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NUMERICAL ANALYSIS OF THE DECREASE IN INJECTIVITY OF WELLS IN THE OTAKE GEOTHERMAL FIELD, JAPAN

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ABSTRACT

The field tests of injecting geothermal hot water into two wells have been conducted for 638 to 656 days in the Otake geothermal field. The permeability-thickness product decreased from 224 to 0.79 darcy-m for Well R-1, and from 91 to 5 darcy-m for Well R-2. This is probably caused by the decrease in permeability due to the deposition of silica in cracks around the wells. A mathematical model, which describes the permeability decrease caused by the silica deposition in a porous reservoir, has been used to analyze the field data. The rate constants of silica deposition used in calculation were determined by the laboratory experiments on silica deposition in porous media. A reasonable match was obtained between the measured and the calculated water levels for Well R-1. The zone where the permeability decreased significantly was calculated to be in the vicinity of the well, within 8 m in radius. Outside this area, the decrease in permeability is negligible small.

INTRODUCTION

In some water-dominated geothermal systems, it is a serious problem that reinjection wells for waste water have decreased rapidly in their injectivity(Kinoshita, 1980, Inoue and Shimada, 1985, Hauksson and Gudmundsson, 1986, Itoi et al. ,1987). This is probably due to silica deposition in fractures near the injection wells that reduces the reservoir porosity and permeability. The permeability decrease due to silica deposition involves a rate equation of silica deposition on solid surfaces (Bohlmann et al.,1980, Rimstidt and Barnes, 1980, Weres et al., 1982, Bird et al.,1986). Lai et al.(1985) incorporated a rate equation into the numerical model which simulates the silica deposition in single fractures under the non-isothermal flow. The analysis of of well injectivity decrease, however, has scarcely been made in relation to the decrease rate of well injectivity and the silica deposition.

New Energy Development Organization promoted extensive studies on silica deposition, laboratory experiments, and field injection tests in Otake, which were carried out by Kyushu Electric Power Company(Itoi et al., 1984, Nishiyama et al., 1985, Itoi et al.,1987). In this study, we have numerically analyzed the results of the field tests on the decrease in injectivity of wells, using a mathematical model which describes the permeability decrease due to silica deposition in a radial coordinate systems for an isothermal flow(Itoi et al., 1986).

OUTLINE OF THE INJECTION TESTS

Injection tests have been performed outside the developed field, about 800 m north-east of the Otake power station, to avoid the influence of current reinjection(Fig.1). At the test site, two injection wells were drilled to depths 365 m(R-1) and 387 m(R-2) together with observation wells K-1(410 m) and K-2(450 m). All the wells were cased except the intervals of circulation loss(about 330 m below the ground surface) where the slotted liners were set. Temperature of the reservoir ranges from 120°C to 162°C. The Otake water was pumped to the injection site. The pumped water is about 85°C and its silica concentration 570 mg/l. Then, the water was injected at a constant volumetric flow rate at temperatures 50, 60, and 80 °C; the temperatures, 50 and 60°C, were attained by passing the water through a heat exchanger before the injection. The lower temperature means higher degree of supersaturation of silica in the water. The total volumes of the injected water into R-1 and R-2 were $4.59 \times 10^5\ m^3$ for 638 days and $5.49 \times 10^5\ m^3$ for 656 days, respectively. When the injection terminated, the water level in the Well R-1 was at the well head, whereas that in the Well R-2 located 55 m in depth below the ground surface. During the injection experiments, the falloff test, the maximum injectivity test and the tracer test were repeated.(Itoi et al., 1987).

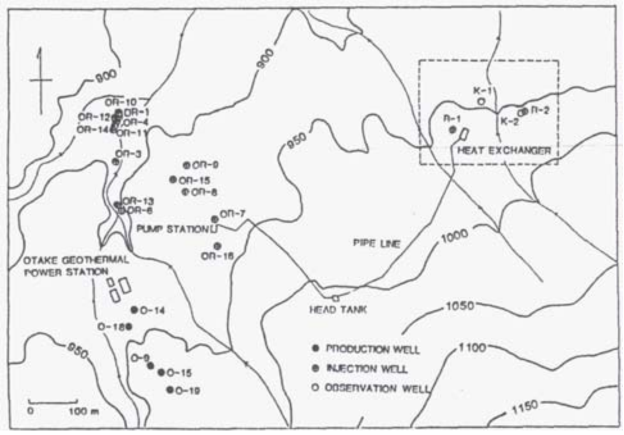

Fig.1 Well location map at the Otake geothermal field. Injection experiments were conducted in the broken line zone.

