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PRODUCTION/INJECTION CHARACTERISTICS OF SLIM HOLES AND LARGE-DIAMETER WELLS AT THE SUMIKAWA GEOTHERMAL FIELD, JAPAN

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ABSTRACT

Production and injection data from slim holes and large-diameter wells at the Sumikawa Geothermal Field, Japan, were analyzed to determine the effect of wellbore diameter on (1) the productivity/injectivity indices, and (2) on the discharge rate. The injectivity indices for Sumikawa boreholes do not depend on borehole diameter in any systematic manner; furthermore, the productivity indices (for boreholes with liquid feeds) are more or less equal to the injectivity indices. For boreholes with liquid feed zones, discharge rates scale with diameter according to a relationship previously presented by Pritchett. Pritchett's scaling rule does not appear to apply to discharge data from boreholes with two-phase feed zones; however, discharge characteristics of slim holes with two-phase feed zones can be used to infer production rates from large-diameter two-phase geothermal wells.

1. INTRODUCTION

Under its drilling research program, 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 behavior of large-diameter wells (Combs and Dunn, 1992). DOE/Sandia plan to drill and test pairs of small-diameter slim holes with large-diameter production wells in several geothermal fields in the western United States; the first of these tests was completed in mid-1993 at the Steamboat Hills Geothermal Field, Nevada (Finger, *et al.*, 1994). In addition, DOE/Sandia are supporting the examination of existing Japanese data on the use of slim holes in geothermal exploration and reservoir assessment; in the first of these studies, Garg, *et al.* (1994) analyzed production and injection data from the Oguni Geothermal Field, Japan. In this paper, we examine the existing production and injection flow test data for both small-diameter slim holes and large-diameter production wells at the Sumikawa Geothermal Field.

A brief overview of the Sumikawa Geothermal Field is presented in Section 2. This section also gives the feedzone location, temperature, and pressure for eighteen Sumikawa boreholes for which some production or injection data are available. Injection and production data from both slim holes and large-diameter production wells are analyzed in Section 3 to determine injectivity/productivity indices. In Section 4, the injectivity/productivity indices for Sumikawa boreholes are compared with those for the Oguni Geothermal Field boreholes. The variation of discharge rate with borehole diameter is discussed in Section 5.

2. SUMIKAWA GEOTHERMAL FIELD

The Sumikawa Geothermal Field is located in the Hachimantai volcanic area in northern Honshu, Japan, about 1.5 kilometers to the west of Ohnuma geothermal power station operated by Mitsubishi Materials Corporation (MMC). The Hachimantai area also includes the Matsukawa and Kakkonda Geothermal Fields. An extensive well drilling and testing program was initiated in October 1981 with the spudding of boreholes S-1 and S-2 by MMC and the Mitsubishi Gas Chemical Corporation (MGC). The New Energy and Industrial Technology Development Organization (NEDO) became involved in the field characterization effort with the drilling of borehole N59-SN-5 (~ 2 km west of S-1 and S-2) in 1984–1985. The field exploration and characterization program at Sumikawa was successfully concluded in 1990 with a decision to build a 50 MWe power plant. The Sumikawa geothermal power plant is expected to be commissioned some time in 1995.

The Sumikawa/Ohnuma geothermal area is shown in Figure 1. The Sumikawa Geothermal Field lies in the western part of the area. Mt. Yake lies to the southwest of the Sumikawa area, and Mt. Hachimantai is just to the southeast (outside the area illustrated in Figure 1). Between the Sumikawa prospect (which may be regarded as centered in the neighborhood of the S-series boreholes, S-1, S-2, S-3, and S-4) and the Ohnuma borefield is a north-south region of relatively low ground surface elevation where natural hot springs and fumaroles are found. The Sumikawa/Ohnuma area lies within a north-south oriented regional graben structure which extends many kilometers both north and south of the Sumikawa area. Indeed, the Sumikawa field itself appears to be located along the western edge of the graben.

