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Use of Slim Holes for Geothermal Exploration and Reservoir Assessment: A Preliminary Report on Japanese Experience

Sabodh K. Garg
S-CUBED
P.O. Box 1620
La Jolla, CA 92038-1620

Jim Combs
Geo Hills Associates
27790 Edgerton Road
Los Altos Hills, CA 94022

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Abstract

The publicly available Japanese data on the use of slim holes in geothermal exploration and reservoir assessment are reviewed in this report. Slim holes have been used for (1) obtaining core for geological studies, (2) delineating the stratigraphic structure, (3) characterizing reservoir fluid state (pressure, temperature, etc.), and (4) defining the permeability structure for reservoir assessment. Examples of these uses of slim hole data are presented from the Hoho Geothermal Area and the Sumikawa Geothermal Field. Discharge data from slim holes and production wells from the Oguni Geothermal Field indicate that it may be possible to infer the discharge rate of production wells based on slim hole measurements. The Japanese experience suggests that slim holes can provide useful data for cost-effective geothermal reservoir assessment. Therefore, plans for a full scale evaluation of Japanese slim hole data are outlined.

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ABSTRACT

The publicly available Japanese data on the use of slim holes in geothermal exploration and reservoir assessment are reviewed in this report. Slim holes have been used for (1) obtaining core for geological studies, (2) delineating the stratigraphic structure, (3) characterizing reservoir fluid state (pressure, temperature, *etc.*), and (4) defining the permeability structure for reservoir assessment. Examples of these uses of slim hole data are presented from the Hohi Geothermal Area and the Sumikawa Geothermal Field. Discharge data from slim holes and production wells from the Oguni Geothermal Field indicate that it may be possible to infer the discharge rate of production wells based on slim hole measurements. The Japanese experience suggests that slim holes can provide useful data for cost-effective geothermal reservoir assessment. Therefore, plans for a full scale evaluation of Japanese slim hole data are outlined.

1. INTRODUCTION

The principal cost associated with the identification, assessment, and development of geothermal reservoirs for electrical power production is the high cost of drilling the exploration, production, and injection wells. A major impediment to the exploration of new geothermal areas is the high cost of conventional rotary drilling. A conventional 1200 to 1800 m deep rotary-drilled well can cost millions of dollars. Compared to conventional large-diameter wells, the drilling costs for small-diameter (less than 10 cm) slim holes are relatively low. Because of this cost differential, it would be desirable to use slim holes for geothermal exploration and reservoir assessment. At present, there exists little experience in the U. S. geothermal industry in the use of slim holes for exploration and reservoir assessment purposes. Combs and Dunn (1992) have argued the need for a U. S. Department of Energy (DOE)-industry coupled slim hole research and development program. Among other things, this R & D program will include Proof-of-Concept experiments to demonstrate that low-cost slim holes can be used to provide

reservoir parameter estimates that are comparable to those obtained from large-diameter wells. These experiments will involve drilling and testing pairs of small-diameter slim holes and large-diameter production wells in several geothermal fields in the western United States.

In contrast to the situation in the United States (*i.e.*, lack of sufficient experience with slim holes in geothermal exploration), the Japanese routinely employ small-diameter core holes in geothermal exploration and reservoir assessment. Besides obtaining core for geological studies, slim holes have been used for characterizing reservoir fluid state and reservoir permeability structure. The Japanese experience with slim holes should be useful in developing a cost-effective, DOE-industry coupled, geothermal slim hole R & D program.

Most of the Japanese data pertaining to slim holes are proprietary, and it will be necessary to obtain permission from various government and private agencies in Japan prior to carrying out a full-scale study. Sufficient published data are, however, available to produce a preliminary report on Japanese experience, provide some tentative conclusions about using slim holes to predict production capability of large-diameter wells, and to plan for a full-scale evaluation of the Japanese data.

The publicly-available Japanese data on the use of slim holes in geothermal exploration and reservoir assessment are reviewed in Section 2 of this report. It is often difficult to induce deep small-diameter holes (depths $\gg$ 300 m) to discharge. A parallel theoretical study discussing the effect of well-diameter on the production behavior of geothermal boreholes is presented elsewhere (Pritchett, 1992); important conclusions of that study are summarized in Section 3. The data required for inferring the production characteristics of large-diameter wells on the basis of tests performed in small-diameter core holes are also described in Section 3. Data that may be available in private company files are briefly described in Section 4. Finally, in Section 5, plans for a full-scale study of the Japanese slim hole data are outlined.

