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Overview of the Hijiori Shallow Reservoir Circulation Tests and Reservoir Fluid Storage Analysis

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1.Abstract

Since 1985, NEDO has advanced a]Hot Dry Rock project in Hijiori, Japan. Circulation tests have been performed in FY1991 (in a shallow reservoir), and in FY1995 (in both shallow and deep reservoirs). In 1991 circulation test, the result was that 78% fluid recovery at an injection rate of 60 tons/hour and production temperatures of 150 ℃ – 190 ℃ . However no detailed analysis of flow conditions was given. Therefore, a simplified HDR model has been proposed to understand the Hijiori HDR reservoir. We have analyzed the 1991 circulation test using the model. This study is very important for analyzing the circulation test in both of shallow and deep reservoir which was conducted in 1995.

This paper summarizes the 1991 circulation test at the Hijiori HDR test site, and estimation of the reservoir fluid storage by using "unrecovered" flow from the new conceptual idea of HDR reservoir model.

2.Introduction

The results of the 1991 shallow reservoir circulation test were 78% fluid recovery at in injection rate of 60 tons/hour and production temperatures of 150 ℃ – 190 ℃ [1] . But no studies to assess the results of 1991 circulation test were conducted. Therefore, in order to assess the result, we proposed a simplified system model which allowed analysis of 1991 circulation test data in both steady–state and transient flow conditions for the shallow reservoir at the Hijiori site. This model was designed to allow estimation of the critical hydraulic parameters in the circulation system. The "steady–state" flow analysis of the circulation test revealed the system impedance [2] .

This paper explains "transient" flow analysis of the 1991 circulation test. Transient flow analysis allowed estimation of the fluid storage volume within the circulation system and how the fluid storage changed with time and reservoir stimulation during the circulation test.

3.Overview of the Hijiori HDR site and the 1991 Circulation Test

First, we shall describe the progress of shallow reservoir system (see Figure 1) [1] . In FY1986, a hydraulic fracture was created in the SKG–2 well which was already existing wellbore, using 1,000 tons of water. In FY1987, HDR–1 well as a production well was drilled based on the target location from fracture mapping of the 1986 fracture treatment which was obtained by the acoustic emission (AE) events. In FY1988, a short term circulation test (2 weeks) was performed, injecting from SKG–2 well, and producing from HDR–1 well. In FY1989, a second production well, HDR–2, was drilled and a circulation test (one month) was conducted. In the circulation test, stable production from the HDR–1 and HDR–2 wells was attained with a heat–energy production of about 4.5 MW, however, the recovery efficiency from the two production wells was only about 40%. A third production well, HDR–3, was drilled, based on the AE mapping of the circulation test in FY1990.

Then, the 1991 circulation test involved one injection well (SKG–2) and three production wells (HDR–1, HDR–2, HDR–3), eventually, Hijiori site was a multi–production well system. Figure 2 shows a map of surface well locations and downhole trajectories for all four wells. PTS logs were run in all production wellbores at many times throughout the circulation test to locate the zones of fluid production. In this paper, a reference depth of 1760 meters (in the center of the most productive zones) was used for calculation. At the reference depth of 1760 meters, the production wells are located 38m–60m away from the SKG–2 well injection point.

The 1991 circulation test involved the injection of 134,510 tons of water into the SKG–2 well (about 90 days) and production of 94,300 tons of hot water and steam from three production wells (HDR-1, HDR-2 and HDR-3). The recovery efficiency was 78% at the end of the 90 days circulation test. Figure 3 shows the wellhead pressure for the SKG-2, HDR-1, HDR-2 and HDR-3 wells. Water injection rate at the SKG-2 well was held nearly constant at 60t/hr during the 90 days' circulation test, except for two high-rate injections of 180ton/hr and 120tons/hr which were performed to test reservoir fill-up and achieve hydraulic stimulation of the reservoir. There were three periods of isolated production from only a single wellbore, which were performed for each production well. These three isolation tests were performed during the middle of the circulation test, as shown in Figure 3. There were twelve different transient events during the test, and a description of each is given in Table 1. These events are also labeled in Figure 3.