A MATHEMATICAL MODEL

For the numerical analysis of the injection tests, we use a mathematical model which explains the permeability decrease due to silica deposition in a porous reservoir for an isothermal flow(Itoi et al., 1986). The rate equation, however, is simplified compared with the former model. The rate constants in the equation are determined using the empirical formulas derived from the analysis of the laboratory experiments. The model is expressed by following equations.

The conservation equation for incompressible fluid in a radial coordinate is expressed as

$$-\frac{1}{r}\frac{\partial(rv)}{\partial r} = 0 \qquad (1)$$

where r is the radial distance and v is the velocity given by Darcy's law.

The conservation equation of silica is given by

$$\frac{\partial C}{\partial t} + \frac{v}{\varepsilon}\frac{\partial C}{\partial r} = \frac{1}{r}\frac{\partial}{\partial r}(rD\frac{\partial C}{\partial r}) - \beta_1 A(1 + \beta_2 Q_s)C \qquad (2)$$

where A is the surface area of rocks in contact with the fluid to a unit volume of the reservoir, C is the silica concentration, D is the diffusion coefficient, Q_s is the specific deposit of silica defined by the ratio of the weight of deposited silica to a unit weight of rocks, t is the time, β_1 and β_2 are the rate constant of silica deposition, and ε is the reservoir porosity.

The time derivative and the diffusion terms in Eq. (2) are neglected, because 1) these terms seem to have very small effect on Concentration change in the course of silica deposition, and 2) numerical calculation including these terms requires a large computing time to avoid the truncation error. Hence, Eq. (2) can be simplified as

$$\frac{v}{\varepsilon}\frac{\partial C}{\partial r} = - \beta_1 A(1 + \beta_2 Q_s)C \qquad (3)$$

By introducing a dimensionless distance, $R=\ln(r/r_w)$ where r_w is the well radius, Eqs. (1) and (3) can be rewritten as

$$- \frac{1}{r_w e^R} (v + \frac{\partial v}{\partial R}) = 0 \qquad (1)'$$

$$\frac{1}{r_w e^R}\ \frac{v}{\varepsilon}\ \frac{\partial C}{\partial R} = -\beta_1 A(1 + \beta_2 Q_s)C \qquad (3)'$$

The rate equation of silica deposition expressed as

$$\frac{\partial Q_s}{\partial t} = \frac{\varepsilon}{(1-\varepsilon_o)\rho_m} \beta_1 A(1 + \beta_2 Q_s)C \qquad (4)$$

where ε_o is the initial reservoir porosity. Evaluating the value of A in situ will be a difficult task, because of the complexity of flow path in a reservoir. As the first step, therefore, the Kozeny equation is used to calculate a value of the surface area, A, as follows:

$$A = (1 - \varepsilon_o)S_v \qquad (5)$$

$$S_v = (\frac{\varepsilon_o^3}{kk_c(1 - \varepsilon_o)^2})^{0.5} \qquad (6)$$

where S_v is the surface area to a unit volume of rocks, and k_c is the Kozeny constant (k_c=5 is given).