An east-west cross section corresponding to line A-A′ is depicted in Figure 2. Extensive faulting has rendered the detailed geological structure at Sumikawa somewhat obscure, but the abundance of drilling logs from the various boreholes in the area has revealed the following geological sequence: (1) *ST formation*—Surficial andesitic tuffs, lavas, and pyroclastics of recent origin (from Mt. Yake); (2) *LS formation*—Lake sediments, Pleistocene tuffs, sandstones, siltstones, and mudstones; (3) *DA formation*—Pliocene dacites, dacitic tuffs, and breccias, (4) *MV formation*—"Marine/volcanic complex" containing interbedded Miocene dacitic volcanic rocks and "black-shale" oxygen-poor marine shales and sediments; (5) *AA formation*—Altered andesitic rocks that apparently are extensively fractured, and (6) *BA formation*—

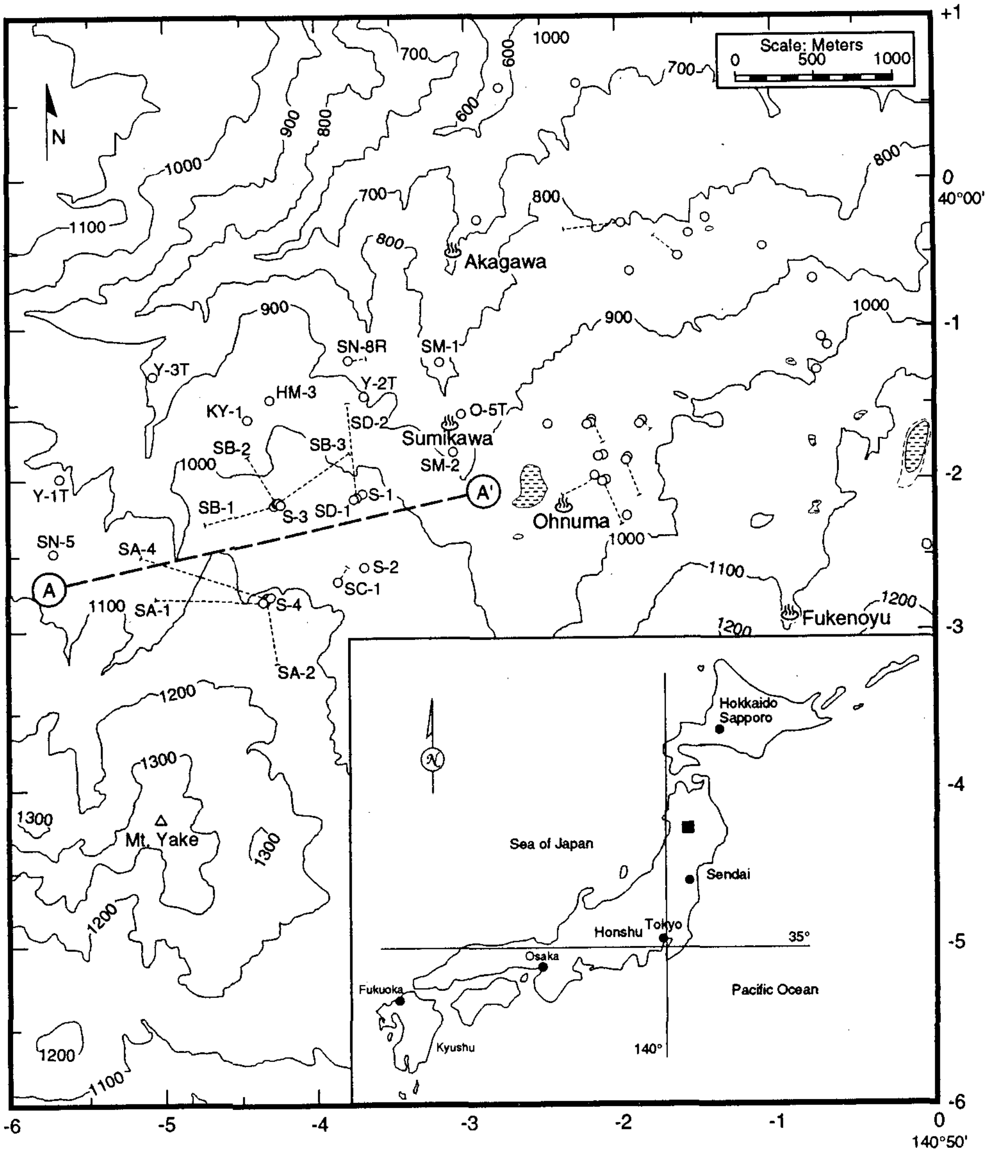


Figure 1. The Sumikawa/Ohnuma area, showing locations of wells and cross-section A–A′. The origin of the local co-ordinate system is 40°N latitude and 140°50′E longitude. The inset map of Japan shows the location of the Sumikawa/Ohnuma Area (dark retangle).

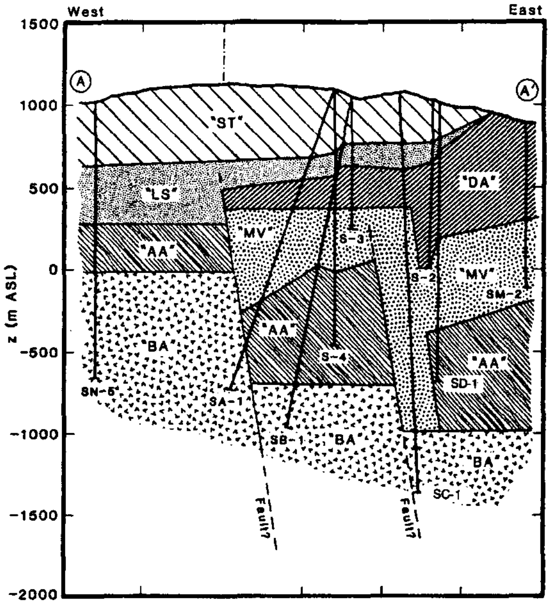


Figure 2. East-west A–A′ (total length = 3 km) geological cross-section through the Sumikawa area.

Crystalline rocks (mainly granodiorite and diorite). The BA formation is the deepest so far encountered by drilling (well SC-1 bottomed in this formation at 2486 m depth), but the pre-Tertiary basement, which presumably underlies the above sequence, has not yet been reached.

