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PREDICTION OF CHANGES IN WELL-BOTTOM FLUID CONDITIONS FROM WELLHEAD MEASUREMENTS

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ABSTRACT

In order to investigate the behavior of the reservoir during production and the effects of reinjection of separated water on production wells **in** *the Otake geothermal area, changes with time in fluid conditions at the wellbottom and feed point in the reservoir for Otake production wells, 0-7, 0-9 and O-10, were predicted from wellhead measurements. For the purpose of that, initially, changes in the wellbottom pressures* P_b *for each well were predicted. Secondly, on the basis of the predicted* P_b*, the water saturation S and fluid enthalpy in place at the feed point* H_i *were estimated.*

1.0 INTRODUCTION

Plant and reservoir engineers are interested in reservoir behaviors with production, and particularly changes in thermodynamic conditions of pore fluid which are directly reflected in changes in steam production. They may be also interested in how the injected water of temperature lower than the original reservoir's affects the steam production for cases of the water dominated reservoir. Estimation of the effects can be made to a certain extent from surface measurements. However, to make it more precisely, changes in fluid conditions at the feed point of the reservoir should be known, which are also available for inner boundary conditions to simulate reservoir behaviors.

In this study, assuming that Otake reservoir is a fracture type, S and H_i at the feed point were estimated from surface production histories. And from the results, some considerations on the effects of reinjection on the fluid conditions were made.

2.0 BASIC EQUATIONS

2.1 Wafer Saturation and Fluid Enthalpy in Place

The flowing enthalpy in the two-phase reservoir can be expressed as [Belen Jr. et al., 2000]

$$H_f = \frac{\frac{k_{rw}}{v_{rw}} H_w + \frac{k_{rs}}{v_{rs}} H_s}{\frac{k_{rw}}{v_w} + \frac{k_{rs}}{v_s}} \tag{1}$$

Rewriting Eq. (1) yields

$$\frac{k_{rw}}{k_{rs}} = \frac{v_w}{v_s}\frac{H_s - H_f}{H_f - H_w} = \frac{v_w}{v_s}\frac{1-X}{X} \tag{2}$$

or

$$\frac{k_{rw}}{k_{rs}} = \frac{v_w}{v_s}\frac{M_w}{M_s} \tag{3}$$

where M_w and M_s are respectively water and steam mass flow rates, and

$$X = \frac{H_f - H_w}{H_s - H_w} \tag{4}$$

is the dryness fraction of the flowing fluid. On the other hand, the fluid enthalpy in places can be given by

$$H_i = \frac{\rho_w S H_w + \rho_s (1-S) H_s}{\rho_w S + \rho_s (1-S)} \quad (5)$$

In this study, the fracture-type reservoir was adopted, and then assuming that each of the phases does not impede the flow of the other phase, the relation

$$k_{rw} + k_{rs} = 1 \quad (6)$$

is available. Equating Eqs. (3) and (6) gives k_{rw} and k_{rs} like as

$$k_{rw} = \frac{1}{1 + \frac{v_w}{v_s}\frac{M_w}{M_s}} \quad (7)$$

$$k_{rs} = 1 - \frac{1}{1 + \frac{v_w}{v_s}\frac{M_w}{M_s}} \quad (8)$$

k_{rw} is a function of the water saturation, and can be expressed as follow

$$k_{rw} = S^* \quad (9)$$

where

$$S^* = \frac{S-SW,}{1-SW,-S_{ws}} \quad (10)$$

0.3 and 0.05 are commonly given for S_{rw} and S_{rs}, respectively.

2.2 Prediction of the Wellbottom Pressure from Wellhead Measurements

The wellbottom pressure can be numerically obtained from wellhead measurements by using following pressure losses equation (Bojrnsson et al., 1987 and Fukuda et al., 2000):

$$\Delta P_t = \Delta P_h + \Delta P_a + \Delta P_f \quad (11)$$

where

$$\Delta P_h = \rho_m g \Delta L \quad \text{[potential losses]}$$

$$\Delta P_a = G_t^2 (v_{m,2} - v_{m,1}) \quad \text{[acceleration losses]}$$

$$\Delta P_f = \Phi_{lo}^2 \frac{\lambda_{lo}}{2D} \frac{G_t^2}{\rho_w} \Delta L \quad \text{[friction losses]}$$

