WELL TEST ANALYSIS RESEARCH

H.J. Ramey, Jr., R.N. Horne, F.G. Miller, and W.E. Brigham
Stanford University

INTRODUCTION

Well test analysis offers a rapid way to perform an initial assessment of geothermal systems. Well testing includes both pressure drawdown and buildup testing, and interference testing. Development of new well test analyses receives major emphasis in the Stanford Geothermal Program. During the year, quite a few studies were completed, and reports and papers presented on a variety of well test analysis methods. The following summarizes some of the more important results.

(a) Constant Pressure Testing

Although the conditions which result in constant pressure flow often exist for geothermal production and injection wells, the methods for analyzing the resulting rate transients and pressure buildup for such wells have been incomplete or nonexistent. The objective of this work was to review the existing methods of analysis and to contribute new solutions where needed in order to produce a comprehensive well test analysis package for wells produced at constant pressure. The work was completed during the year, and a technical report, SGP-TR-36, has been published. Other publications of results from this project are given by Ehlig-Economides and Ramey (April, September, November 1979).

(b) Parallelepiped Models

These models have been successful in demonstrating three-dimensional boundary effects in geothermal reservoirs. Last year's work in this area focused on a three-dimensional reservoir contained on all sides and at the top by impermeable boundaries, with a constant pressure boiling surface at the base. These models (either with a partially penetrating well or fracture) were used successfully to analyze well test data from The Geysers and the Travale-Radicondoli fields (see Economides et al., 1980). This year's activities extended the model to include the configuration of a three-dimensional reservoir with a boiling surface at the base and a condensation surface at the top. This situation is characteristic of the Kawah Kamojang field in Indonesia, and also of some parts of The Geysers. Typical drawdowns for such a system are illustrated in Fig. 1. The objective of this study is to produce generally useful type-curves with an emphasis on detection of the outer limits of the reservoir. It is also intended that these models be used to represent the entire drainage volume for a power plant (encompassing ten or more wells).

(c) "Slug Test" DST Analysis

The solutions for the slug test (decreasing flowrate) drill stem test (DST), including wellbore storage and skin effect, were presented by Ramey et al. in 1975. In field data from slug test DSTs, an initial period of constant flowrate can often be observed. A new model which includes the initial constant flowrate for a slug test was developed. Type-curves were graphed which were then matched with field data. The slug test type-curves can be applied to both the flow period and the pressure buildup after a short initial shut-in in a DST. A special feature of the new type-curves is that they may be used to estimate the initial formation pressure from the initial cleanup flow pressure buildup data even when the flow is so short that a Horner buildup graph is not possible (see Shinohara and Ramey, 1979a).

In deep, high-rate wells, the inertia and momentum of the liquid moving in the wellbore become important. Most available pressure transient solutions neglect these phenomena. Sometimes the inertia effect can cause oscillation of the liquid level in the wellbore. An approximate method using an exponentially damped fluctuation was presented by van der Kamp in 1976. However, this method cannot be applied to the early time pressure behavior, which is often of interest. A complete analytical solution for this problem was found, and the resulting type-curves were graphed and matched with field examples. Figure 2 shows some of the new solutions. The parameter x_D represents the fractional liquid level rise following the sudden removal of the liquid from a static wellbore. This acts like opening a bottomhole valve in a DST when there is air in the drill pipe. The parameter α^2 is:

$$\alpha^2 = \frac{L}{g}\left(\frac{k}{\phi\mu c_t r_w^2}\right)^2$$

where L is the well depth and g is the acceleration of gravity. Other symbols have their usual interpretation. The term α^2 is a parameter which considers momentum or inertia of fluid in the wellbore. A value $\alpha^2 = 0$ is the usual slug test. When α^2 reaches values of 10^5 or more, the results differ greatly from the slug test. Oscillations occur when $\alpha^2 = 10^8$ or more. Both the skin effect and wellbore storage affect the results significantly.

This theory can also be applied to closed-chamber DSTs and water injection falloff tests. These results were published by Shinohara and Ramey (1979b), and by Shinohara (1980), to be published as SGP-TR-39.