At Sumikawa, underground temperatures are highest to the south and decline to the north and northwest. The estimated temperatures at sea level (~700–1100 m depth) in the area (based mainly on temperature surveys in shut-in boreholes) are shown in Figure 3. The highest temperature so far measured in the field is at the bottom of well SA-2 (320°C at 840 m below sea level); this is also the southernmost deep borehole at Sumikawa. Temperatures are significantly higher at Sumikawa (near the S-series boreholes) than at the nearby operating Ohnuma borefield. On the whole, temperatures appear to increase monotonically with depth; large-scale temperature inversions (with the exception of well SC-1) are not observed.

Pritchett, *et al.* (1990) have examined the various downhole feedpoint pressure determinations available from boreholes in the Sumikawa/Ohnuma area in detail. The reservoir pressures are surprisingly uniform throughout the area; apart from a small region immediately adjacent to the Ohnuma power station, deep shut-in pressures may be determined from the empirical correlation

$$P(\text{bars}) = 61.170 - 79.985\,Z - 6.492\,Z^2$$

where Z is elevation, measured in kilometers with respect to sea level (km ASL). The pressure data from several boreholes in the Ohnuma borefield (0-1R, 0-2R, 0-3R-a, 0-3R-b), obtained prior to the startup of Ohnuma power plant, are also in good agreement with the deep correlation obtained above (see Figure 4). The Ohnuma geothermal power plant started producing electric power in 1973. The sparse pressure data available for the Ohnuma boreholes suggest that the pressures at Ohnuma have fallen by several bars during the last 20 years. Since the pressure measurements upon which the deep pressure correlation is based were made between 1968 and 1988 (average date = 1980), it is apparent that any pressure disturbance induced by operations associated with the Ohnuma power station must be of limited areal extent.