and

$$G_t = \frac{M_t}{A} \quad \text{[mass velocity]}$$

2.3 Pressure at the Feed Point in the Reservoir and the Permeability-Reservoir Thickness Product

Under the condition of two-phase radial flow with a constant mass flow rate M_t, changes in the pressure at the feed point in the reservoir can be given by

$$P = P_0 - \frac{M_t v_t}{4\pi kh} Ei\left(\frac{\phi\mu_t c_t r_w^2}{4kt}\right) \quad (12)$$

where P_0 and r_w are the initial pressure and a well radius respectively, and

$$\frac{1}{\mu_t} = \frac{k_{rw}}{\mu_w} + \frac{k_{rs}}{\mu_s}, \quad \frac{1}{v_t} = \frac{k_{rw}}{v_w} + \frac{k_{rs}}{v_s} \quad (13)$$

c_t is the compressibility of the mixture like as introduced by Grant [1978], Grant et al. [1979] and Garg [1980]. When $(\phi\mu_t c_t r_w^2 / 4kt) < 0.01$, Eq. (12) can be approximated [Garg, 1980] as

$$P = P_0 - \frac{M_t v_t}{4 d h}\left[\ln(t) + \ln\left(\frac{4k}{\phi\mu_t c_t r_w^2}\right) - 0.5772 \right] \quad (14)$$

indicating that P_b linearly changes with ln (t) at large t with a slope of m. Then kh is given by

$$kh = \frac{M_t v_t}{4\pi m} \quad (15)$$

3.0 PREDICTION OF WELLBOTTOM FLUID CONDITIONS IN OTAKE PRODUCTION WELLS

Otake Power Plant started commercial operation in 1942 with an installed capacity of 12 MW by exploiting O-6, 0-7, 0-8, 0-9 and 0-10 (auxiliary), which were producing geothermal fluid from the shallower reservoir around 300 m deep. The water separated from steam was injected into formations at depths of 300m~500m through three wells, OR1, OR2 and OR3. In these production wells, fluid flow rates have been measured once every month since the beginning of the operation. Figures I-a, 1-b and 1-c show the production histories [Onodera et al., 19771, where the start of continuous discharge (t=0) is assumed to be April 1967, 4 months before the power plant operation started. In the figures, dotted lines denote starts of the reinjection wells, OR1~OR3. Since the well logging during discharge was not carried out in these years, neither downhole pressure nor temperature was measured. Therefore, in this study, wellbottom pressures P_b and fluid mass flow rates M_w and M_s at feed points were calculated from wellhead measurements, and using these results, the water saturation S and fluid enthalpy H_i were predicted.

3.1 Prediction of Changes in the Water Saturation and the Fluid Enthalpy

Following assumptions were made. In the calculation of downhole pressure:

1. two-phase flow through the well is isenthalpic: that is, the flowing enthalpy H_f at wellbottom is equal to the discharging enthalpy H_d at the wellhead
2. an uniform well diameter **(D=0.201m)**
3. effects of non-condensable gases are neglected.

For the prediction of fluid conditions at the feed point in the reservoir:

4. Fracture permeabilities are available, and the irreducible water and steam saturations with $S_{wr}=0.3$ and $S_{sr}=0.05$ can be adopted.

3.2 O-7

Figure 2 shows the predicted wellbottom pressures P_b and water saturations S, and Figure 3 fluid enthalpies H_i together with the discharging enthalpies H_d (the same ones with Figure 1). P_b gradually decreases until June 1971 (t = 50) and turns to recover. S and H_i behave similarly though the change in the fatter is slight The decrease in S implies that the fluid was drying and the increase afterward indicates water flowed into the production zone.

