2. Select a match point (p_D, Δp) and (r_D^2/t_D, t), and solve the following equations for X and D_ℓ:

$$-Ei(-X) = \frac{2\,(p_i - p_s)}{\Delta p}\, p_D \tag{14a}$$

$$t_D/r_D^{\,2} = D_\ell\, t/r^2 \tag{14b}$$

where

$$X = \lambda^2\, D_t/D_\ell \tag{14c}$$

and r denotes the distance of the observation well from the production well. Here, it is assumed that the reservoir temperature T (and hence saturation pressure p_s) and initial pressure p_i are known from other measurements.

3. Calculate two-phase kinematic mobility k/ν_t from the observed pressure response in the production well. Compute two-phase diffusivity from Equations (6) through (9). Note that the calculation of D_t requires a knowledge of the enthalpy of the produced fluid in addition to formation porosity and thermal capacity. Estimating formation porosity and thermal capacity (see above) is difficult; uncertainty in these parameters will adversely affect the computed values for two-phase diffusivity D_t and formation transmissivity kh/ν_ℓ.
4. Given X, D_ℓ and D_t, compute λ from Equation (14c).
5. Calculate formation transmissivity kh/ν_ℓ from

$$kh/\nu_\ell = \frac{M}{4\pi}\exp\left(-\lambda^2\right) \cdot \frac{2\,p_D}{\Delta p}\exp(X) \tag{15}$$

Concluding Remarks

In order to define the limits of applicability of the preceding theory, a numerical reservoir simulator was used to generate a series of drawdown/buildup histories. A detailed examination of these simulated pressure interference histories showed that the theoretical method can always be used (even in the presence of a large two-phase zone) to provide a first estimate for reservoir transmissivity. If the two-phase zone created during drawdown is very large, then the apparent mass flow rate will be a small fraction of the actual production rate. In the latter case, the analytical method will yield only a first rough estimate of reservoir transmissivity; a more accurate estimate may then be obtained by forward modeling (history-matching) using a numerical reservoir simulator. Because of nonlinear effects in two-phase flow, the superposition principle does not usually apply in two-phase problems. More specifically, Garg and Pritchett (1984) showed that the buildup response of the production well cannot be constructed from the drawdown solution. The present numerical results, however, suggest that the buildup response in the observation well, after the return of the reservoir to single-phase conditions, does obey the superposition principle. Buildup data can, therefore, be used to check the consistency of formation properties derived from an analysis of drawdown pressures.

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TEMPERATURE, PRESSURE AND KH DISTRIBUTION IN THE KIRISHIMA GEOTHERMAL FIELD

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ABSTRACT

Since 1979, active drillings and research have been conducted to define the geothermal resources in the Kirishima geothermal field. Geophysical logs and well tests were carried out in all the wells. Pressure interference tests were introduced in the Ginyu area where a superior permeable reservoir exist. According to the results of these tests, temperature, pressure and permeability-thickness product (kh) distribution in the Kirishima geothermal field became clear. Two ENE-WSW trending permeable zones were detected in the Ginyu and the Shiramizugoe areas. The two permeable zones were estimated to be separate because of the difference in reservoir pressure. The highest temperature area lies in the southeastern part of the area. A constant temperature area of 232 ℃ extends widely in the Ginyu area. Those reservoir characteristics are interrelated each other, and also related with the geological features of the field.

INTRODUCTION

Nippon Steel Corporation and Nittetsu Mining CO., Ltd. have drilled 21 wells since 1979 as a cooperative project for the development of geothermal energy in the Kirishima Geothermal Field, Kagoshima, Kyushu. To promote the development of geothermal energy, 15 wells have been drilled around the Kirishima geothermal field by the NEW ENERGY DEVELOPMENT ORGANIZATION (NEDO). A geological study of the core and cuttings, geophysical logs, well tests and a geochemical analysis of the fluid were carried out to investigate the features and properties of the reservoir. Longterm discharge tests, pressure interference tests and tracer tests were carried out to estimate the extent of the reservoir and the longterm behavior of the reservoir. During simultaneous discharges in the four months since January 1987 for of all the wells in the Ginyu area, neither a decline nor a change in fluid geochemistry could be observed. Due to the research and tests, a great deal of data on geology, geophysics and reservoir engineering has been accumulated. The geothermal reservoir system of the field became clear and a numerical model was developed to estimate the capacity of the Kirishima geothermal field.