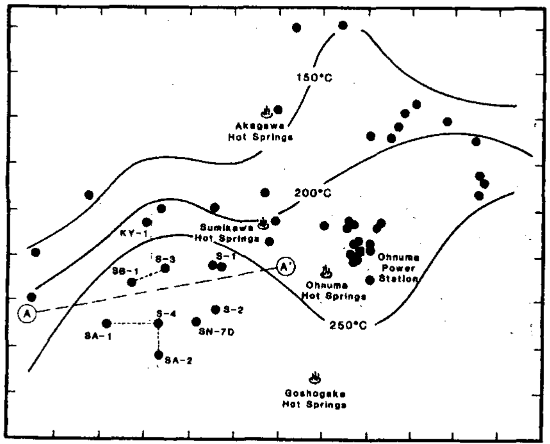


Figure 3. Temperatures at sea-level elevation in the Sumikawa/Ohnuma area (adapted from Kubota 1988).

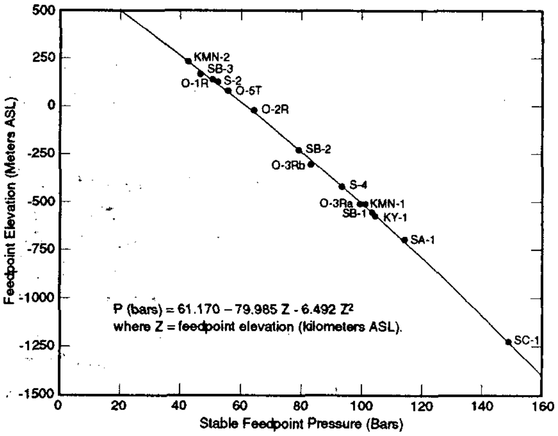


Figure 4. Selected deep feedpoint pressures and algebraic fit. (from Pritchett, *et al.* 1990).

Samples collected from discharging Sumikawa boreholes indicate that the reservoir fluid is of low salinity (<3000 ppm) and that the noncondensible gas content is very low (typically < 0.1 percent by volume of the steam). The reservoir fluids are mainly of the Na-Cl type with a near neutral pH.

It is virtually certain that a two-phase (water and steam) flow region is present in the southern part of the reservoir system at depth, extending from the lower part of the lake sediment layer (600 m ASL to 800 m ASL) down to a considerable depth. Slim hole S-1 (feedpoint elevation ~ 580 m ASL) discharged nothing but dry steam. Furthermore, it appears that the two-phase region in the neighborhood of slim hole S-3 extends at least as deep as +400 m ASL. Since temperatures generally increase to the south in the Sumikawa area, it would appear that the depth of the bottom of the two-phase zone will likewise increase to the south.

The vertical permeabilities at Sumikawa are small in comparison with horizontal permeabilities. Permeability in the field is due primarily to the pervasive network of fractures. Both the volcanic and sedimentary country rocks between the fractures appear to be essentially impermeable. The lake sediments are nearly impermeable and act as a caprock for the underlying geothermal reservoirs. Pressure transient tests have been interpreted (see *e.g.*, Pritchett, *et al.*, 1990; Garg, *et al.*, 1991) to imply the presence of two high-transmissivity geothermal aquifers within the "altered andesite" and the deeper "granodiorite" formations. The shallower of these two reservoirs (in the andesite formation) is usually encountered between 1000 and 1800 meters depth, and has been penetrated by several wells. At present, only well SC-1 produces a substantial quantity of hot fluid from a permeable horizon in the "granodiorite" formation. Pressure interference data have also been used to confirm the presence of a moderately transmissive layer in the "marine-volcanic complex" formation. Because of its low vertical permeability, the "marine-volcanic complex" formation will be used for injecting waste brine.

