PROCEEDINGS, Eleventh Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 21-23, 1986
SGP-TR-93

THE SIGNIFICANCE OF EARLY TIME DATA IN INTERFERENCE TESTING FOR LINEAR BOUNDARY DETECTION

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ABSTRACT

This paper considers the significance of early time data for detecting linear boundaries using interference testing. When the ratio r_2/r_1 is greater than 5, existing methods of analysis may be used. For ratios of r_2/r_1 smaller than 5, special considerations are needed. When the ratio of r_2/r_1 is smaller than 2, there is no significant indication of the presence of a linear boundary in the pressure response. The effects of missing pressure data during the early time flow period, and earth tides on the linear boundary analysis are described and demonstrated with a flow test in the Ohaaki geothermal field in New Zealand.

INTRODUCTION

The detection of impermeable linear boundaries of reservoirs is of great importance in predicting the behavior of these reservoirs under exploitation. These linear boundaries may be detected and located by the analysis of their effect on nearby wells, both observation and source wells. *Stallman* [1952] presented log-log type curves for a constant rate line source producing near a linear boundary. *Stallman* extended the line source solution presented by *Theis* [1935], using the method of images to generate the linear boundaries. The pressure-time response can be matched to the *Stallman* [1952] curves, and the ratio r_2/r_1 may be estimated.

The estimation of the ratio r_2/r_1 using the log-log match is difficult. The curves are closely spaced and interpolating between the curves can lead to a great deal of uncertainty. *Davis and Hawkins* [1963], *Witherspoon et. al.* [1967], and *Earlougher* [1977] developed the semi-log double straight line analysis method. This method is based on the observation that the infinite acting early time data produce a semi-log straight line after a dimensionless time of ten, and the late time data cause the slope of this straight line to double. *Davis and Hawkins* [1963] and *Witherspoon et. al.* [1967] discussed the several limitations of the double straight line analysis method. If either of the semi-log straight lines has not developed, the method cannot be used. Interference responses typically display boundary effects prior to a dimensionless time of ten, hence, may not produce the first infinite acting semi-log straight line.

Sageev et. al. [1985] presented a dimensionless semi-log analysis method for detecting the distance between the image and the observation wells. In the case of analyzing pressure data from the source well, this method yields the distance between the source well and the linear boundary. *Sageev et. al.* [1985] presented a method that requires either the two straight line development or one of the straight lines and the transition between them. Their semi-log type curve is applicable for ratios of r_2/r_1 greater than 5. *Leaver et. al.* [1985] presented applications of this semi-log type curve matching method for the drawdown or injection flow periods for detecting a linear boundary in the Ohaaki geothermal field in New Zealand. *Leaver et. al.* [1985] also presented applications of two buildup analysis methods for detecting linear boundaries developed by *Fox* [1984] and *Eipper* [1985].

This paper concentrates on the detection of impermeable linear boundaries from interference tests with small values of the ratio r_2/r_1. First, the theoretical effects of a linear boundary are described in view of the log-log and semi-log pressure-time responses, and the semi-log pressure derivative responses. Then, the effects of missing pressure data during the early time flow period are described. Finally, the potential effects of earth tides and barometric pressure on the early time pressure response of an observation well are discussed. Pressure-time data from the Ohaaki geothermal field in New Zealand are used to demonstrate the effects of missing data and earth tides.

THEORY

The method of images of line sources is used to generate the effects of an impermeable linear boundary (*Carslaw and Jaeger* 1960, *Kruseman and De Ridder* 1970, and *Ramey et. al.* 1973). A schematic diagram of a semi-infinite system bounded by an impermeable linear boundary is presented in Figure 1. The dimensionless pressure solution for this system is:

$$P_D = -\frac{1}{2}\left[E_i(-X_1) + E_i(-X_2)\right] \quad (1)$$

where the dimensionless terms are defined as:

$$X_i = \frac{r_{Di}^2}{4t_D} \quad (2)$$

$$p_D = \frac{2\pi kh(p_i - p)}{q\mu} \quad (3)$$

$$t_D = \frac{kt}{\phi\mu c_t r_w^2} \quad (4)$$

$$r_D = \frac{r}{r_w} \quad (5)$$

The dimensionless pressure responses of semi-infinite systems bounded by an impermeable linear boundary are