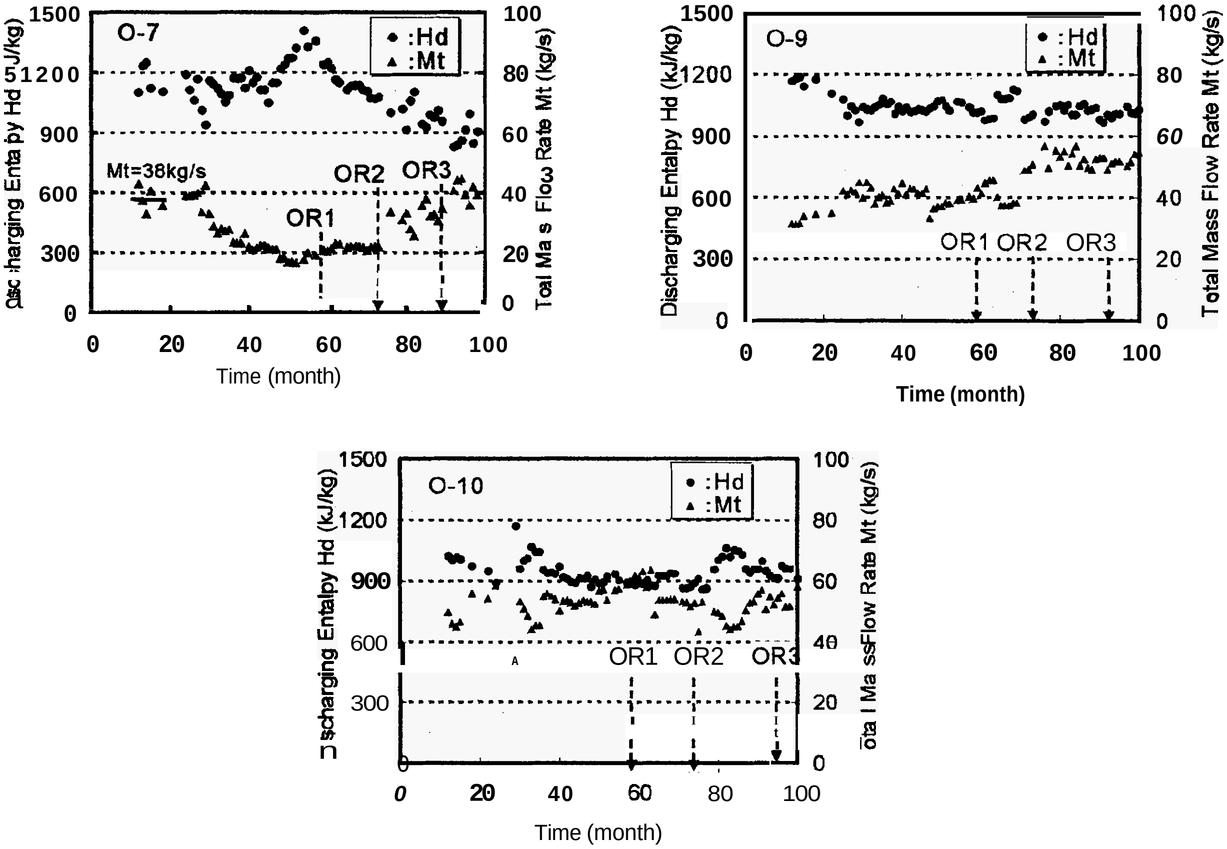

Figure 1. Discharging enthalpies and total mass flow rates, (a) 0-7, (b) 0-9 and (c) 0-10.

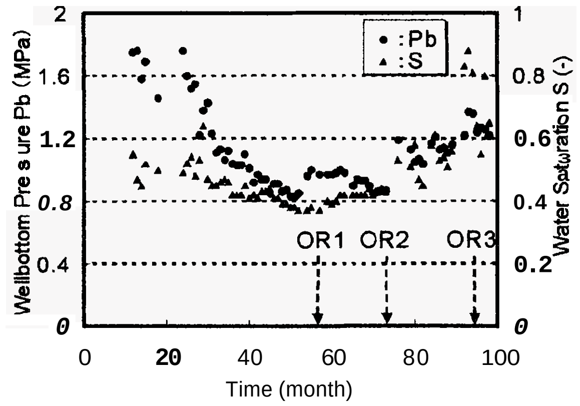

Figure 2. Predicted wellbottom pressures and water saturations, O-7.

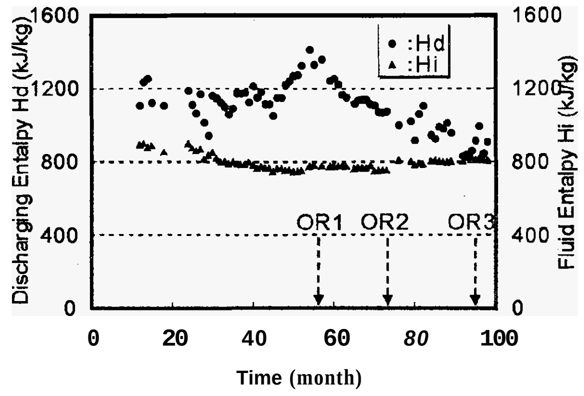

Figure 3. Discharging enthalpies and predicted fluid enthalpies, O-7.

