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NEDO'S PROJECT ON GEOTHERMAL RESERVOIR ENGINEERING – A RESERVOIR ENGINEERING STUDY OF THE KIRISHIMA FIELD, JAPAN

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INTRODUCTION

In order to promote the development of geothermal energy resources, it is important to understand and (to the extent possible) to alleviate potential risks associated with each proposed development project. Further, it is essential to estimate the generation capacity of the reservoir prior to full-scale commitment so that the power plant design may be intelligently formulated. Starting in 1984, the New Energy Development Organization (NEDO) in Japan undertook a four-year program to develop technical methods for the evaluation of potential geothermal resources and for the prediction of production capacity and the appropriate level of electrical generation to be anticipated.

EVALUATION OF GEOTHERMAL RESERVOIRS

Figure 1 outlines NEDO's general approach to theoretical reservoir evaluation. For fields in which long-term fluid discharge tests have taken place and in which several survey wells have been drilled, NEDO is carrying out studies of the following types:

(1) *Well Tests:* In each field, single-well pressure transient tests (as well as some interference tests) are performed to obtain information concerning the reservoir permeability distribution and the locations and types of reservoir boundaries.

(2) *Natural-State Reservoir Simulation:* Numerical reservoir simulations are carried out, based upon available analyses of well-test measurements, geophysical survey results, geological data, and other relevant information. These simulations are carried out in an iterative manner, varying the various unknown parameters in the mathematical model to maximize agreement between measurements (for example, pressure and temperature distributions) and computed results. These calculations are time-dependent in character, but are carried forward for long periods of time so that a nearly steady natural-state representation is obtained. The unknown parameters are adjusted until a consistent model of the reservoir's natural condition results which is in adequate agreement with the available field measurements.

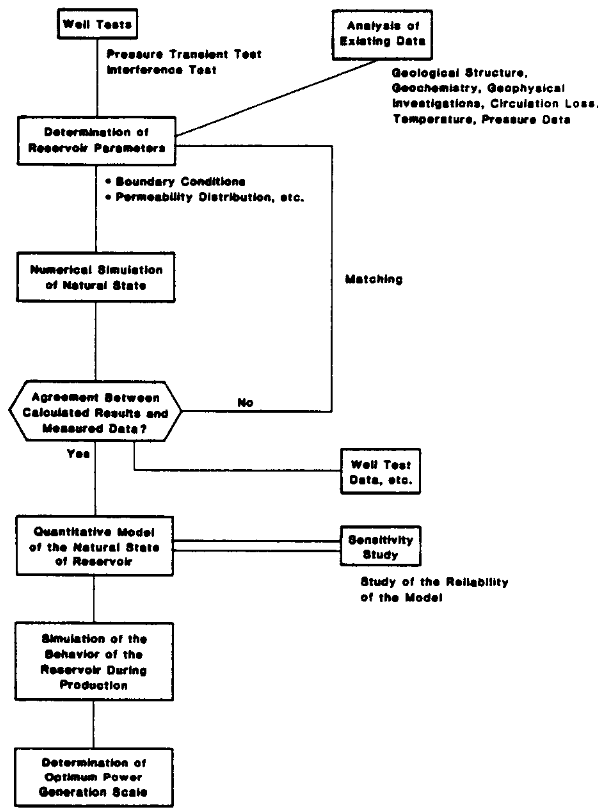

Figure 1. Pre-exploitation evaluation procedure for geothermal reservoirs.

(3) *Simulation of Reservoir Response to Production:* Once an internally consistent natural-state model is obtained which is in adequate agreement with measurements, changes in reservoir conditions (pressure, temperature, steam saturation, etc.) with time are computed based on a variety of scenarios concerning various reservoir development strategies (principally locations and flow rates of fluid production and reinjection). Sensitivity studies are carried out to estimate the reliability of the resulting predictions, and an optimum reservoir development plan is devised.

NEDO'S PROGRAM FOR EVALUATION TECHNOLOGY DEVELOPMENT

Table 1 indicates the schedule of NEDO's four-year project. Four main goals are identified, as indicated: the development of numerical reservoir simulators, the drilling of observation wells, the performance of pressure-transient and flow tests in wells, and reservoir simulation studies. Progress along these lines to date is as follows.