2. REVIEW OF PUBLISHED JAPANESE SLIM HOLE DATA

The first commercial scale geothermal power station in Japan (Matsukawa Geothermal Power Plant) was commissioned in 1966. As of March 1991, the total installed capacity stood at ~ 270 MW (see Table 1). In addition to the power plants listed in Table 1, geothermal power plants are under development at several sites in the Tohoku and Kyushu districts (see Table 2 and Figure 1).

Since the first oil crisis in 1974, the Japanese government (primarily through the Geological Survey of Japan, Agency of Industrial Science and Technology, New Energy and Industrial Technology Development Organization (NEDO)) has actively promoted the exploration and development of geothermal resources (see JGEA, 1992). As discussed by Maki and Kawano (1988), NEDO has been carrying out government subsidized geothermal surveys throughout Japan since 1980. Under its "Geothermal Development Promotion Survey" program, NEDO drilled 189 wells. The report by Maki and Kawano (1988) presents a statistical analysis of penetration rates for 47 HQ (98 to 101 mm) and NQ (76 to 78 mm) core holes drilled during Japanese fiscal years 1984–1986. Most of the boreholes drilled by NEDO have been injection tested; in addition, a small number (5 to 10 percent) of boreholes have been discharged (Kawano, personal communication, 1992).

Dr. Allan Jelacic (personal communication, 1992) of the U. S. Department of Energy has been in contact with his counterparts in the Japanese Ministry of International Trade and Industry in an attempt to determine the types of core-hole data that may be available. The Japanese have responded favorably by forwarding a sample report containing drilling and injection test data for three boreholes in an area adjacent to the Takigami geothermal field, Kyushu, Japan.

In addition to core holes drilled by NEDO and other governmental agencies, a large number of core holes have been drilled by

private developers. Unfortunately, because of proprietary and other (e.g., language) reasons, most of the data obtained from these core holes are not easily accessible. In the following paragraphs, we briefly describe the publicly available reports on the use of core holes for reservoir assessment purposes.

2.1 HOHI GEOTHERMAL AREA

During the years 1978–1985, the Ministry of International Trade and Industry conducted (through the Agency of Natural Resources and Energy, Agency of Industrial Science and Technology, New Energy and Industrial Technology Development Organization, Electric Power Development Corporation (EPDC), etc.) a regional exploration survey in the Hoho area, Kyushu, Japan. The main area of the survey encompassed 200 km² centered on Mt. Waita (see Figure 2 for location of survey area). As part of this exploration program, both small-diameter core holes ("DB" and "DW" series) and large-diameter production-size wells ("DY" series) were drilled (see Table 3 for a list of boreholes). It is apparent from Table 3 that only a few large-diameter holes were drilled.

All of the "DB", "DW", and "DY" series boreholes were injection tested. Since no downhole pressure measurements were made during these injection tests, the injection test data are not useful for inferring formation properties for reservoir assessment purposes. None of the small-diameter "DB" and "DW" series slim holes were discharged; of the "DY" series wells, only two wells (DY-1 and DY-5) could sustain discharge. Murakami, *et al.* (1986) discuss the discharge characteristics of well DY-1. The well was continuously discharged for a six-month period in 1982 at discharge rates between 16 kg/s and 60 kg/s. The measured performance curve for production well DY-1 is illustrated in Figure 3.

Pritchett, *et al.* (1985) present a preliminary reservoir engineering study of the western portion of the Hoho area (see Figure 4). Although the southeastern part of the study area contains the Hatchobaru and Ohtake geothermal fields, no data from these fields were

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Table 1. Japanese geothermal power plants in operation in 1990 (adapted from JGEA, 1992).

Name of Power Plant (Name of Owner)	Installed Capacity (MW)	Maximum Power (MW)
Matsukawa (Japan Metals & Chemicals Co., Ltd.)	22.0	22.0
Otake (Kyushu Electric Power co., Ltd.)	12.5	12.5
Ohnuma (Mitsubishi Materials Corporation)	9.5	9.2
Hatchobaru I (Kyushu Electric Power Co., Ltd.)	55.0	54.9
Hatchobaru II (Kyushu Electric Power Co., Ltd.)	55.0	55.0
Onikobe (Electric Power Development Co.)	12.5	12.5
Kakkonda (Japan Metals & Chemicals co., Ltd. and Tohoku Electric Power Co., Inc.)	50.0	50.0
Mori (Donan Geothermal Energy Co., Ltd. and The Hokkaido Electric Power Co., Inc.)	50.0	30.0
Suginoi (Suginoi Hotel)	3.0	1.75
Kirishima International Hotel I (Daiwabo Kanko Co., Ltd.) II III	0.45	0.43
TOTAL	270.0	248.28

Table 2. Geothermal power plants under development in Japan (data from JGEA, 1992).

