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Transient Analysis of the 1991 Hijiori Shallow Reservoir Circulation Test

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Abstract

Like any dynamic system, HDR reservoirs cannot be fully characterized by their steady-state behavior. Circulation tests analysis should be performed on both the steady-state response and the transient response of HDR systems. Transient analysis allows not only estimation of critical reservoir parameters and how these parameters change with operating conditions / history, but transient analysis also aids in evaluating the feasibility of various modes of HDR system operation (base load, load following, etc.).

This paper details the transient analysis of NEDO's FY1991 Shallow Reservoir Circulation Test at the Hijiori HDR site in Japan. Reservoir fluid storage is carefully bounded through the employment of two distinct methods for calculation of the fluid storage from the observed transient response. A brief discussion is also included of the distribution of reservoir fluid storage; the relationship between pressure, reservoir stress, and apparent reservoir capacitance; and appropriate circulation test design to facilitate transient analysis.

Introduction

Hot Dry Rock (HDR) power production involves mining the heat from a hot dry geothermal reservoir[1]. Heat mining is accomplished by hydraulically circulating fluid through hot dry rock and extracting the absorbed heat from the produced hot water and steam. Careful engineering of HDR power production systems requires quantitative, but simplified (usable), physical models of the processes involved. This paper discusses one (key) operational process that must be engineered: hydraulic circulation of fluid through the reservoir.

A general quantitative understanding of HDR system hydraulics will allow estimation of the effects of different operating procedures (such as production back-pressure, water injection rate, and stimulation procedures) on the energy extraction rate, production flowrates, total fluid recovery efficiency, and, perhaps most importantly, the overall system economics. Operating conditions must be designed to achieve certain economic and environmental goals, for example: The injection rate must be chosen to maintain a sufficient energy extraction rate while keeping total fluid loss (recovery efficiency) at an acceptable level.

The authors began in 1994 development of a general HDR fluid circulation model as part of an effort to analyze, in detail, the 1991 circulation test that was performed in the Hijiori Shallow (1600 - 1900m) Reservoir. This hydraulic system model does not attempt to capture the detailed processes of the fluid flow and rock deformation; instead it allows the calculation and representation of the complete system impedances[2] (the pressure drop per unit of flow), fluid storage elements, and hydrostatic drives based on actual circulation test data. The HDR hydraulic system model was used to fully analyze the steady-state and transient behavior of the Hijiori Shallow Reservoir using the 1991 circulation test data[3]. Development of the system hydraulics model presented in this paper is the first phase of a larger effort to develop a comprehensive HDR evaluation and design package which will integrate reservoir heat transfer[4], system hydraulics, and production economics.

Test Overview

Since 1985, the New Energy Industrial Technology Development Organization (NEDO) has been working on the development of the Hot Dry Rock Project at the Hijiori HDR site, located

