A STUDY OF PRODUCTION/INJECTION DATA FROM SLIM HOLES AND LARGE-DIAMETER PRODUCTION WELLS AT THE OGUNI GEOTHERMAL FIELD, JAPAN

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ABSTRACT

Production and injection data from slim holes and large-diameter wells at the Oguni Geothermal Field, Japan, were examined in an effort to establish relationships (1) between productivity of large-diameter wells and slim holes, (2) between injectivity and productivity indices of slim holes and large-diameter wells, and (3) between productivity index and borehole diameter. The production data from Oguni boreholes imply that the mass production from large-diameter wells may be estimated based on data from slim holes. Test data from both large- and small-diameter boreholes indicate that to first order the productivity and the injectivity indices are equal. Somewhat surprisingly, the productivity index was found to be a strong function of borehole diameter; the cause for this phenomenon is not understood at this time.

1. INTRODUCTION

Since a major impediment to the exploration for and assessment of new geothermal areas worldwide is the high cost of conventional rotary drilling, it would be desirable to be able to utilize low-cost slim holes (≤ 15-cm diameter) for geothermal exploration and definitive reservoir assessment. Garg and Combs (1993) presented a review of the publicly available Japanese data regarding slim holes. Slim holes have been successfully used in Japan (Garg and Combs, 1993) for (1) obtaining core for geological studies and delineating the subsurface stratigraphic structure, (2) characterizing the geothermal reservoir fluid state, and (3) as shut-in observation boreholes in pressure interference tests. In order to establish the utility of slim holes for definitive reservoir assessment, it is also necessary to be able to predict the discharge characteristics of large-diameter wells based on injection/discharge tests on small-diameter slim holes. At present, there do not exist sufficient published data, either in Japan or elsewhere, to establish a statistically meaningful relationship between the injectivity/productivity of small-diameter slim holes and large-diameter production and/or injection wells.

The U.S. Department of Energy (DOE) through Sandia National Laboratories (Sandia) has initiated a research effort to demonstrate that slim holes can be used (1) to provide reliable geothermal reservoir parameter estimates comparable to those obtained from large-diameter wells, and (2) to predict the discharge behavior of large-diameter wells (Combs and Dunn, 1992). As part of its research program, DOE/Sandia plans to drill and test pairs of small-diameter slim holes with existing large-diameter production wells in several geothermal fields in the western United States; the first of these tests was recently completed in mid-1993 at the Steamboat Hills Geothermal Field, Nevada (Finger *et al.*, 1994). Because of fiscal constraints, it is unlikely that sufficient U.S. data will become available in the near future. Fortunately, the Japanese geothermal industry has had extensive experience in the use of slim holes for geothermal exploration and reservoir assessment. The existing Japanese data in conjunction with planned field tests on pairs of slim holes and large-diameter wells in the United States should help in establishing a statistically valid relationship between the injectivityl productivity of slim holes and of large-diameter wells.

The Oguni Geothermal Field, Kumamoto Prefecture, Kyushu, Japan, is a particularly good candidate for a case history on the use of slim holes in geothermal exploration and reservoir assessment. Since 1983, Electric Power Development Co., Ltd. (EPDC) has carried out an extensive exploration and reservoir assessment program in the area. As of mid-1993, EPDC had drilled and tested more than twenty boreholes ranging in depth from 500 to 2000 meters. EPDC has utilized slim holes not only for selecting large-diameter well locations, but also for predicting the production capacity of the large-diameter wells being drilled. A preliminary paper discussing some of these Oguni data was presented by Garg, *et a/.* (1994) at the 19th Stanford Geothermal Reservoir Engineering Workshop.

In the present paper, data from eleven slim holes and ten large-diameter wells at the Oguni Geothermal Field are examined. A brief overview of the Oguni Geothermal Field is presented in Section 2. Representative drilling information and downhole pressure, temperature and spinner surveys are analyzed in Section 3 to determine feedzone locations, pressures, and temperatures, *etc.* Injectivity indices and estimates of reservoir permeability-thickness product (kh) obtained from injection and fall-off data are discussed in Section 4. The discharge test data, productivity indices, and estimates of kh product given by pressure buildup data are presented in Section 5. The following topics are discussed in Section 6, (1) the variation of discharge rate, productivity index, and injectivity index with borehole diameter, (2) the relationship between productivity and injectivity indices, and (3) the kh determined from short-term injection and longer-term discharge tests.

2. OGUNI GEOTHERMAL FIELD: AN OVERVIEW

The Oguni and the Sugawara Geothermal Fields together comprise the northwestern Hohi geothermal region, Kumamoto and Oita Prefectures, Kyushu, Japan (see Figure 1). An area of numerous hot springs, it is approximately 40 km southwest of the coastal resort of Beppu, and some 20 km north of Mt. Aso, an active caldera. The New Energy and Industrial Technology Development Organization (NEDO) carried out a regional (200 km^2 area) exploration program in the Hohi area during the years 1979–1985; this work resulted in the identification of a high permeability geothermal area in the northwestern Hohi area. EPDC initiated a geothermal exploration program in the Oguni area in 1983. The Oguni Geothermal Field is located at the northeast end of Kumamoto Prefecture; Oita Prefecture is to the north and northeast of the Oguni area. The Sugawara field, to the north of the Oguni area, is being surveyed by NEDO as a possible site for the demonstration of a binary power plant. Although the northern Hohi area has been subdivided into two separate geothermal fields (Oguni, Sugawara), the area constitutes a single hydrological unit.

