PULSE TESTING - STATE OF THE ART

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ABSTRACT

Pulse testing was developed in the early 1960's for the purpose of obtaining reservoir description between wells. Since then, several papers have been published advancing this technology to the point where it can now be considered conventional well testing. This paper reviews the advances that have been made in pulse testing technology and presents the state of the art of pulse testing as it is being used today. A method of design and analysis of pulse tests is presented along with example applications. Some of the topics considered are enhancement of pressure response by filtering, desuperposition of data, effects of wellbore storage and skin, unequal rate pulses, and limitations of pulse testing.

INTRODUCTION

Pulse testing is a multi-well pressure transient test which consists of measuring the pressure at one or more observation wells while making a series of rate changes at a pulsing or active well. Typically, a pulse test has a number of cycles, each cycle having an injection or production period and a shut-in period at the active well. The pressure is monitored before and during the test at the observation well.

The type of pressure response that might be seen in the observation well is shown in Figure 1. The pulse rate and schedule of the active well is also shown in Figure 1. The terminology and a number of quantities that are used in the tangent method[1] of analysis are identified. Among these quantities, two are found from the pressure curve: the time lag, t_L; and the response amplitude, Δp.

Using the time lag and the response amplitude, values of diffusivity, η, and transmissibility, T, can be calculated, and from these quantities the storage, S, may be determined. The definitions of diffusivity, transmissibility, and storage can be found in the nomenclature.

Two of the major advantages of pulse tests over conventional interference tests are that a smaller area of the reservoir is sampled in pulse tests, and pulse tests allow determination of reservoir properties several times in each test, thus giving more confidence in those properties. The reason for these advantages is the shorter time required for pulse tests due to the nature of the pulse signal. That is, a coded pressure signal is generated at the active well which in general can be easily distinguished from random fluctuations in the reservoir pressure.

In the sections which follow, a brief review of the development of pulse testing will be presented. Pulse testing theory is then discussed, followed by an outline of an analysis and design procedure for pulse tests.

HISTORICAL DEVELOPMENT

Pulse tests were first proposed for use in the petroleum industry by Johnson, Greenkorn and Woods in 1966.[1] Many papers have been published since Johnson et al, advancing the analysis and interpretation of pulse tests. We will now review those papers, beginning with those that discuss the determination of reservoir properties, then reviewing those that interpret and apply pulse test results.

Analysis Methods

The original paper by Johnson et al,[1] suggested two methods of pulse test analysis: least-squares curve fitting and a graphical technique that they called the tangent method. They explained the tangent method in detail, and suggested it as a simple method of routine pulse test analysis. In order to use the tangent method, however, a number of lengthy calculations would have to be made for each test.

Brigham[2] simplified pulse test design and analysis by developing a chart that related diffusivity and time lag, and one that related transmissibility and response amplitude. These charts permit one to obtain the response amplitude and time lag from the observation well pressure, and in a straightforward manner determine transmissibility and diffusivity. The only limitations with these charts was the assumption of equal time lags, and the assumption that the flow and shut-in periods of each cycle are equal in length.

Jahns[21] and Startzman[3] pursued a different method of analysis. They suggested matching the observation well pressures with pressures computed from a reservoir simulator. This method has the definite advantage of accounting for an irregular pulse rate and schedule; however, it also requires the use of a computer.

Kamal and Brigham[4] developed charts similar to those of Brigham[2], but they did not assume equal pulse and shut-in periods or equal time lags. In addition, they showed that the cycle length and response amplitude are related to the time lag by exponential functions. The coefficients of these exponential functions are dependent on the ratio of flow to shut-in periods at the active well.

In a subsequent paper[5], Kamal and Brigham presented a method of pulse test design and analysis using either the charts or the exponential relations they had previously developed[4]. They also made recommendations for designing the flow and shut-in periods to yield the maximum response. Therefore, in reservoirs where a small pressure response is expected, Kamal and Brigham's method of design could be used to obtain the maximum pressure response.

Pierce,[6] in a field application of pulse testing, presented pulse test interpretation charts which were prepared as described in the appendix of reference 1. These charts form the basis of the design and analysis method presented herein. They are based on the same equations as those of Kamal and Brigham[4] but are presented in a different form and use the terminology of Johnson et al[1].

Stegemeier[7], in a field application of pulse testing, developed a design and analysis method that allows one to estimate the degree of reservoir heterogeneity. He correlated the time lag with the directional and the geometric mean permeabilities; the difference in these two gives an indication of the heterogeneity of the reservoir.

Interpretative Methods

Johnson et al,[1] observed that pulse testing could be used to locate heterogeneities and to quantify diffusivity and transmissibility values. In order to accomplish this, the reservoir would have to approximate the ideal model assumed for analysis, and the heterogeneities present would have to be larger than one well spacing in size.

If the reservoir is fairly complex, Johnson et al suggested that qualitative information about reservoirs could be obtained. This information could include determination of: 1) presence of heterogeneities between wells; 2) fracture orientation; and 3) between-zone communication.

They also showed that the response amplitude increases with an increase in rate or pulse length, while the time lag is relatively insensitive to either the rate or pulse length. In addition they found that the response amplitude generally increases and the time lag decreases with increasing transmissibility.

McKinley, Vela, and Carlton,[8] presented a field application of pulse testing which verified the accuracy of reservoir properties determined from pulse tests. This was accomplished by comparison with core data, oil-water production data and interference test results.

They pointed out that analysis of multiple pulses could provide an estimate of the experimental error in the method, and that a good way to interpret the results of pulse tests is to plot the calculated properties on contour maps. That is, for each well pair tested, the values of diffusivity, transmissibility and storage could be treated as point values midway between wells. One could then construct contour maps of these properties. Of course, for this to be of value, a number of well pairs would have to be pulse tested.