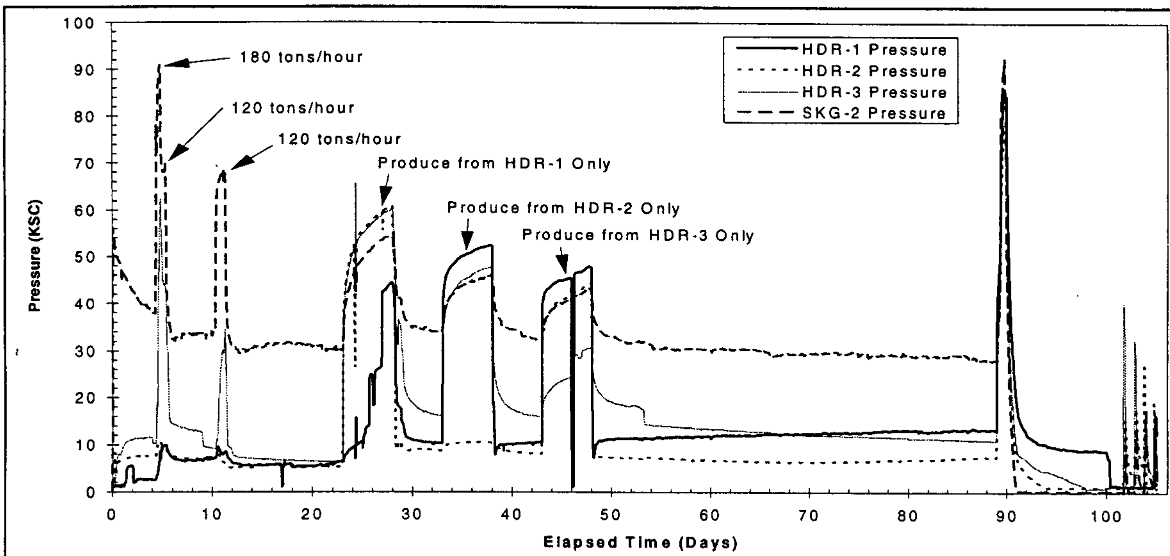

Figure 1. Surface Flowrates and Pressures for SKG-2, HDR-1, HDR-2, and HDR-3 from the Hijiori 1991 Shallow Reservoir Circulation Test.

inside a small caldera in Yamagata prefecture in northern Honshu Island, Japan. The circulation test performed in 1991 involved injecting 134,510 tons of water into the SKG-2 injection well over roughly 90 days; and producing 94,300 tons of hot water and steam from three production wells (HDR-1, HDR-2, and HDR-3).

The surface injection and production pressures over the 90-day test for all four wells are shown in Figure 1. The water injection rate at the SKG-2 well was held nearly constant at 60 ton/hr over the three month period, except for the one twelve-hour period high-rate injection of 180 ton/hr and two twelve-hour periods of 120 ton/hr (indicated on Figure 1) which were performed to test reservoir fill-up and achieve hydraulic stimulation of the reservoir. Analysis is presented of the impact on the reservoir hydraulics of these brief periods of high-rate injection (stimulation). There were also three, roughly five-day periods, of isolated production from only a single wellbore which were performed for each production well. These three periods during the middle of the circulation test are also indicated on Figure 1.

For the steady-state analysis, the model is used primarily to characterize the component flow impedances for the different parts of the circulation system (including inlet impedance, outlet impedance, reservoir impedance, and wellbore impedance), and to explore methods to reduce these impedances in order to optimize HDR power production (see Ref. 3 for a detailed description of the steady-state analysis results from the FY 1991 circulation test). Transient flow analysis, on the other hand, was undertaken in order to understand the transition between two distinct steady-state flow equilibriums. The transient analysis allowed estimation of the fluid storage within the circulation system and how the fluid storage changed over time.

Steady-State Analysis

The complex HDR reservoir dynamics are approximated by a simplified "lumped" system model. Complex fracture systems are represented as lumped flow paths with variable impedances and variable reservoir capacitance (storage). The model was designed to allow quantitative evaluation of the critical hydraulic parameters for an HDR system, with an arbitrary number of wellbores and reservoirs, and to calculate how these parameters (appear to) change with time and reservoir stimulation. Figure 2 shows a simplified two wellbore HDR system model.

The wellbore impedance in the injection and production well, the inlet and outlet impedances connecting the wellbores to the reservoir, and the reservoir impedance itself are all represented as resistive elements in the model. The surface pumping units and the hydrostatic heads, as well as the static reservoir pressure, are all represented as active elements. Steady-state analysis requires as the static reservoir pressure, are all represented as active elements. Steady-state analysis requires consideration of only the resistive and active system elements