However, S never reaches 1, the fluid remaining in the two-phase condition. The recover of P_b and increase in S seem to be caused by the reinjection because the turning time roughly coincides with the start of OR1.

3.3 O-9

Figures4 and 5 show for 0-9. As seen in Figure 4, P_b and S keep nearly constant values before OR1 starts, and increase aftetward. H_i in Figure 5 shows the similar behavior with these **two** parameters though the increase is small like as Q-7.

3.4 O-10

Although results shown in Figures 6 and 7 are rather scattered, it can also be said that this well is affected by the reinjections as a whole.

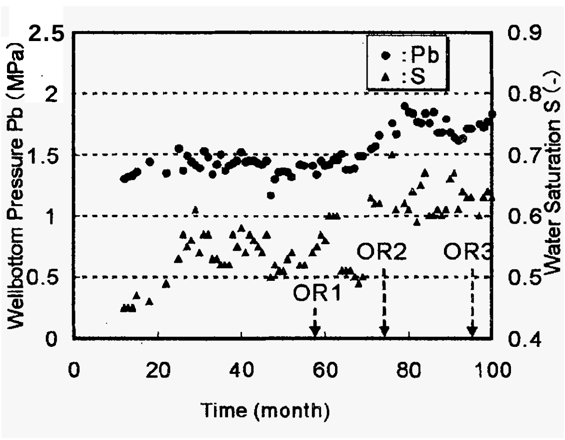

Figure 4. Predicted wellbottom pressures and water saturations, O-9.

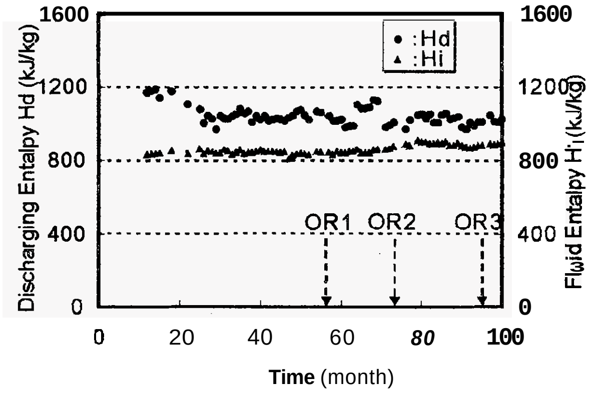

Figure 5. Discharging enthalpies and predicted fluid enthalpies, O-9.

3.5 Rough Estimation of Permeability Thickness Product for O-7

The permeability thickness product kh for Q-7 was estimated using changes in the predicted wellbottom pressures P_b. P_b and t are plotted on a semi-logarithmic paper as shown in Figure **8,** where a linear relation with a slope of m = -6.1×10^5 kg/ms^2 is obtained for the period before OR1 starts. To apply Eqs. (14) and (15) to the straight line to estimate kh, a total kinematic viscosity ν_t and a total mass flow rate M_t at the wellbottom were determined. Figure 9 shows changes in ν_t, where values of ν_t are nearly constant for the first 6 months, (t=12~18) averaging $\nu_t = 4.3\times10^{-7}$ m^2/s. M_t = 38 kg/s is obtained as an average value for these months from Figure I-a. Substituting the above values into Eq. (15) gives approximately kh = 2×10^{-12} m^3. Apart from this study, a recovery test was made in OR1 [Fukuda et al. 1978], where the

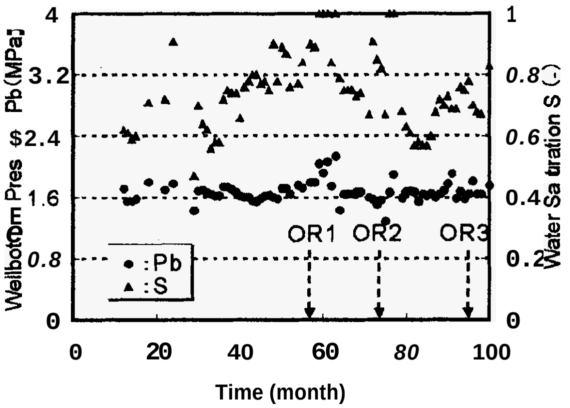

Figure 6. Predicted wellbottom pressures and water saturations,O-10.

