RESERVOIR ENGINEERING APPROACH TO DEEP GEOTHERMAL SYSTEMS

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ABSTRACT

For characterization of deep-seated geothermal reservoirs, pressure transient/interference testing is also a basic tool. In the Sumikawa geothermal field, NEDO carried out production tests of well SN-7D and successfully measured the pressure transient response, which allows us to estimate the volume and permeability of a deep reservoir discovered around intrusive granodiorite rocks. In the Kakkonda field, NEDO's exploratory well WD-1 encountered very high temperatures near the upper surface of intrusive granite body. In anticipation of pressure transient tests to be carried out in the near future, we started numerical simulation studies to predict pressure transient response in a deep reservoir under sub- and super-critical conditions.

INTRODUCTION

In geothermal reservoir engineering, pressure-transient testing is a fundamental tool to establish reservoir properties on a macroscopic (reservoir-wide) scale. If an individual well is discharged and the flowing downhole pressure within the well is monitored as a function of time, conclusions can be drawn concerning the transmissivity of the reservoir in the vicinity of the well (i.e., permeability-thickness product) and the relationship between the overall reservoir storativity (i.e., porosity-compressibility-thickness product) and the well skin factor. Even more valuable is interference testing, in which the pressure influence from the discharge of a well is measured in one or more nearby shut-in observation wells. Such pressure records reflect the spatially-integrated properties of the reservoir in the region between the discharging well and the observation well(s), and thus provide direct information regarding average reservoir properties on a large scale which are unobtainable by any other technique.

Well SN-7D (a 2,486 m depth exploratory well drilled by NEDO in the Sumikawa field) is one of the best producers we have ever had in Japan; total (water plus steam) flow rates up to 500 tons/hour were recorded during various discharge tests carried out between 1988 and 1991. NEDO successfully performed drawdown/buildup tests of well SN-7D. The volume and permeability of the deep reservoir discovered around intrusive granodiorite rocks were estimated from the buildup data.

Well WD-1 drilled by NEDO in the Kakkonda field encountered a very high temperature: about 500 °C at 3,727 m depth (Uchida et al., 1996). Temperatures are higher than 350 °C at about 3,000 m depth near the contact between intrusive granite body and shallower pre-tertiary formations, where substantial permeability is expected. These temperatures are much higher than observed in the deep feed zones of well SN-7D (250 to 310 °C). If the salinity of the deep fluid is not so high, super critical conditions may exist in the vicinity of the well. In anticipation of real field data to be acquired in the near future, we carried out numerical simulations to predict pressure transients of deep reservoirs at sub- and super-critical conditions.

BUILDUP DATA OF SN-7D

Downhole pressures were monitored using a downhole capillary tube gauge in three separate discharge tests of well SN-7D (two in 1988 and one in 1989). The pressure buildup data obtained after the first 1988 test are shown in Figure 1 (Ishido et al., 1992), a multi-rate Horner plot in which buildup pressures are plotted against "reduced time":

$$\text{reduced time} = \Sigma_{i=1}^{N}(q_i/q_N)\log[(t_N + t - t_i)/(t_N + t - t_{i-1})]$$

The permeability-thickness product is about 37 darcy-meters based upon the slope of the Horner plot for early times (prior to ~10 hours of shutin time, or ~1.2 "reduced time).

At later times, the effects of boundaries appear to make themselves manifest. Another straight-line segment (of greater slope) may be perceived between ~20 and ~50 hours of shutin, and a third segment (of even greater slope) appears to prevail after ~50 hours. The solid curve shown in Figure 1 was computed from a mathematical model which assumes the following properties:

ϕ(rock porosity)=0.02
μ(fluid viscosity)=10^{-4} Pa-s
C_t(total compressibility)=1.5×10^{-9} Pa^{-1}
ρ(in-situ fluid density)=800 kg/m^3
k(permeability)=74 md
h(formation thickness)=500 meters
p_i(initial pressure)=14.89 MPa

L_1(distance to the first impermeable boundary) =990 meters
L_2(distance to the second impermeable boundary) =1650 meters

The radius of investigation corresponding to the producing interval (9 days) is:

$$Ri = \sim 8.7 \text{ kilometers} = 8.8\ L_1 = 5.3\ L_2$$

which implies that the test was of sufficient duration to unambiguously identify these boundaries.