(1) *Development of Reservoir Simulators:* NEDO is developing two general-purpose three-dimensional unsteady geothermal reservoir simulators ("SING-I", restricted to single-phase flow; and "SING-II", also capable of treating two-phase water/steam systems). In addition, NEDO has developed the "WENG" code, which treats the steady flow of single-phase and two-phase (water/steam) mixtures up a borehole (including such effects as heat transfer through the casing, frictional effects, and slip between liquid and gaseous phases), permitting the prediction of wellhead conditions based on downhole conditions.

(2) *Drilling of Observation Wells:* Two model fields have been selected for study. At each of these two fields (the Sumikawa field in northern Honshu and the Kirishima field in Kyushu), two deep (1500 m - 1700 m) observation wells were drilled by NEDO. Both fields are also under development by private companies, so that several other wells are also present in each case. Temperature and pressure logs during heat-up as well as short-term injection tests were carried out in each NEDO well to gather basic information. The NEDO wells were also used as monitor wells during subsequent pressure interference testing.

(3) *Well Tests:* Pressure transient tests (both single-well tests and pressure interference tests) were carried out in each of the model fields (Kirishima and Sumikawa) using both existing wells drilled by the private developers and the new NEDO wells. For these tests, downhole pressures were measured using gauges of the capillary-tube type.

(4) *Reservoir Simulation:* Reservoir simulation studies of the type outlined above (involving both natural-state and production calculations) were carried out for each field, using the SING-I and SING-II numerical reservoir simulation programs developed by NEDO (described above).

THE KIRISHIMA GEOTHERMAL FIELD

In the remainder of this paper, we will describe some results obtained from the NEDO well-testing program in the Kirishima field. Kirishima lies in the southern part of Kyushu, the southernmost of the main islands of the Japanese archipelago. Starting in 1972, the Nippon Steel Company and the Nittetsu Mining Company have been jointly engaged in survey work in the area with the ultimate objective of constructing a geothermal power plant. These companies have carried out a variety of geological and geophysical surveys in the Kirishima area, and have also drilled a number of fairly deep wells (the 400 m to 2000 m "KE" series wells).

TABLE 1

NEDO PROJECT SCHEDULE

	1984	1985	1986	1987	coment
1. Development of reservoir simulators					• I-phase, II-phase reservoir simulator (SING-I, SING-II) and wellbore simulator(WENG).
2. Drilling of observation wells	(Kirishima field)				
	1500m×1	1600m×1			
		(Sumikawa field)			
		1600m × 1	1700m × 1		
3. Well tests		(Kirishima field)			• Injection test • Interference test
		(Sumikawa field)			
4. Reservoir simulation					• Reservoir simulation of Kirishima and Sumikawa field

Figure 2 is a general map of the Kirishima field, showing many of the wells and natural hot springs in the area. Kirishima lies at an elevation between 800 meters and 1000 meters above sea level, and several hot springs are present (notably Ginyu and Kinyu, as indicated in Figure 2). The Kirishima volcanos are located about five kilometers to the northeast of the explored geothermal area. Figure 3 shows the distribution of mapped faults and surface lineaments as established by geological surveys and aerial photography. The trend of these faults is mainly northeast – southwest. The most important faults in the area are the "Ginyu fault" and the "Shiramizugoe fault"; many wells were drilled along these faults in an attempt to find permeable horizons.

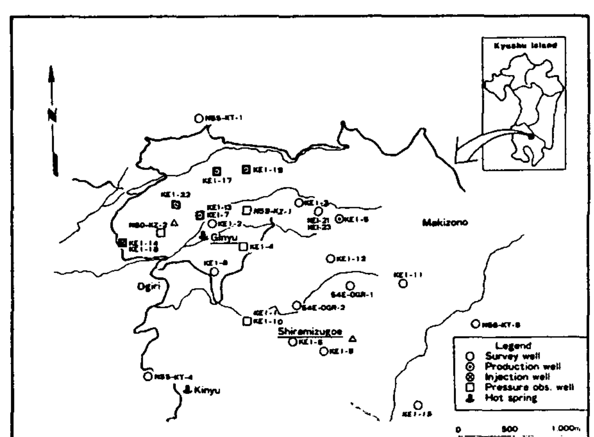

Figure 2. Map of Kirishima geothermal area.

