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ANALYSIS OF PRESSURE TRANSIENT DATA FROM THE SUMIKAWA GEOTHERMAL FIELD

T. Ishido, T. Kikuchi, Y. Yano, Y. Miyazaki and S. Nakao
Geological Survey of Japan
Tsukuba, Ibaraki 305, Japan

K. Hatakeyama
Mitsubishi Materials Corporation
Kazuno, Akita 018-51, Japan

ABSTRACT

The permeability structure of the Sumikawa geothermal field in northern Japan has been the subject of an extensive pressure-transient testing investigation since 1986. In this paper, various pertinent data sets are presented and analyzed, including results showing reservoir heterogeneity (i.e. boundary) effects and apparent double porosity behavior. Interference tests between wells SB-3 and SD-2 (both of which have feedpoints in dacitic layers in the "marine-volcanic complex" formation) were carried out during 1990. The results have been interpreted to indicate the presence of a moderately high permeability (~ 4 darcy-meters) layer with two impermeable boundaries intersecting at a right angle. The 1988 pressure buildup data for well SN-7D are also explained by assuming two impermeable boundaries in a high transmissivity reservoir within the deep "granodiorite" formation. Interference tests between wells S-4 and KY-1 have suggested that a very permeable north-south channel is present in the "altered andesite" layer. Although the response was successfully interpreted using an "anisotropic line-source model" by Garg et al.(1991), a "double porosity channel model" seems to be particularly applicable for explaining both the short-term and long-term behavior observed in this series of tests.

INTRODUCTION

The Sumikawa geothermal field is located in the Hachimantai volcanic zone of the Sengan thermal area in northern Honshu, Japan. Exploratory studies have been in progress at Sumikawa since 1981 by Mitsubishi Materials Corporation (MMC) and Mitsubishi Gas Chemical Corporation (MGC); this comprehensive program incorporates a variety of geochemical and geophysical surveys and an extensive drilling investigation. The drilling program has revealed a complex geological structure and has made possible a very thorough pressure-transient testing program involving both short-term single-well and long-term multi-well pressure interference tests. These studies were first carried out jointly by MMC and NEDO (the New Energy and Industrial Technology Development Organization) from 1985 to 1989, and then by MMC and GSJ (Geological Survey of Japan) in 1990 and 1991.

The area depicted in Figure 1 is about 42 square kilometers; the Sumikawa field lies in the western part of the area, which may be regarded as centered in the neighborhood of the S-series wells (S-1, S-2, S-3, and S-4). To the east, the Ohnuma geothermal power station has been producing about 10 MW of electricity for several years. Within the area, the ground surface averages about 1000 meters above sea level (ASL), but slopes sharply down from south (> 1300 m ASL near Mt. Yake) to north (< 700 m ASL near the Akagawa hot spring area). The major geological formations in the area are as follows, in order of increasing depth:

"ST" Formation: Surface andesitic tuffs, lavas and pyroclastics of Recent origin.

"LS" Formation: Lake sediments; Pleistocene tuffs, sandstones, siltstones and mudstones.

"DA" Formation: Pliocene dacites, dacitic tuffs and breccias.

"MV" Formation: "Marine/Volcanic Complex"; interbedded Miocene dacitic volcanic rocks and "black shale" marine sediments.

"AA" Formation: Altered andesitic rocks which are apparently extensively fractured.

"GR" Formation: Crystalline intrusive rocks, mainly granodiorite and diorite.

The various pressure transient tests performed so far have helped to clarify the permeability structure of the Sumikawa reservoir (see e.g. Garg et al., 1991). Three of the above formations ("DA", "AA" and "GR") appear to be fairly permeable; the "LS" layer is an impermeable aquitard, and the "MV" formation, while permeable to horizontal fluid motion, acts as a barrier to vertical flow.

In this paper, we discuss pressure transient measurements indicative of reservoir heterogeneity (i.e. impermeable boundary) effects; first, the 1990 interference test between wells SB-3 and SD-2 (both of which have feedpoints in the "MV" formation), and then the 1988 buildup test of well SN-7D (which penetrates the "GR" formation).