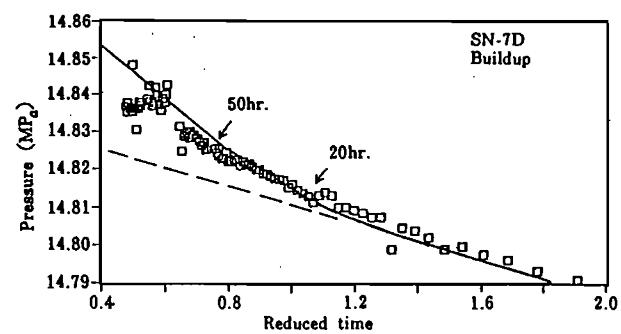


Fig. 1. Comparison of measured and computed (solid curve) pressure buildup histories after first 1988 SN-7D discharge test.

It appears that the volume of the deep permeable zone within the granodiorite formation tapped by well SN-7D is at least a few cubic kilometers. During the SN-7D discharge tests, five other wells were equipped with downhole pressure gauges. No signal attributable to the discharge of SN- 7D was observed in any of these wells; this implies that the deep reservoir penetrated by well SN-7D is probably isolated from the shallower reservoir in the "altered andesites".

HYPOTHETICAL WELL PENETRATING DEEP RESERVOIR AT SUPER CRITICAL CONDITIONS

For our numerical simulation study, we used the "STAR" general-purpose geothermal reservoir simulator (Pritchett, 1995), incorporating the "HOTH2O" equation of state package for simulation of high pressure and temperature conditions. HOTH2O treats pure water for pressures to one kilobar (100 MPa) and temperature to 800 °C. The critical point is defined as 374.15 °C and 22.12 MPa in the HOTH2O package.

Near the critical point, the physical properties of water tend to change drastically with small changes in temperature and/or pressure, and some properties become singular at the critical point. Theoretically, as the critical point is approached, the constant pressure specific heat, coefficient of volume expansion, compressibility, and thermal conductivity become infinite (e.g. Dunn and Hardee, 1981; Ingebritsen and Hayba, 1994).

Pressure transient response

A simple one-dimensional reservoir configuration was used for our numerical study, as illustrated in Figure 2; pertinent parameter values are listed in Table 1. We consider a horizontal single-layer homogeneous porous-medium reservoir containing a single fully-penetrating production well which may be regarded as a line-sink. The outer radius is sufficient that the system may be considered infinite in lateral extent. Both upper and lower boundaries are impermeable and insulated.

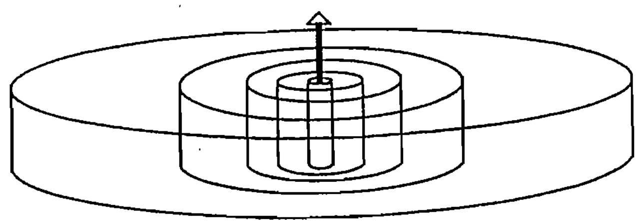


Fig. 2 Numerical simulation model.

In Figure 3, three cases (A, B and C) of pressure drawdown in the wellblock are shown. For these three cases, the same production rate (15.7 kg/sec), production interval duration (278 hours), and initial pressure (30 MPa) were used, and only the initial temperature distribution was varied. In all cases, a skin zone of high permeability (1 darcy) was used (blocks 2-5; to 0.9 meters) to avoid generation of a two-phase zone. Case A used a

Table 1. Model parameters used for the numerical simulation of pressure transient tests of deep reservoirs.