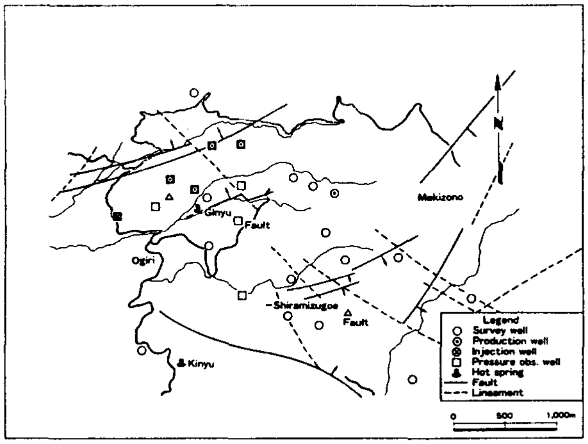

Figure 3. Locations of faults and lineaments.

TEMPERATURE AND PRESSURE DISTRIBUTIONS AT KIRISHIMA

In most of the Kirishima wells, repetitive surveys of downhole temperature and standing water level were carried out for at least several days after cold-water circulation was terminated. These heat-up surveys permit the estimation of reservoir pressure and temperature. Figure 4 shows the estimated natural-state temperature distribution in a horizontal plane 500 meters below sea level (approximately 1.4 kilometers depth) in the study area. Two major features are evident. First, there is a general tendency for temperatures to decrease from east to west; this implies that the thermal anomaly is associated with the volcanos located northeast of the field. Second, a local high-temperature (over 220°C) feature is found at this level in the center of the study area. Based on these isotherm shapes, we conclude that the Ginyu fault is responsible for the local geothermal feature located in this part of the Kirishima field.

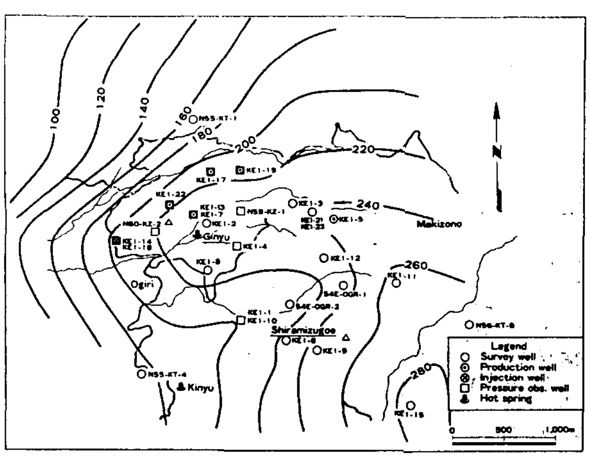

Figure 4. Distribution of temperature (°C) 500 meters below sea level.

As discussed above, simultaneous downhole temperature surveys and measurements of standing shut-in water level were carried out during heat-up for most of the wells in the area. These measurements permit the determination of the stable feedpoint pressures for the various wells. These results indicate that underground pressures are significantly different between the Ginyu part of the Kirishima field (to the north) and the Shiramizugoe area (farther south). This suggests, in turn, that an impermeable boundary is present separating these two parts of the field, and that little communication between these two areas should be expected.

INTERFERENCE TESTING AT KIRISHIMA

Table 2 shows the two-year test program which was carried out at Kirishima starting in April 1985. A total of five production wells, two reinjection wells, and nine shut-in observation wells were involved at one time or another during the test period.

TABLE 2

INTERFERENCE TEST SCHEDULE

Year	1985									1986												1987		
Month	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3
Discharge Well																								
KE1-5	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
KE1-7	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
KE1-17												—	—	—	—	—	—	—	—	—	—	—	—	—
KE1-19S																	—	—	—	—	—	—	—	—
KE1-22																						—	—	—
Reinjection Well																								
KE1-14	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
KE1-18												—	—	—	—	—	—	—	—	—	—	—	—	—
Pressure Measurement Well																								
KE1-4	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
KE1-13S	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
KE1-10									—	—	—	—	—	—	—	—	—							
N59-KZ-1					—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
N60-KZ-2													—	—	—	—	—	—	—	—	—	—	—	—
KE1-14									—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
KE1-18																		—	—	—	—	—	—	—
KE1-19S																		—	—	—	—	—	—	—
KE1-22																								—

Figure 5 illustrates the capillary-tube type downhole pressure monitoring system used in these tests. The chamber and the capillary tube are filled with helium gas, and the pressure within the downhole chamber is transmitted to the surface equipment by means of the capillary tube. A quartz transducer transforms the pressure fluctuations in the tube to an electrical signal which is digitized and recorded on a hardcopy printer and stored on magnetic disk by an on-site microcomputer. The transducer accuracy is very good (± 0.01 psi, or about one millibar).