The topography of the Oguni Geothermal Field is dominated by Mt. Waita (Figure 1), which rises to an elevation of about 1500 m ASL (meters above sea level) to the southeast of the field. Many of the boreholes are located on the **flanks** of Mt. Waita. The Oguni boreholes are in Kumamoto Prefecture. Striking WNW-ESE is the valley containing the hot spring areas (and towns) of Takenoyu and Hagenoyu. To the

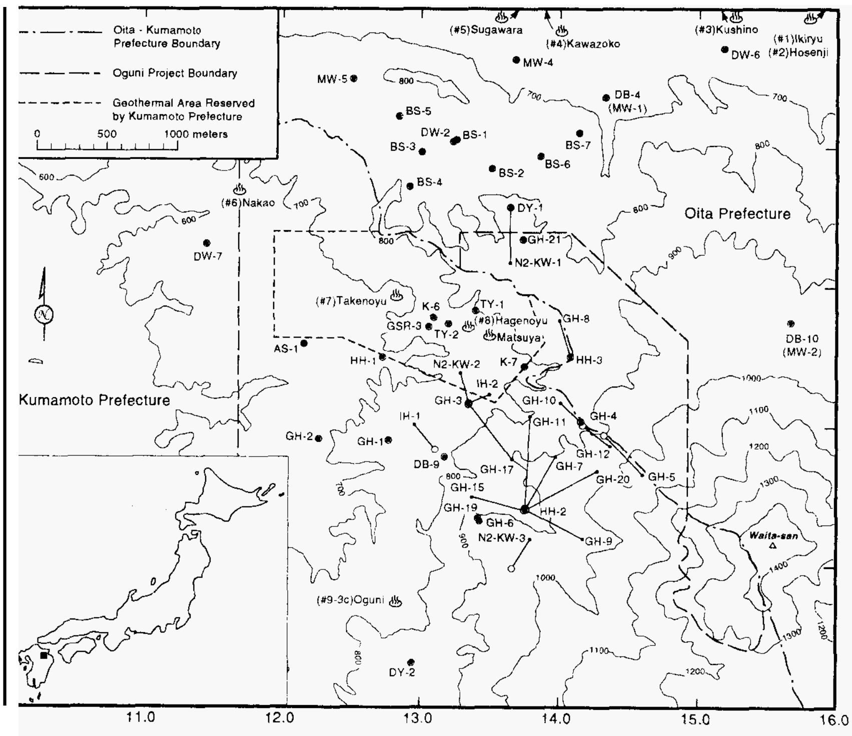

Figure 1. The northem Hohi geothermal area, Kyushu, Japan. The inset map of Japan (lower left hand comer) shows the location of the Hohi geothermal area (dark rectangle).

north of the valley is the Sugawara plateau (in Oita Prefecture) where NEDO has drilled a number of boreholes (BS series. Figure I) for a binary power plant. The Takenoyu/Hagenoyu valley forms **a** natural division of the field into two parts, north and south of the valley.

The subsurface stratigraphic structure in the northern Hohi area **is** shown in Figure 2. The granitic basement was encountered in only two boreholes (DW-7 and DY-2) at about –960 m **ASL** in the Oguni area, and drops off steeply to the northeast in the Sugawara area. The stratigraphic sequence above the basement consists of the Pliocene Taio formation, the late Pliocene/early Pleistocene Shishimuta formation (pre-Kusu group), the lower to middle Pleistocene Hohi and Kusu formations, and the upper Pleistocene Kuju formation. The Nogami mudstones (part of the Kusu group) and the Kuju volcanics appear to function as **a** caprock for the geothermal system. Based upon feedpoint locations, it appears that the Hohi formation and the upper part of the Shishimuta formation constitute the principal geothernial aquifers.

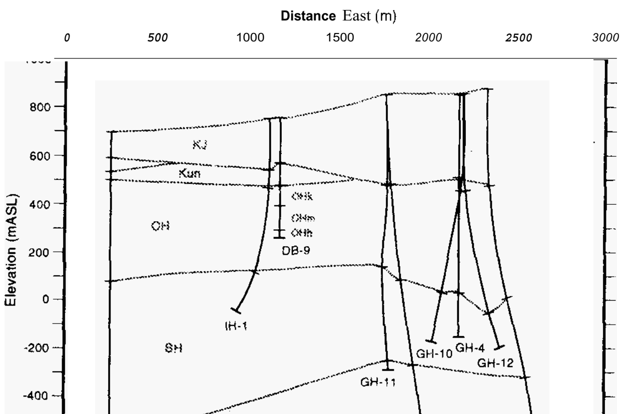

Figure 2. An east-west stratigrapic cross-section in the Oguni area, The following abbreviations are used for formation names: **KJ** (Kuju); Kun (Kusu/Nogami mudstone); OH (Hohi); OHk (Hohi/Kotobakiyama lava); OHm (Hohi/Nambira lava); OHh (Hohi/Hatchobaru lava); SH (Shishimuta); TA (Taio).

The feedzone pressures imply that the northern Hohi region consists of two pressure zones (a high pressure zone in the area of boreholes GH-15, GH-19, GH-6, HH-2, N2-KW-3 and DY-2 in the southern part of the Oguni Geothermal Field; **a** low pressure zone in the central and northern parts of the area shown in Figure 1). At present, the reasons for the existence of two different pressure regions in close proximity to each other (within at most a few hundred meters) are poorly understood.

The vertical pressure gradient in the low pressure area (Figure 3) is 8.53 kPa/m and corresponds to **a** hydrostatic gradient at ~ 195°C. This implies fluid upflow in regions of the reservoir where temperature exceeds 195°C. The pressure correlation also implies that pressures decrease to the north; the pressure gradient is ~ 0.65 bars/km. Thus, in the natural state there exists **a** regional flow (to the north) in the northern Hohi area.

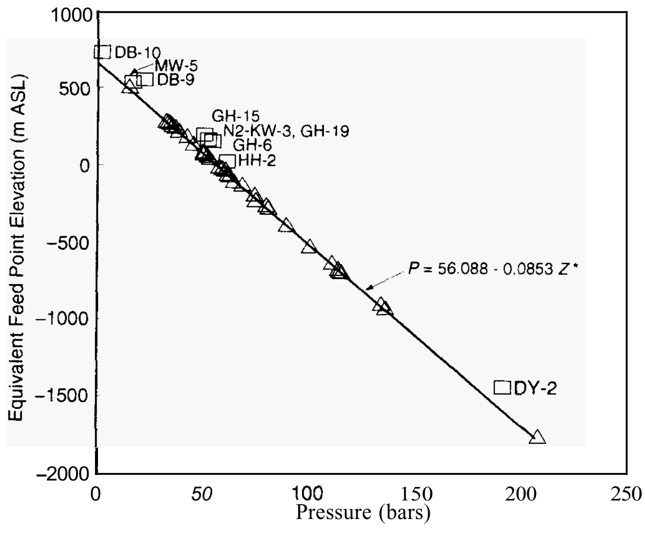

Figure 3. Correlation of pressure with equivalent feedpoint elevation of low-pressure zone boreholes (**A**). Also shown as ☐ are boreholes (DB-10, **MW-5,** DB-9, GH-15, N2-KW-3, GH-19, GH-6, HH-2, DY-2) not included in the pressure correlation.