(d) Analysis of Wells with Phase Boundaries

The analysis of pressure tests in geothermal reservoirs is often complicated by two-phase effects. This work investigated the effect of a phase boundary at a constant radial distance from the well, produced, for example, by the flashing of a water reservoir during production or by the injection of water into a steam or two-phase reservoir.

The results indicate the possibility of determining compressibility and permeability contrasts across the phase boundary. This enables estimation of the reservoir porosity and relative permeabilities in the two-phase region. In some cases, wellbore storage effects can disguise the pressure response and make parameter determination difficult.

Figure 3 shows an injection falloff in Broadlands well number BR26 which proved accessible to the new method of analysis.

This work was presented by Horne and Satman (1980), and Horne, Satman, and Grant (1980a). As an informal cooperative program with the New Zealand Department of Scientific and Industrial Research, it was also presented at the 1980 New Zealand Geothermal Workshop in November 1980, as Horne, Satman, and Grant (1980b).

(e) Internal Well Flows

Experience in analysis of temperature and pressure profiles in geothermal wells has indicated that flow frequently occurs from one production (interval) level to another--even though the well may be shut in at the wellhead. This flow occurs because pressure gradients in the reservoir are frequently greater than hydrostatic, while those in the well are restricted to be hydrostatic unless the fluid is moving. The recognition of these flows has been the subject of study by Grant (1979) based on a number of observations, including temperature profiles during heatup, injection, etc. The present study investigated the difference between the observed pressure gradient in a shut-in well, and the inferred hydrostatic pressure gradient calculated using the simultaneously measured temperature.

Analyzing a shut-in temperature/pressure log from well M-9 at Cerro Prieto, it was determined that internal flow occurred below a depth of 2500 feet since the observed well pressure gradient changed sharply from hydrostatic at this depth (see Fig. 4). This well proved to be an excellent demonstration of the method because it is actually perforated at this depth; thus confirming the conclusion of the pressure gradient comparison.

Further tests using different Cerro Prieto wells are in progress. It is anticipated that the method may be useful for the one-step recognition of producing levels and internal flows, and may even be able to detect other perturbations such as casing leaks. The rapid evaluation of internal flows is of importance in the correct interpretation of all other pressure tests, and should be considered a first step in any pressure test.

(f) Naturally Fractured Reservoirs

This study presents solutions for declining production rates under constant pressure production in a naturally fractured reservoir. Solutions for dimensionless flowrate are based on the model presented by Warren and Root (1963). The model was extended previously by Mavor and Cinco-Ley (1979) to include wellbore storage and skin effect. In the present study, the model was extended to include constant producing pressure in both infinite and finite systems. Figure 5 shows the results obtained for a finite, no-flow outer boundary. The flowrate shows a rapid decline initially, becomes nearly constant for a period, and then a final decline in rate takes place. The new type-curves of the analytical solutions are graphed in terms of the following dimensionless parameters:

$$q_D = \frac{141.2\ qB\mu}{k_f h(p_i - p_{wf})}$$

$$t_D = \frac{2.637\text{x}10^{-4}\ k_f t}{[(\phi vC)_f + (\phi vC)_m]\mu r_w^2}$$

$$\lambda = \alpha \frac{k_m}{k_f} r_w^2$$

$$\omega = \frac{(\phi vC)_f}{(\phi vC)_m + (\phi vC)_f}$$

where k_f and k_m are fracture and matrix permeabilities, respectively, v is the volume fraction of the fractures or matrix, $\phi_f C_f$ and $\phi_m C_m$ are fracture and matrix porosity-compressibility products, respectively, and α is the interporosity shape factor. The two parameters ω and λ are new governing dimensionless groups, and the remaining symbols have their standard SPE interpretation.

Portions of this work were presented at the SPE of AIME Annual Fall Meeting in Dallas, Texas, 1980 (Da Prat, Cinco-Ley, and Ramey, 1980). Work will continue in this area.