Name of Power Plant (Name of Owner)	Nominal Capacity (MW)	Projected Completion Date
Uenotai (Akita Geothermal Energy Co., Ltd.)	27.5	1994
Sumikawa (Mitsubishi Materials Corporation)	50.0	1995
Yanaizu (Okuaizu Geothermal Co., Ltd.)	65.0	1995
Kakkonda II (Japan Metals and Chemicals co., Ltd.)	30.0	?
Yamakawa (Japex Geothermal Kyushu Co., Ltd.)	30.0	1995
Ohgiri (Nittetsu Kagoshima Geothermal Co., Ltd.)	30.0	1995
Takigami (Idemitsu Geothermal Co., Ltd.)	25.0	1996
Oguni (Electric Power Development Co., Ltd.)	?	?

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Figure 1. Geothermal power plants and places of geothermal development in Japan (from JGEA, 1992).

Figure 2. Location map of the Hohi Geothermal Area. Slim holes are indicated by ● and production wells are represented by ■.

Table 3. List of boreholes drilled under the NEDO Hoho project
(data from NEDO, 1987).

Type	Name	Wellhead Elevation (m)	Drilled Depth (m)	Final Diameter (mm)
Heat-flow Hole	DB-1	560	504.2	98
	DB-2	769	502.4	98
	DB-3	1,001	503.0	98
	DB-4	657	503.0	98
	DB-5	832	504.3	98
	DB-7	774	503.0	98
	DB-8	731	505.0	98
	DB-9	760	502.0	98
	DB-10	922	501.9	98
	DB-11	957	501.6	98
Exploration Well	DW-1	1,063	1,500.0	98
	DW-2	770	1,500.0	98
	DW-3	840	1,203.0	98
	DW-4	760	1,100.0	98
	DW-5	1,205	1,500.0	98
	DW-6	609	1,550.0	98
	DW-7	647	1,800.0	98
Investigation Well	DY-1	824	2,618.0	216
	DY-2	866	2,401.5	216
	DY-3	954	2,303.0	216
	DY-5	980	3,206.0	216
	DY-6	838	3,003.2	216
	DY-6A	—	1,950–2,900	216
Injection Well	DX-1	822	440.0	143
	DX-2	865	720.0	143
	DX-5	980	1,400.0	143

Figure 3. Measured wellhead pressures as a function of discharge rate for large-diameter production well DY-1 at Hoho. The solid curve shows the results of calculations of flow within the wellbore performed using a wellbore simulator (from Murakami, *et al.*, 1986).

Figure 4. Outline of western Hoho study area showing boreholes, hot springs and surface elevation contours (m ASL) (from Pritchett, *et al.*, 1985). Slim holes are indicated by ● and production wells are represented by ■.

made available for Pritchett, *et al.*'s (1985) study. Available downhole data consisted of (1) drilling data (circulation loss data, well completion information, and geologic data), and (2) repeat temperature and water level surveys. No downhole pressure measurements were taken; feedpoint pressures were estimated from temperature and water level data. Production data (mainly water and steam flow rates, and wellhead pressure) were available from only one well (*i.e.*, DY-1). Core-hole data were invaluable for defining (1) the stratigraphic sequence, and (2) reservoir temperature and pressure distribution (see Figures 5-7). It can be seen from Figures 5 and 6 that a very large volume of hot reservoir rock is present in the northwestern part of the study area. The feedzone pressures for seven boreholes (five slim holes DB-4, DW-2, K-7, DW-6, and DW-7; and two large-diameter production wells TY-1 and DY-1) in the northwestern area all lie on a straight line (Figure 7); this straight line comprises a lower bound on all the data. Apparently, the northern reservoir forms a separate hydrological entity. The circulation loss data from the northern wells indicated that most of the permeability in the northern reservoir is associated with a horizontal fracture zone in the upper part of pre-Kusu formation near sea-level elevation. Using the reservoir pressure distribution derived essentially from the slim-hole data and the hot spring flow data, Pritchett, *et al.* (1985) estimated a permeability-thickness product of 40 darcy-meters for the northern reservoir.

Since the completion of the above mentioned regional survey of the Hoho area, EPDC and NEDO have carried out additional drilling and well testing programs in the northern Hoho area (Oguni and Sugawara geothermal fields). These new data from production wells have in the main confirmed the conceptual model of Pritchett, *et al.* (1985) for the northwestern Hoho area (surface area ~ 40 km²; Figure 4) based primarily on the data obtained from slim holes.