WELL LOGS

Temperature, normal resistivity, caliper and sonic logs are carried out following drilling. Temperature logs are performed three times to study temperature recovery. ALL the logging data, except for the sonic log, are obtained by a personal computer controlled data acquisition system. Data on drilling and well deviation is also entered into the computer.

The productive geothermal reservoir in the Kirishima field is characterized by a steep temperature summit on the temperature profile, a fracture zone detected from the intensity log of the sonic log, an enlarged hole diameter on the caliper log and a low resistivity on the electric log. Results of the geophysical logs in KE1-11 is shown on Fig.1. The major permeable fracture is identified by a qualitative evaluation of the fracture.

A blind drilling method is usually introduced for liner hole drilling in the Kirishma field. It is not too difficult, due to the fresh water or very light mud used in blind drilling,

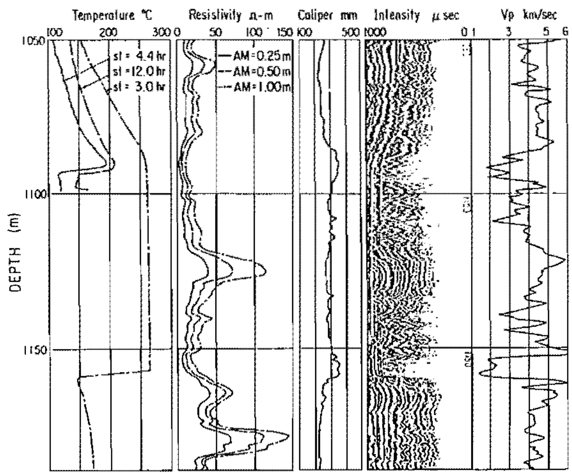


Fig.1 Result of well logs in KE1-11

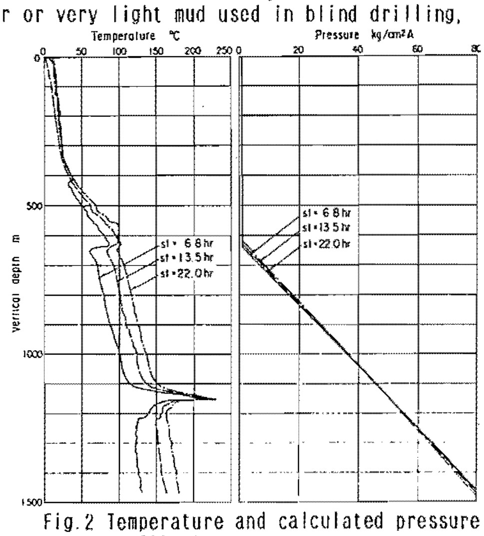
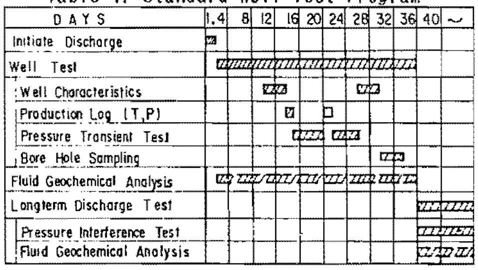


Fig.2 Temperature and calculated pressure profile in KE1-17

to estimate the pressure distribution in the hole by a calculation using the water level and the water density during temperature log. The pivot point is observed at the depth of the major permeable fracture, when it has superior permeability. Fig.2 shows the temperature profile and calculated pressure profile in KE1-17. The pivot point is observed at a vertical depth of 1153m, coinciding with the major permeable fracture depth. The pivot point is observed at a shallower depth when it has low permeability, then the pressure at the main permeable fracture decreases with time. Reservoir pressure and kh value could be calculated by a fall-off plot of the calculated pressure in some wells. Reservoir pressure from a temperature log was usually employed, because pressure buildup test were not generally carried out on large-hole discharge wells. And also we could not observe the difference between reservoir pressure by the temperature log and that by the pressure buildup test.

The equilibrium formation temperature was estimated by a Horner plot of the temperature during heat-up.

Table 1. Standard Well Test Program



WELL TESTS

Well tests are carried out on a standard program.(Table.1) Pressure transient tests, production logs(T,P), measurement of well characteristics, geochemical fluid analysis and borehole sampling are included in the well test. Pressure transient tests were carried out at all the discharge wells. Injection tests were carried out at a structural and reinjection wells.

Objectives of the production log are to confirm the feed point and flush point. The depth of the feed point was also confirmed by the bore-hole sampling and fluid analysis. Major permeable fractures identified by the well logs generally coinside with the feed points confirmed by the well test.