(g) Temperature-Induced Wellbore Storage Effects

Wellbore storage is usually attributed to pressure changes occurring in the well. This study found that wellbore storage is also affected by heat transmission and the resulting temperature changes that result from flow in the well. The inner boundary condition for solution of the diffusivity equation for a single-phase well in an infinite radial reservoir was stated so as to include a wellbore storage term depending on temperature changes. Using Laplace transform methods, an exact solution describing the pressure behavior of the fluid in the system was sought. However, due to the form of the term describing temperature changes in the wellbore, it was not possible to find a simple solution form. Nonetheless, the problem was prepared for solution using numerical inversion. Two-phase systems were also considered, and the inner boundary condition describing such a situation was also derived. Several examples of two-phase systems were described wherein the importance of temperature changes was apparent. A Master's Report was completed by Araktingi (1980). Further work is planned on this important class of problems.

CONCLUDING REMARKS

In addition to the preceding, many other field applications of well test analysis were conducted and reported during the year. Tests were performed and analyzed in the Ching-Shui Field, Taiwan (see Ramey and Kruger, eds., 1979), a new type-curve for interference testing was reported by Ramey (Third LBL Well Testing Workshop, 1980), and planning and analysis of preliminary well tests in the Miravalles Field, Costa Rica, were completed (Ramey, November 1980) during July 1980. Research on well test analysis should continue to be fruitful, and opportunities for field applications are becoming more frequent.

REFERENCES

Araktingi, U.: "Thermally-Induced Wellbore Storage Effects," Master's Report, Stanford University, Stanford, California, October 1980.

Da Prat, G., Cinco-Ley, H., and Ramey, H.J., Jr.: "Decline Curve Analysis Using Type-Curves for Two-Porosity Systems," Paper SPE 9292, presented at the 55th Annual Conference, SPE of AIME, Dallas, Texas, Sept. 21-24, 1980.

Ehlig-Economides, C.A.: "Well Test Analysis for Wells Produced at Constant Pressure," Ph.D. Dissertation, Stanford University, Stanford, California, June 1979; to be published as SGP-TR-36.

Ehlig-Economides, C., and Ramey, H.J., Jr.: "Pressure Buildup for Wells Produced at a Constant Pressure," Paper SPE 7985, presented at the 49th Annual California Regional Meeting, SPE of AIME, Ventura, California, Apr. 18-20, 1979(a).

Ehlig-Economides, C., and Ramey, H.J., Jr.: "Transient Rate Decline Analysis for Wells Produced at Constant Pressure," Paper SPE 8387, presented at the 54th Annual Technical Conference and Exhibition, SPE of AIME, Las Vegas, Nevada, Sept. 23-26, 1979(b).

Ehlig-Economides, C., and Ramey, H.J., Jr.: "Constant Pressure Testing for Geothermal Wells," Proc., New Zealand Geothermal Workshop, Auckland, New Zealand (Nov. 1979c), 255.

Economides, M.J., Ogbe, D., and Miller, F.G.: "Pressure Buildup Analysis of Geothermal Steam Wells Using a Parallelepiped Model," Paper SPE 8886, presented at the 50th Annual California Regional Meeting, SPE of AIME, Pasadena, California, Apr. 1980.

Grant, M.A.: "Interpretation of Downhole Measurements in Geothermal Wells," Department of Scientific and Industrial Research, Applied Mathematics Division, Report No. 88 (Dec. 1979).

Horne, R.N., and Satman, A.: "A Study of Drawdown and Buildup Tests in Wells with Phase Boundaries," Trans., Geothermal Resources Council (Sept. 1980), 4, 345.

Horne, R.N., Satman, A., and Grant, M.A.: "Pressure Transient Analysis of Geothermal Wells with Phase Boundaries," Paper SPE 9274, presented at the Fall Meeting, SPE of AIME, Dallas, Texas, Sept. 21-24, 1980(a).

Horne, R.N., Satman, A., and Grant, M.A.: "Pressure Transient Analysis of Geothermal Wells with Phase Boundaries," Proc., New Zealand Geothermal Workshop 1980, Auckland, New Zealand (Nov. 1980b).