4.Development of The Shallow Reservoir Model

Using electrical circuit elements, f igure 4 shows schematically the complete system model for the 1991 test conducted in the shallow reservoir at the Hijiori HDR test site.

The resistive elements (I) include wellbore and inlet impedance for the injection well, SKG-2, individual impedances associated with each of the production wellbores, associated outlet impedances for each production wellbore, and total fluid loss impedance. The inlet, outlet, and wellbore impedances can all be measured from the pressure response to sudden changes in injection rates. These frictional impedances are all modeled as power-law functions of fluid flowrate. After characterizing the wellbore and inlet/outlet impedances, the other impedances can be calculated from the measured flow and pressure data throughout a test.

The pump elements (P) in the system include the surface pumping units, the hydrostatic head in each wellbore, and the far-field reservoir pressure. The hydrostatic head is modeled (and predicted) in the wellbores using a two-phase steam-water system with component densities dependent on both pressure and temperature. The agreement is quite close between the calculated hydrostatic head and the hydrostatic head as measured by PTS logs during the 1991 circulation test.

The storage elements (S) represent reservoir fluid storage. The hydraulic system model lumps the total reservoir fluid storage into individual storage components associated with the reservoir fluid pressure immediately outside the near-wellbore region for each wellbore. The system model includes four storage elements. The storage elements, called capacitors, hold an amount of fluid (called the stored volume, Vs) dependent on pressure (P), where C is the reservoir capacitance.

$$V s = \int_{P=0}^{P} C \, d p$$

5.Reservoir Fluid Storage Analysis and Result

The reservoir volume was calculated directly by integrating the unrecovered flow. The unrecovered flow (the leakoff flow and the flow into reservoir storage) was calculated as the flow injected minus the sum of the produced flows. After a sudden increase in injection flowrate, the leakoff gradually changes (as the reservoir pressure changes) to that at the new, lower steady-state pressure. The unrecovered flow is immediately reduced, then slowly drifts up to the equilibrium level - the difference between the leakoff flow and the unrecovered flow is the flow out of reservoir storage.

Figure 5 shows an example of the unrecovered flow versus time after a distinct change in the production conditions. Before the event, the unrecovered flow is steady: this is the leakoff flow at the initial pressure. In the figure, the leakoff flow at the initial pressure is 35 tons/hour. When the injection pressure changes the unrecovered flow drops suddenly, then slowly approaches its new steady-state value of 14 tons/hour. If there were no transient response (i.e., no reservoir storage), the unrecovered flow would drop suddenly to the new steady-state value (14 tons/hour). However, the reservoir storage volume is different at the different reservoir pressures, so there is a transient that is related to the reservoir storage. The integral of the difference between the unrecovered flow and the leakoff rate (which we have assumed to vary linearly with pressure during each transient event) is shaded in the figure, and the shaded area is equal to the change in reservoir storage volume associated with the given change in reservoir pressure.

The flow into reservoir storage can be related to the reservoir capacitance, C. The reservoir storage should change linearly with pressure (if the capacitance is constant over that range of pressure), so the constant of proportionality (the capacitance) can be calculated as

$$C=\frac{\Delta V\ s}{\Delta P}$$

where △ Vs is the amount of fluid that flowed into reservoir storage (or out-of, if △ Vs is negative), and △ P is the change in reservoir pressure near the injection well. For the Figure 5, the reservoir pressure at the SKG-2 well changes from 208 KSC to 194 KSC, so △ P=14KSC. The integrated change of reservoir storage volume is △ Vs=789 tons, so capacitance is calculated as 56 tons/KSC.