In addition, they proved the principle of reciprocity, which says that a pulse test from Well A to Well B would yield the same formation properties as a pulse test from Well B to Well A. This principle is useful in a number of ways: 1) it reduces the number of wells required for reservoir description; 2) it allows the selection of active and observation wells to be a matter of convenience; and 3) it facilitates data analysis when wellbore storage affects the data.

Woods[9] conducted a mathematical study of the pulse test response of a two-layer reservoir. He concluded that the apparent transmissibility calculated from a pulse test in a two-layer reservoir is always equal to or greater than the total transmissibility; and that the apparent storage is always less than or equal to the total storage. Total properties are the sum of the individual layer properties. In layered reservoirs, this might be an explanation for differences in reservoir properties determined from pulse tests and reservoir properties determined from single well tests. A method was presented that estimates individual zone properties using a combination of pulse test values, single well test results and flowmeter surveys. Also, the effect of skin, inter-layer communication, and varying ratios of transmissibility, storage and diffusivity on pulse test results was investigated.

Vela and McKinley[10] investigated the effect of areal heterogeneities on pulse tests. They presented the following equation to calculate the approximate area investigated by a pulse test

$$r_{inf} = 4.2 \times 10^{-3} \sqrt{\frac{T\Delta t}{S}}, \quad ft;$$

where T = transmissibility, md - ft/cp

S = storage, ft/psi

and Δt = pulse length, min.

This equation defines the radius of a circle about the pulsing well, and according to the reciprocity principle a circle of equal radius must also be centered about the responding well. Therefore, the area investigated in a pulse test is approximately the area enclosed by two circles with radius r_{inf}, and centered at the active and the responding wells.

They found that the presence of heterogeneities in the area investigated by a pulse test may distort the reservoir properties calculated from that test. In addition, heterogeneities less than about 1/3 well spacing in size did not appear in true perspective in the pulse test results. To restore the pulse test results at least in part to true perspective, a correction method was presented. This method could be used when several wells in a pattern were tested.

Another important point made in their paper was the pulse test value of diffusivity is more dependent on between-well properties than either the transmissibility or storage. Thus, the diffusivity is a better indicator of between-well communication than the transmissibility or storage.

Rijnders[14] presented an application of pulse testing in Oman. This study showed that pulse testing could be successful in reservoirs with wide well spacings. In addition, he indicated that for wide well spacings, wellbore storage and skin at either well may be neglected.

Pierce, Vela and Koonce[12] conducted a study of pulse tests in hydraulically fractured wells. They concluded that if several wells around the fractured well were pulse tested both before and after the fracture treatment, then inspection of time lag differences would allow a rough determination of fracture orientation. To obtain a more quantitative estimate of fracture orientation and a value of fracture length, results of the pulse tests were matched to a reservoir simulator. In addition, an estimate of fracture conductivity is required, although the pulse test results are not particularly sensitive to the fracture conductivity.

Ekie, Hadinoto and Raghovan[13] presented a method to determine fracture orientation from pulse tests conducted after a fracture treatment. They claim that the principal advantage of this work over previous works is that pre-fracturing pulse test data are not needed; however, reservoir heterogeneity may adversely affect results from their analysis method.

The method they proposed uses estimates of formation permeability from single-well tests, fracture length and the time lag to calculate fracture orientation. At least two responding wells are required for analysis by their method.

Abobise and Tiab[14] extended and improved the work of Ekie et al. by developing a correlation which eliminates the need for an estimate of formation permeability to determine fracture orientation. In fact, their method allows one to determine a pulse test value of diffusivity, and thereby to some degree account for reservoir heterogeneity. A detailed, step-by-step method of design and analysis was presented.

Strobel, Gulati and Ramey[15] presented an application of pulse-tests for reservoir limit tests in a naturally fractured reservoir. Basically, they matched the pulse test data with data generated by simulating several combinations of drainage shape, boundary conditions and reservoir properties. In order to obtain parameters for the simulations, a number of other types of tests were employed. However, their work did show that pulse tests could be used as an aid in determination of reservoir limits.

Pierce[6] described the use of pulse tests to predict the performance of a water-flooding project. The results of the pulse tests conducted in this field showed that several faults identified by other techniques were nonsealing; a major fault was found to be sealing; and a zone of low communication, possibly a fault, was identified.

Vela[16] examined the effect of a linear boundary on interference and pulse tests, and in so doing derived an exact expression for the area investigated, or influence area, of a two-well test. The influence area is defined by an ellipse containing both wells. The effect of a linear boundary in the influence area of a pulse test is a lengthening of the time lag. The response amplitude may either increase or decrease depending upon the location of the boundary. An important conclusion of this study was for a linear boundary to influence a pulse test, it must be closer than one well spacing from either well.

Rathbone, Unneberg and Cull[17] presented a field application of pulse testing. This paper is important in that it details several practical considerations in conducting pulse tests. These include: the need for pressure stabilization of the observation wells; the use of high precision pressure gauges; and the necessity of maintaining constant rates in wells not involved in the test. In addition, they presented a moving average smoothing technique, which removed cyclic noise from the pressure data.

Hutfilz, Cockerham and McIntosh[18] presented an example of pulse testing in a high permeability reservoir with wide well spacing. The results of the tests identified a thickness variation in the reservoir and the presence of a high permeability streak. The results of the pulse tests also supported data obtained from logs and single-well tests, and thereby showed that pulse testing was effective in this type of reservoir environment.