It is worthwhile to recall here that Pritchett, *et al.*'s model for the northern Hoho area was based almost entirely on data from (1) seven boreholes (DB-4, TY-1, DW-2, K-7, DW-6, DW-7 and DY-1) of which five were slim

holes and (2) surface geological and geophysical surveys (including hot spring discharge rates and temperatures). Of the seven boreholes, five (DB-4, DW-2, DW-6, DW-7 and DY-1) were drilled under the NEDO program; the remaining two wells (TY-1 and K-7) were drilled by local authorities. As already mentioned, production data were available for only one well (DY-1). The modeling experience for the northern Hoho area indicates that a minimum amount of borehole data (water level and temperature data, stratigraphy and circulation loss data from drilling surveys, discharge data from 1 hole) along with surface surveys (*i.e.*, hot spring data, gravity survey) can be used to derive a preliminary estimate of the power potential of a geothermal area. It should be stressed here that while the amount and type of data required for reservoir assessment will vary from case to case, small-diameter core holes can be used to obtain many of the data (*e.g.*, reservoir pressure and temperature estimates, stratigraphy, *etc.*) needed in reservoir engineering studies.

2.2 SUMIKAWA GEOTHERMAL FIELD

Because of their limited capacity, small-diameter core holes are often unsuitable as production or injection wells in a pressure interference test. (Pressure interference tests are essential for establishing reservoir connectivity and for computing interwell transmissivity. The amplitude of the pressure signal generated by production from or injection into a core hole is often too weak to be monitored in neighboring wells.) On the other hand, small-diameter core holes can be used as monitoring wells. Garg, *et al.* (1991) present a discussion of the pressure-interference testing of the Sumikawa geothermal wells.

The Sumikawa Geothermal Field is located in the Hachimantai volcanic area in northern Honshu, Japan. The region of particular interest is shown in Figure 8. The Sumikawa Geothermal Field lies in the western part (area around boreholes S-1, S-2, S-3 and S-4) of the region depicted in Figure 8. To the east, the Ohnuma power station has been producing about 10 MW of electrical power for several years. The subsurface stratigraphic structure in

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Figure 5. Stratigraphic sequence at Hohi (from Pritchett, *et al.*, 1985).

Figure 6. Vertical temperature distribution at Hohi along a line extending from borehole DB-2 to borehole DB-4 (from Pritchett, *et al.*, 1985).

Figure 7. Pressure as a function of elevation for all boreholes in the western Hoho area (from Pritchett, *et al.*, 1985). Slim holes are indicated by ● and production wells are represented by ■.

Figure 8. The Sumikawa/Ohnuma area, showing locations of boreholes and crosssections A-A' and B-B' (from Garg, *et al.*, 1991).

the Sumikawa area is shown in Figures 9 and 10. These structural interpretations are based almost exclusively on drilling experience. The major formations in order of increasing depth are (1) surficial andesite tuffs, lavas and pyroclastics (ST formation), (2) lake sediments (LS formation), (3) Pliocene dacites and tuffs (DA formation), (4) interbedded Miocene dacitic volcanic rocks and black shale (MV or marine/volcanic complex), (5) altered and fractured andesites (AA formation) and (6) crystalline intrusive rocks (GR formation).

In 1986, deep large-diameter production well S-4 was discharged from September 2 to November 3. During this test, a downhole gauge of the capillary tube type was installed in a slim hole (KY-1); the response of slim hole KY-1 to production from S-4 is shown in Figure 11. In April and May 1989, cold water was injected into several wells (SA-1, SA-2, SA-4, S-4, SB-1, SB-2 and SB-3). Slim hole KY-1 responded to injection into wells S-4, SB-1 and SB-2 (see *e.g.*, Figure 12). Apparently, wells S-4 and SB-1 communicate with slim hole KY-1 through the altered andesite layer (AA formation); well SB-2 is connected to slim hole KY-1 through an interbedded dacite layer in the marine/volcanic complex formation.

Pressure response of slim hole KY-1 to production (injection) from well S-4 was interpreted by Garg, *et al.* (1991) to indicate the presence of a very high permeability channel in the altered andesite layer (main production zone at Sumikawa). Pressure interference between slim hole KY-1 and well SB-2 was used to confirm the presence of a moderately high transmissivity layer in the "marine-volcanic complex" formation (main injection zone at Sumikawa). The experience at Sumikawa (as well as several other fields in Japan) has clearly shown that the small diameters of core holes pose no limitations on their use as pressure monitoring wells.