The stable preproduction temperature measurements in the Oguni/ Sugawara boreholes were used to estimate the natural subsurface temperature distribution in the area. The temperature distribution along an east-west plane in the Oguni area is shown in Figure 4. The temperatures decline rapidly to the east and west of the subsurface zone defined by Oguni boreholes GH-4, GH- 10,GH-11 and GH-12. The maximum temperature (– 240°C) in the area occurs near Oguni boreholes GH-4, GH-10, GH-I 1, and Kumamoto Prefecture well K-7.

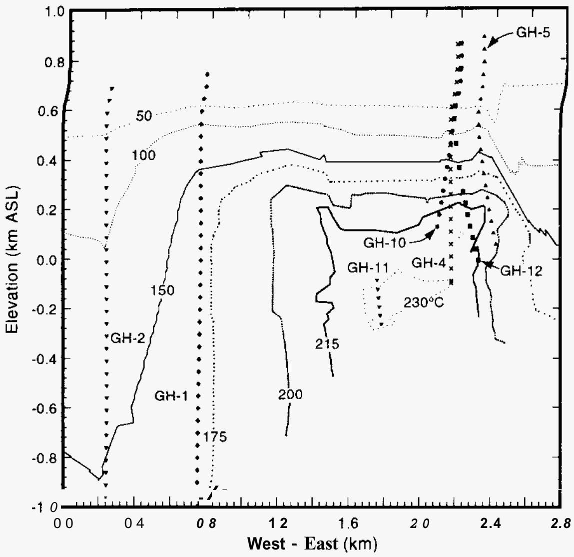

Figure 4. Temperature distribution along **a** west-east vertical plane in the Oguni area.

The Oguni reservoir fluid appears to be a relatively homogenous sodium-chloride brine of moderate salinity (average chloride concentration – 1100± 100 mg/l). Carbon-dioxide constitutes the bulk of non-condensable gases in the reservoir fluid. The average carbon-dioxide content is about 700 mg/l. The Oguni reservoir fluid is single-phase liquid. The geothermal boreholes do not provide any direct evidence of a two-phase zone at depths greater than 300 meters in the Oguni area. The feedzones for all of the Oguni boreholes are deeper than 400 meters. The presence of boiling at shallow depths (*i.e.*, depths less than 300 meters) is, however, suggested by the occurrence of warm and boiling steam-heated sulfate and bicarbonate spring waters in the Takenoyu and Hagenoyu areas.

EPDC has performed numerous pressure transient tests to define the detailed permeability structure in the Oguni/Sugawara area. The available data set includes (1) cold fluid injection and fall-off tests in single boreholes, (2) pressure drawdown (*i.e.*, production tests) and buildup tests in single boreholes, and (3) pressure interference tests involving multiple boreholes. The injection and production test data from single boreholes will be discussed in detail in Sections 4 and **5**, respectively, of this paper. A consideration of pressure interference data is, however, outside the scope of this paper. Analyses of pressure interference data from the low-pressure zone boreholes imply that the northern Hohi reservoir has a transmissivity of a b u t 100–250 darcy-meters. In contrast to the high transmissivity obtained in the low-pressure zone, the pressure interference data indicate that the high pressure zone has only a modest transmissivity (– 15 darcy-meters).

3. FEEDZONE LOCATIONS AND TEMPERATURES

As part of its drilling and testing program, EPDC has drilled both small-diameter core holes (9 GH-series and 3 HH-series) and large-diameter production size wells (8 GH and 2 IH-series). In addition, NEDO has drilled three small-diameter core holes (N2-KW-I, N2-KW-2 and N2-KW-3) in the Oguni area. With the exception of four core holes (GH-1, GH-2, HH-I and HH-3), some production and/or injection data are available for all of the Oguni boreholes. The available drilling data (circulation loss, borehole completion and geologic data) and downhole PTS (*i.e.*, pressure, temperature and spinner) surveys have been analyzed by the authors, to obtain feedzone depths, pressures and temperatures for the twenty-one boreholes listed in Table 1. An example of the downhole data from these boreholes is presented in Figures 5–8 for well GH-11.

Heatup surveys 1, 2, and 4 (Figure *5)* for well GH-11 show a persistent temperature depression at – 1120 m TVD. The available PTS surveys (Figure **5**, temperature profile 7; Figure 6, pressure profile 3; Figure 7, spinner profiles 1 and 2) indicate the presence of a liquid entry (temperature – 237°C) at about 1140 m TVD. A circulation loss zone was recorded nearby at – 1137 m TVD. Thus, the major permeable zone for well GH-11 is located at 1140 m TVD. The long shutin time temperature survey **5** (Figure **5)** exhibits an isothermal profile below ~ 1020 m TVD; this indicates internal flow (upflow?) in the wellbore between the feedzone at 1140 m TVD and another (possibly minor) permeable horizon at – 1020 m TVD. The latter permeable horizon is most likely associated with a minor circulation loss zone at –1029 m TVD. Pressure profiles, computed from water level and temperature data, are plotted in Figure 8; the pressure at 1140 m TVD (–282 m ASL) is – 80 bars. The latter pressure value is in good accord with that (– 80 bars) recorded by a downhole gauge in January 1990 (Figure 6).

4. INJECTION TESTS

It is common practice at Oguni to conduct a short term (a few hours) injection test soon after the drilling and completion of a borehole. The

Table 1. Various parameters of Oguni boreholes with production or injection data.

Borehole Name	Measured Depth (meters)	Vertical Depth (m TVD)	Feedzone Depth (m TVD)	Final Diameter (mm)	Downhole Flowing Temp (°C)	Production/ Injection Data
A. voir						
GH-3	1500	1498		79	214	P
GH-4	1001	1001	900	76	235	P
GH-5	1501	1421	1100	76	187	P
GH-7	1547	1442	980/1400	98	220	P
GH-8	1300	1255	1220	78	212	P,I
GH-10	1063	1027	1010	159	241	P,I
GH-I 1	1381	1143	1140	216	237	P,I
GH-12	1100	1045	750	216	232	P,I
GH-17	1505	13.54	760	216	—	I
GH-20	1790	1576	1560	216	241	P,I
GH-21	810	810	650	216	—	I
IH-1	900	810	590	159	—	I
IH-2	650	616	550	216	226	P,I
N2-KW-I	1000	898	860	76	—	1
N2-KW-2	1000	978	860	76	—	I
B. High-Pressure Reservoir						
GH-6	1003	1003	770	76	215	P
GH-9	1600	1481	?	78	—	I
GH-15	1190	1048	680	216	Two-Phase	P,I
GH-19	773	773	750	216	—	I
HH-2	1000	999	850	76	Two-Phase	P
N2-KW-3	1350	1317	810	76	227	P,I