Figure 6 shows the total discharge rate from the flowing wells (KE1-7, 17, 19S, and 22) as a function of time during the test period. Also shown is the recorded downhole pressure history in observation well KE1-13S. The total discharge rate was about 170 tons per hour (on the average) for the first eighteen months of the test; thereafter, however, the discharge increased gradually, reaching 670 tons per hour in March 1987. As Figure 6 clearly shows, this increase in discharge rate resulted in a significant pressure decrease in observation well KE1-13S, amounting to about 0.2 MPa (~ 2 bars). The correlation between discharge rate changes and downhole pressure changes is seen to be very good, both on the overall time-scale and shorter time-scales (1-2 months; associated with short-term fluctuations in discharge rate). Similarly, Figure 7 shows the pressure histories recorded in wells KE1-13S, KE1-19S and KE1-22 from April 1986 to March 1987. The signal recorded in well KE1-13S shows a very clear response to the changes in discharge from the various flowing wells. These pressure signals were analyzed to try to establish the permeability distribution and other relevant properties of the reservoir. Analyses of these signals are still continuing. In the following, preliminary results are presented.

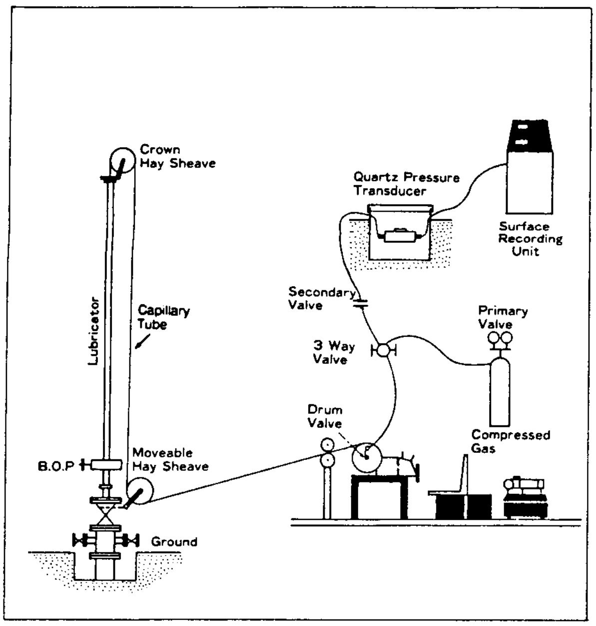

Figure 5. Capillary-tube downhole pressure observation system.

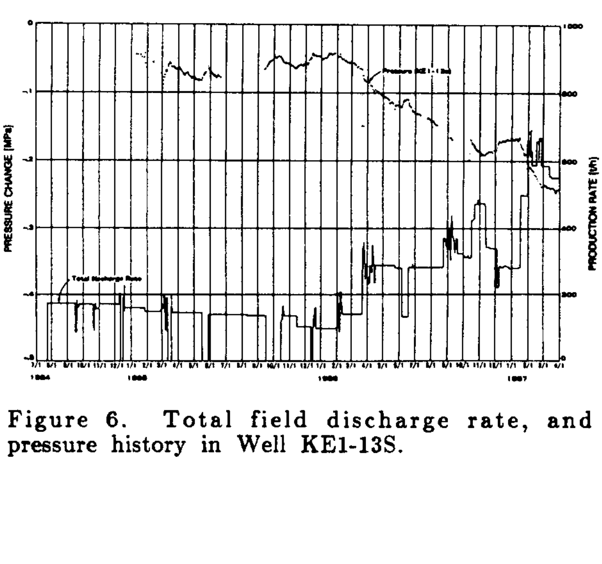

Figure 6. Total field discharge rate, and pressure history in Well KE1-13S.

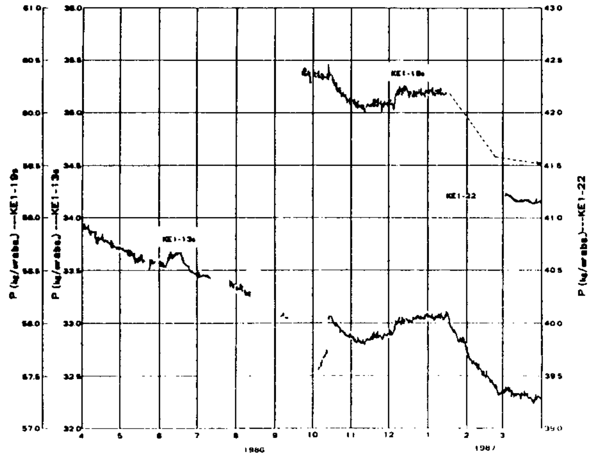

Figure 7. Pressure histories in Wells KE1-13S, KE1-19S and KE1-22 from April 1986 to March 1987.