PULSE TESTING THEORY

The mathematical model that is commonly used to describe unsteady-state fluid flow through porous media is the line source solution to the diffusivity equation. The assumptions incorporated in this model are: horizontal flow; negligible gravity effects; a homogeneous and isotropic porous medium; a single phase, slightly compressible fluid; and ϕ, c_t, μ, k independent of pressure.

Using the line source solution and the principle of superposition, the equation for the pressure at a distance r from an active well which is making a series of rate changes is:[1]

$$p = p_i + \frac{70.6B}{T} \sum_{i=1}^{n} (q_i - q_{i-1}) \ Ei \left(- \frac{r^2}{4\eta(t-t_i)}\right)$$

(symbols defined in the nomenclature).

Returning now to Figure 1, one can see that two characteristics of the pressure response are identified. These characteristics are called the time lag, t_L and the response amplitude, Δp. Using the analysis chart[6] presented in Figure 2, the transmissibility and storage of the area investigated by the pulse test can be determined. The ratio of transmissibility to storage yields the diffusivity. Use of this chart requires knowledge of the pulse length, ratio of between-pulse length to pulse length, pulse flowrate, and distance between wells. Calculation of the transmissibility, storage and diffusivity was demonstrated in reference 6, and will not be repeated here.

Figures 3 and 4 are analysis charts for the first inverse and second response, respectively. Analysis of these responses, in addition to the first pulse response, yields three values for each of the desired quantities. Comparison of these values gives an estimate of the experimental error present in a particular test.

The method of analysis outlined above is one form of the tangent method of analysis. It has proven to be a simple and accurate method of analysis. However, when no pulse response is evident, or when factors other than pulses at the active well affect the data, modifications to this method are necessary.

The method now outlined can be broken down into two parts: data handling and modifications for non-ideal behavior. Parts of this analysis method have been used in field studies[17,18] while other parts have not appeared in the literature.

DATA HANDLING

The first thing that one must do when given some pulse test data is identify a pressure response at the observation well caused by the rate pulses at the active well. This may be accomplished by several manipulations of the data. These include removal of a pressure trend, averaging the data, and/or stacking the pulses.

Removing the reservoir pressure trend from the data allows one to plot the data on an expanded scale. All this step consists of is subtracting a linear pressure trend from each data point. For instance, if the pressure trend to be subtracted is -0.6 psi/hr and 3 hours after beginning the test the observation well pressure is 2108.8 psi, then the observation well pressure, after subtracting the trend, is 2110.6 psi. This allows one to plot the data on a scale which is justified by gauge sensitivity and thereby accentuate the pressure response. An example of data with the trend and without the trend is presented in Figures 5 and 6, respectively.

If a pressure response can be identified, but there is a significant amount of data scatter or high frequency noise, then an averaging technique may be employed. This averaging may be nothing more than a moving average of the pressures, if the data are taken at equally spaced time intervals.

The number of data points, or molecule size, to be included in the moving average at each step depends upon the frequency of the noise one wants to remove and on the pulse length. If the frequency of the noise to be removed is approximately equal to the frequency of the rate pulses, removal of the noise by this method will cause attenuation in the actual pressure response of the observation well to the active well rate pulses.

For example, if the cycle length of a test is 24 hours, and one wants to remove noise that has a diurnal or 12 hour cycle length, then an averaging technique using a molecule length of 12 hours would be required. Depending upon the magnitude of the noise, the actual pressure response in this case might be reduced to 65% of its actual value.

Therefore, when averaging pulse test data, the length of the moving average molecule should be somewhat less than the pulse cycle length. An example of data smoothed with a 5.5 hour moving average is shown in Figure 7. The rate pulses for this example were 48 hours long.

When no response is evident or is difficult to identify, a technique known as pulse stacking may be used. Basically, this is just a means of accentuating the response and removing cyclic noise by plotting pressure differences. For a two cycle test with pulse interval Δt, we would plot time versus $p(t)_s$, where $p(t)_s$ is given by this equation:

$$p(t)_s = p(t) - p(t+\Delta t).$$

where $p(t)$ = observation well pressure at time t
and $p(t+\Delta t)$ = observation well pressure at time $(t+\Delta t)$.

Analysis of this plot would be accomplished in the same manner as the analysis of the first pulse response would ordinarily proceed. The one difference is that the response amplitude, Δp, should be divided by two. In addition, to use this method the pulse length and between-pulse length should be equal.

An example of unstacked and stacked data is shown in Figures 8 and 9, respectively. Note that stacking removed the noise or pressure peaks that had a 24 hour cycle.

MODIFICATIONS FOR NONIDEAL BEHAVIOR

The tangent method of analysis, used in conjunction with the line source solution, may be used to analyze pulse tests. This method, however, does not account for wellbore storage or skin at either the responding or active well.

When there are significant wellbore storage effects (or afterflow) at either well, the response amplitude that is measured will be too low, and the time lag may be too long. The amount of error in these quantities depends upon the well spacing, the wellbore storage coefficient, and to some extent, upon the skin factor.

No quantitative rule is available to determine when afterflow effects are significant, although the effects are greatest when there is close well spacing and a large wellbore storage coefficient. For example, if the well spacing is 200 ft and the dimensionless wellbore storage coefficient for either or both wells is 10^3, then the pulse test data probably are affected by wellbore storage.

The skin factor is important in that it prolongs the duration of afterflow. It has been shown[19] that when wellbore storage is not present, wellbore damage or skin does not affect the pressure data. A method to correct for wellbore storage and skin at both wells does not exist for pulse testing. A method does exist, however, to account for them in interference testing[19]. Therefore, an analysis method using desuperposition is suggested here that allows pulse test data to be analyzed as an interference test. Then the method presented in reference 19 may be used to analyze the data.