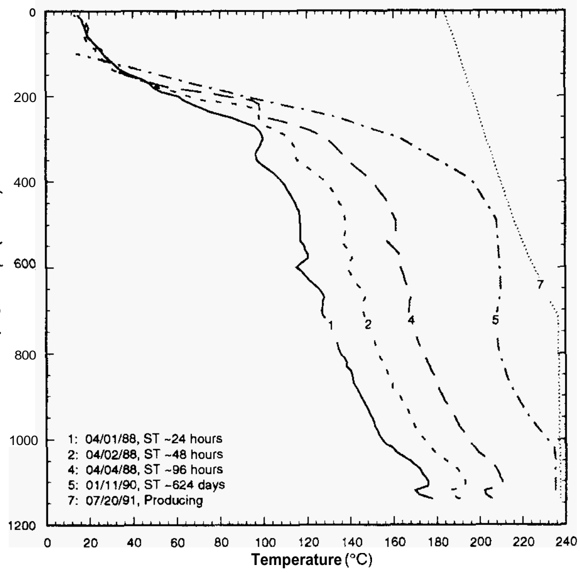

Figure **5.** Selected temperature surveys for well GH-I1.

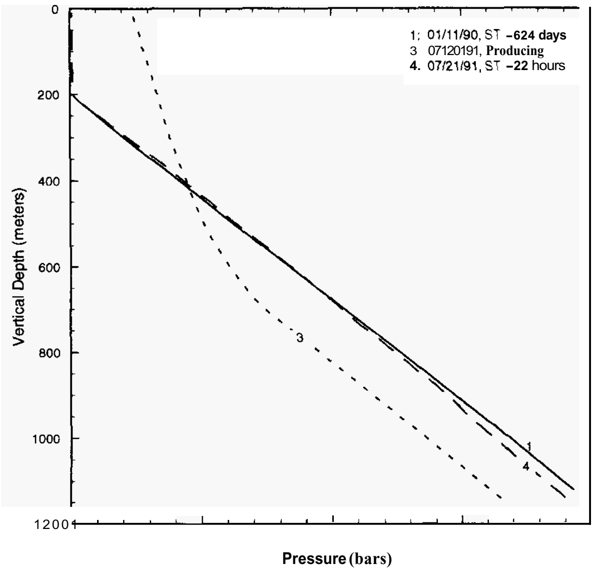

Figure **6.** Selected pressure (bars, gauge) surveys taken in well **GH-11.**

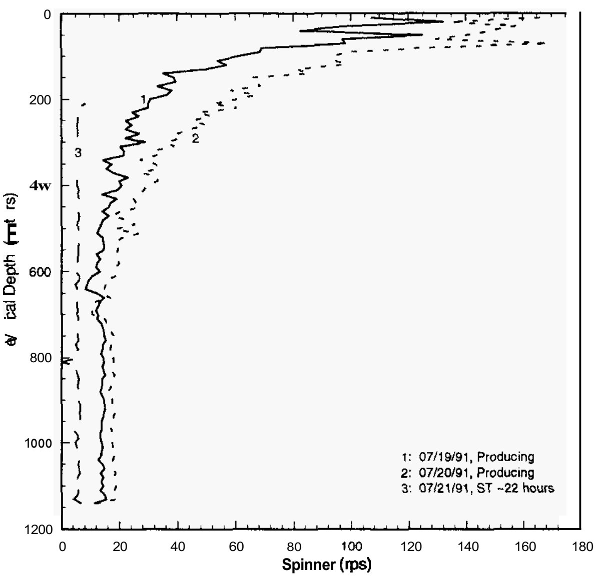

Figure **7.** Spinner surveys recorded in well **GH-**11.

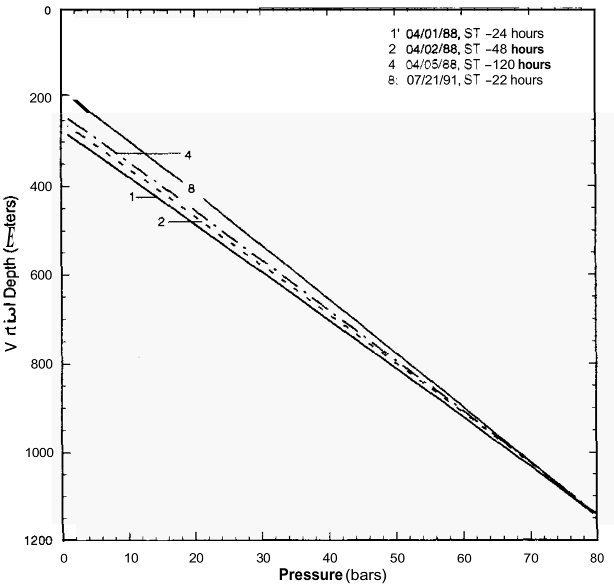

Figure **8.** Pressure profiles, computed from water level and temperature data. for well GH-11.

injection test consists of injecting cold water into the borehole and simultaneously recording pressure and temperature downhole. The pressure and temperature tool in most of the injection tests was placed either near or beneath the principal feedzone. Most of the Oguni boreholes exhibit an anomolous pressure behavior (*i.e.,* rapid pressure rise followed by a slow pressure decay) during the injection phase of the test; these pressure data are not useful for inferring formation transmissivity. The fall-off data from injection tests can, however, be analyzed to obtain formation transmissivity.

Although pressure data recorded during the injection phase are not generally useful for determining formation transmissivity, these data are required for evaluating the injectivity index (II). **II** is defined as follows:

$$II = \frac{M}{P_f - P_i} \tag{1}$$

where M is the mass rate of injection, P_f is the flowing pressure and P_i is the initial (or static) pressure at the gauge depth. It was noted earlier that the flowing pressure P_f was observed to fall in many of the Oguni injection tests; in such cases, the computed injectivity index represents a lower limit.

During injection testing of well GH-11, the pressure gauge was located within 20 meters of the principal feedzone. Apressure of 76.5 bars was recorded at the gauge depth prior to the start of cold water injection. The pressure measurements taken at the end of each injection interval were used to compute the injectivity index.