As of early-1990, MMC and NEDO had drilled and tested thirteen slim holes (diameter ≤ 15 cm) and eleven large-diameter (diameter > 15 cm) wells. With the exception of four slim holes (0-3T, Y-1T, Y-2T, and Y-3T) and two large-diameter wells (SD-2, SN-8R), some injection and/or production data are available for all of the Sumikawa boreholes. The authors have analyzed drilling data (circulation losses, well completion and geologic data) and downhole PTS (*i.e.*, pressure/temperature/spinner) surveys for the eighteen boreholes for which some production and/or injection data are available. The feedzone depth, final borehole diameter and feedzone temperature are listed in Table 1.

Table 1. Sumikawa boreholes with production or injection data

Borehole Name	Measured Depth (meters)	Vertical Depth (m TVD)	Feedzone Depth (m TVD)	Final Diameter (mm)	Feedzone Temperature (°C)	Production/ Injection Data
50-HM-3	501	501	460?	79	—	I
N60-KY-1	1604	1604	1560	101	205	I
O-5T	749	749	747?	64	>210	I
S-1	448	448	436	143	—	P,I
S-2*	905	905	900	101	>225	P,I
S-2	1065	1065	940	101	240	P,I
S-3	805	805	700	101	240	P,I
S-4	1552	1552	1520	159	295	P,I
SA-1	2001	1832	1800	216	305	P,I
SA-2	2005	1943	1450	216	≥300	P,I
SA-4	2009	1739	1240	216	≥290	P,I
SB-1	2086	2006	1600	216	>260	P,I
SB-2	1384	1308	1270	216	~250	I
SB-3	1542	1366	880	216	~210	I
SC-1	2486	2472	2310	216	246	P,I
SD-1	1704	1691	1550	216	250	P,I
52E-SM-1	1003	1003	730?	79	—	I
52E-SM-2*	803	803	550	101	>170	P,I
52E-SM-2	1001	1001	980	79	>230	P
N59-SN-5	1701	1701	1600	101	>260	I

*Partially-drilled hole

3. INJECTION AND PRODUCTION TESTS

Injection tests have been performed on eighteen Sumikawa boreholes. It is a standard practice at Sumikawa to perform a short (a few hours) injection test soon after (usually within a few days) the drilling and completion of a borehole. In an effort to improve the productivity and injectivity of wells SA-1, SA-2, SA-4, S-4, SB-1, SB-2 and SB-3, MMC injected large amounts of cold river water in these wells in April and May 1989; step-rate injection tests were performed (with downhole pressure gauges) both prior to (wells SA-1, SA-2, and SA-4 only) and subsequent to (all seven wells) the river water injection. A typical injection test at Sumikawa consists of injecting cold water into a borehole at several different rates and simultaneously monitoring pressure (and temperature) downhole. While exceptions do exist, in most of the tests, the pressure tool was placed substantially above the feedzone depth. Because of wellbore cooling, the measured change in pressure at the gauge depth (gauge depth << feedzone depth) will underestimate the change in pressure at the feedzone depth. The discrepancy in rates of change at the gauge and feedzone depths will decline with continued injection. After the injection of a few wellbore volumes (say 2 or 3), the rates of pressure change at the two depths should be similar. Since in most of the Sumikawa injection tests several wellbore volumes of cold water were injected, the measured pressures can be used to infer the injectivity index (II). The injectivity index (II) is defined as follows:

$$II = \frac{\Delta M}{\Delta P}$$

Here $\Delta M/\Delta P$ is the slope of the straight-line fit to the multi-step injection rate versus injection pressure (at gauge depth) data.

Measurements taken during a typical Sumikawa injection test are shown in Figure 5. Well SC-1 was injection tested on November 15, 1987 soon after well drilling and completion. The pressure gauge in this test was set fairly close to the principal feedzone at 2310 m TVD; the slope of the straight line in Figure 5 implies an injectivity index of 5.5 kg/s-bar. The available injectivity data for the various Sumikawa boreholes are summarized in Table 2.