The integrated flow into storage was used to calculate system capacitance for each transient event, A-L, and the results are shown in Table 2. Unfortunately, the injection flowrate changes at events F, H, and J were not sudden enough to allow accurate integration of the reservoir storage flow, so the results were unreliable and are not shown in table. Events A, B, and D were not analyzed because the time between events was not long enough to reach equilibrium.

6.Conclusion

In order to estimate the volume of reservoir fluid storage, we proposed a simplified system model which includes reservoir storage elements, for the shallow reservoir of Hijiori site. Thus we could calculate reasonable reservoir capacitance, and how the fluidstorage changed with time and reservoir stimulation. The reservoir capacitance calculated by integrating unrecovered flow, in the shallow reservoir was 8 ~ 31tons/KSC.

Analysis of the 1995 circulation test has been aided by using the expanded system hydraulics model from this study. Simplified analytic tools are required for analysis of the 1995 circulation test due to the complexity of a multi-well system with flow into both the deep and shallow reservoirs.

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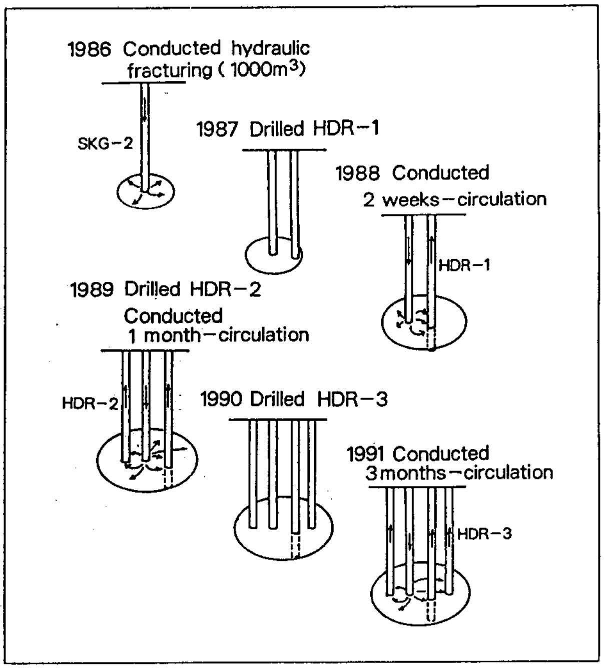