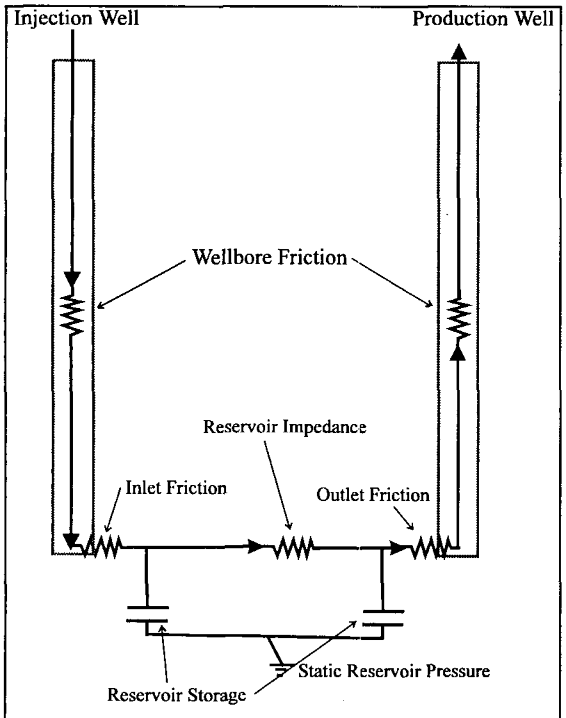

Figure 3. Schematic of a Simple Hot Dry Rock Power Generating System Model.

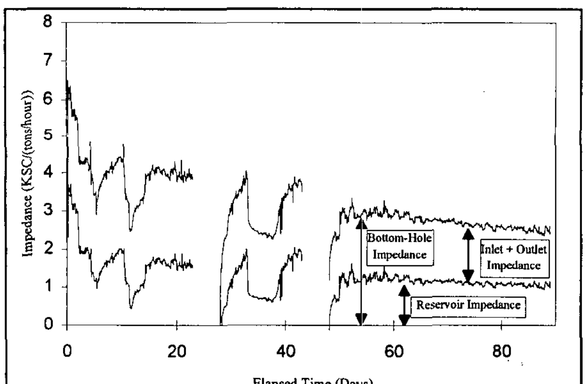

Figure 2. Hijiori 1991 Shallow Reservoir Circulation Test: HDR-2 Reservoir and Bottom-Hole Impedance.

Steady-state analysis of the 1991 Circulation Test allowed determination of system impedances and evaluation of how the reservoir was affected by the injection rate increases (stimulations), production well shut-ins, and long-term reservoir flow / cooling. Steady-state analysis yielded continuous measurements of the component impedances. Figure 2 shows some sample impedance results. Note how the system impedances declined during the test, particularly in response to the high rate reservoir stimulations that were performed early in the test[3]. The results from the steady-state analysis were very important in the subsequent analysis of the transient events.

Transient Analysis

The Hijiori 1991 Shallow Reservoir Circulation Test provided a wealth of transient data for analysis. There were a total of thirteen different transient events (such as changing the injection rate or shutting-in a production well), with the response measured at three production wellbores and one injection wellbore -- giving a total of 52 transient events to analyze. Some of these events were unusable because of other, overlapping changes in operating conditions, however there remained an abundance of analyzable transient events.

Analysis Methods

While steady-state analysis allows identification of critical long-term changes in component impedances (on the order of a few days or more), the effects of reservoir fluid storage must also be considered when engineering an economic HDR system. Therefore, we must include the storage (or capacitive) elements into the system model. These storage elements (capacitors) have a fluid storage volume, V_S , that is dependent on the Reservoir Pressure (P), where C is the reservoir capacitance.