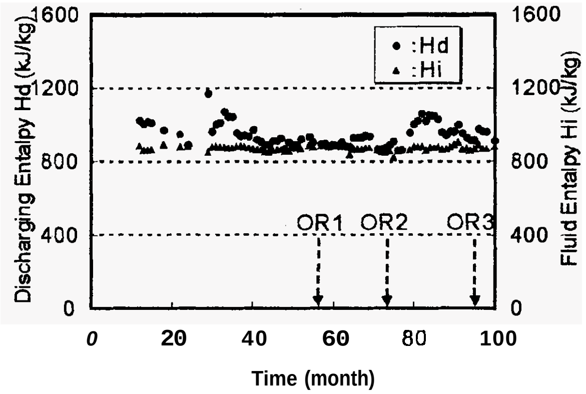

Figure 7. Discharging enthalpies and predicted fluid enthalpies,O-10.

separated water was injected and kh =0.24 m^2/h was estimated. If the temperature of the injected water is taken into account, it becomes 1.9×10^{-12} m^3, showing a good agreement with the result obtained in this study. This agreement indicates that the reservoir connecting 0-7 with OR1 can be deemed to be a fracture type or a near fracture type.

4.0 CONCLUSIONS

From the results, following conclusions can be reached.

1. The fluid at feed point in the Otake reservoir generally remained in two-phase condition, though, for O-10, it seems to have turned to the water single phase for a while after the reinjection started.

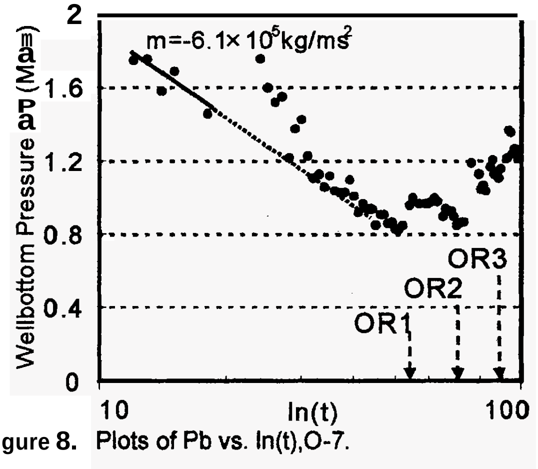

Figure 8. Plots of Pb vs. ln(t),O-7.

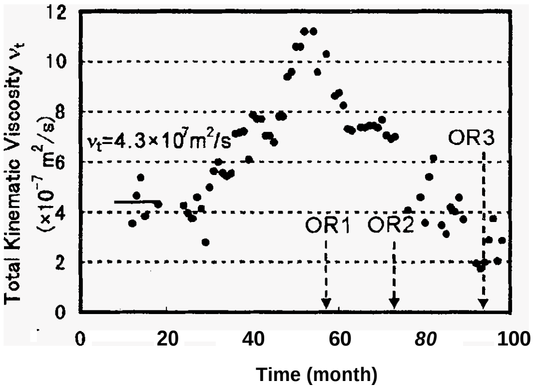

Figure 9. Total kinematic viscosities,O-7.

2. Effects of the reinjection on 0-7 and 0-9 are evident because P_b and S in these wells tend to increase after the reinjection started, and its effect on O-10 is recognized from temporary increases in S though not so clear as the others.

3. The reservoir connecting 0-7 and OR1 is considered to be a fracture- or a near fracture type.

SYMBOLS

A : cross sectional area of pipe
c : compressibility
D : pipe diameter
G : mass velocity
g : acceleration due to gravity
H : enthalpy
h : reservoir thickness
k_{ri} : relative permeability

L : path length
M : mass flow rate
P : pressure
r : radial distance
S : water saturation
S_{ri} : irreducible saturation
t : time
v : specific volume
ϕ : two-phase friction multiplier
λ : pipe friction factor
μ : dynamic viscosity
ν : kinematic viscosity
ρ : fluid density

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