. The reservoir porosity which decreases as silica deposits is expressed as

$$\varepsilon = \varepsilon_o - \frac{(1 - \varepsilon_o)\rho_m Q_s}{(1 - f_\sigma)\rho_s} \qquad (7)$$

where f_σ is the porosity of deposited silica, and ρ_m and ρ_s are the densities of rocks and deposited silica, respectively. For the relation between the amount of deposited silica and the permeability, the Kozeny-Stein equation (Camp, 1964) is used.

$$\frac{k}{k_o} = \frac{\left\{\varepsilon_o-(1-\varepsilon_o)\frac{\rho_m Q_s}{\rho_s(1-f_\sigma)}\right\}^3}{\varepsilon_o^3\left\{1 + \frac{\rho_m Q_s}{\rho_s(1-f_\sigma)}\right\}^2} \left\{\frac{\rho_m Q_s}{3\rho_s(1-f_\sigma)} + \frac{1}{2} + \sqrt{\frac{1}{4} + \frac{\rho_m Q_s}{3\rho_s(1-f_\sigma)}}\right\} \qquad (8)$$

A set of above equations are numerically solved for the initial and the boundary conditions:

initial condition:

$t=0 \qquad p=p_o$
$\qquad\qquad C=C_o$

boundary condition:

$t>0 \qquad R=0(r=r_w) \qquad Q=\text{const.}$
$\qquad\qquad\qquad\qquad\qquad\qquad C=C_o$

$\qquad\qquad R=R_e(r=r_e) \qquad p=p_o$

where r_e is the radius of outer boundary, Q is the volumetric flow rate, and p_o is the initial pressure of the reservoir.

DEPOSITION MECHANISM AND RATE CONSTANTS

Experiments on silica deposition in porous columns packed with aluminum beads were repeated to understand the effects of silica concentration, pH, and temperature on the deposition rate (Itoi et al., 1984, Nishiyama et al., 1985). In the experiments, the Otake and the Hatchobaru waters were passed through the porous column at temperatures of 50 ℃ to 90 ℃, and at pH of 5.5 to 8.5. Silica concentrations of the waters varied from 450 to 582 mg/l for the Otake water and from 615 to 831 mg/l for the Hatchobaru water. They contain most monosilicic acid, and a small amount of polysilicic acid. The concentration of polysilicic acid was unchanged between the inlet and the outlet of the column (50 cm long). Hence, we assume that only monosilicic acid deposits on the surface of the beads in accordance with the chemical reaction:

$$\equiv Si-O^- \;+\; Si(OH)_4 \longrightarrow \equiv Si-O-Si(OH)_3 \;+\; OH^-$$
(Silica Scale) (Water) (Silica Scale) (water)

The rate equation of silica deposition can be expressed by a second order reaction: It is proportional to the product of the concentration of silanol group ($\equiv Si-O^-$) on the surface of the beads (or silica scale) and the concentration of monosilicic acid which is supersaturated with respect to amorphous silica. As a result, the deposition rate can be related to a variable defined as

$$Z = (\frac{K_a}{K_a + a_H})(\frac{a_H}{K_1 + a_H} C_m - C_s) \qquad (9)$$

where K_a and K_1 are the dissociation constants of poly- and mono-silicic acid, a_H is the hydrogen ion concentration, C_m is the concentration of monosilicic acid, and C_s is the equilibrium concentration of silica calculated using the geothermometer for amorphous silica (Fournier, 1981). We use the formula by Ryzhenko (1967) for calculating a value of K_1. For a value of K_a, an least squared equation using the experimental data on the reaction between polysilicic acids by Shimada et al. (1982) is used. K_a, K_1 and a_H are calculated by following formulas

$$K_a = 1.803\times10^{-5} - 1.175\times10^{-7}T + 1.929\times10^{-10}T^2 \qquad (10)$$

$$K_1 = 10^{6.368-0.016346T-3405.9/T} \qquad (11)$$

$$a_H = 10^{-pH} \qquad (12)$$

where T is the temperature of water in K.

Numerical analysis of the porous column experiments showed a reasonable agreement with the measured profile of the deposited silica when a very small value of 1-2 mg/l was given at the inlet of the column as the boundary condition of silica concentration. This implies that only a very small portion of monosilicic acid can deposit in the column. From this fact, we calculated the amount of silica which can deposit in the column. The results, then, is related to the

Table 1. Experimental conditions and calculation conditions for the injection tests.