2.3 OGUNI GEOTHERMAL FIELD

In at least some cases, small-diameter core holes have been discharged (1) to collect fluid samples, and (2) to obtain first indications of the

productivity of a geothermal formation. Abe (1988) gives tabular values for water and steam flow rates from both the small-diameter core holes and large-diameter production wells in the Oguni Geothermal Field (the Oguni Geothermal Field forms a part of the northern Hoho area). According to Abe (1988), several HQ and NQ size core holes have been successfully discharged (see Table 4). Of course, the production rate of the small-diameter core holes is a small fraction of the large-diameter production-size wells. Ideally, one would like to predict the productivity of large-diameter production wells based on results of injection into or production from small-diameter core holes. The question of the scale-up of production/injection data from core holes to forecast the production behavior of large-diameter wells is considered in Section 3.

3. EFFECT OF BOREHOLE DIAMETER ON PRODUCTION CHARACTERISTICS

Production characteristics of a geothermal borehole are in the main determined by (1) pipe friction and heat losses in the wellbore, and by (2) pressure losses associated with flow in the reservoir rocks. Ignoring pressure transient effects, the flow resistance (or pressure losses) of the reservoir rocks can be represented by the productivity (or injectivity) index. The productivity (or injectivity) index is defined as:

$$PI = \frac{M}{P_{ns} - P_{wf}} \quad (1)$$

where

M = production (or injection) rate, kg / s

P_{ns} = reservoir pressure at the feedzone depth

P_{wf} = flowing feedzone pressure in the well.

Since the flowing feedzone pressure P_{wf} is a function of reservoir permeability-thickness (kh) product and wellbore skin (s), it follows that the productivity index (PI) is also a function of kh and s . Wellbore skin (s) is a measure of near wellbore permeability reduction (or enhancement) as a result of drilling and/or well treatment (*e.g.*, acid treatment).

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Figure 9. East-west A-A' geological cross-section through the Sumikawa area (from Garg, *et al.*, 1991).

Figure 10. North-south geological cross-section B-B' through the Sumikawa area (from Garg, *et al.*, 1991).

Figure 11. Comparison of computed 1986 pressure disturbance in small-diameter core hole KY-1 at Sumikawa to measurements (—computed, • measurements) (from Garg, *et al.*, 1991).

Figure 12. Comparison of computed pressure response of small-diameter core hole KY-1 at Sumikawa with measurements due to cold water injection into well S-4 (—computed, • measurements) (from Garg, *et al.*, 1991).

Table 4. Diameter, depth, maximum temperature, and production rate for small-diameter core holes and large-diameter production wells in the Oguni area (from Abe, 1988).

Well Name	Final Stage Well Dia. mm	Drilling depth m	Max temp. °C	Steam flow rate t/hr	Hot water flow rate t/hr	Completion year	Note
HH-1	76	700	206	—	—	1984	
HH-2	76	1,000	231	3	2	1984	
HH-3	76	500	210	—	—	1984	
GH-1	76	1,950	175	—	—	1983	
GH-2	76	1,800	155	—	—	1984	
GH-3	76	1,500	223	5	15	1985	
GH-4	76	1,000	239	6	18	1985	
GH-5	76	1,500	235	2	17	1985	directional
GH-6	76	1,000	220	8	28	1985	
GH-7	98	1,544	213	8	20	1985	directional
GH-8	78	1,300	212	7	28	1986	directional
GH-9	81	1,600	243	—	—	1986	directional
GH-10	159	1,063	239	49	119	1986	directional
GH-11	216	1,381	212	45	172	1987	directional

Pritchett (1992) has carried out a theoretical study of the discharge characteristics of slim holes compared to production wells. To compare the fluid carrying capacity of a borehole as a function of diameter, it is convenient to define the "area-scaled well discharge rate" M^* as follows:

$$M^* = M \times \left(\frac{25 \text{ cm}}{D} \right)^2 \quad (2)$$

where M is the actual borehole discharge and D is the internal borehole diameter (cm). Assuming that (1) the boreholes feed from an all liquid-zone, and (2) the feedzone pressure and temperature are independent of borehole diameter, calculations were carried out for a variety of borehole diameters varying between 5 cm and 35 cm; the results of these calculations are displayed in Figure 13. The wellhead pressure/flowrate relationships for the various borehole diameters do not collapse to a single curve (Figure 13), even when flow rates are adjusted to account for differences in cross-

sectional area. Clearly, the area-scaled discharge rate declines with a decrease in borehole diameter. As discussed by Pritchett (1992), both frictional pressure gradient and heat loss effects are more significant for the smaller-diameter slim holes than for the larger-diameter wells. The difference in heat loss effects is probably responsible, at least in some cases, for the difficulty encountered in inducing deep slim holes (depths $\gg 300$ m) to discharge. Theoretical results suggest that to induce deep slim holes to discharge, it may be necessary to employ unusual techniques such as preheating the borehole prior to startup.