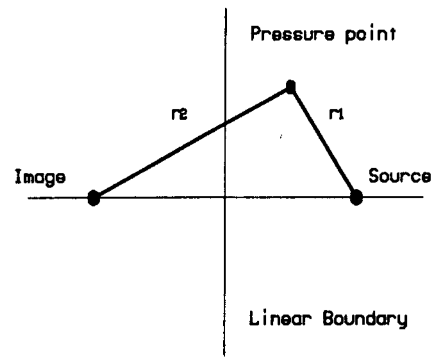

FIGURE 1: A schematic diagram of semi-infinite system.

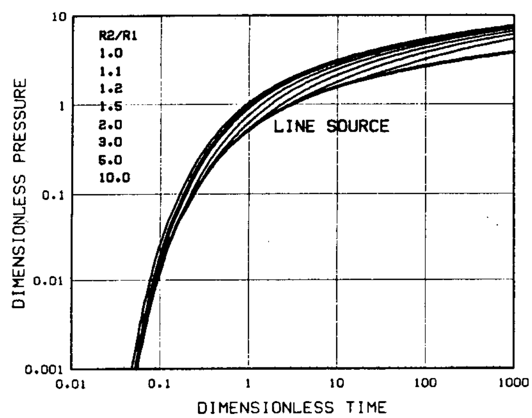

FIGURE 2: Log-log type curve for a semi-infinite system. (After *Stallman*, 1952).

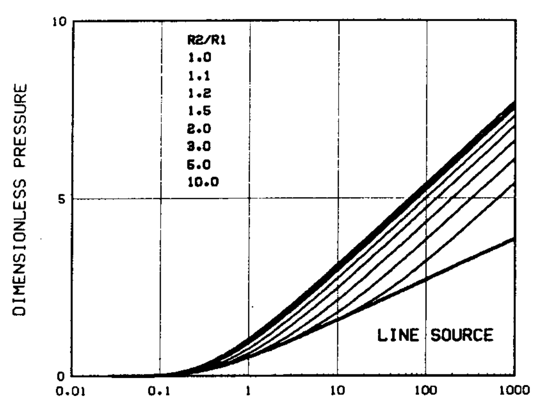

FIGURE 3: Semi-log type curve for a semi-infinite system.

presented in Figures 2 and 3. Figure 2 is similar to the log-log *Stallman* [1952] type curve. The ratio r_2/r_1 varies between 1 and 10. The lowermost curve in Figure 2 represents the *Theis* line source solution. The uppermost curve represents a semi-infinite system where the observation point is adjacent to the boundary, yielding an r_2/r_1 of unity. In view of Equation 1, this curve is a sum of two identical exponential integrals, and is shifted by a factor of 2 in the vertical direction form the line source curve. As the value of the ratio r_2/r_1 increases, the dimensionless pressure response departs from the line source solution at later times, as the effects of the impermeable boundary become significant at the observation point.

Figure 3 is a semi-log presentation of the same data as in Figure 2. *Sageev et. al.* [1985] showed how all the semi-log curves for r_2/r_1 ratios greater than 5 may be collapsed to a single curve. The curves having r_2/r_1 ratios smaller than 5 depart form the line source curve before the first semi-log straight line develops, and are not similar to each other in early times. Hence, these curves may not be collapsed to a single curve. The curves having r_2/r_1 ratios between 1 and 1.5 are closely spaced in both Figures 2 and 3, making log-log and semi-log type curve matching difficult.

The similarity of the curves for small values of the distance ratio is presented in Figure 4. In this figure, the line source curve is translated along the time and pressure axes by factors of 1.075 and 1.96 respectively, to match the curve for an r_2/r_1 of 1.1. The two curves match well. The square of the difference between these two curves is presented in the lower thin curve in Figure 4. The two minima in the error curve represent the fact that the two matched curves cross each other twice. The difference between the two curves is smaller than the resolution expected even from very sensitive pressure recording devices. Hence, transient pressure data from wells near an impermeable linear boundary with an r_2/r_1 ratio of 1.1 can be matched successfully to the line source solution. Based on the translation of the line source curve, this match would yield almost the correct storativity but a transmissivity which is a factor of 2 lower. No indication of the presence of an impermeable boundary would be present.