Well	t (days)	Q (m^3/h)	θ (°C)	pH (-)	Cm (mg/1)	Co (mg/1)	β_1 ($\times10^{-5}$ m/s)	β_2 (-)
R-1	$0<t\le227$	30	50	8.2	495	1.76	8.93	27
	$227<t\le503$	30	60	8.1	552	1.94	7.99	44
	$503<t\le638$	30	80	8.2	551	1.12	6.11	114
R-2	$0<t\le53$	90	80	8.2	559	1.17	6.11	114
	$53<t\le282$	30	80	8.2	559	1.17	6.11	114
	$282<t\le468$	30	60	8.3	533	1.67	7.99	44
	$468<t\le656$	30	50	8.1	533	2.10	8.93	27

t: injection period, Q: flow rate, θ: water temperature, C_m: monosilicic acid concentration, C_o: silica concentration at R=0, β_1, β_2: rate constants of silica deposition.

Table 3 Relation between surface area of reservoir rocks(A) and initial porosity(ε_o) for Well R-1.

ε_o (-)	A(1/m)
0.003	28
0.0035	36
0.004	44
0.005	61

Table 2. Parameters used for calculation.

Parameters	R-1	R-2
Well radius(r_w), m	0.0451	0.0689
Radius of outer boundary, (r_e), m	45.1	68.9
Reservoir thickness(h), m	32.7	38.92
Initial pressure(p_o), Pa	1.34×10^6	1.67×10^6
Initial permeability-thickness product(k_oh), $\times10^{-12}$ m^3	224	91
Initial porosity(ε_o), -	0.003	
Density of rock(ρ_m), kg/m^3	2720	
Density of silica scale (ρ_s), kg/m^3	2040	
Porosity of silica scale (f_σ), -	0.93	

variable Z of Eq.(9) by the method of least squares, and expressed as

$$C_o = 3.920\times10^{-3}Z + 8.564\times10^{-6}Z^2 \qquad (13)$$

In the numerical calculation of the porous column experiments, silica concentrations calculated using Eq.(13) were used for the boundary condition at the inlet of the column. Then, the rate constants of silica deposition, β_1 and β_2, were determined so as to fit the experimental results. These constants were also approximated by the the method of least squares as a function of temperature:

$$\beta_1 = (3.176\times10^{-1} - 2.190\times10^{-3}\theta)/A_b \qquad (14)$$

$$\beta_2 = 2.52 \exp(4.76\times10^{-2}\theta) \qquad (15)$$

where θ is the water temperature in °C, and A_b is the surface area of the beads(2 mm in diameter) to a unit volume of the porous column(2331 1/m was used as A_b).

CALCULATION CONDITIONS

The experimental condition and the water chemistry are summarized in Table 1 together with Co calculated using Eqs.(9) to (13), and the rate constants calculated using Eqs.(14) and (15). The values of Co are used as the boundary condition of silica concentration at R=0. Other parameters used in the calculation are summarized in Table 2. The initial values of permeability-thickness were determined by the analysis of the falloff test. The water is assumed to have been injected along the depth intervals of slotted liners. A simple analysis of the tracer test yields the initial porosity of the reservoir, ε_o=0.003. The calculation was stopped when the water level in the well reaches the ground surface or when calculating time exceeds the test period.

RESULTS AND DISCUSSION

1.Well R-1

Figure 2 shows the decrease in permeability-thickness product with time in dimensionless form, kh/k_oh, for four different initial porosities of reservoir. Measured values are also shown. At early times of the injection, a rapid decrease in kh/k_oh was found. The decrease rate, kh/k_oh, becomes large with an increase in the initial porosity. The calculated curves for the initial porosities of 0.003 and 0.0035 show a reasonable match with the measured values except the period from 200 to 400 days. The measured kh/k_oh after 638 days is as low as 0.0035(0.79 darcy-m), whereas the calculated ones are 0.021 after 638 days for the initial porosity of 0.003, and 0.0074 after 622 days for that of 0.0035.