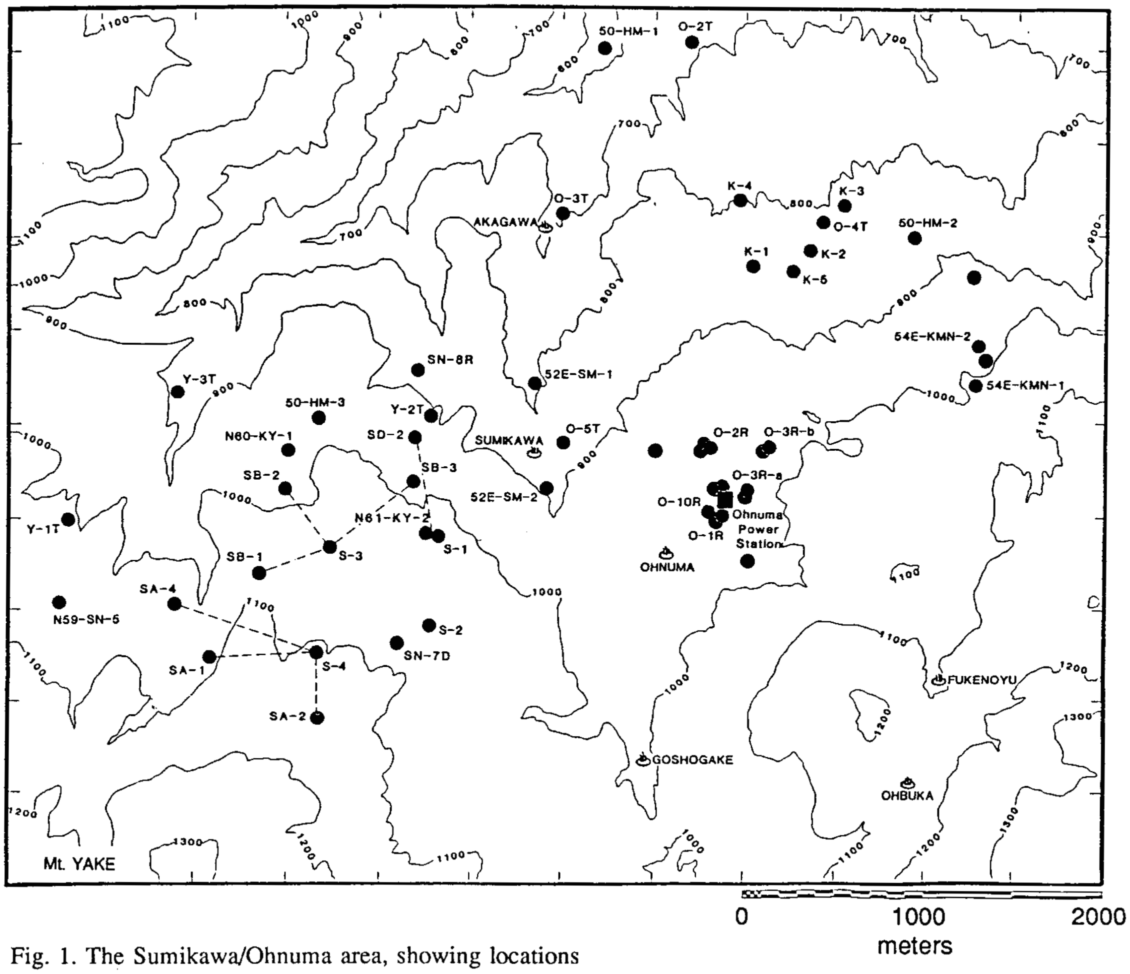

Fig. 1. The Sumikawa/Ohnuma area, showing locations of wells.

Finally, we present a new model for the very permeable north-south channel in the "AA" layer (which has been revealed by several pressure interference experiments involving flowing of well S-4 and the observation of pressure in well KY-1).