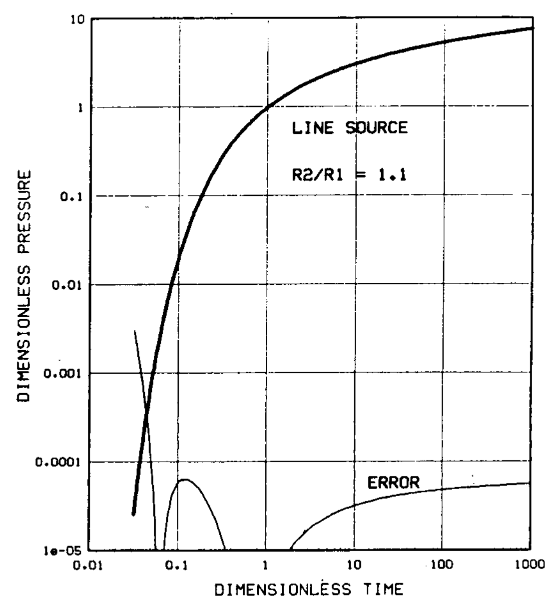

FIGURE 4: A log-log match of the line source curve to the curve for $r_2/r_1 = 1.1$.

A standard procedure in analyzing interference pressure data that match the line source solution is to evaluate the minimum reservoir area that is free of any boundaries. In the case of a linear boundary, this area is elliptical in shape, as described by *Vela* [1977]. This analysis with interference data coming from a configuration with a distance ratio less than 2 will over estimate the reservoir area free of boundaries. The magnitude of this over estimation depends on the duration of the test. For example, if a pressure response with a distance ratio of 1.1 matches the line source up to a dimensionless time of 20, the minimum distance ratio determined from this match would be 10. This match would locate the linear boundary at a distance ten times further than the actual boundary location.

The results from an interference test with a distance ratio smaller than 2 should be compared with results from other responses in observation wells or the source well. In the case of the source well, the distance ratio is large and the distance ratio and transmissivity may be estimated. The difference between the transmissivities of the source well and the observation well may indicate the correct match of the interference data.

Although the curves for r_2/r_1 ratios of 1.1 and 1.5 are very similar to the line source, the curve for an r_2/r_1 ratio of 2 is unique, and cannot be matched to the line source curve. Figure 5 presents the two curves without any translation. This yields an early time match to the infinite acting line source response, but after a dimensionless time of 1, the two curves are different. This can also be seen in the error curve. The error is small at early time, and increases rapidly with time. Figure 6 presents a late time match of the line source to the curve for an r_2/r_1 ratio of 2. Here, the early time line source behavior is not matched, as described by the error curve. The minimum in the error curve is caused by the two curve crossing one another. Hence, the line source curve cannot match simultaneously the early time and the late time responses of an observation well with a r_2/r_1 ratio of 2, and the detection of a linear boundary is possible.

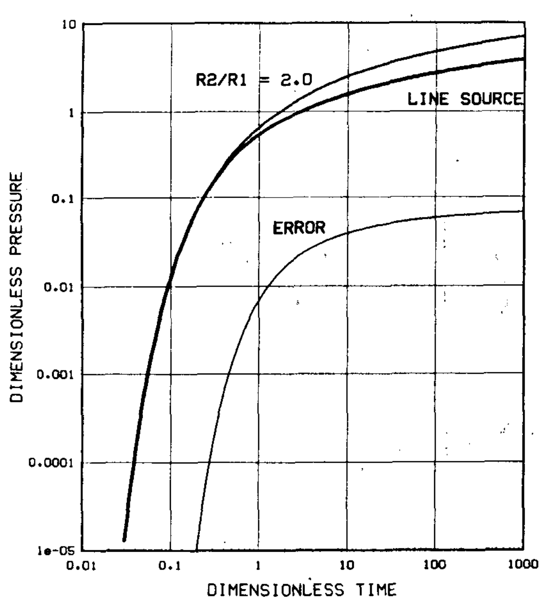

FIGURE 5: A log-log response of the line source and a semi-infinite system with $r_2/r_1 = 2.0$.