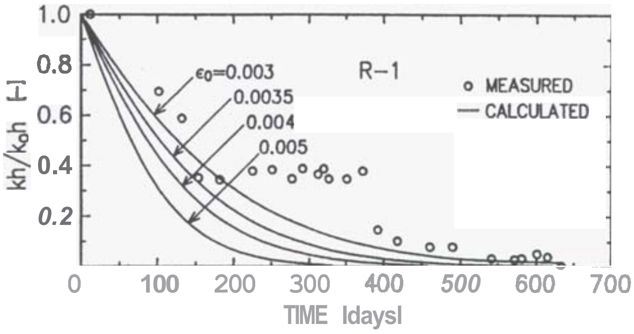

Fig.2 Comparison between calculated and measured permeability-thickness products for Well R-1.

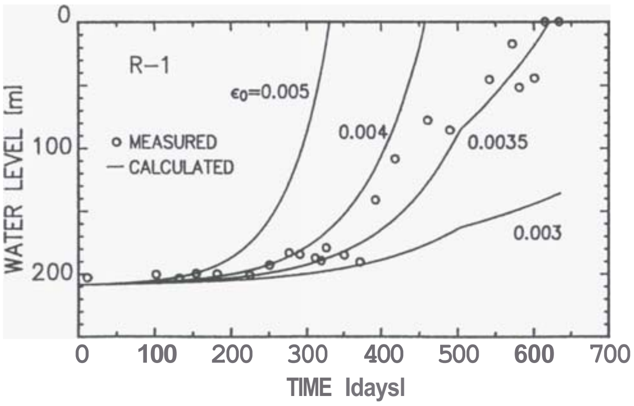

Fig.3 Comparison between calculated and measured depths of the water level in Well R-1.

In Fig.3, the transient behavior of the depth of calculated and measured water levels are illustrated. It is clear that the initial porosity markedly affects the decrease rate of well injectivity. In the measured values, the pressures observed at 340 m below the wellhead(at 300 m at later times) during the maximum injectivity test are converted into the hydraulic head. The temperature of water during the maximum injectivity test was 80 °C for all the experiments since its flow rates are beyond the capacity of the heat exchanger. In the initial stages of the injection, the rise in the water level is less than 10 m in height in all measured values, being well matched with the calculated curves, As time passed, the water levels for larger initial porosities begin to rise faster and reach the ground surface as early as after 332 days. On the other hand, the water level at $\varepsilon_0=0.003$ was still about 130 m deep when the injection test was terminated after 638 days. This reason is probably attributed to the difference in the surface area of rocks, A, in Table.3. As the value of A increases, the coefficient, $\beta_1 A$, in the rate equation of silica deposition becomes larger, which resulted in the acceleration of silica deposition in the reservoir. Of these four curves, the curve for $\varepsilon_0=0.0035$ gives a good match with the observed values.

Distributions of silica scale, permeability, and pressure with time around Well R-1 at the initial porosity of 0.0035 are illustrated in Fig. 4,5, and 6. Silica deposits chiefly near the well; the area of silica deposition extends little with time(Fig.4). The radius of the deposited area was only 7 m even when the water level reached the wellhead after 623 days. The permeability, k/k_0, near the well became as small as 0.0036 after 623 days(Fig.5). At places more than 8 m far from the well remains its initial value. The pressure distribution around Well R-1 shows that the pressure drops steeply within 2 m in radius at later stages of injection(Fig.6). This is because that the permeability decreased by one or two order in this area. At far places, the effect of permeability decrease on a pressure increase is negligible small due to the large initial permeability.

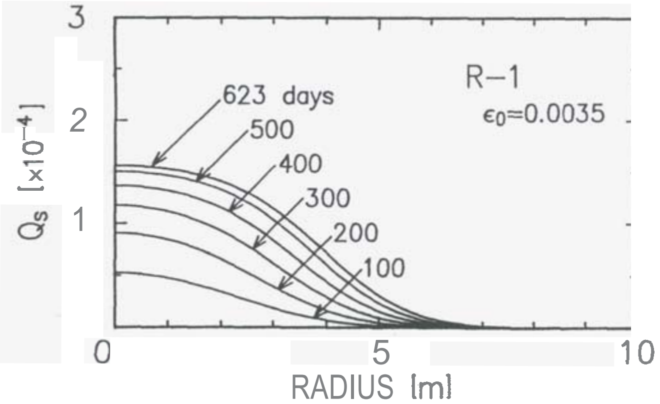

Fig.4 Calculated profile of the amount of deposited silica at different times for Well R-1.