PERMEABILITY DISTRIBUTION AT KIRISHIMA

The classical radial-flow model was used for the preliminary interpretation of the pressure-transient test pressure measurements. Figure 8 shows a typical result in graphical form. (Figure 9 indicates the geometry assumed for the interference test interpretation.) The scatter in Figure 8 is due mainly to uncorrected effects of atmospheric temperature fluctuations on the quartz transducer. In Figure 8, downhole pressures recorded every two hours are plotted against a reduced time which is derived from the discharge rate history. The value of the permeability-thickness product (kh) obtained from the slope of the best-fit straight line in Figure 8 is 4.19×10^{-11} m^3 (41.9 darcy-meters).

The wells which were employed in this study apparently penetrate the Ginyu reservoir (as contrasted to the Shiramizugoe reservoir farther south), so that the values of kh (permeability-thickness) obtained are presumably representative of that system. Table 3 summarizes the results of these analyses. A total of fourteen sets of data were analyzed, including those listed in Table 3. Permeability-thickness values ranging from 11 to 185 darcy-meters were obtained from these analyses; the average value was about 63 darcy-meters. Owing to the relatively short durations of the test periods considered in these analyses (about one month), these values are considered to represent mainly the permeabilities in the neighborhoods of the individual wells. To examine larger-scale permeability structures, long-term (January 1985 to April 1987) analyses were also conducted. These yielded the following average values for the permeability-thickness (kh) and porosity-compressibility-thickness (ϕch) products:

kh = 40.5 darcy-meters

ϕch = 5.0×10^{-8} meters per Pascal.

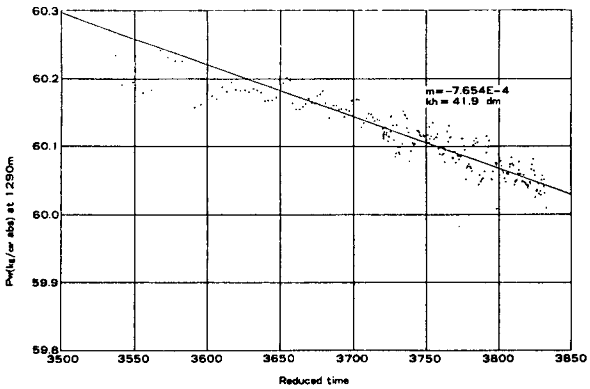

Figure 8. Interference test analysis (Well KE1-19S).

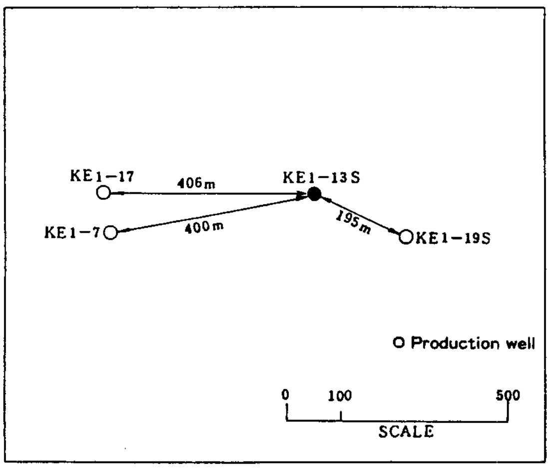

Figure 9. Bottomhole locations for wells involved in interference test.

TABLE 3

RESULTS OF WELL TEST ANALYSES

Period of Observation	Observation Well	Active Well	KH Value (darcy·m)
1986-4-17 ~6-5	KE1-13S	KE1-7,KE1-17	25.5
1986-6-18 ~7-12	KE1-13S	KE1-17,KE1-7	53.7
1986-10-23 ~11-11	KE1-19S	KE1-7,KE1-17	41.9
1987-3-3 ~3-13	KE1-22	KE1-7,KE1-17, KE1-19S	11.4

ONGOING STUDIES OF THE KIRISHIMA FIELD

Further analyses of the pressure-transient test results are now being carried out using numerical simulation techniques to take into account more complicated phenomena such as two-phase flow effects. Based on the available results from the well-test experiments, large-scale reservoir simulation studies are also being performed to try to estimate the productive capacity of the Kirishima field.

ACKNOWLEDGMENTS

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