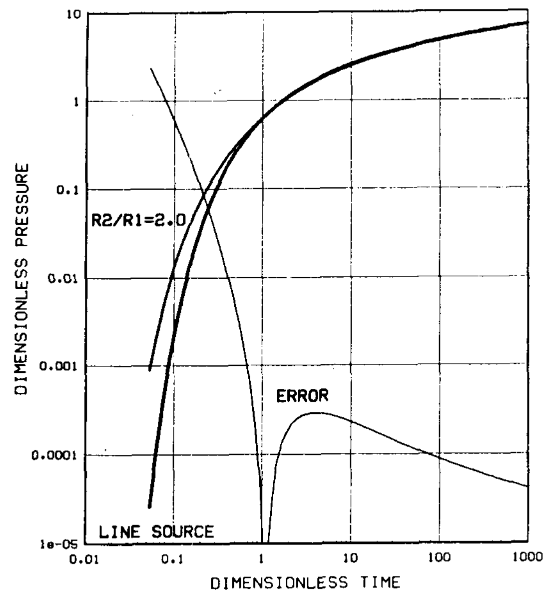

FIGURE 6: A log-log response match of the line source curve to the curve for $r_2/r_1 = 2.0$.

The log-log and the semi-log responses are summarized in Figure 7. The upper family of curves represents the log-log pressure responses, as presented in Figure 2. The lower family of curves, translated by a factor of 5 for display purposes, represents the semi-log pressure derivatives. From the pressure derivative curves, it is clear that for r_2/r_1 ratios greater than 5 the semi-log type curve matching technique is applicable because there is a distinct transition between the infinite and the semi-infinite behaviors. Pressure responses from cases with r_2/r_1 ratios between 2 and 5 can be analyzed using the type curves presented here, since these responses are significantly different from the line source. Also, pressure responses with r_2/r_1 ratios smaller than 2 can be matched to the line source curve, and may lead to erroneous estimations of some reservoir parameters.

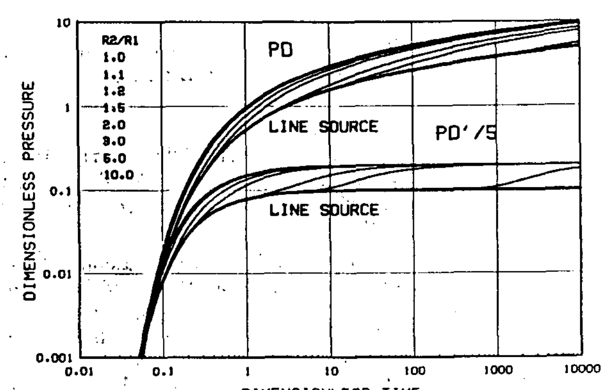

FIGURE 7: Log-log type curve for dimensionless pressures and semi-log dimensionless derivatives for a semi-infinite system.

MISSING DATA

The detection of linear boundaries from transient pressure tests is based upon the transition between the infinite acting and semi-infinite acting pressure responses. If this transition is not present little can be done to detect the linear boundary. Some tests may have the required time span for the detection of a linear boundary, but, for human or mechanical reasons, some of the pressure data are missing. Local sampling problems that arise from discretizing the time and pressure domains are not considered. Local sampling is assumed adequate. Concern is with a time period of missing pressure data that is significantly longer than the sampling intervals required for transient pressure analysis.