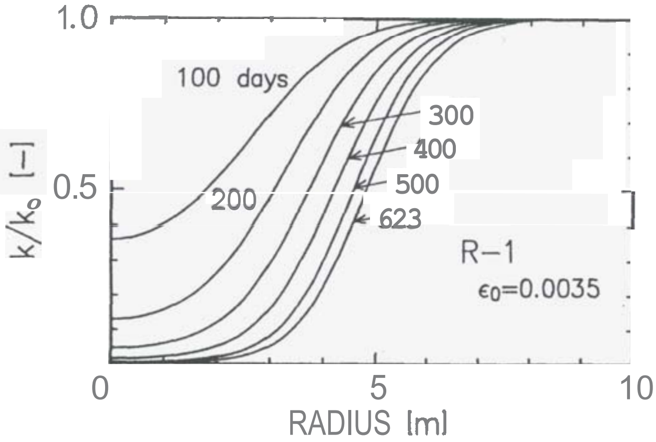

Fig.5 Calculated profile of permeability at different times for Well R-1.

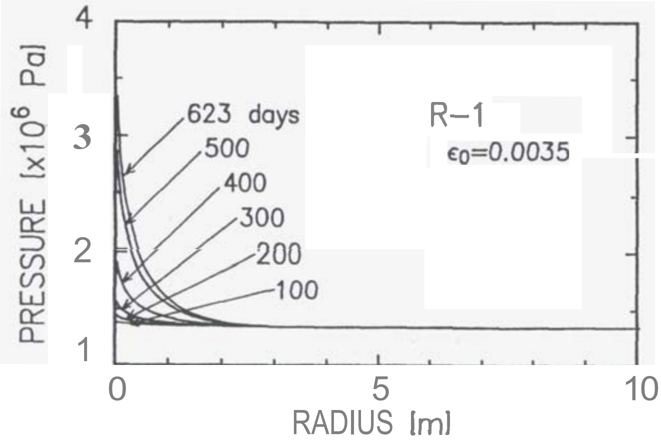

Fig.6 Calculated profile of pressure at different times for Well R-1.

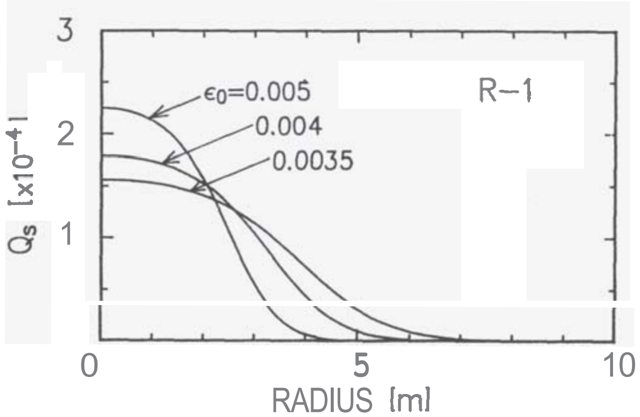

Fig.7 Effect of initial porosity on the profile of specific deposit of silica around Well R-1.

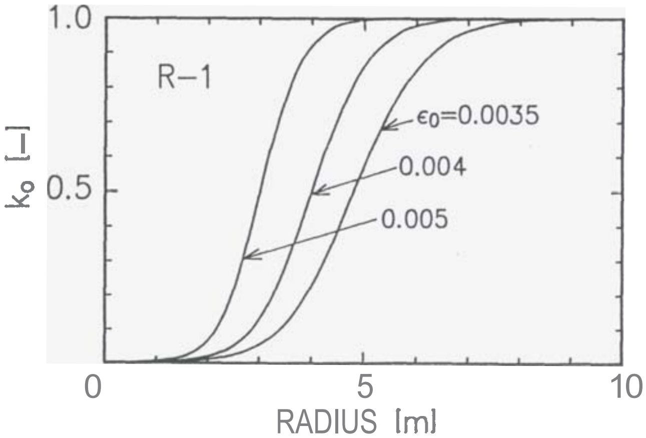

Fig.8 Effect of initial porosity on the profile of permeability around Well R-1.