Mavor, M.J., and Cinco-Ley, H.: "Transient Pressure Behavior of Naturally Fractured Reservoirs," Paper SPE 7977, presented at the 49th Annual California Regional Meeting, SPE of AIME, Ventura, California, Apr. 18-20, 1979.

Ramey, H.J., Jr.: "Drawdown and Buildup Type-Curve for Interference Testing," Third Invitational Symposium on Well Testing, Lawrence Berkeley Laboratory, Berkeley, California, Mar. 1980.

Ramey, H.J., Jr.: "The Miravalles Geothermal Reservoir, Costa Rica," Stanford Geothermal Program Seminar, Nov. 6, 1980.

Ramey, H.J., Jr., Agarwal, R.G., and Martin, I.: "Analysis of 'Slug Test' or DST Flow Period Data," J. Can. Pet. Tech. (July-Sept. 1975), 1-11.

Ramey, H.J., Jr., and Kruger, P., eds.: "Proceedings, Fifth Annual Workshop on Geothermal Reservoir Engineering," Stanford, California, Dec. 1979.

Shinohara, K.: "A Study of Inertial Effect in the Wellbore in Pressure Transient Well Testing," Ph.D. Dissertation, Stanford University, Stanford, California, Apr. 1980; to be published as SGP-TR-39.

Shinohara, K., and Ramey, H.J., Jr.: "Analysis of 'Slug Test' DST Flow Period Data with Critical Flow," Paper SPE 7981, presented at the 49th Annual California Regional Meeting, SPE of AIME, Ventura, California, Apr. 18-20, 1979(a).

Shinohara, K., and Ramey, H.J., Jr.: "Slug Test Data Analysis, Including the Inertia Effect of the Fluid in the Wellbore," Paper SPE 8208, presented at the 54th Annual Fall Meeting, SPE of AIME, Las Vegas, Nevada, Sept. 23-26, 1979(b).

van der Kamp, G.: "Determining Aquifer Transmissivity by Means of Well Response Tests: the Underdamped Case," Water Resources Research (Feb. 1976), 12, No. 1, 71-77.

Warren, J.E., and Root, P.J.: "The Behavior of Naturally Fractured Reservoirs," SPE J. (Sept. 1963), 245-255.