Figure 8 presents an example of missing pressure data form a drawdown buildup test in the Ohaaki geothermal field in New Zealand. Test C3 was started on May 1, 1984 and the drawdown portion of it lasted for 339 hours. The active well, BR20, produced at a constant rate of 84 *l/s*, and pressures were measured with a quartz crystal gauge at the observation well, BR34. The distance between the two wells was 1145 meters. The pressure scale in Figure 8 is normalized by the flowrate measured during the test. Pressures were not recorded from the 12th to the 54th hour of the test. The early time data of this test, prior to 10 hours, are affected by earth tides and barometric pressure changes, and will be discussed in the next section.

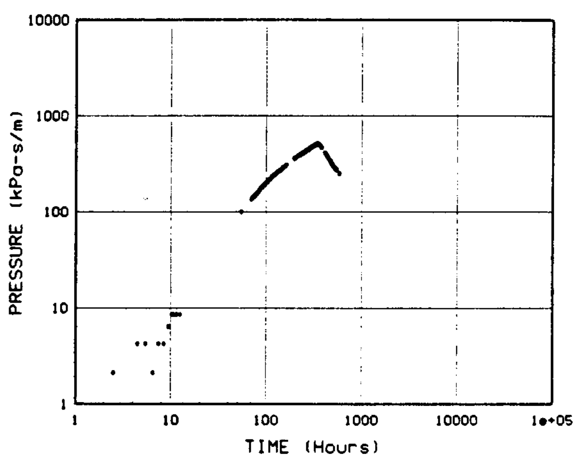

FIGURE 8: Pressure data from Test C3 in the Ohaaki geothermal field, New Zealand.

How does the fact that some of the pressure data are missing affect the analysis of the test? We will consider a hypothetical case and then present the attempts to analyze the test from Ohaaki.

Consider the interference pressure response from a semi-infinite reservoir with a distance ratio of 2. Figure 9 presents four cases of pressure responses, three of which have missing pressure data. Figure 9A is the complete response that spans the transition flow period, and can be successfully analyzed for the detection of the linear boundary. In Figure 9B, a log cycle of the data during the transition is missing. Yet, the early time infinite acting response and the late time semi-infinite response are well defined. The two portions of the pressure data cannot be

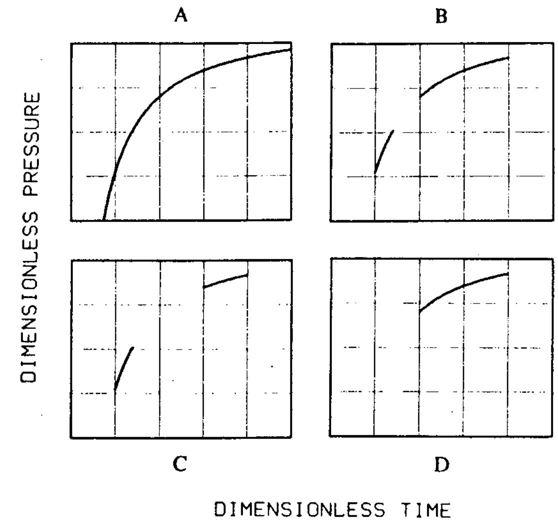

FIGURE 9: Hypothetical cases for missing pressure data, $r_2/r_1 = 2.0$.

matched to the line source simultaneously, and the data can still be successfully analyzed for detecting the linear boundary.

The pressure response presented if Figure 9C has a longer period of missing data than the response of Figure 9B. Yet, this pressure response can be successfully analyzed since the infinite and the semi-infinite responses are well defined. In the pressure response presented in Figure 9D, all the infinite acting pressure response is missing. The late time semi-infinite response can erroneously be matched to the line source curve, hence, yielding incorrect reservoir parameters, and providing no indication of the presence of a linear boundary.

The first ten hours of the test from Ohaaki are influenced by earth tides and barometric pressures, making the condition of data in this test similar to the response presented in Figure 9D. Various matches of the drawdown data of this test are presented in Figure 10. The distance ratio varies between 1.2 and infinity (for the line source).