Injection Test **1:** II = 1.03 kg / **s**-bar
Injection Test 2: II = 1.28 kg / s-bar
Injection Test 3: II = 1.53 kg / s-bar

The injectivity index increases with each increase in the injection rate. The best estimate for II is 1.53kgls-bar.

The pressure fall-off data recorded after Injection Test 1 are displayed in Figure 9a. At small shutin times ($\Delta t <$ 15 minutes), the pressure falls rather rapidly; after a shutin time of about 15 minutes, the pressure fall-off slows down considerably. The late shutin time ($\Delta t \geq$ 15 minutes) fall-off data are replotted in Figures 9b. These late-time fall-off data can be approximated by a straight line. Because of insufficient gauge resolution, there is considerable uncertainty associated with the slope m of the straight line fit. With a kinematic viscosity ν of 1.44×10^{-7} m^2/s (corresponding to liquid water at a temperature of 225°C), the formation transmissivity (kh) is estimated to be 3.7 darcy-m.

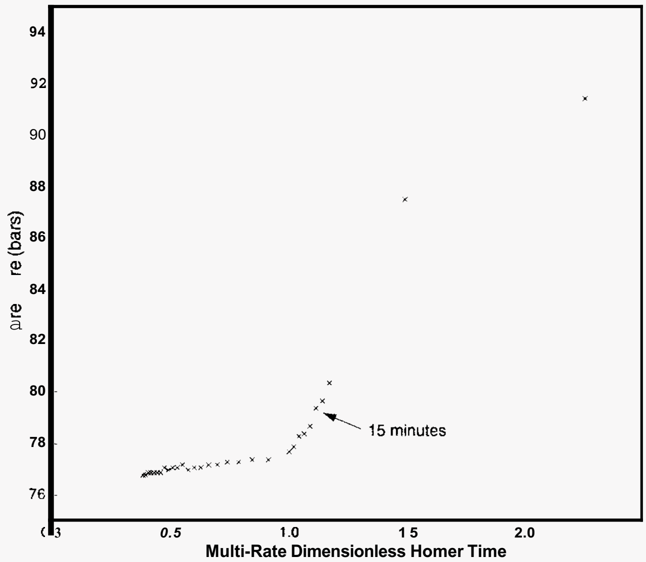

Figure 9a. Homer plot of pressure fall-off data no. 1 for well GH-11 (March 30, 1988).

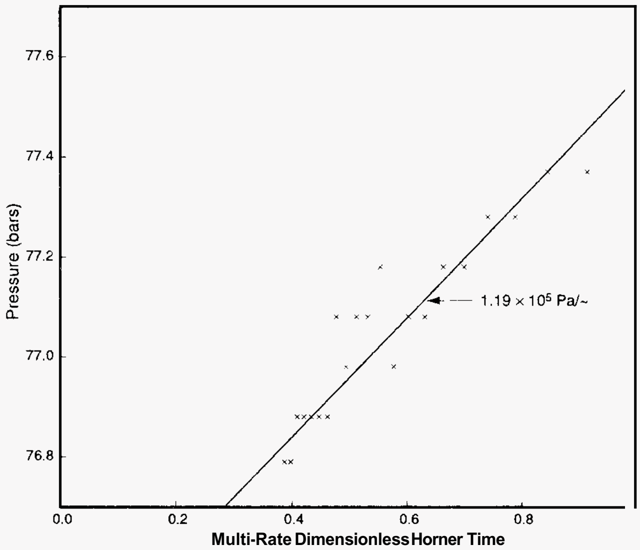

Figure **9b.** Horner plot of pressure fall-off data no. 1 (late shut-in time) for well GH-11 (March 30, 1988).

5. DISCHARGE TESTS

A borehole must be discharged to ascertain its productive capacity. **A** total of eight slim holes and six large-diameter Oguni wells have been discharged at one time or another. With the exception of two boreholes in the high pressure reservoir (boreholes HH-2 and GH-15), all-liquid conditions prevail at the feedzone depth in Oguni boreholes under discharge conditions. The feedzone temperatures for Oguni boreholes producing from liquid feedzones are given in Table 1. **As** part of the discharge tests of Oguni boreholes, the characteristic output curves (*i.e.*, mass and enthalpy versus wellhead pressure) were also obtained. The mass output curve for slim hole GH-7 is shown in Figure 10; the maximum discharge rate (30t/hr) occurs at a wellhead pressure of about 2 bars.

During all of the discharge tests, pressure and temperature (or pressure, temperature and spinner) surveys were run. These pressure/temperature surveys can be used to calculate the productivity indices for the Oguni boreholes. Productivity index, PI, is defined as follows:

$$PI = \frac{M}{P_{ns} - P_{fp}} \tag{2}$$

where M is the discharge (*i.e.*, mass production) rate, P_{ns} is the stable (static) feedzone (or gauge depth) pressure, and P_{fp} is the flowing feedzone (or gauge depth) pressure. The computed productivity indices for the various Oguni boreholes are listed in Table 2.

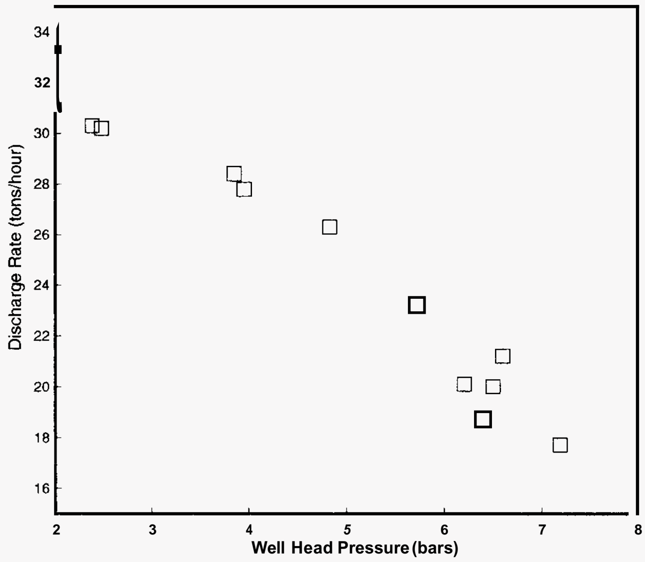

Figure **10.** Discharge rate versus wellhead pressure for slim hole GH-7 (January 1987).