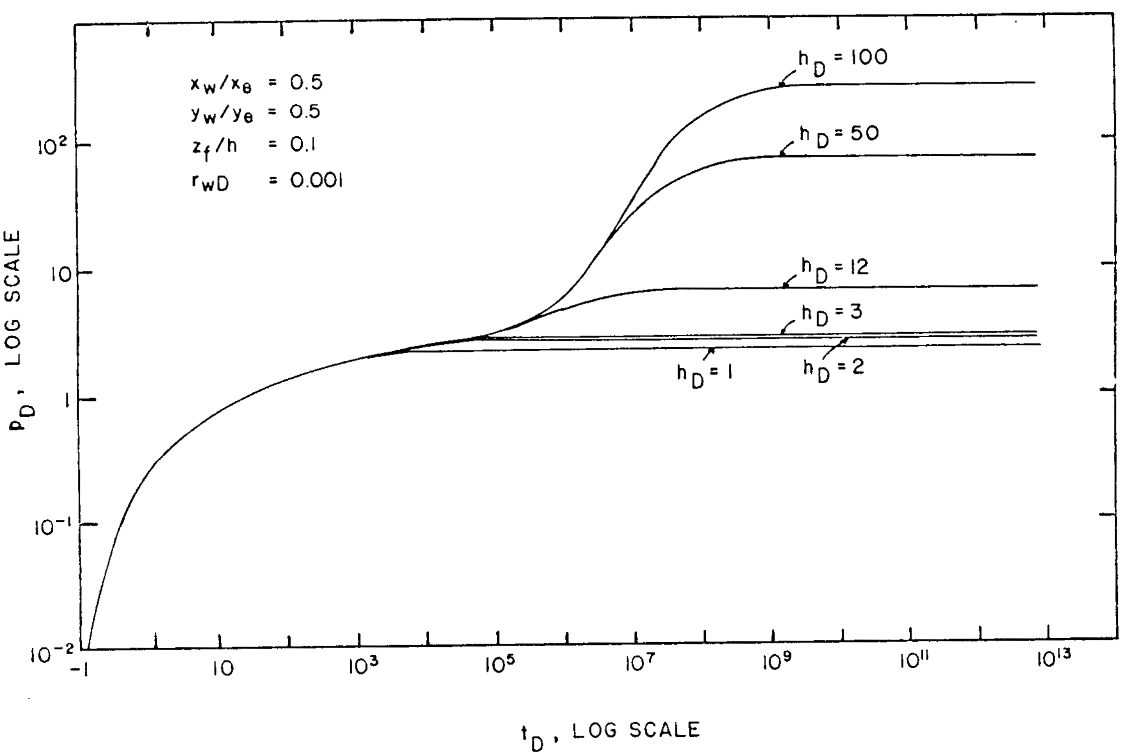

FIG. 1: LOG-LOG TYPE-CURVE FOR A PARALLELEPIPED MODEL

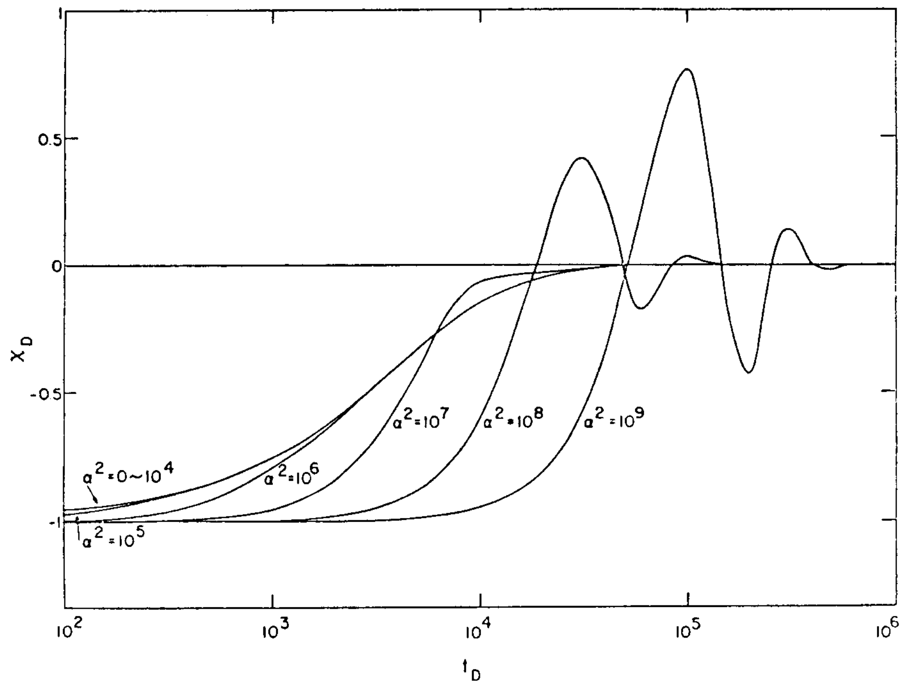

FIG. 2: UNDAMPED SLUG TEST (Shinohara, Apr. 1980)

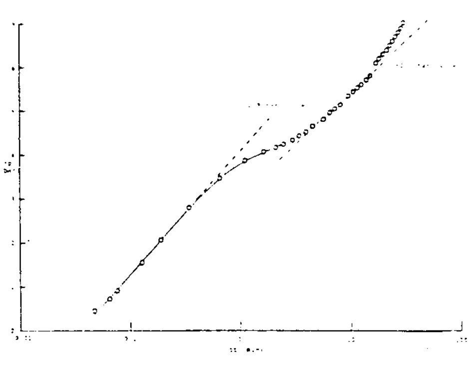

FIG. 3: PROJECTION FALLOFF TEST ON WELL BR26. SEMILOG COORDINATES.