Basically, desuperposition as suggested here is the addition of the pressure response at time $(t-\Delta t)$ to the pressure response at time t. That is, the pressure at time t and the pressure measured one pulse interval behind in time are added together to give the desuperposed pressure at time t. It can be shown that the desuperposed data are mathematically equivalent to data from an interference test, where the active well is flowed at rate q since time t=0. An example of pulse test data and desuperposed data is shown in Figure 10.

The equation used to desuperpose pulse test data is:

$$p(t)_d = p(t) + p\,(t-\Delta t)$$

where $p(t)_d$ = desuperposed pulse test pressure at time t

$p(t)$ = observation well pressure at time t

and $p(t-\Delta t)$ = observation well pressure at time $(t-\Delta t)$

After performing this desuperposition, the appropriate type curve is selected from reference 19, and a type curve match is performed. From this match diffusivity and transmissibility may be calculated. The mechanics of this procedure are explained in reference 19.

A word or two about this method of desuperposition is in order. In using this method, our results have been mixed. Apparently it is very sensitive to changes in reservoir pressure trend and fluctuations in pressure data. In addition, in order to use this method the flowrates of each pulse must be equal, the ratio of pulse interval to between pulse interval must also be equal, and the reservoir pressure trend must be removed. Pulse tests where it should be applicable are those in which the pressure trend in the reservoir is known, and where nearby well rates are constant.

The proper way to account for wellbore storage and skin at both wells would be to superimpose a number of rate changes using the equations presented by Tongpenyai.[19] An analysis curve with the specific values of wellbore storage coefficients, skin factors and well spacing for a particular test could then be generated.

Another use of desuperposition is for pulse tests that have short time lags. For instance, the measurement of one or two minute time lags is difficult and easily subject to error. We have successfully analyzed several pulse tests that had approximately one minute time lags using the method of desuperposition.

When wellbore storage effects are present in only one well, a method proposed by Prats and Scott[20] may be used. They developed charts which could be used to correct the time lag and the response amplitude for wellbore storage effects at the observation well. The principle of reciprocity[8] indicates that their charts should work equally well for wellbore storage effects at the active well, provided the wells have equal radii. Therefore, one could determine the time lag and response amplitude from the observation well pressure, and then knowing the well spacing and the wellbore storage coefficient of the well affected, correct the time lag and response amplitude to their actual values.

The method proposed by Prats and Scott did not consider skin effect, although they suggested using the effective wellbore radius in their charts as a first approximation. Tongpenyai[19] indicates the effect of skin is much less important than wellbore storage effects. For this reason, the approximate method suggested by Prats and Scott, while not rigorously correct, should provide reasonably accurate answers.

The final factor in pulse test analysis that we will consider is rate variation. If the active well flowrate varies significantly between cycles, then the analysis method using Figures 2, 3 or 4 may be in error. To correct this error, a modified method needs to be used.

Simulations have shown that if there is a small variation in pulse rates q_1, q_2, and q_3, such that q_2 and q_3 are within 30% of q_1, then the first pressure pulse should be analyzed using Fig. 2 with $q = q_1$. The inverse and second pressure pulses should be analyzed using Figs. 3 and 4, respectively, with $q = q_2$.

The values of transmissibility and storage calculated for these three responses may then be averaged to obtain one value for each parameter. This method should reduce the error in the results to less than 5 percent.

It should be mentioned that since the time lag is generally independent of the flowrate, the pulse test value of diffusivity should not be affected by a variable flowrate. Our simulations showed this to be the case.

DESIGN

The method of pulse test design that we recommend uses Figure 2, estimates of storage and flowrate, and an assumed pulse length. The procedure is as follows:

1) estimate a flowrate and formation storage, S
2) assume a pulse length, Δt
3) on Fig. 2, pick a point on the R=1 curve in the lower set of curves
4) obtain a value for $\frac{S\ r^2 \Delta p}{\Delta t\ q}$ from the ordinate
5) solve for Δp
6) obtain a value for $T \frac{\Delta p}{q}$ from the abcissa
7) solve for T and then determine k
8) repeat steps 3 thru 7 several times

By picking several points off of the R=1 curve for each value of Δt, a plot of log k vs. log Δp can be constructed for various pulse lengths. From this plot, the value of pulse length necessary to give a measurable response amplitude can be determined for any formation permeability. An example of this plot is shown in Figure 11.

LIMITATIONS

Pulse testing is limited for the most part by our ability to accurately measure pressures. Reservoir conditions which lead to small pressure responses, therefore, may make pulse testing impractical or simply impossible. These conditions include low permeability, high compressibility, wide well spacing, and, to a lesser extent, thick formations.

From the results of pulse tests it is not possible to differentiate between rock and fluid heterogeneities. Transmissibility and diffusivity contain both rock and fluid properties, and therefore it may be difficult to determine the cause of a particular pulse test result.

Pulse testing is not a technique that can be used to determine vertical stratification in a quantitative fashion. That is, the equations we use to interpret pulse tests assume flow in the horizontal direction only. However, pulse testing may be used in a qualitative manner to determine the continuity of an impermeable layer between wells. For instance, one well might be perforated above the layer while the other well could be perforated below the layer. Absence of a pulse test pressure response in one well would allow one to place an upper limit on the degree of communication across the layer.

Underlying aquifers and overlying gas caps make pulse testing difficult, as part or all of the pressure transient may be greatly attenuated, even if both wells are completed only in the oil zone.