Reservoir geometry
Horizontal layer: Thickness = 100 m
Numerical blocks : r(1) = 0.1 m, $\Delta r(i+1) = \Delta r(i) \times 1.3$
r(max) = r(40) = 12,039 m
Well block: $k = 10^{-10} m^2$, $\phi = 0.99$
Reservoir blocks: $k = 10^{-14} m^2$, $\phi = 0.05$
Common rock parameters:
rock grain density = 2.7 g/cm^3
rock grain heat capacity = 1000 joules/kg-K)
rock grain thermal conductivity = 2.5 W/m-K

homogeneous initial temperature distribution of 300 °C. In Case B, the initial temperature is heterogeneous and equal to 300 °C for radii out to 82 meters (out to block 21) and 400 °C beyond that distance. In Case C, the initial temperature is equal to 400 °C everywhere. Comparing the three drawdown histories in Figure 3, it is evident that Cases A and C have similar slopes, although their absolute pressures are different. Also, the earlier part of the Case B drawdown is the same as that of Case A, whereas at late times Case B approaches Case C.

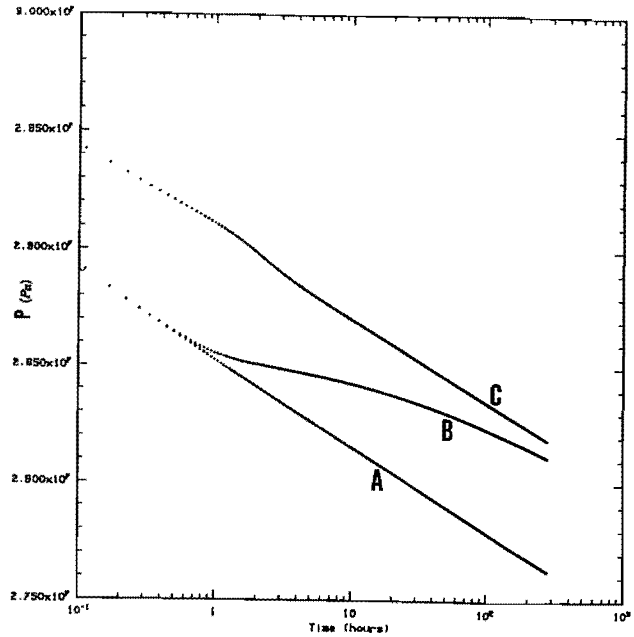


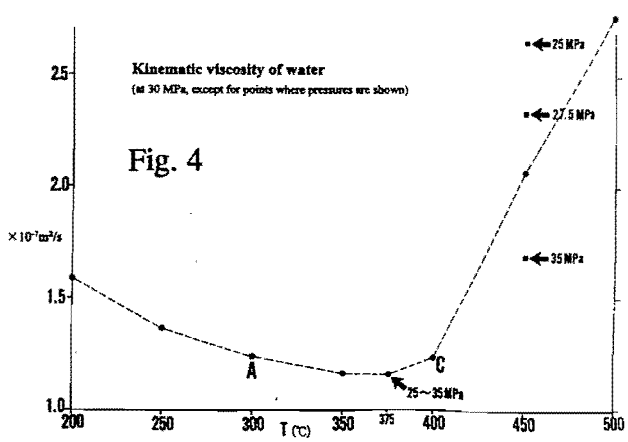
Fig. 3 Simulated pressure drawdowns with different initial temperature distributions.

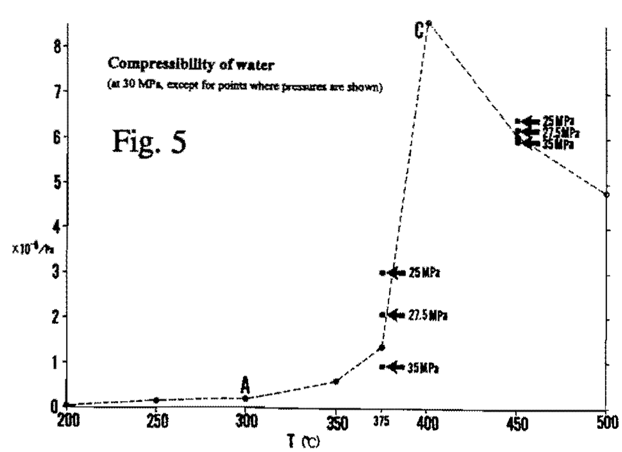
The slope m on the semi-log plot of pressure drawdown is