The pressure transient test, usually a two-rate test in two direction, i.e., increase and decrease of the discharge rate, was measured by the Kuster pressure gauge. Kh and skin factors, assuming ϕch value, are obtained by semilog analysis.

Fig.3 shows the result of the pressure buildup test for well KE1-9. A straight line with a slope of 1.45 kg/㎠/log cycle can be drawn on the plot, and it gives a kh=3.1 dm. Skin factor can be obtained by assuming a pseudo-steady state before the buildup test. It gives a positive skin factor of 31, assuming $\phi ch=6.0\times10^{-9}$ m/Pa. This large positive skin factor would not only be due to formation damage but to the inferior permeability of the fracture around the well bore and flushing in the formation. The skin factor of the wells in the Kirishima field range mostly from -4 to -10. It means that the geothermal reservoir in the area is a fracture type. Five wells out of nineteen have the positive skin factors ranging from 3 to 30. These positive skin factors are estimated to be due to the inferior permeability around the well bore.

Fig.4 shows the result of pressure buildup test for well KE1-7. Pressure change caused by the discharge stop was about 0.1kg/㎠, and its value is almost the same as the accuracy of the Kuster gauge. The Kh value of well KE1-7 was estimated to be 60 ~90 dm, regardless of the large deviation in the data. In the Ginyu reservoir wells, including KE1-7 in which productivity is higher than 300 t/h/kg/㎠, the pressure change caused by the change of dicharge rate is very small compared to the accuracy of the Kuster instruments. We tried a few tests to obtain a reliable kh value.

Discharge characteristics of KE1-7 were measured every month for a year from the initial discharge. During this period, about a 3% decline in the discharge rate at the same well head pressure was observed. A draw-down of the bottom hole pressure, which corresponds with the decline of the discharge rate, was estimated by the well simulator developed by Tachimori(1983). A semilog analysis of the draw-down indicated kh=51.8 dm.

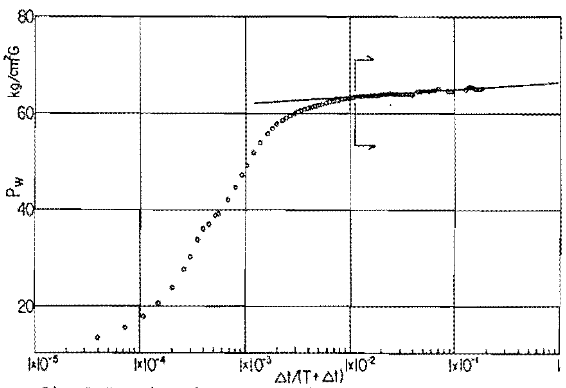


Fig.3 Result of pressure buildup test for KE1-9

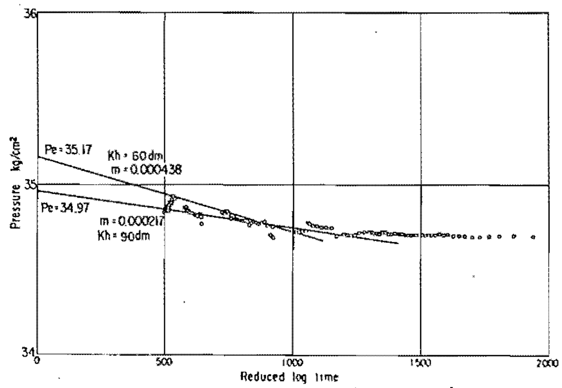


Fig.4 Result of pressure buildup test for KE1-7

Pressure interference tests were introduced between wells KE1-7 and KE1-13S. KE1-13S, 10m apart from KE1-7, was drilled directionally and intercepted the same fracture at a depth of 960m, 145m apart from the feed point of KE1-7. Taking advantage of well KE1-13S having been shut-in for a long time, we planned to measure the water level precisely in KE1-13S by a low range high temperature strain-gauge type pressure transducer installed just 50m below the water level. Pressure interference in well KE1-13S caused by five days of a discharge stoppage of well KE1-7 since Dec. 11, 1984 is shown in Fig.5. This test gave kh=124dm, ϕch=2.5×10⁻⁶m/Pa. The large ϕ ch value implies an effect of the two phase zone at the top of the Ginyu reservoir.

Capillary tube-type pressure gauges have been installed since 1985 to the present in eight wells in the NEDO project for an evaluation of the geothermal reservoir. NSC and NHC also installed capillarytube-type pressure gauges in two wells. Observation of the bottom hole pressure has been carried out to study the behavior of the reservoir along with the long-term discharge test.