Table **2.** Productivity/injectivity indices of Oguni boreholes

	(mm)	Productivity (kg/s-bar)	Injectivity (kg/s-bar)
GH-3	79	0.53	—
GH-4	76.	1.44	—
GH-5	76.	1.19	—
GH-7	98.	1.05	—
GH-8	78.	1.01	—
GH-10	159.	3.88	3.39
GH-11	216.	5.65	1.53
GH-12	216.	5.77	5.12
GH-17	216.	—	0.46
GH-20	216.	15.2	7.82
GH-21	216.	—	12.1
IH-1	159.	—	0.84
IH-2	216.	11.9	33.
N2-KW-1	76.	—	2.11
N2-KW-2	76.	—	0.86
GH-6	76.		
GH-9	78.		
	216.		
	[illegible]		
	76.		
	76.		

Pressure buildup data are available for all of the Oguni boreholes that have been discharged. In all cases, the pressure buildup responses were recorded by lowering a mechanical pressure gauge (usually a Kuster tool) into the borehole, either just before or right after, the completion of the discharge test. Because of instrument limitations, it was in several cases necessary to pull (and reinsert) the gauge out of the hole after **a** few hours; this resulted in a gap in the pressure buildup record.

A multi-rate Homer plot of pressure buildup data for slim hole GH-5 is shown in Figure 11. Pressure buildup data in Figure 11 can be approximated by a straight line; the slope of the straight line yields a permeability-thickness value of **4.5** darcy-m for borehole GH-5. The ***kh*** values inferred from the pressure buildup data for the various Oguni boreholes are listed in Table 3.

6. RESULTS AND DISCUSSION

6.1 Formation Transmissivity

EPDC has carried out a number of pressure interference tests on the boreholes in the Oguni Geothermal Field. Analyses of pressure interference data from the low-pressure reservoir boreholes indicate that the northern Hohi area has good transmissivity ***(kh*** = 100 to *250* darcy-meters); the transmissivity ***(kh)*** value for the high-pressure reservoir is of the order of 10 darcy-meters. Permeability-thickness values

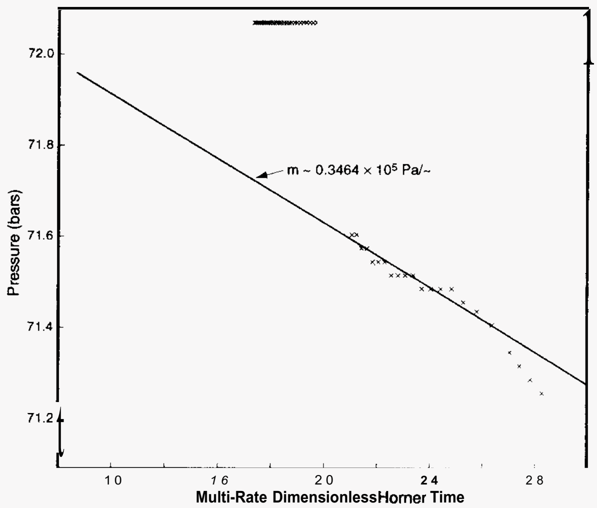

Figure **11.** Multi-rate Homer plot of pressure buildup data for slim hole GH-5. Pressures were recorded at 1 150 m MD (1097 m TVD) from *At* = 0 minutes to *At* = 240 minutes, and from *At* = 330 minutes to *At* = 569 minutes. Note the offset between the early-time *(At*= 0 to 240 min) and late-time *(At*= 330 to 569 minutes) pressure data. The straight line used for computing *kh* extends over less than one log-cycle; hence, the estimate for *kh* may not be too reliable.

Table *3.* Permeability-thickness *(kh)* inferred from pressure fall-off (injection tests) and pressure buildup (discharge tests) data for Oguni boreholes.

Borehole Name	Final Diameter (mm)	Production *kh* (darcy-m)	Injection* *kh* (darcy-m)
	A. Low-Pressure Reservoir		
GH-3	79	0.44	—
GH-4	76.	—	—
GH-5	76.	4.5	—
GH-7	98.	1.3	—
GH-8	78.	29.	—
GH-10	159.	92.	—
GH-I 1	216.	83.	6.9
GH-12	216.	32.	5.1
GH-17	216.	—	0.14
OH-20	216.	55.	6.1
GH-21	216.	—	14.
IH-1	159.	—	0.73
1H-2	216.	44.	25.
N2-KW-1	76.	—	9.3
N2-KW-2	76.	—	0.58
	B. High-Pressure Reservoir		
GH-6	76.	-	.
GH-9	78.	.	0.03
GH-15	216.		2
OH-19	216.		.
HH-2	76.	-	.
N2-KW-3	76.	-	

* Average value obtained from the various fall-off tests for a borehole.

inferred from pressure fall-off and pressure buildup data from individual Oguni boreholes are listed in Table 3. Pressure buildup data from individual "low-pressure reservoir" boreholes yield *kh* values in the range 0.4 to 92 darcy-meters; interestingly, smaller *kh* values are generally associated with small-diameter slim holes. For large-diameter wells, *kh* values inferred from buildup tests vary from 32 to 92 darcy-meters. The *kh* values obtained from short-term injection tests range from 0.1 and 25 darcy-meters for all the low-pressure zone boreholes; the *kh* values for large-diameter wells (excluding well GH-17) vary from *5* to 25 darcy-meters.

In fractured geothermal reservoirs, interference tests commonly yield higher *kh* values than those given by pressure buildup (and pressure fall-off) tests. An individual borehole intersects at most **a** few major fractures. These major fractures join the fracture network at some distance from the borehole. The reservoir radius investigated during **a** borehole test is roughly proportional to the square root of time. **A** pressure buildup test generally samples **a** smaller region of the reservoir than that investigated by an interference test. The *kh* values obtained from pressure buildup tests (32 to 92 darcy-meters) for large-diameter wells at Oguni are smaller by a factor of about three from those given by pressure interference tests (100 to 250 darcy-meters). In contrast with longer term discharge tests (days to months in duration), short term injection tests **(a** few hours) sample only the near wellbore region. The pressure fall-off data yield *kh* values *(5* to *25* darcy-meters for large-diameter wells) which are much smaller than those obtained from pressure buildup and pressure interference tests. These results suggest that short term injection tests are likely to yield **a** lower bound on reservoir transmissivity.