Pulse testing in gas reservoirs, because of the high compressibility of gas, would at first seem impossible. However, in some cases the higher mobility of gas makes pulse testing feasible. We have successfully pulse tested gas reservoirs and reservoirs with a gas cap.

CONCLUSION

From the foregoing, one can see that pulse testing is a valuable tool that can be used to obtain accurate reservoir description. Applications range from determining communication across a fault to estimating the compass orientation and length of hydraulic fractures.

In reviewing the literature, we have tried to point out the highlights and contributions of each paper, although certainly many important points were not discussed. From the review presented, however, it is felt that the reader can grasp the current state of the art; from the calculation of reservoir parameters from pulse test data to the interpretation of these parameters for reservoir description.

In the pulse test design and analysis method presented here, a practical method of obtaining diffusivity and transmissibility values was described. Factors that should be considered in many pulse test analyses were discussed, and techniques to account for these factors were outlined in the method. In some areas, though, the method is only qualitative, the reason being more work needs to be done in these areas. However, we feel that the method can be used in at least a qualitative sense in order to recognize the effects of various factors on pulse tests.

NOMENCLATURE

B - formation volume factor, res bbl/STB

C - wellbore storage coefficient, ft^3/psi

C_D - dimensionless wellbore storage coefficient, $(=C/\phi r_w^2 hc)$

c - compressibility, psi^{-1}

h - net formation thickness, ft

k - permeability, md

$p(t)_d$ - desuperposed pulse test pressure, psi

$p(t)_s$ - stacked pulse test pressure, psi

Δp - response amplitude, psi

q - pulse rate, STB/D

R - pulse ratio $(= \Delta t_b/\Delta t)$

r - distance between wells, ft

r_w - radius of wellbore, ft

S - storage $(=\phi ch)$, ft/psi

T - transmissibility $(= kh/\mu)$, md-ft/cp

t - time since first pulse, minutes

t_L - time lag, minutes

Δt - pulse interval, minutes

Δt_b - between-pulse interval, minutes

η - hydraulic diffusivity, ($0.00633\ k/\phi c\mu$), ft^2/day

μ - viscosity, cp

ϕ - porosity, fraction

ACKNOWLEDGEMENTS

The authors wish to recognize the contributions of past and present members of the Well Testing Group at Exxon Production Research Company for the analysis method outlined herein. Special thanks go to R. M. McKinley, R. S. Barnum, C. A. Porterfield R. C. Stevenson and Hubert Winston for their contributions to the pulse test analysis method contained herein. We also thank the management of Exxon Production Research Company for permission to publish this paper.

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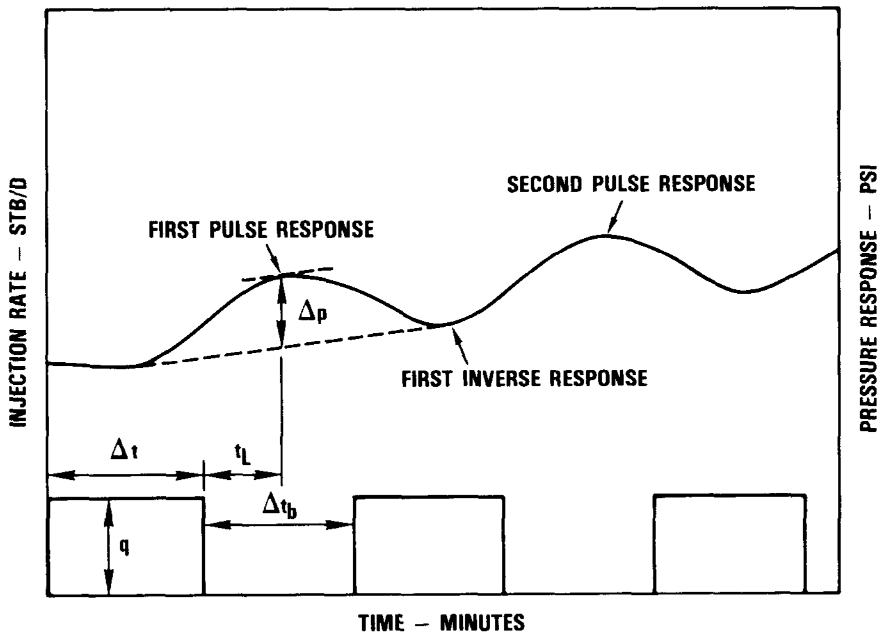