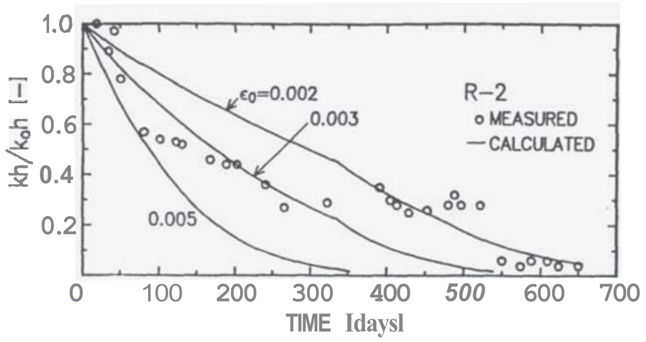

Fig.9 Comparison between calculated and measured permeability-thickness products for Well R-2.

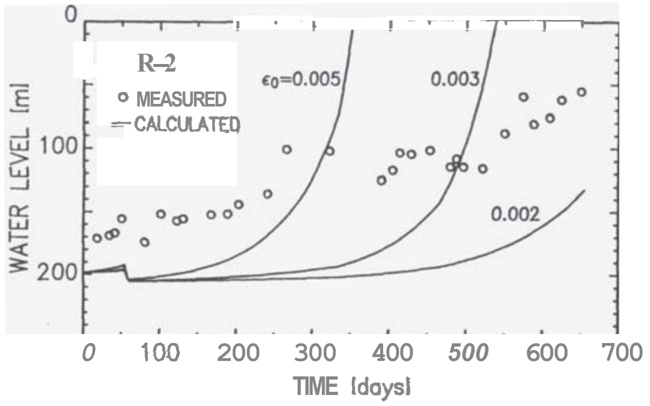

Fig.10 Comparison between calculated and measured depths of the water level in Well R-2.

The effect of the initial porosity on the behavior of silica deposition was examined and shown in Fig.7. The calculated values of specific deposit, Q_s, around Well R-1 when the water level is at the well head are plotted. The curve for $\varepsilon_0=0.005$ has the maximum value of Q_s, 2.25×10^{-4}. As the initial porosity is lowered, the area where silica deposits extends, for example 7 m in radius for $\varepsilon_0=0.0035$. The maximum amount of deposited silica, however, reduces with the decrease in the initial porosity. Since the porosity decrease causes an increase in the pore velocity of the water, the silica in water can travel a longer distance resulted in its wider deposition,

The area where permeability decreases becomes wider when the initial porosity is smaller, for example 8 m in radius for $\varepsilon_0=0.0035$. The damaged area in terms of the permeability, therefore, is limited within 10 m in radius in the range of the given initial porosity in the calculation.

2. Well R-2

In Fig.9, the decrease in permeability-thickness product, kh/k_oh, with time is shown for the initial porosities of 0.002, 0.003, and 0.005. Measured values show a rapid decrease in kh/k_oh at early times of the injection as seen in Fig. 2 for Well R-1. The observed values make a good match with the curve at $\varepsilon_0=0.003$ for 323 days, but does a poor match at later times. The measured kh/k_oh after 656 days is 0.004(5 darcy-m), whereas the calculated one declines to 0.02 after only 520 days.

Measured and calculated depths of the water level are plotted in Fig. 10. The measured values were obtained in the same manner as with Well R-1, using the observed pressures at a depth 375 m below the ground surface during the maximum injectivity test. The rising behavior of the water level is quite different between the measured and the calculated results. The former go up in a linear manner with time without any rapid rise as shown by the calculated curves. The injectivity decrease of Well R-2 may be affected by other factors not included in the model.