$$V_s = \int_{p=0}^{P} C\,dp$$

The capacitance of the storage elements is certainly not a constant; but is dependent on the reservoir pressure and current fracture / flow system geometry. Reservoir storage is also physically distributed throughout the reservoir, but is simplified in the lumped model to a single capacitive element surrounding each wellbore. Figure 4 shows a schematic of the (rough) pressure dependence of the reservoir capacitance: below the reservoir closure stress, the capacitance is very low, but the capacitance increases dramatically when the pressure rises above the insitu closure stress. This is because when the pressure is below the closure stress, all of the stored fluid is in the rock matrix (porosity) and fracture system, therefore the reservoir storage volume (and the capacitance) is dependent on the "effective" porosity and fluid compressibility of the "accessed" rock mass. However, when the pressure is above the closure stress, the fracture system volume grows substantially with changes in the pressure as the fracture system hydraulically opens, greatly increasing the incremental reservoir capacitance. We have approximated the capacitance as a step function with one value below the closure stress, and another (much greater) value above closure stress:

$$\boldsymbol{C} = \begin{cases} \boldsymbol{C_0} & \boldsymbol{P < P_0} \\ \boldsymbol{C} & \boldsymbol{P > P_0} \end{cases}$$

where $\boldsymbol{P}$ is the reservoir pressure, $\boldsymbol{C}$ is the capacitance, and $\boldsymbol{P_0}$ is the reservoir closure stress.

To test the validity of this simplified approach, the capacitance values were measured using two independent methods: one method relied on measurements of the system response time (Time Constant Method); and the other measured the "apparent" change in reservoir fluid storage volume accompanying a change in the steady-state operating conditions (Unrecovered Flow Method).

Time Constant Method

The transient resistive-capacitive system described above, a simplified version of which is shown in Figure 3, has a characteristic time constant, τ, which can be defined as

$$\tau = \boldsymbol{CI_{SC}}$$

where $\boldsymbol{C}$ is the capacitance, and $\boldsymbol{I_{SC}}$ is the "short-circuit" system impedance that is seen by the reservoir storage element. Any sudden change in operating conditions (like the injection flow-rate), called an "event", will cause a response in the injection and production reservoir pressures that follows the relation:

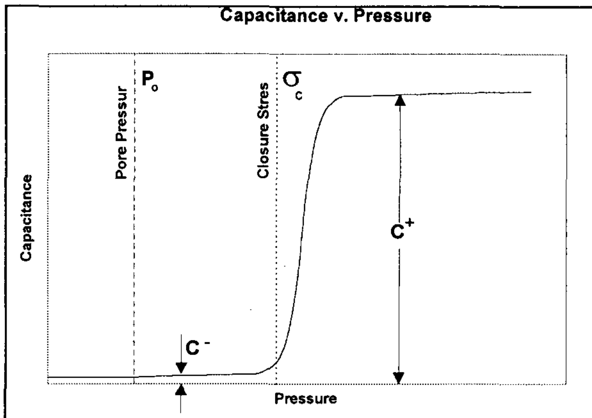

Figure 4. Reservoir Capacitance Versus Reservoir Pressure.

$$P(t) = P_{last} + \left(P_{first} - P_{last}\right)e^{\left(t - t_{first}\right)/\tau}$$

where P is the pressure at the current time, t; P_{first} is the pressure at the time of the event, P_{last} is the steady-state stabilized pressure after the event; and t_{first} is the time of the event. These simplified equations are for a linear first-order system with constant parameter (C & I) values throughout the range of operating conditions ecountered during the transient event. The second-order effects, such as interactions between production well reservoir storage and the injection well reservoir storage, are quite small in this particular case due to the large differences in Impedance paths and capacitance values at the injection and production wellbores (since the reservoir pressure at the injection wellbores is lower than the closure stress). Non-linearities were ignored in the development of this model because in any sufficiently simple HDR circulation test, there will not be enough data to rigorously define functional dependence of the capacitance, whereas there is enough data to characterize a linear system -- and how the linear system parameters change gradually (i.e. not during a transient event) throughout the course of the test.