Figure 1: A Plan View of Trajectories of SKG-2,HDR-1,HDR-2, and HDR-3 Wells

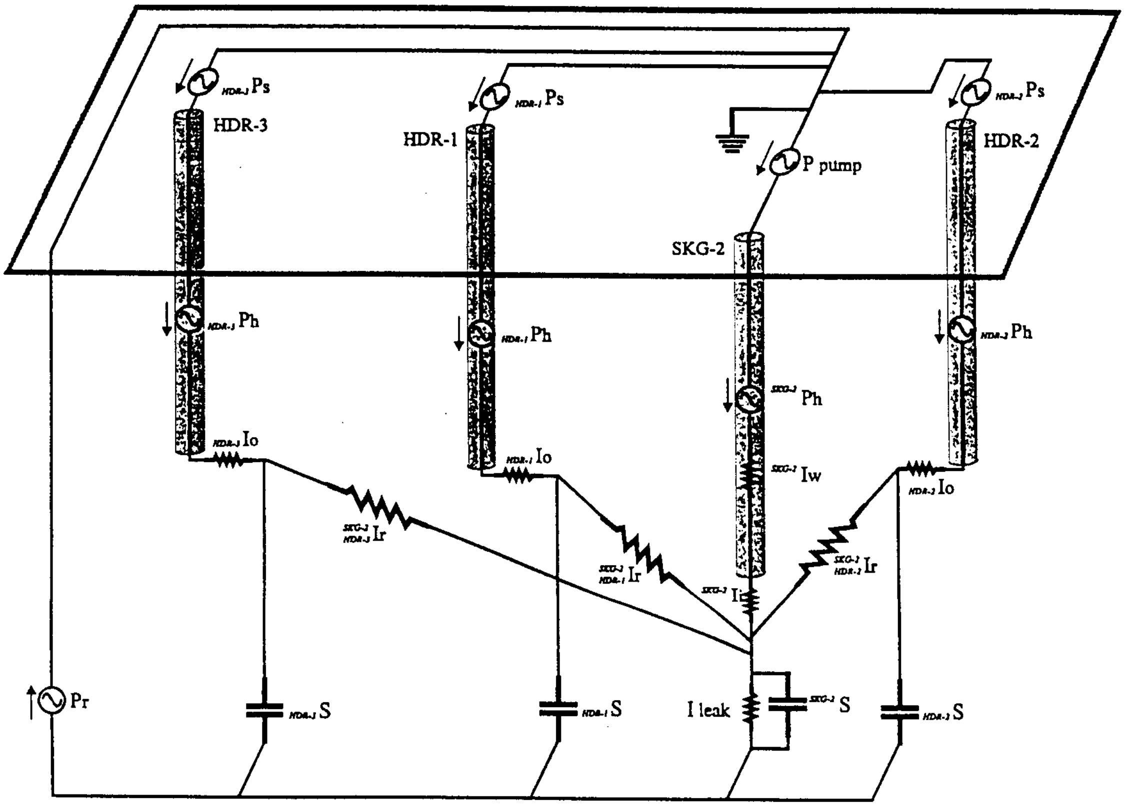

Figure 4:Shallow Reservoir Model

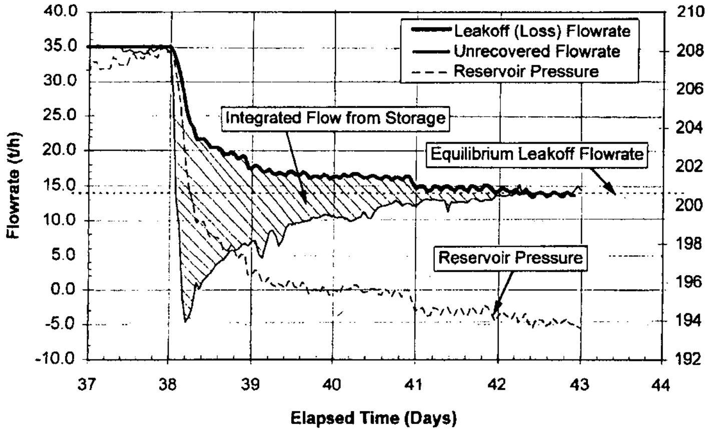

Figure 5:Example of Transient in Unrecovered Flow

Table 2:Capacitance Calculated by Integrating Transient Areas

Transient Event	Change in Pressure (KSC)	Pressure Difference (KSC)	Change in Storage (tons)	Capacitance (t/KSC)
C → D	220→193	27	391	14.5
E → F	214→191	23	641	27.8
G → H	217→195	22	1100	50.0
I → J	208→194	14	789	56.4
K → L	205→194	11	622	56.5
L → M	231→183	48	6934	144.0