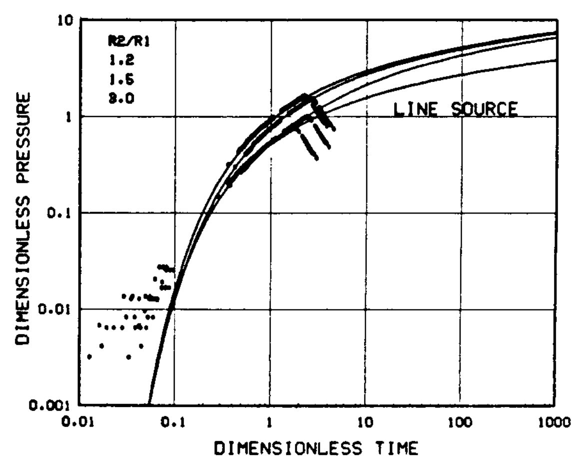

FIGURE 10: Four possible log-log matches of Test C3 data to the *Stallman* type curves.

The storativities derived from the log-log match vary by a factor of less than 2, but the transmissivities vary within an order of magnitude. Without information from other flow tests, the analysis of the pressure data is ambiguous. In this case, the pressure data are missing in the time period that is required to establish the infinite acting response of the reservoir, and the late time data represent the semi-infinite behavior. Hence, a unique analysis of this tests is not possible.

EARTH TIDES AND BAROMETRIC PRESSURE

Some pressure recording techniques require adjustments and corrections that account for pressure changes caused by earth tides and barometric pressure. The data from the test in the Ohaaki field were obtained by a quartz crystal gauge and corrections were applied. In this section, we describe the effects of the combined earth tides and barometric pressure and present an attempt to reconstruct the background atmospheric pressures. Then, some simulated interference responses are described along with some practical aspects of processing the early time data. A generalized analysis method for earth tides and barometric pressures is not presented.

Figure 11 presents a record of the barometric pressure at the Ohaaki field during the the time that the flow test was carried out. Daily oscillations are detectable on this large scale figure, and major trends of the barometric pressure over periods of days and weeks can be established. The first ten days of this record are presented in Figure 12. We concentrate on a five day period between 24 and 144 hours of this record. In this period, a linear overall decline of the barometric pressure is evident. In addition, the daily oscillations are distinct, and are a combination of two sine waves with different amplitudes.

The first sine wave has a daily cycle, and the second sine wave has two cycles per day. This second sine wave with the higher frequency is responsible for the small depressions at the top of each pressure cycle that occurs at noon time in each of the five days. Hence, there is one linear overall pressure decline that represents the regional barometric trend, and two oscillatory pressure functions, superimposed on the linear pressure trend, caused by the sun and the moon.

Figure 13 presents a simulated pressure response of these three pressure functions. The thick oscillating curve that displays similar characteristics to the Ohaaki barometric record, is the sum of the three other curves on the figure. The amplitude of the high frequency wave is 0.7 the amplitude of the low frequency wave. Also, there is a phase shift of 0.6π assigned to the high frequency wave.

Figure 14 presents a match of the simulated barometric pressure of Figure 13 to the five day record presented in Figure 12. The match is quite good. The intention is to demonstrate that knowing the barometric pressure during the flow test, and matching it to simulated responses may help in the future to filter out their effects from reservoir pressure data. Also, it may be possible after deconvolving the barometric pressure into its components, to evaluate reservoir properties such as storativity and transmissivity.

The effects of earth tides may be significant during the early time response of an observation well. On a dimensionless match to the line source, there are three parameters that determine the importance of earth tides: the amplitude, the phase with respect to the start of the test,

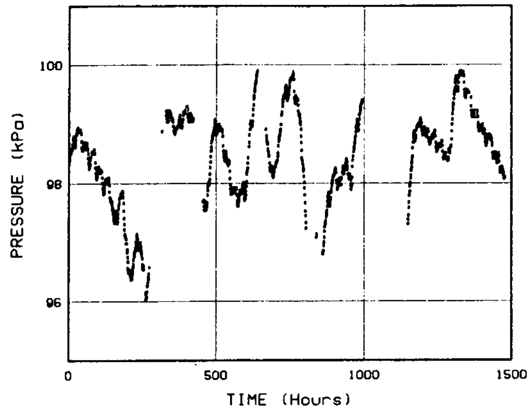

FIGURE 11: Barometric record during Test C3.