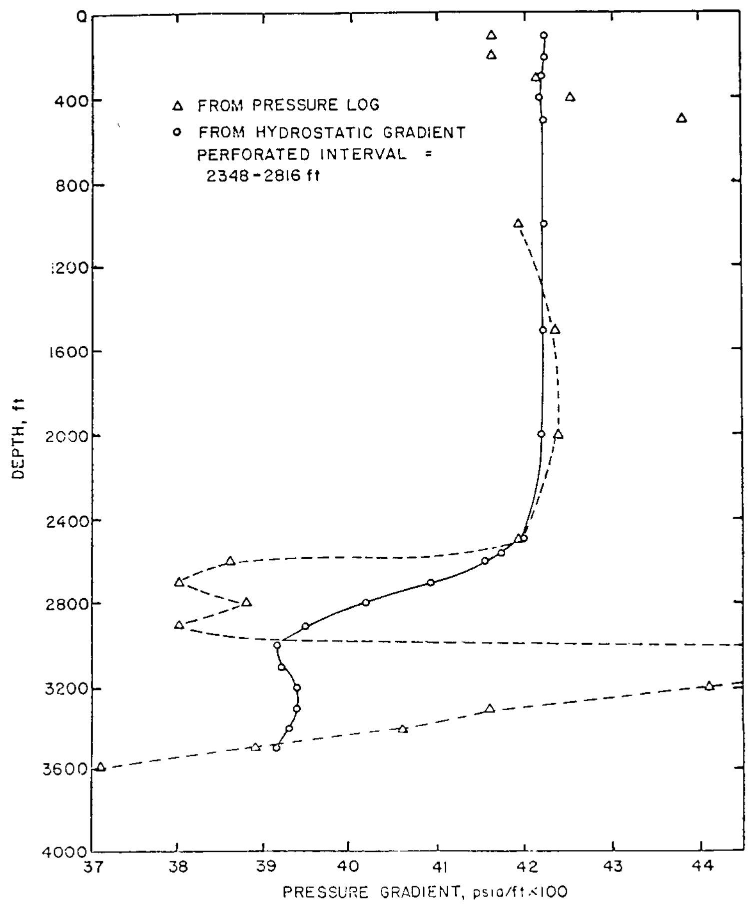

FIG. 4: PRESSURE VS DEPTH FOR WELL M-9, CERRO PRIETO, MEXICO

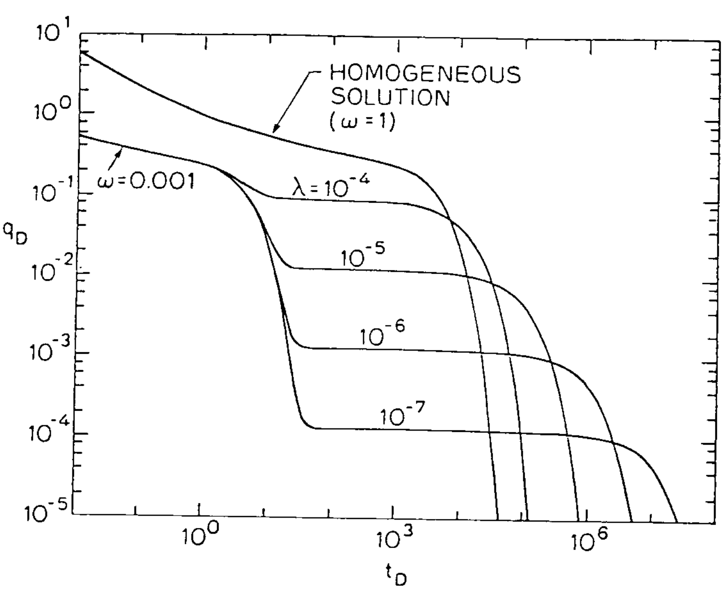

FIG. 5: q_D VS t_D FOR CONSTANT PRESSURE PRODUCTION; CLOSED BOUNDARY (r_{eD} = 50, SKIN FACTOR = 0)