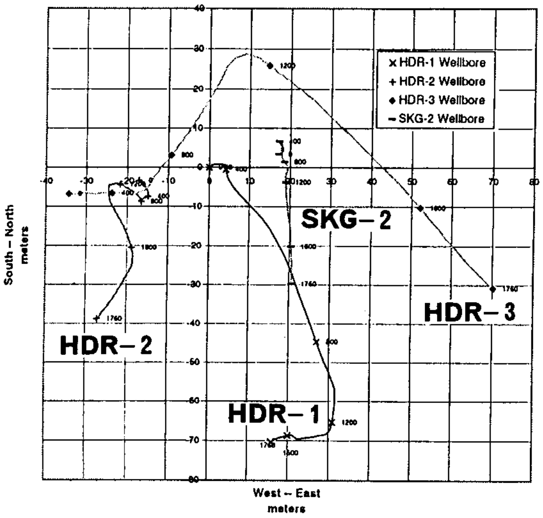

Figure 2: View of the Four–Well system at the Hijiori Site

Table 1:Difinition of Transient Events

Transient Event	Description
A → B	Increase in flowrate from $1m^3$ / min to $3m^3$ / min
B → C	Decrease in flowrate from $3m^3$ / min to $2m^3$ / min
C → D	Decrease in flowrate from $2m^3$ / min to $1m^3$ / min
D → E	Increase in flowrate from $1m^3$ / min to $2m^3$ / min
E → F	Decrease in flowrate from $2m^3$ / min to $1m^3$ / min
F → G	HDR-2 and HDR-3 shut-in, producing from HDR-1 only
G → H	Producing from all wells, HDR-1, -2, -3
H → I	HDR-1 and HDR-3 shut-in, producing from HDR-2 only
I → J	Producing from all wells, HDR-1, -2, -3
J → K	HDR-1 and HDR-2 shut-in, producing from HDR-3 only
K → L	Producing from all wells, HDR-1, -2, -3
L → M	SKG-2 shut in, decrease flowrate from $3m^3$ / min

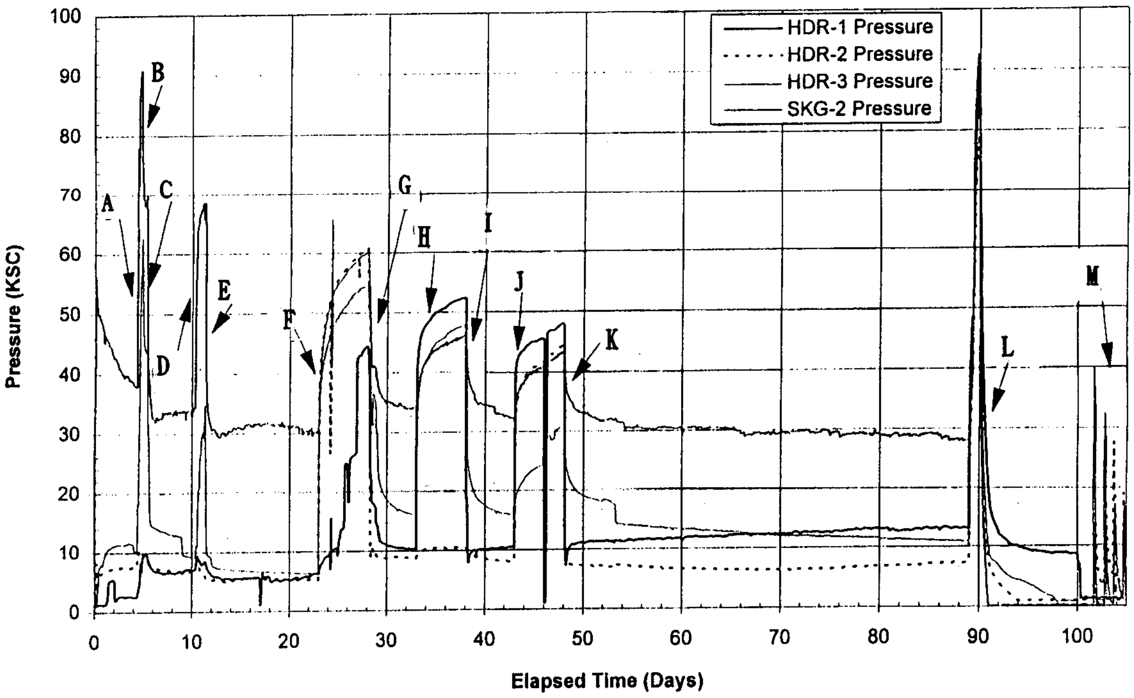

Figure 3:Well Head Pressure of Four–Wells and Transient Events