RESERVOIR BOUNDARIES

The pressure signal recorded in well SD-2 using a downhole gauge of the capillary tube type clearly shows a response to a four-hour injection of cold water into nearby well SB-3 which started at 09:00 on June 6, 1990 (see Figure 2). The pressure signal appears to propagate through a dacite aquifer embedded within the "MV" formation which is intercepted by both wells. The spatial separation between the SB-3 feedpoint and the upper SD-2 feedpoint (in the "MV" formation) is 354 meters. The reported injection rate history for well SB-3 is as follows:

Time Interval 06/06/90	Injection Rate
prior to 09:00	0 kg/s
09:00 to 09:30	51.7 kg/s
09:30 to 10:00	61.4 kg/s
10:00 to 10:30	77.8 kg/s
10:30 to 11:00	77.9 kg/s
11:00 to 11:30	79.4 kg/s
11:30 to 12:00	83.9 kg/s
12:00 to 12:30	84.9 kg/s
12:30 to 13:00	76.2 kg/s
after 13:00	0 kg/s

We used the classical line-source solution throughout to analyze this test. Initial estimates of transmissivity and diffusivity were obtained (assuming an unbounded aquifer) by type-curve matching, considering only the buildup (flowing) portion of the pressure record. Then, repetitive forward calculations were carried out to refine these estimates (still assuming an infinite aquifer and considering buildup only). The following values were finally obtained in this way:

$T=kh/\mu=3.0\times10^{-8}$ m^3/Pa-s

$\eta=k/\phi C_t\mu=5.7$ m^2/s

Next, to improve the match for the falloff (shutin) portion of the pressure record, we introduced linear impermeable boundaries and performed additional repetitive calculations, this time varying the distances to the boundaries from case to case. The best match was obtained by assuming that the aquifer was constrained by two impermeable boundaries intersecting at a right angle - this match is shown as the line in Figure 2. This aquifer boundary geometry may be treated as equivalent to the total effect (at the observation well location) of the actual flowing well together with three fictitious "image" wells in an unbounded aquifer, which in turn may be represented using superposition of line-source solutions. This final representation yields the following values for the distances between observation well SD-2 and the two primary "image" wells (the first reflections of the flowing well SB-3 across each boundary):

$R1 = R2 = 1000$ m

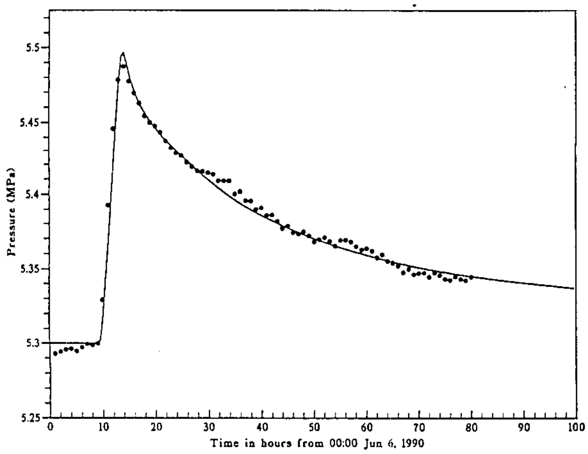

Fig. 2. Comparison of pressure measurements in well SD-2 with computed response due to cold water injection into well SB-3 on June 6, 1990 (t=9 to 13 hours). Measured pressures are corrected for a linear background trend (150 Pa/hour) observed over a five-day period prior to the test.

The distance between the third image well and observation well SD-2 is given by:

$\sqrt{R1^2 + R2^2 - L^2}$

where L (354 m) is the distance between wells SB-3 and SD-2.

SN-7D BUILDUP DATA

Well SN-7D is the deepest well (total depth about 2486 m) at Sumikawa. The major feedpoint for well SN-7D is located in the granodiorite/granite/diorite rocks ("GR" formation) at about 2320 m depth. Well SN-7D 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.

Downhole pressures were monitored using a downhole capillary tube gauge in three separate discharge tests (two in 1988 and one in 1989). The pressure buildup data obtained after the first 1988 test are shown in Figure 3, a multi-rate Horner plot in which buildup pressures are plotted against "reduced time":

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

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 3 was computed from a mathematical model which assumes the following properties (Ishido et al., 1989):

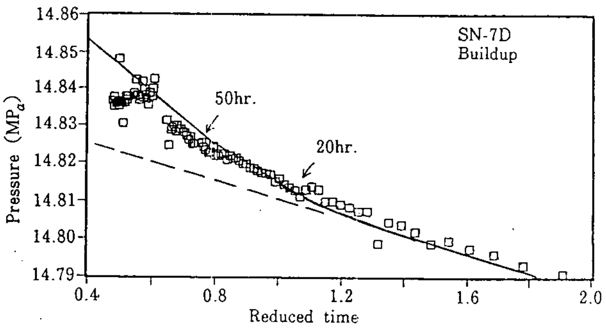

Fig. 3. Comparison of measured and computed (solid curve) pressure buildup histories after first 1988 SN-7D discharge test.