It appears that the differences in *kh* values inferred for slim holes and large-diameter wells may be caused by the differences in drilling techniques (*i.e.*, core drilling versus rotary drilling). The core drilling is more likely to plug the near wellbore fractures with rock flour and/or mud than rotary drilling. **At** Oguni, the formation permeability is mainly associated with a horizontal fracture zone located in the lower Hohi and upper Shishimuta formations. Many of the slim holes were drilled with a complete loss of circulation fluid. The circulation fluid, in most cases, consisted of **a** dilute (mud density ~ 1.00 to 1.05 gm/cm^3) bentonite based mud. In contrast with slim holes, blind drilling was rarely used for rotary drilled large-diameter wells. It is thus possible that core drilling (at least in the case of Oguni Geothermal Field) causes greater formation plugging than that resulting from rotary drilling. This speculation regarding formation plugging can only be verified by comparing "*kh*" values obtained from a large number of core- and rotary-drilled boreholes in several different geothermal fields.

6.2 Productivity and **Injectivity** Indices

Ignoring pressure transient effects. the flow resistance (*i.e.* pressure losses) of the reservoir rocks can be represented by the productivity (or injectivity) index. The productivity and injectivity indices (see Sections 4 and *5)* for the various Oguni boreholes are listed in Table 2. Both the productivity and injectivity indices are available for seven of the Oguni boreholes; these data are displayed in Figure 12. It appears from Figure 12 that to first order the productivity and injectivity indices for the Oguni boreholes are equal. The latter observation is at variance with the results of the classical porous-medium flow analyses (see *e.g.*, Garg and Pritchett, 1990) which suggest that the injectivity index should be **a** strong function ofthe sand face injection temperature. Grant *et al.* (1982), however, maintain that the classical analyses do not apply to geothermal systems which are mostly associated with fractured formations; and that injectivity is at least **as** great as productivity in discharge tests. The Oguni data are consistent with Grant, *et al.*'s viewpoint and imply that in the absence of productivity data, injectivity index may be used to characterize the flow resistance of the reservoir rocks.

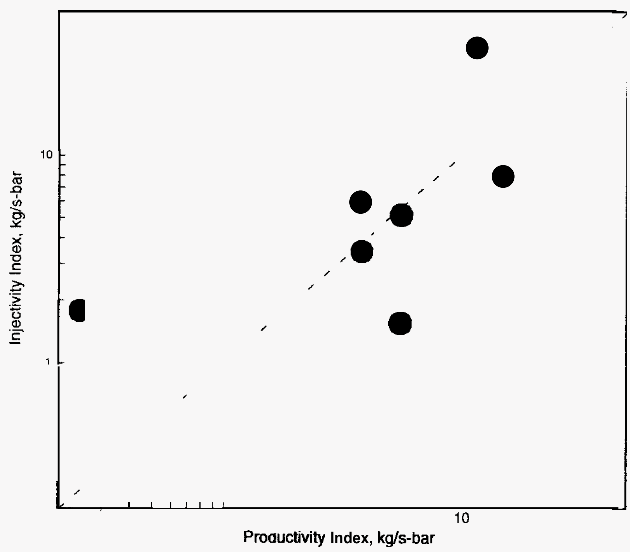

Figure **12.** Productivity versus injectivity index for Oguni boreholes.

Theoretical considerations (Pritchett, 1993 and Hadgu *et al.*, 1994) suggest that apart from any differences associated with differences in wellbore skin (*i.e.*, near borehole formation damage or stimulation), the productivity (or injectivity) index should exhibit only a weak dependence on borehole diameter. The available productivity/injectivity index data for low-pressure zone boreholes (see Table **2**) are displayed in Figures 13a and 13b. Both the productivity and injectivity indices (and hence wellbore skin) display a strong dependence on borehole diameter. At present, the exact cause for the latter phenomenon remains unknown. It appears that similar to the apparent dependence of formation transmissivity on borehole diameter, the apparent variation of productivity/injectivity indices with borehole diameter is caused by differences in drilling techniques (*i.e.*, rotary versus corehole drilling). Clearly, there is a need to better quantify the formation damage (*i.e.*, fracture plugging) caused by core and rotary drilling techniques.

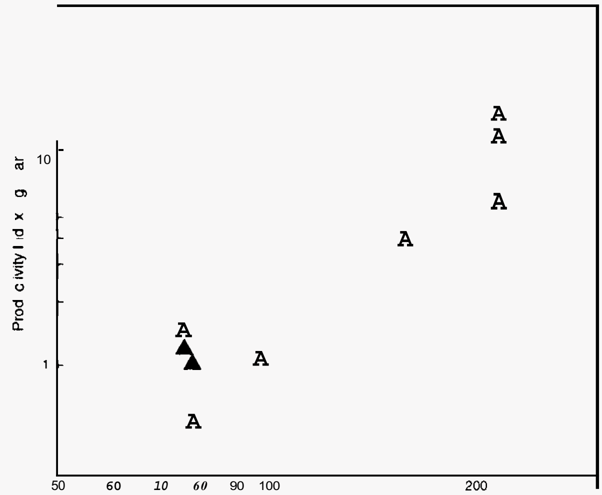

Figure 13a. Productivity index versus diameter for low-pressure reservoir Oguni boreholes.

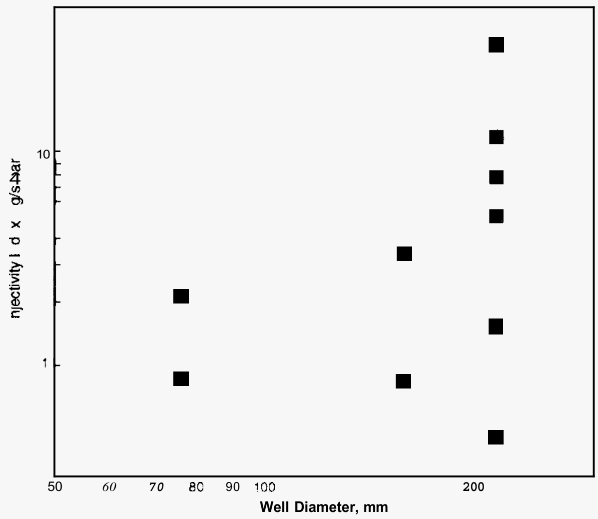

Figure 13b. Injectivity index versus diameter for low-pressure reservoir Oguni boreholes.