$$m = 2.303\, M\nu / 4\pi k h$$

where M is mass flow rate, ν is the kinematic viscosity, and k and h are the reservoir permeability and thickness respectively. All three cases in Figure 3 have the same M and kh. At 30 MPa, the kinematic viscosity of water at 300 °C is 1.24×10^{-7} m^2/sec, and that at 400 °C is 1.23×10^{-7} m^2/sec (see Figure 4). Therefore, a similar slope (m) is obtained for Cases A and C. The difference of the absolute values of pressure for both cases arises from the difference in water compressibility at 30 MPa pressure. The compressibility of water at 400 °C (Case C) is much greater than at 300 °C (Case A) (see Figure 5), which results in less pressure decrease for Case C.

The reservoir temperature distribution does not change significantly during the production test in Case B. At early times in this case fluid is being withdrawn from storage at small radii (300 °C), whereas at later times fluid is withdrawn from the hotter (400 °C) outer zone. This causes the shift in the curve for Case B shown in Figure 3.





In Figure 6, Horner plots of build-up pressure transients for the three cases are shown. Build-up was simulated for 556 hours of shut-in time. Horner-times of 100 and 10 correspond to 2.8 hours and 30.9 hours of shut-in time, respectively. Buildup response is independent of compressibility for cases of homogeneous fluid properties, so kinematic viscosity is the only parameter which differentiates the transient buildup response between Cases A and C at late times (small Horner times). However, in Case B, fluid properties (particularly compressibility) are heterogeneous. Even though there is little difference between viscosities at 300 °C and 400 °C, the difference of compressibilities makes the behavior of Case B significantly different from that of Cases A and C.

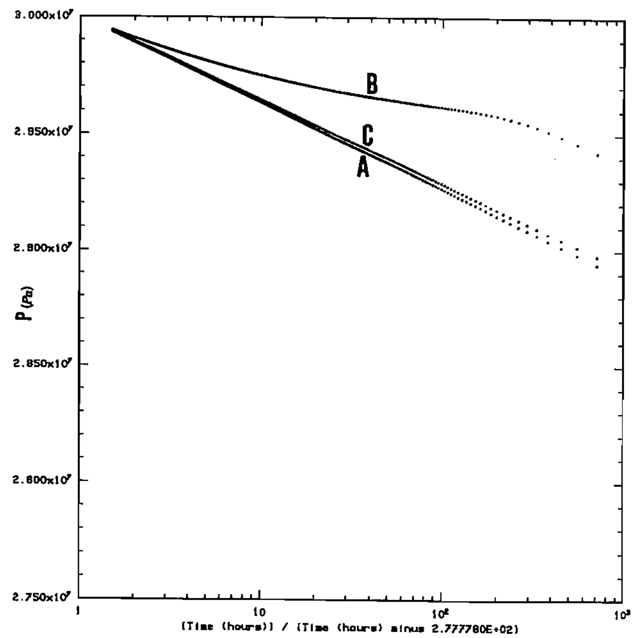


Fig. 6 Horner plots of the simulated buildup pressure transients.

The existence of a super-critical zone brings about the complicated pressure behavior as described above. However, if a two-phase zone is created in the neighborhood of a production well as a result of fluid withdrawal, the non-linear behavior will be largely enhanced. It is probably impossible to distinguish the "super-critical behavior" in the pressure history of the production well itself. In such cases, to detect it in the pressure response, it is required to use observation well(s) remaining in the single-phase part of the reservoir.