After calculating the reservoir pressure versus time, it is possible to estimate the time constant by fitting the above exponential equation with the data. Figure 5 shows an example fit of the exponential function to pressure data immediately after the "event" occurring at 23.0 days (a reservoir pressure to slowly increase. As can be seen in this figure, the data was reasonably approximated by a simple exponential fit. The reservoir pressure surrounding the injection well started at 162.5 KSC, and equilibrated at the end of the transient to approximately 175.3 KSC. The best-fit exponential curve yields a time constant (τ) of 8.8 hours. As the "short-circuit" impedance, determined from the steady-state analysis[3], seen by the injection well capacitor *at this point in time* was 0.25 KSC/(tons/hour), this implies that the reservoir capacitance was 35 tons/KSC.

This methodology was followed to find the observed reservoir time constant at each wellbore for each of the transient events. The majority of the time the exponential curve fit the data very well like the example case shown, however some of the transient events were corrupted by changes in the back pressure during the transient response and these values were not used.

The time constant estimations at the production wells fell over a fairly large range, but at the injection well, the estimations were fairly consistent, showing an increase in the system time constant as the test progressed. Figure 6 shows the time constants measured at the injection well (SKG-2) for the different transient events. The change in time constant was approximated by the three step-changes shown by the line in Figure 6. Using these time constant values and the continuous record of the impedance values versus time (like Figure 4), allowed calculation of the reservoir capacitance (and storage) as a continuos function of time (shown later in Figure 8)

The dominant reservoir capacitance, and therefore the dominant reservoir storage, was at (near) the injector well, SKG-2. The reservoir capacitance at the production wells was smaller than that observed at the injector well by about a factor of 50. We suspect that this large difference in reservoir capacitance is due to the difference in local reservoir pressures. At SKG-2, the reservoir pressure was thought to be above the lower bound estimate of minimum insitu (closure) stress, whereas at the production wells, HDR-1, -2, and -3, the reservoir pressure was definitely below closure stress.

The total reservoir storage was, in turn, calculated using the reservoir capacitance. Recall, the reservoir storage is simply the reservoir capacitance times the reservoir pressure. The Time Constant Method yielded an estimate of about 600 tons of total fluid stored in the shallow reservoir immediately prior to shut-in of the 1991 circulation test (day 89).

Unrecovered Flow Method

The reservoir storage volume (and, therefore, the reservoir capacitance) can be estimated more directly using another independent method[5], which involves measurement of the change in reservoir fluid storage associated with changes in the reservoir pressure. We define a term "unrecovered flow" as the flow injected minus the sum of the produced flows. Unrecovered flow is comprised of the loss flow plus the net flow into (or out of) reservoir storage.

The unrecovered flow method can best be illustrated through an example. Figure 7 shows an example of the unrecovered flow versus time surrounding a transient "event" when a previously shut-in production well was opened. Before the event, the unrecovered flow is steady at about 35 tons/hour, which represents the loss rate at the initial reservoir pressure -- as there is no flow into, or out of, storage in steady-state. After the event, the reservoir pressure falls gradually to a lower equlibrated pressure, and to a lower steady-state loss flowrate of 14 tons/hour. The loss flowrate can be expected to fall gradually between the initial (35 tons/hour) and final value (14 tons/hour), perhaps tracking the pressure decline as shown in Figure 7. However, the reservoir storage volume shows a quite different behavior, even going negative for a brief period, due to the flow out of reservoir storage that accompanies the drop in reservoir pressure. The integral of the difference between the unrecovered flow and the (predicted) loss flow during the transient, indicated as the shaded area in the figure, is equal to the change in reservoir storage volume associated with the change in reservoir pressure.

