservoir parameters from the model were used to obtain contour maps of the porosity, thickness, and permeability for the three layers. By the use of the reservoir description obtained from the model and field, the pressures at the pilot wells were predicted and compared with the actual field pressures. Table 4 shows the comparison between the two sets of values. The good agreement between calculated and actual pressures is an indication of the validity of the obtained reservoir description.

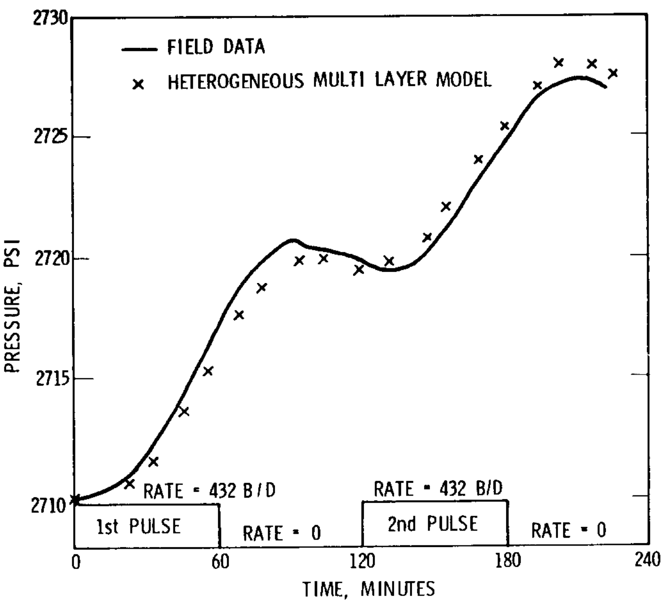

FIGURE 13 HETEROGENEOUS MULTILAYER ANALYSIS WELLS 110-112.

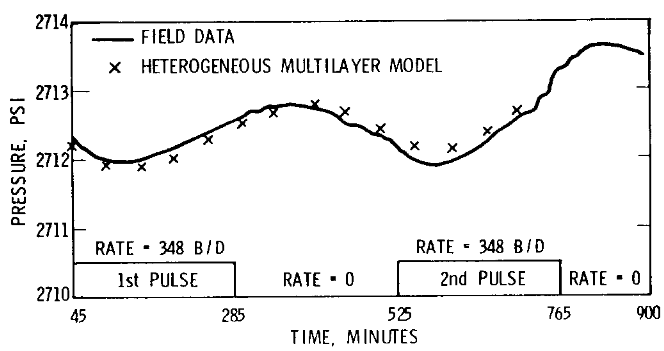

FIGURE 14 HETEROGENEOUS MULTILAYER ANALYSIS WELLS 113-112.

TABLE 4 COMPARISON BETWEEN ACTUAL WELL PRESSURES AND THOSE CALCULATED USING FINAL RESERVOIR DESCRIPTION.

WELL NO.	ACTUAL PRESSURE PSI	CALCULATED PRESSURE PSI	% DIFF.
110	2863	2805	2.0
112	612	625	2.0
113	2972	2961	0.3
114	2956	3162	7
115	2779	3068	10

CONCLUSIONS

1. Pulse test is a multiple-well pressure transient test that can be used to help obtain an adequate reservoir description for homogeneous (both isotropic and anisotropic) and heterogeneous systems.
2. A simple and accurate method for designing and analyzing pulse tests for homogeneous reservoirs is presented.
3. Numerical solutions must be used to analyze pressure transient data from heterogeneous systems.

NOMENCLATURE

B = formation volume factor RB/STB

c_t = total compressibility, psi^{-1}

h = formation thickness, ft

k = permeability, md

k_{xx}, k_{yy}, k_{xy} = components of permeability tensor, md

k_{XX} = maximum principal permeability, md

k_{YY} = minimum principal permeability, md

p = pressure, psi

Δp = response amplitude, psi

Δp_D = dimensionless response amplitude = $kh\Delta p/70.6\ qB\mu$

q = flow rate, STB/D

r_{bw} = distance between wells, ft

Δt = pulse period, minutes

Δt_{cyc} = cycle period, minutes

Δt_{cycD} = dimensionless cycle period = $k\Delta t_{cyc}/56900\ \phi\mu c_t r_{bw}^2$

$t\ell$ = time lag, minutes

$t\ell_D$ = dimensionless time lag = $t\ell \sim \Delta t_{cyc}$

x,y,z = rectangular coordinates

η = hydraulic diffusivity = $k/\phi\mu c$, md psi/cp

θ = angle

μ = viscosity, cp

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