FIGURE 1 — PULSE TEST RESPONSE AND TERMINOLOGY

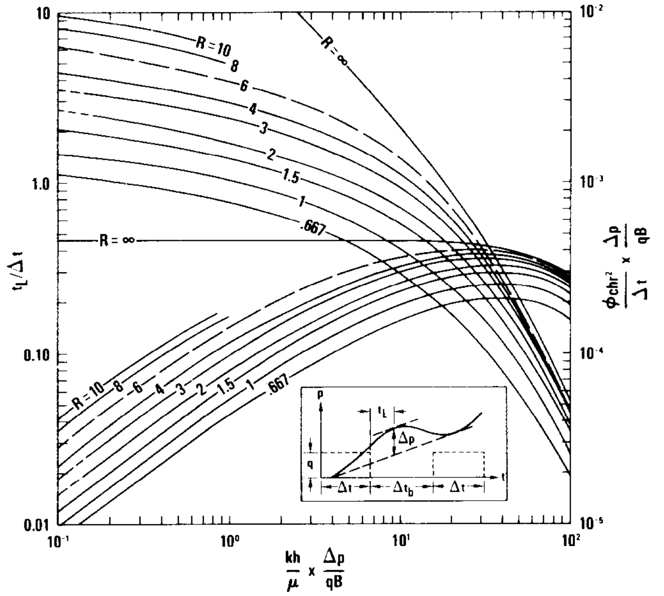

FIGURE 2 PULSE-TEST ANALYSIS CHART · FIRST PULSE RESPONSE

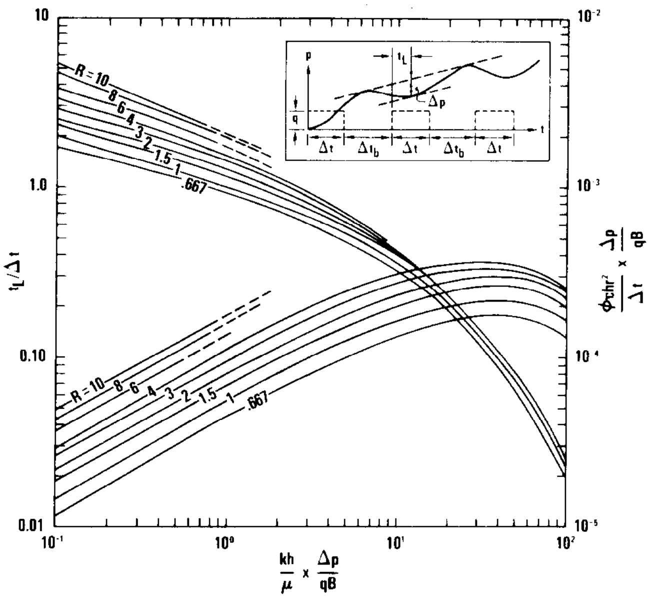

FIGURE 3 — PULSE-TEST ANALYSIS CHART · FIRST INVERSE RESPONSE

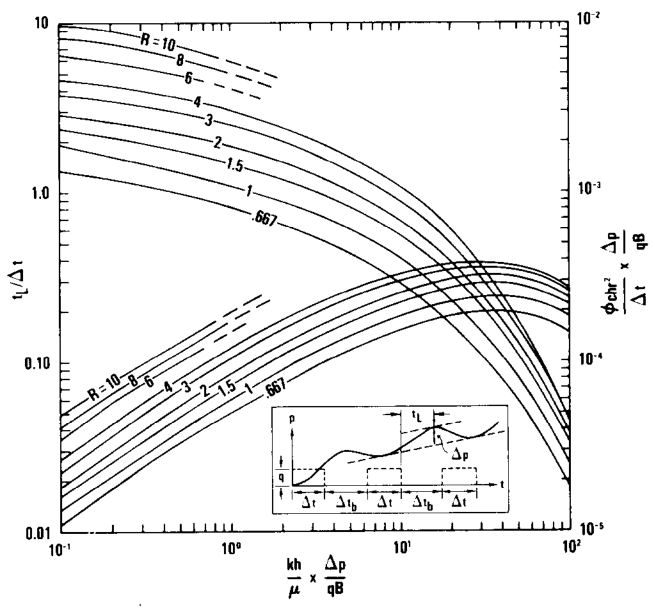

FIGURE 4 — PULSE-TEST ANALYSIS CHART · SECOND PULSE RESPONSE