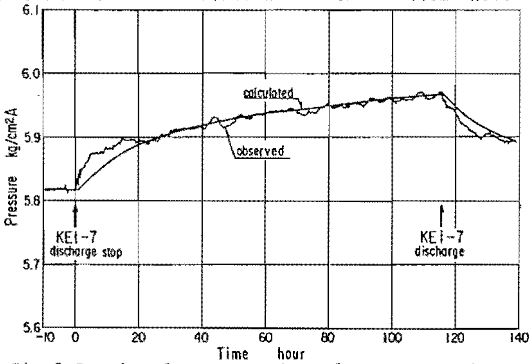


Fig.5 Result of pressure interference test between KE1-13S and KE1-7

TEMPERATURE DISTRIBUTION (Fig.6)

The formation temperature was estimated from temperature recovery tests, shut-in temperature profiles, production logs, a geochemical fluid thermo-meter and the homoge-nization temperature of the fluid inclusions in hydrothermal minerals Temperature distribution in the Kirishima geothermal field clearly indicates that the hottest part lies in the southeastern part of the field, around wells KE1-15, N55-KT-5, and N56-KT-8. Well N56-KT-8 reaches 298.4 ℃ at the bottom of an 1800m depth, which is the maximum measured temperature in the project area. The formation temperature in the Ginyu area is almost a constant 230 ~232 ℃ and temperature reversals have not been observed. This implies the existence of a high permeable fracture in this area. Formation temperature appears to fall rapidly on north side of the Sakkogawa. This implies that cold water infiltrates this area.

PRESSURE DISTRIBUTION

Reservoir pressure at the feed point of each well was estimated from the calculated pressure. The relation between reservoir pressure and the elevation of the feed point reveals that wells in the field are classified into major two groups and others.(Fig.7)

Wells included in the Ginyu group are plotted in a line with a gradient of about 225 ℃ of hot water. Its value is 1.2% greater than the static pressure gradient of the reservoir fluid. It implies an upflow in this area. About 50 kg/sec of upflow was expected from the pressure gradient and the permeability of the Ginyu reservoir. This figure is not too far from the upflow expected from the surface heat discharge.

Wells included in the Shiramizugoe group are plotted in a line with a gradient of about 186 ℃ of hot water. It may mean inferior permeability or greater upflow in this area.

The reservoir in well KE1-2 at a depth of 560m and in well KE1-6 at a depth of 620m are assumed to be two-phase from their pressure and temperature.

Shallow, low temperature wells have an almost constant pressure ranging from 23 to 35kg/cm²A. Caprock was estimated between the high pressure shallow zone and the deeper geothermal reservoir. This elevation coincides with the section of the steep gradient in the formation temperature. Pressure distribution of the wells in northern Sakkogawa area is not clear because of their small number. N55-KT-5 may have higher pressure than in the Shiramizugoe area.

Pressure distribution at 300m below sea level (Fig.8) delineates the two ENE-WSW oriented constant pressure areas. Each area corresponds to the superior permeable zones of the Ginyu and Shiramizugoe areas. Presence of an impermeable zone between these two zones was estimated.

KH DISTRIBUTION

The kh value in the Kirishima area is distributed at 0.003dm to 300dm. The kh value of the permeable zone along the fault is assumed to be greater than 10dm from a correlation of the geological data.(Fig.9) Three peaks are observed in kh distribution. Peak in kh=0.03~0.1dm indicates permeability of the joint and matrix. Peak in kh=3~10dm indicates permeability of the fracture accompanying fault. Peak in kh=30~100dm indicates permeability in the Ginyu fault reservoir. It seems there is no difference in kh distribution between the formations. It means that the reservoir in the Kirishima area is a fracture type.

The schematic kh distribution in the reservoir level delineates the two ENE-WSW trending permeable zones corresponding to each of the Ginyu and the Shiramizugoe areas. (Fig.10) These high permeable zones fairly coinside with the Ginyu fault and the Shiramizugoe fault anticipated from the geological data and the surface geophysical prospecting.