For the conditions (feedzone depth = 1500 m, flowing feedzone pressure = 80 bars, feedzone temperature = 250°C, uniform diameter wellbore) considered by Pritchett (1992), the maximum discharge rate (i.e., flow rate at 1 bar wellhead pressure) scales with borehole diameter according to the following relation:

$$M_{\max} = M_o (d/d_o)^{2.56} \quad (3)$$

Figure 13. Influence of diameter on borehole performance characteristics (from Pritchett, 1992).

where M_o denotes the maximum discharge rate for a borehole of diameter d_o . Equation (3) implies that the "area scaled" maximum attainable flow rate increases approximately with the square root of borehole diameter.

3.1 PREDICTION OF DISCHARGE RATE OF PRODUCTION WELLS FROM SLIM HOLE DATA AT OGUNI GEOTHERMAL FIELD

Abe (1988) does not make it clear if the indicated flow rates for Oguni boreholes in Table 4 are the maximum attainable flow rates for these boreholes. There also exists little reason to expect that the Oguni boreholes conform to the conditions assumed by Pritchett (1992) for his theoretical study. Despite these uncertainties about the Oguni data set, it was decided to investigate the possibility of predicting the discharge rate of the Oguni production well GH-11 from the slim hole data. Scaled discharge rates for production well GH-11 using (1) simple area scaling (Equation 2) and (2) a scaling rule for maximum flow (Equation 3) are given in Table 5. The measured discharge for GH-11 (217 tons/hour) is bracketed by the average area-scaled discharge rate (178

t/h) and by the average scaled maximum discharge rate (314 t/h) obtained from the measured slim hole discharge data. The Oguni data are, therefore, consistent with the premise that it should be possible to infer the discharge rate of large-diameter wells based on production data from small-diameter core holes. It should, however, be stressed that the latter conclusion needs to be tested with data from a statistically significant collection of geothermal fields.

3.2 INJECTIVITY AND PRODUCTIVITY INDICES OF SLIM HOLES AND PRODUCTION WELLS

Theoretical considerations (Pritchett, 1992) imply that apart from any systematic differences resulting from skin effects, the productivity index should exhibit only a weak dependence on borehole diameter. At present, published data comparing the productivity indices (and skin factors) for small-diameter slim holes and production-sized wells are simply unavailable. There is also a need to establish a relationship between injectivity index obtained from cold water injection tests and productivity index obtained from discharge tests. Classical analyses which assume porous-medium flow

Table 5. Predicted discharge rate for the GH-11 production-size well at Oguni (Abe, 1988) derived from scaling measured discharge rates of slim holes at Oguni Geothermal Field.

Well Name	Final Stage Well Diameter (mm)	Measured Discharge Rate (t/hr) ^(c)	Area-Scaled Discharge Rate for GH-11 ^(a) (t/hr)	Scaled Maximum Discharge Rate for GH-11 ^(b) (t/hr)
HH-2	76	5	40	73
GH-3	76	20	162	290
GH-4	76	24	194	348
GH-5	76	19	154	276
GH-6	76	36	291	522
GH-7	98	28	136	212
GH-8	78	35	268	475
Average			178	314

Notes:

- (a) Area-scaled discharge rate based on the equation, $M = M_o (d/d_o)^2$, from Pritchett (1992).
- (b) Maximum scaled discharge rate based on the equation, $M_{max} = M_o (d/d_o)^{2.56}$, from Pritchett (1992).
- (c) Measured value obtained from Abe (1988).

(see *e.g.*, Garg and Pritchett, 1990) suggest that the injectivity index should be a strong function of the sandface injection temperature. (Note that the dynamic viscosity of water varies greatly with temperature and according to Darcy's law, pressure drop or increase is directly proportional to fluid viscosity.)

Grant, *et al.* (1982) have, however, argued that the conclusions derived on the basis of porous medium flow do not apply to geothermal systems. Most geothermal systems are associated with fractured igneous and metamorphic rocks. The following quotation from Grant, *et al.* (1982) is pertinent:

"The productivity of a well is found to be less than injectivity. It was argued above (Section 5.6 and A1.4) that transmissivity measured with injection tests is that of the hot reservoir fluid. That is, transmissivity or injectivity measured in injection tests is equal to transmissivity or productivity in discharge. Often this is so. When it is not so, it is usually the case that injectivity is greater than productivity, despite the lower viscosity of hot water."