CONCLUSIONS

The field injection tests using Well R-1 and R-2 performed at the Otake geothermal field were numerically analyzed. The observed data for Well R-1 show a good agreement with a mathematical model as follows:

1. The model explains well the transient behavior of the water level in Well R-1 when the initial porosity of 0.0035 is given.
2. The area where silica mainly deposited has been calculated to be within 7 m in radius.
3. The decrease in injectivity of Well R-1 is ascribed to the permeability decrease occurred within 8 m in radius.
4. The larger initial porosity of a reservoir resulted in a faster decrease in permeability-thickness product, but a small damaged area in permeability.
5. The injectivity decrease of Well R-2 may be affected by other factors not included in the model.

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REFERENCES

Bird, G, Boon, J. and Stone, T.(1986); Silica Transport during Steam Injection into Oil Sands 1.Dissolution and Precipitation Kinetics of Quartz: New Results and Review of Existing Data, Chemical Geology, 54, p. 69–80.

Bohlmann, E.G., Mesmer, R.E. and Berlinski, P. (1980); Kinetics of Silica Deposition from Simulated Geothermal Brines, SPEJ, vol.20, no. 4, p. 239-248.

Camp, T.R.(1964); Theory of Water Filtration, A.S.C.E., sa 4, vol.90, p.1-30.

Fournier, R.(1981): Application of Water Geochemistry to Geothermal Exploration and Reservoir Engineering, Geothermal Systems, John Wiley & Sons.

Hauksson, T. and Gudmundsson, J. S. (1986): Silica Deposition during Injection in Svartsengi Field, GRC Trans. vol.10, p. 377–383.

Inoue, K. and Shimada, K. (1985): Reinjection Experiences in the Otake and Hatchobaru Geothermal Fields, Proc. of the 7th N.Z.Geothermal Workshop.

Itoi, R., Maekawa, H., Fukuda, M., Jinno, K., Hatanaka, K., Yokoyama, T. and Shimitu, S.(1984); Experimental Study on the Silica Deposition in a Porous Medium, GRC Trans. vol.8, p.301–304.

Itoi, R., Maekawa,H., Tatsuta, K., Fukuda, M., Jinno, K., Hatanaka, K., Notaki, S., Yokoyama, T. and Shimizu, S.(1985); A Mathematical Model of Silica Deposition in a Porous Medium, GRC Trans. vol.9, p.337–340.

Itoi, R., Maekawa,H., Fukuda, M., Jinno, K., Hatanaka, K. , Yokoyama, T. and Shimitu, S. (1986): Numerical Studies of the Decrease in Permeability Caused by Deposition of Silica around an Injection Well, GRC Trans. vol. 10, p.385–388.

Itoi, R., Fukuda, M., Jinno, K., Shimizu, S. and Tomita, T.(1987); Field Experiments of Injection in the Otake Geothermal Field, Japan, GRC Trans. vol.11.

Kinoshita, Y.(1980); The Present Status of the Hatchobaru Geothermal Power Plant: The Thermal and Nuclear Power, vol. 32, no. 2, p. 139–158(in Japanese).

Lai, C.H., Bodvarsson, G.S. and Witherspoon, P.A. (1985): Numerical Studies of Silica Precipitation /Dissolution, Proc. Tenth Workshop on Geothermal Reservoir Engineering, Stanford University report SGP-TR-84, p.279–286.

Nishiyama, E., Hirowatari, K. and Kusunoki,K.(1985); Study on Injecting Low Temperature Geothermal Brine, GRC Trans. vol.9, Part 2, 347–351.

Rimstidt, J.D. and Barnes, H.L.(1980); The Kinetics of Silica-Water Reactions, Geochi. Cosmochim. Acta., vol.44, 1683–1699.

Ryzhenko, B.N. (1967); Determination of Hydrolysis of Sodium Silicate and Calculation of Dissociation Constants of Orthosilicic Acid at Elevated Temperatures, Geochem. Internat.,4, p.99–107.

Shimada, K. and Tarutani, T. (1982); Polymerization of Silicic Acid in Aqueous Solutions at Various pH and Temperatures, Memoirs of the Faculty of Science, Kyushu Univ., Ser.C, vol.13(2), p311-322.

Weres, O., Yee, A. and Tsao, L.(1982); Equations and Type Curves for Predicting the Polymerization of Amorphous Silica In Geothermal Brines, SPEJ, vol.22, no.1, 9–16.