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

L1(distance to the first impermeable boundary) =990 meters
L2(distance to the second impermeable boundary) =1650 meters

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

$$Ri = \sim 8.7 \text{ kilometers} = 8.8L1 = 5.3L2$$

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

It appears that the volume of the deep permeable zone within the "GR" 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". Further pressure transient testing of well SN-7D is needed. The best way to characterize this deep reservoir (confirm and locate reservoir boundaries, appraise volume, etc.) is to drill new wells into the "GR" formation and then to perform long-term interference tests involving these wells and SN-7D.

DOUBLE POROSITY BEHAVIOR

Interference tests between wells S-4 and KY-1

The first large-scale pressure-interference experiment at Sumikawa was carried out in 1986. Deep well S-4 was discharged starting on September 2 and was subsequently shut in on November 3; the liquid fraction of the discharge was simultaneously reinjected into nearby shallow well S-2. A clear pressure response was immediately observed in well KY-1 (see Figure 4), located 1.1 km north of S-4 (see e.g. Kawano et al., 1989). The principal feedpoints for wells KY-1 and S-4 both lie within the "altered andesite" (AA) layer, below the "MV" formation explored by wells SD-2 and SB-3, and above the crystalline "GR" layer penetrated by well SN-7D.

To explain the pressure response observed in well KY-1 due to the 1986 S-4 discharge, Pritchett et. al. (1989) proposed the following one-dimensional "channel-flow" model. It is assumed that a permeable horizontal "channel" of constant cross-section area and constant permeability is present, oriented north-south, which contains the feedpoints of both wells (S-4 and KY-1). The east, west, upper and lower boundaries of the channel are impermeable. To the north, the channel terminates at an impermeable northern barrier; to the south, it ends at a constant-pressure boundary (representing the influence of a two-phase region). Minimization of the deviations between measurements and computed pressures yielded the following parameter values:

Cross-section	=0.51 square kilometers
Permeability	=195 millidarcies
Impermeable boundary position:	1.44 km north of well KY-1
Constant-pressure boundary position:	9.86 km south of S-4

The above parameter values are consistent with the geological structure of the area, to the extent that it is known from drilling logs (see e.g. Pritchett et.al., 1989). The "altered andesite" formation is very permeable, and the cross-section area of the channel is substantial. This permeability is presumably due to the presence of a system of fractures (probably oriented approximately north-south); although well S-4 intersected only one of these fractures at its primary feedpoint, the frequent intersections of the individual fractures within the channel served to distribute the pressure signal from S-4 throughout the entire fracture network in the formation such that the apparent cross-section area and aquifer volume were large.

Subsequently, between 1 May and 4 May 1989, cold water was intermittently injected into well S-4 (each injection episode lasted a few hours). Pressures measured downhole in well KY-1 responded quickly to each change in the S-4 injection rate (see Figure 5). These 1989 tests involved short-term response (time scales of hours) as compared to the long-term response characterized by the 1986 test discussed above (weeks). If the mathematical "channel flow" model outlined above is used to forecast the pressure disturbance in KY-1 due to these short term injection tests, the resulting computed pressure history is not in good agreement with the high-frequency features of the observed pressure signal. Consequently, Garg, et al. (1991) presented an alternative "anisotropic line-source model", which assumes that the east-west permeability is much smaller than the north-south permeability. (The earlier "channel model", on the other hand, assumes that the east-west permeability is sufficiently large that the reservoir behaves in an essentially one-dimensional manner.) This "anisotropic line-source model" (which is not too different from the "channel model" as regards the reservoir cross-section and the distances to the northern and southern boundaries) was successfully used to explain both the 1986 and 1989 test data.

Double porosity channel model

As an alternative, we herein present a "double porosity channel model", which has the same geometry, boundary conditions and global properties (transmissivity and storativity) as those of the "channel model" originally developed by Pritchett, et al. (1989). In the present model, a MINC representation (Pruess and Narasimhan, 1982) is used to represent the influence of fractured reservoir behavior. The essential hypothesis is that the lack of good high-frequency agreement between short-term pressure test results and the original "channel" model arises from the latter's "porous medium" assumption that pressures equilibrate instantaneously between the relatively high-permeability "fracture zone" and the relatively low-permeability "country rock".