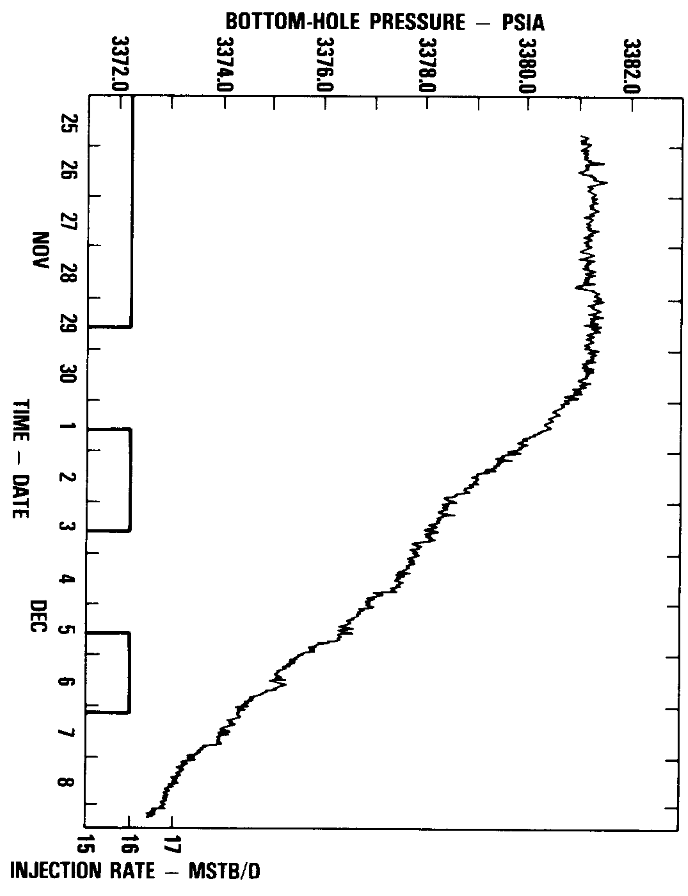

FIGURE 5 — PULSE TEST DATA

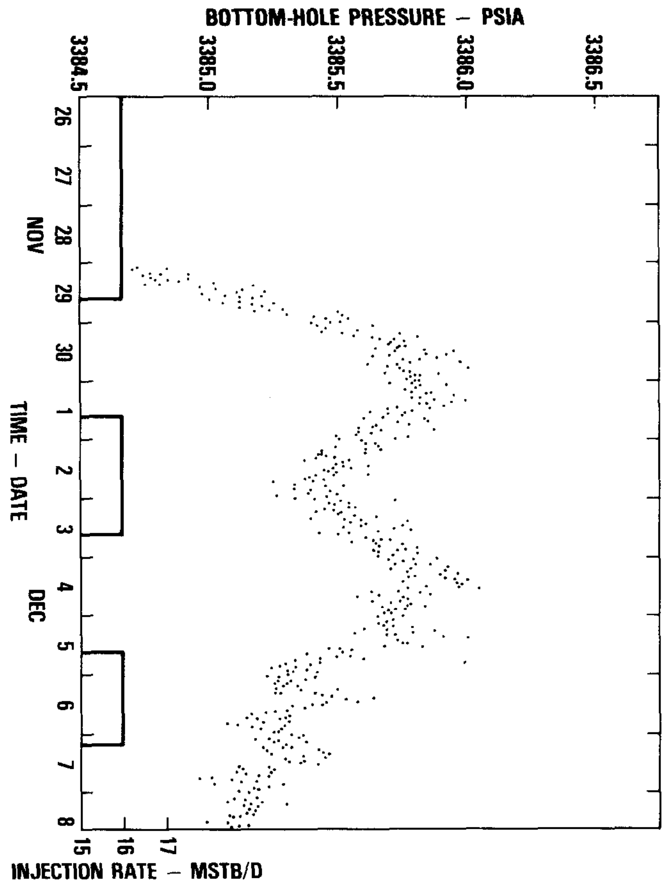

FIGURE 6 — PULSE TEST DATA OF FIGURE 5 WITH TREND REMOVED

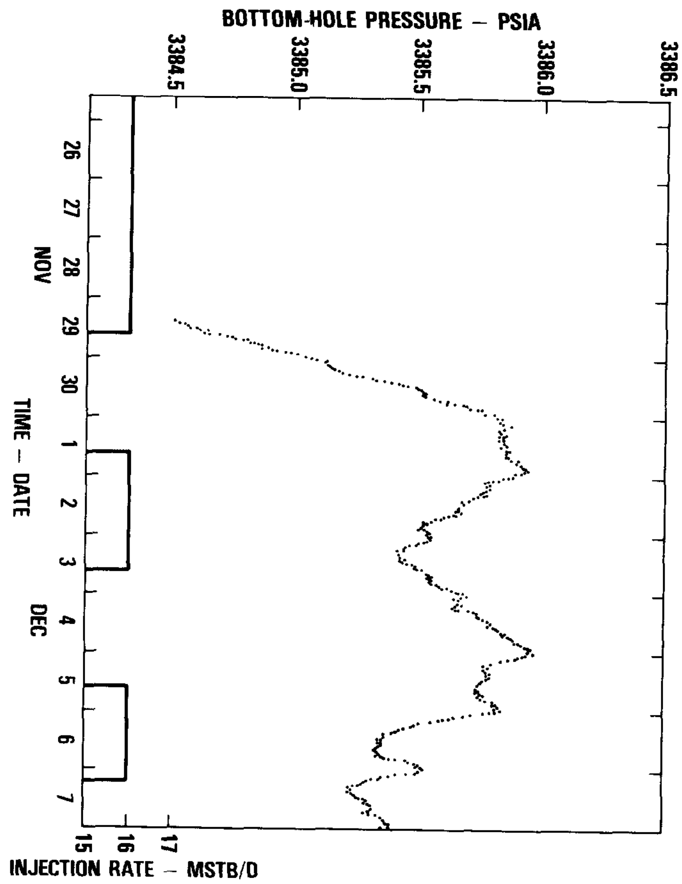

FIGURE 7 — PULSE TEST DATE OF FIGURE 6 WITH 5.5 HOUR AVERAGING

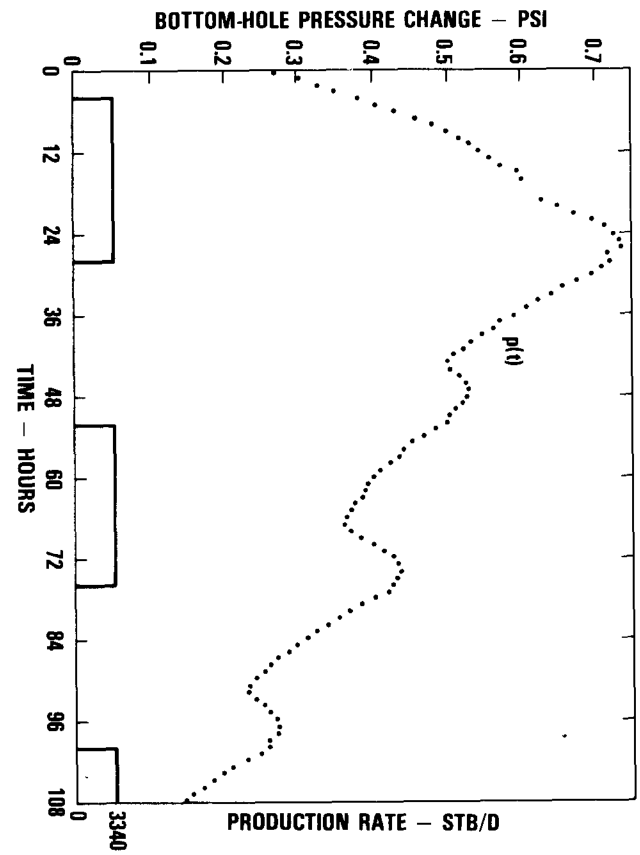