6.3 Effect of Borehole Diameter on Discharge Rate

Production characteristics of a geothermal borehole are mainly determined by (1) pipe friction and heat losses in the wellbore, and by (2) pressure losses associated with flow in the reservoir rocks. At Oguni. the formation permeability (and productivity indices) is sufficiently high such that the pressure losses in the reservoir are insignificant compared to pressure losses in the borehole. Stated somewhat differently, the discharge behavior of Oguni boreholes is principally determined by pipe friction and heat losses in the wellbore. As discussed by Pritchett (1993), both frictional pressure gradient and heat loss effects are more signficant for the small-diameter slim holes than for the large-diameter wells. The differences in heat loss effects are probably responsible, at least in some cases, for the difficulty encountered in inducing deep slim holes (depths >> 300 meters) to discharge.

To compare the fluid carrying capacity of boreholes of varying size, it is useful to introduce the "area-scaled discharge rate" M^* as follows:

$$M^* = M_o(d/d_o)^2 \tag{3}$$

where M_o is the actual borehole discharge rate; and d and d_o are the internal borehole diameters (mm). Based on numerical simulation of fluid flow in boreholes of varying diameters, Pritchett (1993) suggests that the maximum discharge rate M_{max} will increase at a rate somewhat greater than the square of diameter.

$$M_{max} = M_o(d/d_o)^{2+n}, n \geq 0 \tag{4}$$

The exact value of n will of course depend on the downhole conditions (*e.g.*, feedzone depth, flowing pressure and enthalpy, and gas content of the fluid). For the conditions assumed by Pritchett (feedzone depth = 1500 meters, feedzone pressure = 80 bars, feedzone temperature = 250°C, single-phase liquid-water at feedzone, uniform wellbore diameter), n is equal to 0.56. Hadgu, ***et** al.* (1994) have considered single-phase (liquid) adiabatic flow (no heat loss) up a wellbore, and suggest that n equals 0.62. The importance of boiling in the borehole and of heat loss to the formation cannot be overstressed. With the exception of two boreholes (GH-15 and HH-2) in the high pressure zone, all of the Oguni boreholes have single-phase liquid conditions at their principal feedzones. On average, the Oguni feedzones are shallower and the feedzone temperatures are somewhat lower than that assumed by Pritchett (1993) for his computations.

Both the "area-scaled' and "scaled maximum ($n = 0.56$)" discharge rates for the Oguni boreholes are presented in Table 4. For the low-pressure zone large-diameter (216 mm) wells (GH-11, GH-12, GH-20 and IH-2), the average measured maximum discharge rate (311 tons/hour) is bracketed by the averaged "area-scaled' (194 tonshour) and averaged "scaled maximum" (338 tonslhour) discharge rates. Furthermore, using the slim hole data, the predicted M^* and M_{max} for GH-IO (159 mm diameter) are 105 tonslhour and 155 tons/hour, respectively. By comparison, the measured discharge rate for GH-10 is 164 tons/hour. Despite differences between the conditions assumed by Pritchett (1993) and the actual conditions existing in the Oguni boreholes, it would appear that the "scaled maximum discharge rate" provides a reasonable prediction of the production performance of large-diameter geothermal wells based on discharge data from slim holes.

Borehole Name	Final Diameter (mm)	Measured Discharge (tons/hr)	M^* Area Scaled Discharge[t] (tons/hr)	M_{max} Scaled Maximum Discharge:? (tons/hr)
		A. Low-Pressure Reservoir		
GH-3	79	20	151	266
GH-4	76	27	218	391
GH-5	76	22	178	319
GH-7	98	30	146	221
GH-8	78	36	216	488
Average (GH-3 to GH-8)			194	338
GH-10	159	164		
GH-11	216	219		
GH-12	216	279		
GH-20	216	369		
IH-2	216	316		
Average (GH-11 to IH-2)		311		
		B. High-Pressure Reservoir		
GH-6	76	24	194	348
GH-15	216	36*		
HH-2	76	5*	40	72
N2-KW-3	76	28	226	406

†

7. CONCLUSIONS

Discharge and injection data from slim holes and large-diameter wells at the Oguni Geothermal Field, Japan, were examined in an effort to establish relationships (1) between productivity of large-diameter wells and slim holes, (2) between injectivity and productivity indices of slim holes and large-diameter wells, and *(3)* between productivity/injectivity indices and borehole diameter. Based on analyses of pressure transient data from the boreholes in the Oguni Geothermal Field, (1) the *kh* values inferred from pressure interference and pressure build-up tests are significantly greater than those derived from pressure fall-off tests, and *(2)* the slim holes yield *kh* values which are smaller than those obtained from large-diameter wells. The variance in *kh* values between slim holes and large-diameter wells may be caused by the difference in drilling techniques (*i.e.*, core versus rotary drilling). In addition, the Oguni data and results of their analyses suggest that short term injection tests are likely to yield only a lower bound on reservoir transmissivity.

The productivity and injectivity indices are both available for seven of the Oguni boreholes and to first order the indices are equal. These data imply that for fractured reservoirs in the absence of discharge testing and the resultant productivity data, the injectivity index may be used to characterize the flow resistance of the reservoir rocks. Furthermore, the Oguni data indicate that both the productivity and injectivity indices display a strong dependence on borehole diameter. Although the exact cause of the latter phenomenon is presently unknown, the apparent variation of productivity/injectivity indices with borehole diameter may be caused by the difference in formation damage (*i.e.*, fracture plugging) caused by core versus rotary drilling techniques.

At Oguni, the available pressure transient data indicate that the reservoir transmissivity is quite large. As a result, the pressure losses in the reservoir are insignificant compared to pressure losses in the borehole. In other words, the discharge characteristics of Oguni boreholes are primarily determined by pipe friction and heat losses in the wellbore. Hence, although differences exist between the conditions assumed by Pritchett (1993) and the actual conditions existing in the Oguni boreholes, it appears that his "scaled maximum discharge rate" provides a reasonable prediction of production performance of large-diameter geothermal wells based on discharge data from slim holes. Therefore, the analyses of the Oguni borehole data are consistent with the premise that it should be possible to forecast the production performance of large-diameter geothermal wells using discharge data obtained from slim holes.

This latter conclusion must, however, be tested with discharge data from a statistically significant collection of slim holes and production wells from a number of geothermal fields. Ideally. the set of geothermal fields should include ones with both large and moderate transmissivity to characterize the effect of pressure losses in the reservoir on the discharge characteristics of both slim holes and large-diameter production wells. Work is presently underway on the analysis of production and injection data from slim holes and large-diameter production wells in two other Japanese Geothermal Fields, *i.e.*, Sumikawa and Takigami. The results of these analyses will be reported in future publications.

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