We do not know what data were used by Grant, *et al.* (1982) in reaching their conclusions. At present, sufficient published data are unavailable which would enable one to state with a high level of confidence that the productivity and injectivity indices are essentially equal for geothermal boreholes.

To establish relationships between (1) the productivity and injectivity indices of a borehole, and (2) the productivity indices of large-diameter production wells and small-diameter core holes, the following types of data are needed:

1. Drilling data including stratigraphy, circulation losses, and well completion information,
2. Static pressure and temperature, and flowing pressure, temperature and spinner surveys (needed for locating feedzone(s),

and determining feedzone pressure and temperature),

3. Injection test data with pressure and temperature measurements at the feed-zone depth (needed to establish injectivity index and its possible dependence on temperature),
4. Production test data with pressure and temperature measurements at the feed-zone depth (needed to compute productivity index),
5. Pressure falloff (after injection test) and pressure buildup (after production test) response measured at the feedzone depth (needed for determining permeability-thickness product and wellbore skin factor).

The above-mentioned data should be obtained from both the small-diameter core holes and large-diameter production wells drilled in the same geothermal field.

4. PROPRIETARY DATA

During the past ten years, S-Cubed has carried out reservoir engineering studies of many geothermal fields in Japan. Based on our knowledge of proprietary data from these Japanese geothermal fields, we believe that data exist which can be used to more fully define the potential use of slim holes in reservoir exploration and assessment. Specifically, the following types of data are known to exist in private company files for both small-diameter core holes and large-diameter wells.

1. Drilling logs (including penetration rate, mud details, stratigraphy, circulation losses, well completion details),
2. Heatup surveys, water level, and downhole (static) pressure surveys,
3. Injection tests (including flow rate, injection temperature),

4. Production tests (including flow rate, enthalpy),
 5. Pressure/temperature/spinner surveys during injection and production tests, .
 6. Pressure falloff (after injection) and pressure buildup (after production) data, and
 7. Pressure interference data.
5. PLANS FOR A FULL-SCALE STUDY

S-Cubed recommends that a study to characterize the use of slim holes in geothermal exploration and reservoir assessment in Japan should be carried out. A major goal of the study will be to compare the discharge and injection characteristics of small-diameter core holes and large-diameter production wells. Since most of the data required for this study are proprietary, it will be necessary to negotiate with various geothermal developers (see Tables 1 and 2) and government agencies to obtain release of appropriate data. To assure Japanese co-operation, it will be necessary to emphasize the benefits of the proposed study to both parties (i.e., U. S. and Japanese geothermal industries). In addition, assurances will need to be given to protect any confidential data made available for this study; any proprietary data must be sufficiently disguised to make their identification with a particular field all but impossible. In that it is difficult to forecast the amount of data that may be made available by the Japanese, it is difficult at this time to provide a very precise estimate of the level of effort required to conduct the recommended program. For this reason, it is suggested that the program be divided into two phases (Phase 1: data gathering and Phase 2: data analysis and preparation of final report). Phase 1 is expected to last from 4 to 6 months, and Phase 2 work will be carried out over a period of 6 to 12 months. The following statement of work is suggested for Phases 1 and 2 of the proposed study:

■ Phase 1: Data Gathering

□ Task 1: Negotiate with various Japanese geothermal developers and govern-

ment agencies for release of appropriate drilling and well test data.

□ Task 2: Send two geothermal engineers to Japan for a period of up to 4 weeks. These engineers will visit the facilities of all the Japanese companies/government agencies who have agreed to provide data. A personal visit by U. S. engineers will ensure that the appropriate data are collected.

■ Phase 2: Data Assimilation and Analysis

□ Task 3: Assimilate data collected under Task 2. Computerize data as required for analysis purposes under Task 4.

□ Task 4: (a) Analyze drilling and other downhole surveys to determine feedzone depths, pressures, and temperatures.

(b) Analyze injection and production test data (flow rates, flowing feedzone temperature and pressure) to determine injectivity and productivity indices.

(c) Analyze available pressure fall-off and buildup data for formation properties (e.g., transmissivity) and wellbore skin.

(d) Evaluate the results of analyses performed under subtasks (b) and (c) to determine (i) any temperature dependence exhibited by injectivity index and skin factor, (ii) the relationship between injectivity and productivity indices (both determined from the same well), and (iii) the relationship between well diameter and productivity/injectivity index.