These calculations were performed using the STAR general-purpose geothermal reservoir simulator (Pritchett, 1989). In the "double porosity (MINC) medium" representation, on the sub-grid scale the STAR simulator idealizes a "typical" block of country rock (matrix) as a sphere, surrounded by a concentric spherical shell of high-permeability material representing the fracture zone. In the present calculations, the matrix region was subdivided into 10 concentric spherical shells for numerical purposes (for explanation of the MINC representation employed in the STAR code, see e.g. Pritchett and Garg, 1990).

In the "porous medium" limit, the present model gives results identical to the analytical solutions for the "channel model" originally proposed by Pritchett, et al. (1989). As shown in Figure 4, pressure values computed using the present model with a "porous medium" representation are in good agreement with the measured 1986 pressure history. On the other hand, the computed response does not reproduce the measured 1989 data very well (see Figure 5). The overall pressure rise is approximately reproduced, but high-frequency fluctuations are not adequately represented.

To try to improve agreement with the 1989 data, we next carried out a series of calculations using the "double porosity channel model", varying the fracture-to-total storage ratio (ω) and the permeability of the matrix (k_m) within the following range:

$$0.01 < \omega=\psi\phi_f/\phi < 0.3$$

$$10^{-18} < k_m < 10^{-16} \quad (m^2)$$

where ψ is the fracture zone volume fraction, ϕ_f is the porosity of fracture zone, and ϕ ($=\psi\phi_f+(1-\psi)\phi_m$) is the total porosity, fixed at 0.05 (ϕ_m: the porosity of representative matrix block). The upper limit on k_m was set such that the time required for pressure equilibrium to be reached between the fracture zone and the matrix block would exceed 10 hours, the representative time-scale of individual injection events in the 1989 test. This time (see e.g. Pritchett and Garg, 1990) may be expressed as:

$$\tau = \phi_m C_t \rho \nu \lambda^2/10k_m$$

where λ is the fracture spacing (the diameter of the representative spherical matrix block). On the basis of drilling experience in the "AA" formation, λ was assumed

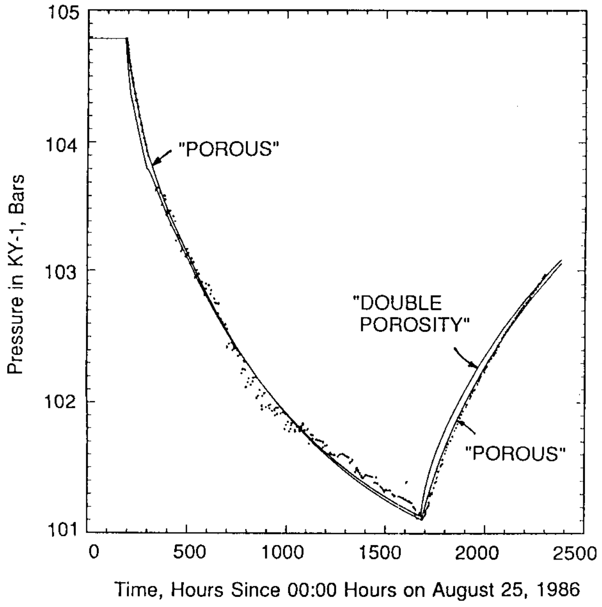

Fig. 4. Comparison of computed 1986 pressure disturbances in well KY-1 with measurements.

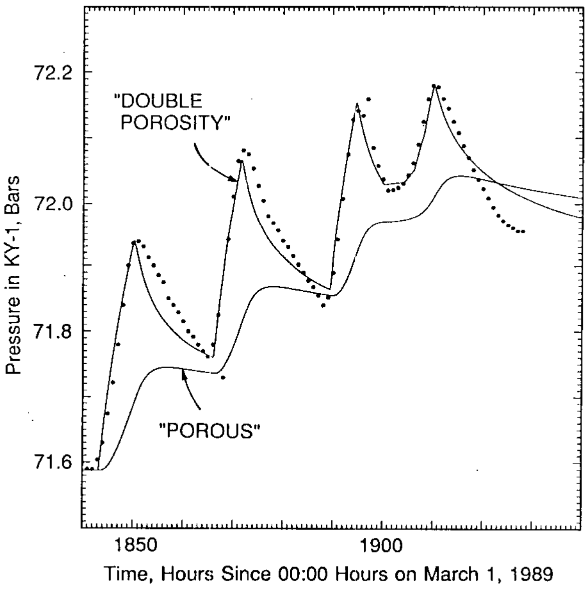

Fig. 5. Comparison of computed pressure response of KY-1 with measurements due to 1989 cold water injection into well S-4.

to be 100 meters and was not changed during the series of calculations.