Production behavior

Production behavior of hypothetical deep wells were investigated, using basically the same reservoir model as in the previous section. Here, we relaxed the restrictions necessary for maintaining the reservoir single-phase throughout; larger production rates and lower initial pressures were used, and no high-permeability skin zone was assumed. Well-head conditions were calculated using the "WELBOR" simulator (Pritchett, 1985). The depth of the feedpoint is 3,000 meters, and casing inner diameter is 35 and 25 cm for upper and lower 1,500 m interval respectively.

The calculated results are shown in Figure 7. The permeability-thickness product is 1 darcy-meter and reservoir initial pressure is 25 MPa. Production rate is fixed as 50 kg/s during 30 years of 375 °C case and first 10 days of 400 °C case. In the 400 °C case, feedpoint condition is switched to fixed pressure (5 MPa) after 10 days.

As seen in Figure 7, the wellhead flowing enthalpy rapidly increases during the first 10 days in 400 °C case. Starting from the initial super-critical condition (400 °C and 25 MPa), the reservoir fluid changes to superheated steam with relatively small pressure decrease (about 5 MPa) under the heat supply from rock matrix. Since the kinematic viscosity of superheated

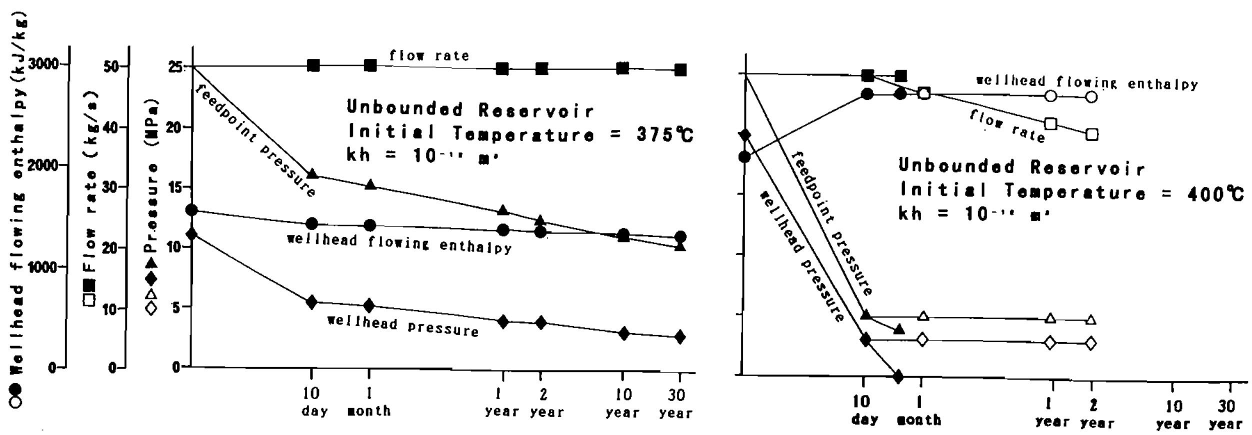


Fig. 7 Long-term production behavior for a hypothetical deep well.

steam is quite large, the pressure gradient needs to be large in the vicinity of the well to sustain the fixed flow rate, resulting in large decline in the feedpoint pressure (and wellhead pressure). As time goes on, the reservoir temperature substantially decreases in the vicinity of the well (about 270 °C in the wellblock after 2 years of production time). However, the heat transfer from rock matrix to fluid is taking place mainly in the outer and large region where the pressure decreases from 25 to about 20 MPa. Thus the fluid entering into the well continues to have high enthalpy after 2 years. The liquid phase appears in the next block to the wellblock after about 2.3 years. This seems to be a "pathological situation" for the numerical simulation; it is difficult to perform further calculation with reasonable computer time.

In the 375 °C case, the neighborhood of the well evolves into a two-phase zone. However, the vapor saturation of the fluid entering the well does not exceed 0.5 (mass fraction of liquid phase is close to one), so the flowing enthalpy does not increase largely even in the early times of production.

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