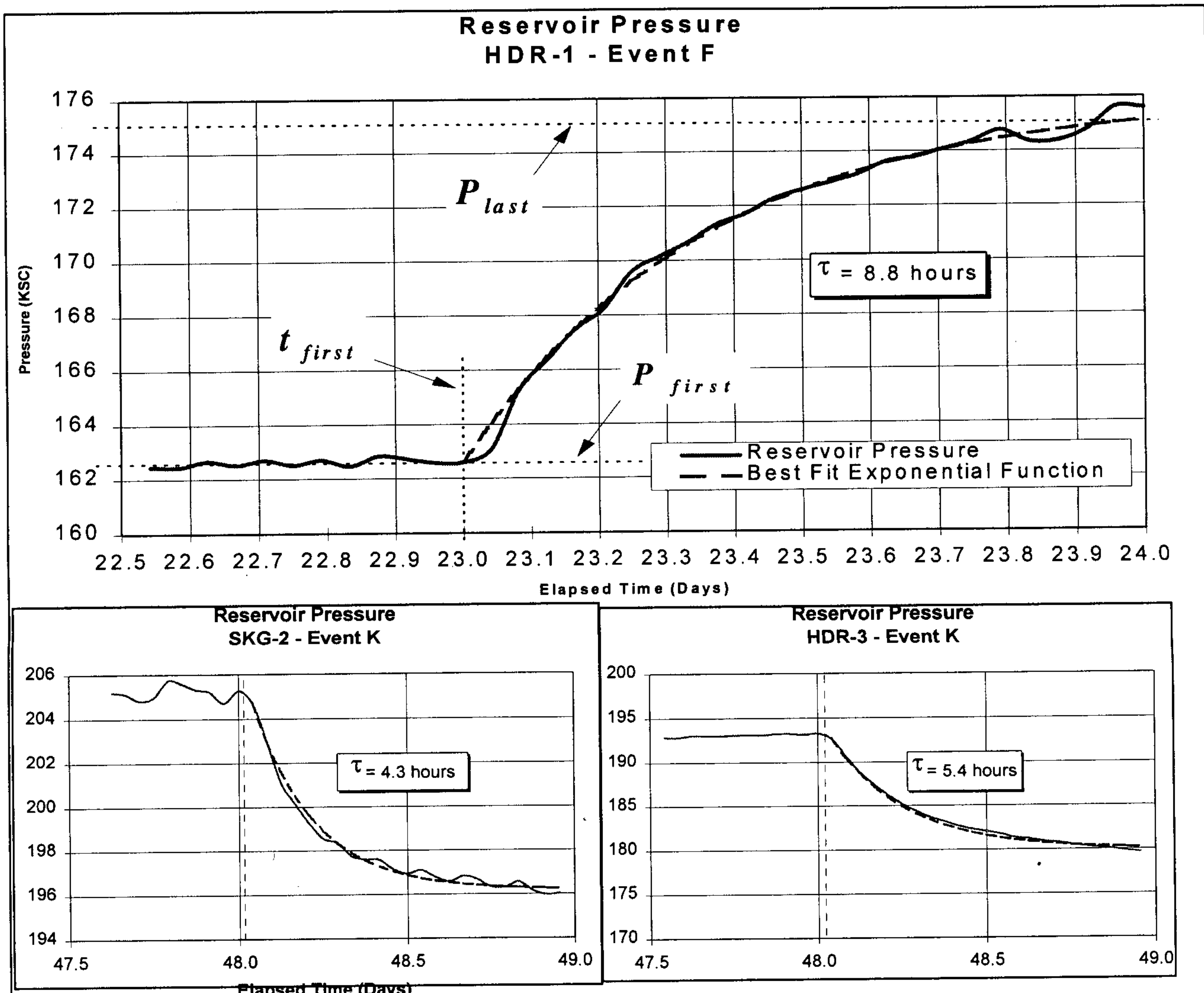

Figure 5. Example of Reservoir Time Constant Measurements.