The 1989 test data was best explained by the present model using the following parameter values:

$\omega = 0.2$

$k_m = 10^{-17}\ m^2$

As shown in Figure 5, the agreement between the measured and computed response is reasonably good. The falloff after each injection in the measured data is slower than the computed response; this is probably explained by the fact that observation well KY-1 does not itself intersect any large permeable fractures (responsible for the observed pressure response); although KY-1 reacts quickly to pressure changes in the "AA" aquifer, the injectivity measured for well KY-1 is very low.

The 1986 pressure response computed using the present "double porosity channel model" with the above parameter values is shown in Figure 4. In view of the uncertainty associated with the 1986 well S-4 flow rate data (see e.g. Garg et al., 1991), the agreement between the measured and computed response, while not as good as that for "porous medium" case, is certainly adequate.

An extensive two-phase (water/steam) flow zone is present in the southern part of the Sumikawa reservoir under natural state conditions (see e.g. Pritchett et al., 1991). When fluid production begins, the volume of the two-phase zone is expected to increase substantially and to invade the north-south channel in the "AA" layer due to production-induced pressure decline. This "AA" aquifer represents the main production horizon for the Sumikawa field. Under two-phase conditions the effective total compressibility (C_t) can be quite large, so that for the present "double porosity channel model" the time required for pressure equilibrium between fracture and matrix zones to be attained can reach as much as 30 years (as compared to 10 days for the single-phase liquid case), which is comparable to the economic lifetime of the reservoir. Under these conditions, as discussed by Pritchett and Garg (1990) some treatment other than the traditional "equivalent porous medium" representation will be required to predict reservoir behavior under exploitation.

REFERENCES

Garg, S.K., J.W. Pritchett, K. Ariki and Y. Kawano (1991) "Pressure-Interference testing of the Sumikawa Geothermal Field", Proc. Sixteenth Workshop on Geothermal Reservoir Engineering, Stanford University.

Ishido, T., T. Kikuchi and T. Noda (1989) "Analysis of Pressure Transient Test Data from Well SN-7D", presented at the Annual Meeting of the Geothermal Research Society of Japan, Tokyo, Oct. 23 - 25.

Kawano, Y., H. Maki, T. Ishido and Y. Kubota (1989) "NEDO's Project on Geothermal Reservoir Engineering: A Reservoir Engineering Study of the Sumikawa Geothermal Field, Japan", Proc. Fourteenth Workshop on Geothermal Reservoir Engineering, Stanford University, pp. 55 - 59.

Pritchett, J.W. (1989) "STAR User's Manual", S-Cubed Report SSS-TR-89-10242.

Pritchett, J.W. and S.K. Garg (1990) "On Similitude, Heat Conduction, and Two-Phase Flow in Fractured Porous Media", Proc. Fifteenth Workshop on Geothermal Reservoir Engineering, Stanford University.

Pritchett, J.W., S.K. Garg, K. Ariki and Y. Kawano (1991) "Numerical Simulation of the Sumikawa Geothermal Field in the Natural State", Proc. Sixteenth Workshop on Geothermal Reservoir Engineering, Stanford University.

Pritchett, J.W., S.K. Garg, H. Maki and Y. Kubota (1989) "Hydrology of the Sumikawa Geothermal Prospect, Japan", Proc. Fourteenth Workshop on Geothermal Reservoir Engineering, Stanford University, pp. 61 - 66.

Pruess, K. and T.N. Narasimhan (1982) "A Practical Method for Modeling Fluid and Heat Flow in Fractured Porous Media", presented at the Reservoir Simulation Symposium of the Society of Petroleum Engineers, New Orleans, Louisiana, Jan. 31 - Feb. 3. (Also see SPE Journal, Feb. 1985, pp. 14 - 26.)