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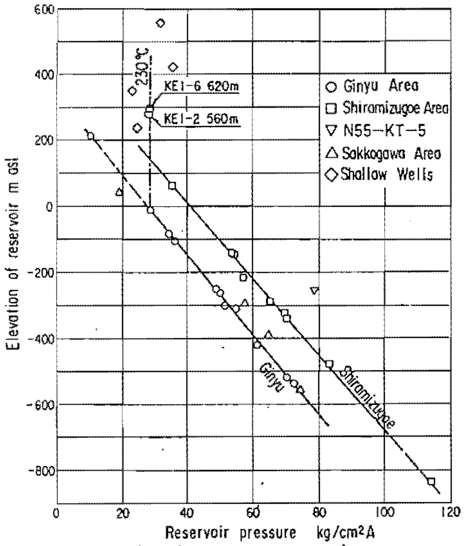

Fig.7 Relation between reservoir pressure and the elevation

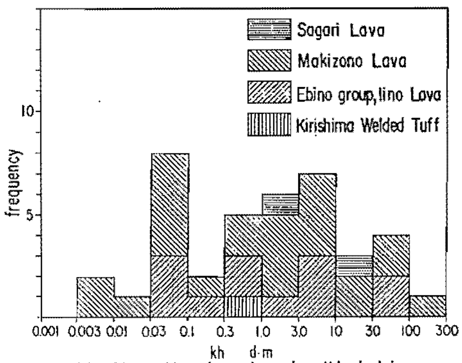

Fig.9 kh distribution in the Kirishima area

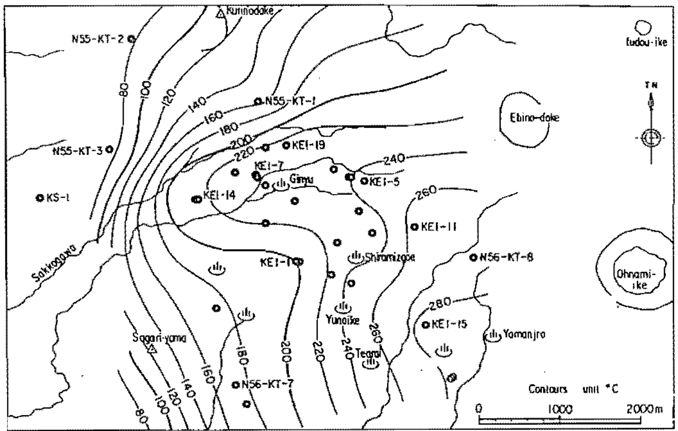

Fig.6 Temperature distribution in the Kirishima area -300m bsl.

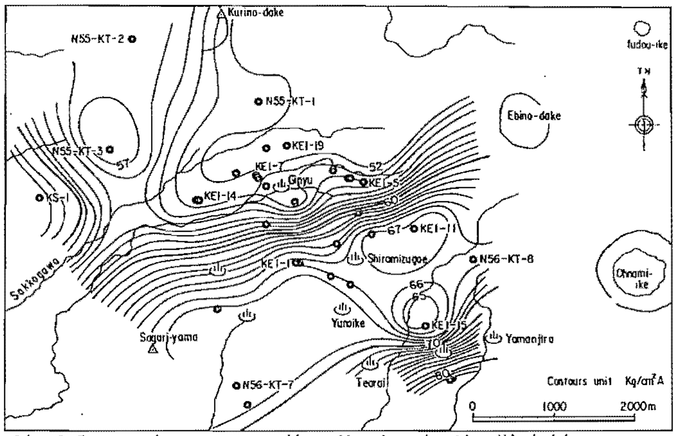

Fig.8 Reservoir pressure distribution in the Kirishima area -300m bsl.

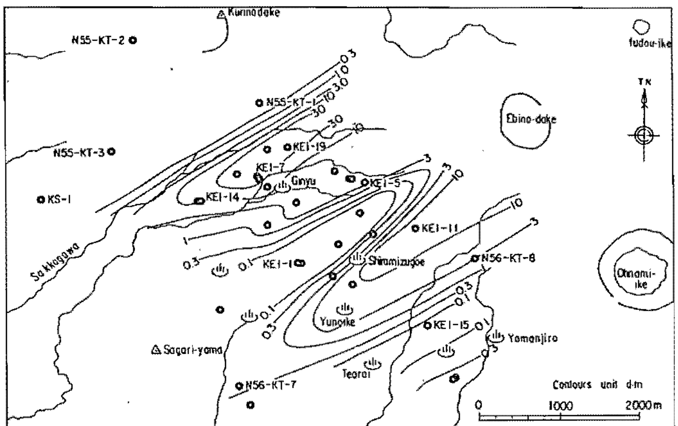

Fig.10 Schematic kh distribution in the Kirishima area at the reservoir level

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