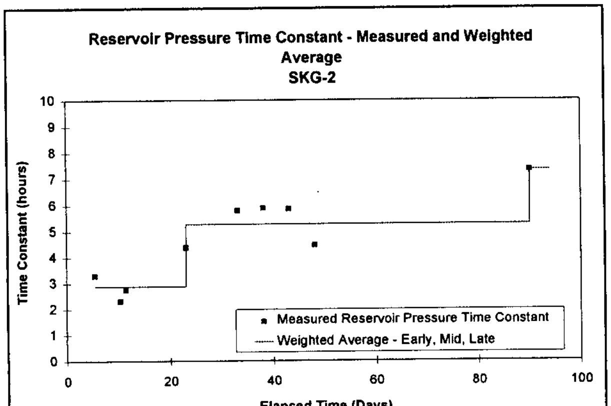

Figure 6. Hijiori 1991 Shallow Reservoir Circulation Test Measured (and estimated) Time Constants for SKG-2.

The estimated reservoir capacitance can be calculated from the simple relation:

$$C = \frac{\Delta V_s}{\Delta P}$$

where ΔV_s is the change in reservoir storage, and ΔP is the change in reservoir pressure. For the example in the figure, the reservoir pressure around the injector well changes from 208 KSC to 194 KSC, so ΔP = 14 KSC. The integrated reservoir storage volume change is ΔV_s = 789 tons, and the capacitance is therefore 56 t/KSC.

The two independent methods of calculating the reservoir storage (capacitance), time constant and unrecovered flow, provided quite similar results.

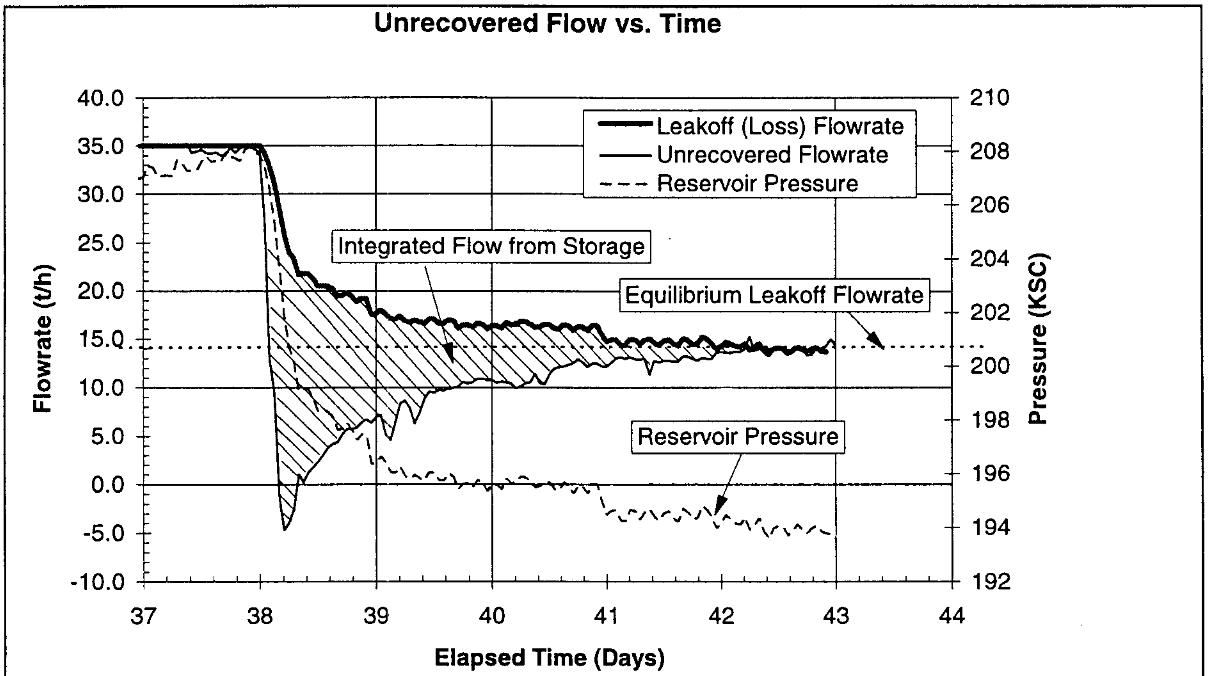

Figure 7. Example of Unrecoverd Flow Integration.

calculated from the time constant method and the integrated flow method are shown together in Figure 8. The reasonable agreement between the measurements from the two different methods verifies—at least approximately—the validity of both methods.