FIGURE 8 — PULSE TEST DATA - NO DISCERNIBLE RESPONSE

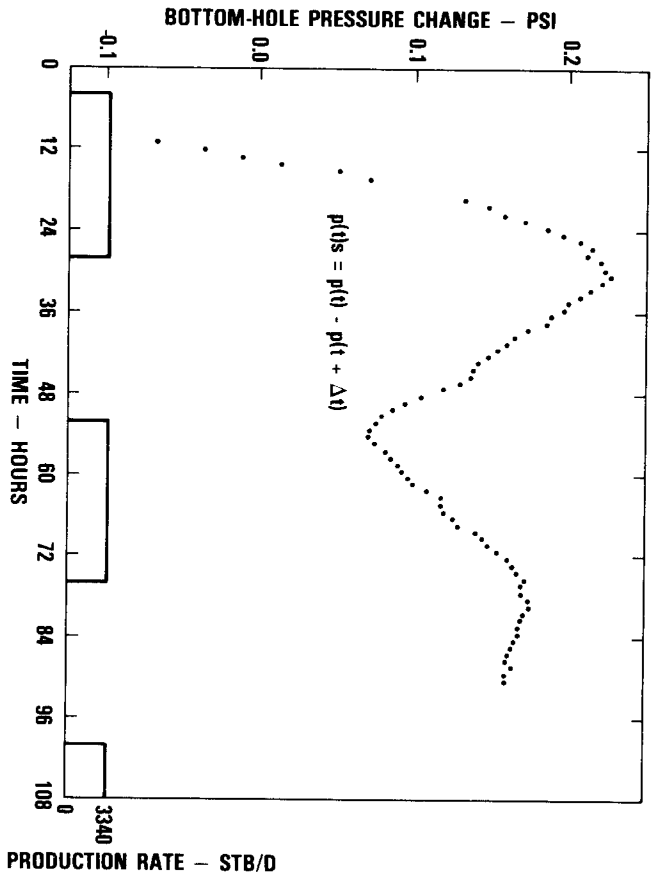

FIGURE 9 — STACKED PULSE TEST DATE OF FIGURE 8

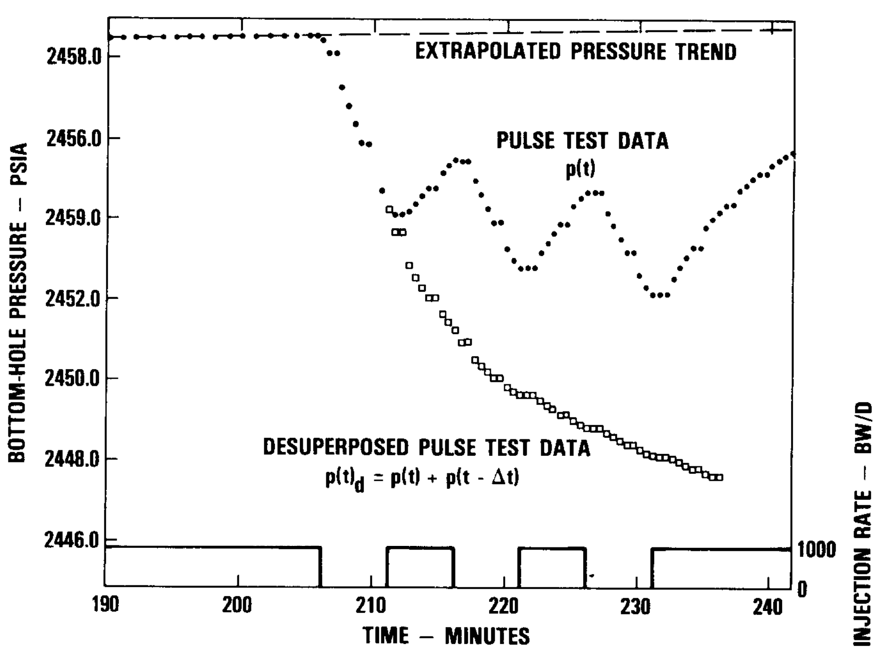

FIGURE 10 — DESUPERPOSITION OF PULSE TEST DATA

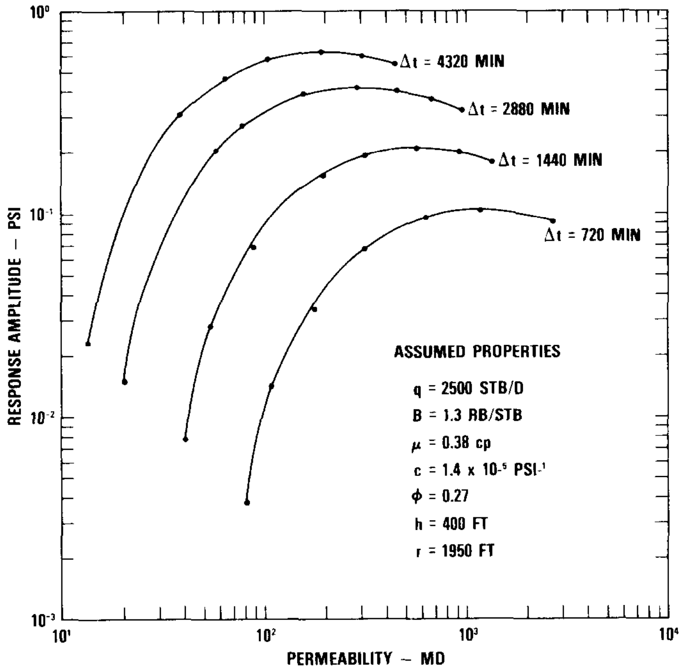

FIGURE 11 — EXAMPLE PULSE TEST DESIGN CHART