□ Task 5: Prepare a comprehensive report on the use of core holes in geothermal exploration and reservoir assessment in Japan. The report will include data (suitably disguised to prevent disclosure of sensitive information) collected under Task 2, and results of analyses performed under Task 4.

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DISTRIBUTION

David N. Anderson
Geothermal Resources Council
PO Box 1350
Davis, CA 95617

Jim Combs
Geo Hills Associates
27790 Edgerton Road
Los Altos Hills, CA 94022

Greg Taylor
Christensen Boyles Corporation
PO Box 30777
Salt Lake City, UT 84130

Alan Melchior
Far West Capital
921 Executive Park Drive, Suite B
Salt Lake City, UT 84117

Colin Goranson
1498 Aqua Vista Road
Richmond, CA 94805

Jim Lovekin
California Energy Co.
900 North Heritage, Bldg D
Ridgecrest, CA 93555

Marc Steffen
Cal-Pine Corporation
1160 North Dutton, Suite 200
Santa Rosa, CA 95401

Walter Haenggi
Magma Power Company
551 West Main Street, Suite 1
Brawley, CA 92227

Bureau of Land Management (2)
Attn: Michael Ferguson
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787 N. Main, Suite P
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Robert Deputy
ARCO Oil and Gas Co.
2300 W. Plano Parkway
Plano, TX 75075

Sue Goff
LANL, MS D-443
Los Alamos, NM 87545

Charles George
Halliburton Services
Drawer 1431
Duncan, OK 73536

Barry Harding
Ocean Drilling Program
Texas A&M University
1000 Discovery Drive
College Station, TX 77840

George Cooper
Dept. of Materials Science &
Mineral Engineering
University of California
Berkeley, CA 94720

Helene Knowlton
Smith International
16740 Hardy Street
Houston, TX 77205

Frank Monastero
US Navy - Geothermal Office
China Lake, CA 93555

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Longyear Company
PO Box 1000
Dayton, NV 89403

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126 Countrywood Lane
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Daniel Lyster
Mono County Energy Mgmt.
HCR 79, PO Box 221
Mammoth Lakes, CA 93546

Desert Drilling Fluids (4)
Attn: Gene Polk
Dave Donald
3316 Girard Blvd NE
Albuquerque NM 87107

Nic Nickels
Eastman Christensen
3636 Airway Drive
Santa Rosa, CA 95403

Steve Pye
Unocal Geothermal
PO Box 7600
Los Angeles, CA 90017

John Sass
USGS
2255 North Gemini Drive
Flagstaff, AZ 86001

Larry Larson
Nabors Loffland
515 West Greens Road, Suite 310
Houston, TX 77067

Tonto Drilling Services (2)
Attn: George McLaren
Larry Pisto
PO Box 25128
Salt Lake City, UT 84125

Tommy Warren
Amoco Production Center
PO Box 3385
Tulsa, OK 74102

G. S. Bodvarsson
Earth Sciences Division
Lawrence Berkeley Lab
1 Cyclotron Road
Berkeley, CA 94720

US Department of Energy (3)
Geothermal Division
Attn: Ted Mock
Lew Pratsch
Marshall Reed
Forrestal Bldg., CE-324
1000 Independence Ave. SW
Washington, DC 20585

Susan Hodgeson
Division of Oil and Gas
20th Floor, MS-20
801 K Street
Sacramento, CA 95814-3530

Elizabeth Johnson
Div. of Oil and Gas - Geothermal
20th Floor, MS-21
801 K Street
Sacramento, CA 95814-3530

Warren Bollmeier
PICHTR
2800 Woodlawn Dr, Suite 180
Honolulu, HI 96822

Dick Benoit
Oxbow Power Services, Inc
200 South Virginia St, Suite 450
Reno, NV 89501

George Darr
Geothermal Program Manager
Bonneville Power Administration
PO Box 3621
Portland, OR 97208-3621

Mohinder Gulati
UNOCAL Geothermal
PO Box 7600, Room M-36
Los Angeles, CA 90051

Thomas C. Hinrichs
Magma Power Company
11770 Bernardo Plaza Ct, Suite 366
San Diego, CA 92128

Tsvi Meidav
Trans-Pacific Geothermal Corp.
1901 Harrison St, Suite 1590
Oakland, CA 94612

Joel Renner
Manager, Renewable Energy Programs
Idaho Nat'l Engineering Lab.
PO Box 1625
Idaho Falls, ID 83415

Richard Thomas
Geothermal Officer
Calif. Div of Oil & Gas
1416 Ninth St, Room 1310
Sacramento, CA 95814

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