Applications of Transient Analysis

The transient analysis method will be useful for predicting reservoir response to various operating conditions. Transient analysis will prove essential for designing variable energy production schedules like the load-following schemes proposed by Duchane[6].

Reservoir characterization, like rock mass contacted and fracture system porosity, could also be greatly aided by careful analysis of the steady-state and transient fluid circulation behavior. eservoir transient time.

Conclusions

- The two methods for estimating the reservoir storage and capacitance (the Time Constant measurement and the Unrecovered Flow measurement) are both simple tests which allow estimation of the reservoir fluid storage versus time. The results from these two methods seem to agree fairly well at the Hijiori HDR site, and the differences will be examined more in the near future.
- The dominant reservoir storage (and reservoir capacitance) in the 1991 HDR Shallow Reservoir Circulation Test was near the injector well, probably due to the high reservoir pressure near the injector well compared to the much lower reservoir pressure around producer wells.
- At the Hijiori HDR site, the fluid loss rate is strongly dependent on the insitu reservoir pressure -- suggesting that the recovery efficiency is very sensitive to changes in the reservoir pressure (injection rate).
- HDR reservoir transient analysis will be invaluable for analyzing, and planning, variable production schedules which will enhance the commercial value of HDR energy.

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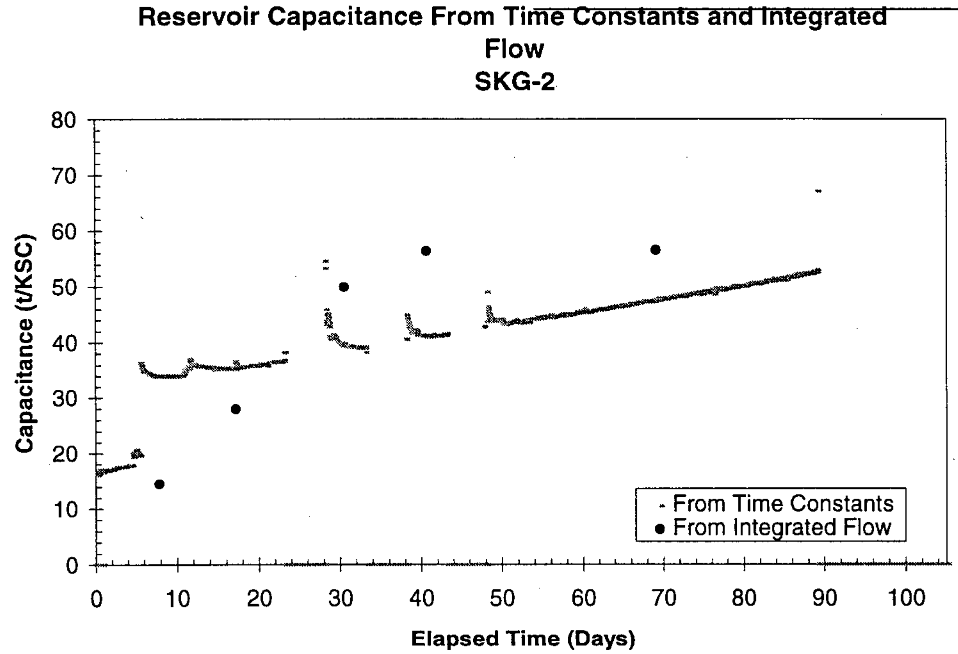

Figure 8. Hijiori 1991 Shallow Reservoir Circulation Test Comparison of Two Methods of Measuring Reservoir Capacitance.

Geothermal Hot Water Power Generation Plant" in MITI's Sunshine Project, Japan. In addition, we would like to express our thanks to Sharon Demetrius for assisting in the circulation test data analysis.

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