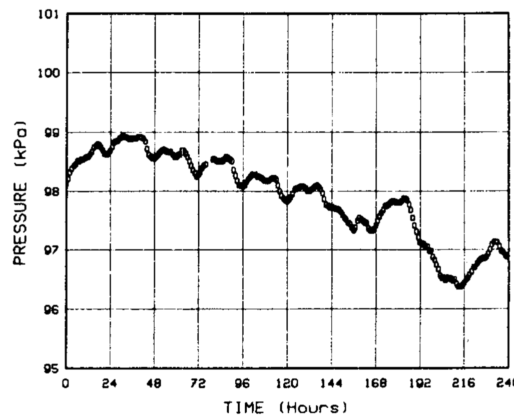

FIGURE 12: The first 240 hour of the barometric record presented in Figure 11.

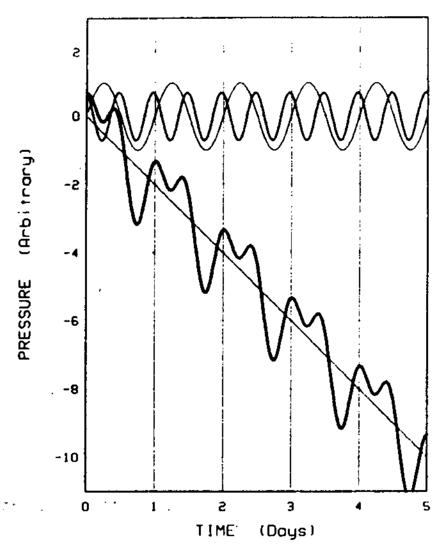

FIGURE 13: A superposition of two earth tide related sine wave functions and one linear barometric pressure function.

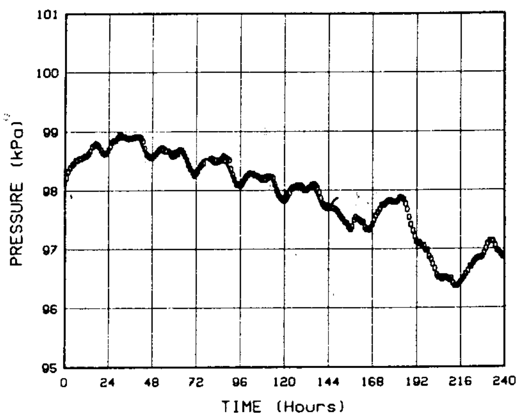

FIGURE 14: A match of five days of the barometric pressure record by a response composed of two sine waves and one linear pressure function.

and the frequency. Figure 15 presents three hypothetical earth tide effects superimposed on the line source curve. The curve denoted by A has a dimensionless pressure (p_D) amplitude of 0.05, a zero phase, and a dimensionless time (t_D) frequency of 0.2. The large amplitude causes the oscillations of the pressure to extend up to a dimensionless time of 1. The other two curves denoted with B and C have a dimensionless pressure amplitude of 0.01, and there are no oscillations present. Both these curves have a zero phase, but have different frequencies. Curve B has double the frequency of curves A and C. With combinations of different phases and frequencies it is possible to get oscillations at early time even with low amplitudes.

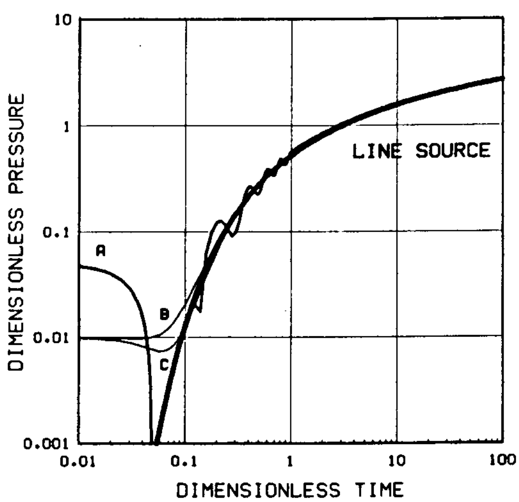

FIGURE 15: Superposition of the line source with a single sine wave.

The data from the Ohaaki test matched to the various curves in Figure 10 indicate a dimensionless pressure amplitude of 0.01, and a dimensionless time frequency of 0.2. This is one of the reasons for the deviation of the early time data prior to 10 hours, that cannot be matched to the line source. The linear barometric pressure decline was not considered since it had a smaller effect than the earth tide effects. Some processing methods may call for smoothing of pressure data or clipping of anomalies where the pressure declines unexpectedly. The magnitude of interference pressure changes in the early time flow period may be of the same order of magnitude as the earth tide and barometric pressure changes. Under such conditions, smoothing or clipping may lead to loss of information.

DISCUSSION

The main advantage of interference testing over source well testing for detecting reservoir limits is the increased characteristic length scale. When analyzing source well pressure data, the characteristic length scale is the diameter of the wellbore, that is typically on the order of a few inches. In interference testing, the characteristic length scale is the distance between the observation well and the source well, that is on the order of tens or hundreds of feet. Also, some near wellbore effects are not significant in interference testing, for example, wellbore skin in the source well in a constant rate test.

The main disadvantage of interference testing is the decreased amplitudes of the pressure changes. As the observation well is located further form the source well, the space resolution increases but the magnitude of the pressure changes decreases. These are competing effects that have to be addressed during the design stages of a test. When the early time pressure changes are small, the effects of earth tides and barometric pressure may be significant, and might lead to large uncertainties in the estimation of reservoir parameters.

In the case of interference testing for linear boundary detection, there is an added problem that is purely geometrical. As we have shown in the Theory section, for distance ratios smaller than 2, it is practically impossible to detect the presence of an impermeable linear boundary, regardless of the actual distance between the observation well and the source well.

CONCLUSIONS

1. Interference tests with a distance ratio greater than 5 may be analyzed for the detection of impermeable linear boundary using the current log-log and semi-log dimensionless type curve matching techniques.
2. Interference tests with a distance ratio between 2 and 5 may be analyzed for the detection of a linear boundary using type curves presented in this paper.
3. Interference tests with a distance ratio less than about 2 have a response similar to the line source, making linear boundary detection impossible.
4. Interference test data with distance ratios smaller than 2 matched to the line source yield an over estimation of the minimum distance between the observation well and the image well.
5. Analysis of interference pressure data for the detection of an impermeable linear boundary require two out of the three flow periods: the infinite acting response, the transition response between the infinite and the semi-infinite flow periods, and the semi-infinite response.
6. When missing pressure data leave only one distinct flow period, a unique analysis is not possible, as demonstrated by test C3 in the Ohaaki geothermal field.

7. Early time interference pressure changes may be of the same magnitude AS earth tide and barometric pressure changes. In such cases, significant deviations from the line source response are expected.
8. Clipping or smoothing of the early time pressure data may cause loss of information. Atmospheric pressures should be recorded, and if necessary, filtered out of the interference data.
9. Five days of the atmospheric pressure record from Ohaaki were matched with a combination of two earth tide related sine waves and a linear barometric function.

ACKNOWLEDGEMENTS

J. D. Leaver acknowledges the permission of the Commissioner of Works, Ministry of Works and Development, New Zealand to publish this paper. Test data collected by M.W.D., Wairakei, was filtered and supplied by Mark McGuinness, Applied Math. Division, DSIR, Wellington. Financial support was provided by M.W.D., New Zealand, N.Z.E., New Zealand, Stanford Geothermal Program, DOE Contract No. DE-AT02-80SF11459, and by Stanford University.

NOMENCLATURE

- c_t compressibility
- h formation thickness
- k permeability
- p pressure
- p_D dimensionless pressure, $2\pi kh(p_i-p)/q\mu$
- q flowrate
- r radius from source well
- r_D dimensionless radius, r/r_w
- r_w wellbore radius
- r_1 distance between observation and source wells
- r_2 distance between observation and image wells
- t time
- t_D dimensionless time, $kt/\phi\mu c_t r_w^2$
- ϕ porosity
- μ dynamic viscosity

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