A total of eleven Sumikawa boreholes (slim holes S-1, S-2, S-3, and 52E-SM-2; production wells S-4, SA-1, SA-2, SA-4, SB-1 and SC-1; injection well SD-1) have been discharged at one time or another. In addition, two partially-drilled slim holes (S-2 and 52E-SM-2) were discharged for brief periods. The discharge test data are needed to define the characteristic output curves (*i.e.*, mass and enthalpy versus wellhead pressure). Wellhead enthalpy measurements suggest that slim holes S-2 (final completion), S-3 and 52E-SM-2 (final completion), and production wells SB-1 and SC-1 produce from

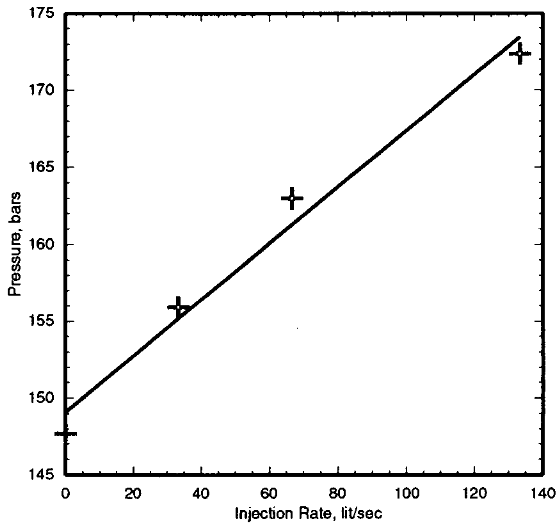


Figure 5. Injectivity test for production well SC-1 performed on November 15, 1987. The pressure gauge was set at 2300 m MD (2290 m TVD).

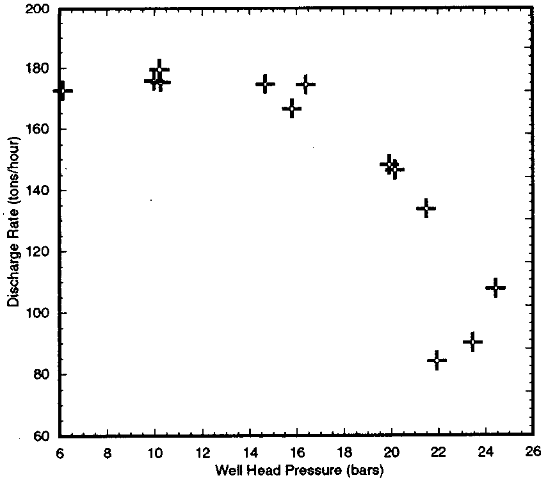
Table 2. Injectivity indices for Sumikawa boreholes.

Borehole Name	Final Diameter (mm)	Feedzone Depth (m TVD)	Test Date	Pressure Gauge Depth (m TVD)	Injectivity Index (kg/s-bar)	Remarks
50-HM-3	79	460	12-02-75	0	0.016	After well completion
N60-KY-1	101	1560	08-07-86	1177	0.012	After well completion
O-5T	64	747	09-22-78	280	0.28	
S-1	143	436	05-20-82	250	1.3	Injection into a shallow horizon (70–100 meters) through a casing break
			05-26-82	300	6.8	
S-2	101	900	06-23-82	400	0.76	Partially-drilled, hole depth = 904.6 m
		900	07-16-82	500	0.76	Partially-drilled, hole depth = 904.6 m
		?	10-04-82	450	0.52	Partially-drilled, hole depth = ?
		940	10-16-82	500	1.62	After well completion
		940	10-23-82	500	1.76	After well completion
S-3	101	?	09-02-82	400	0.79	Partially-drilled, hole depth = 603 m?
		?	10-06-82	300	0.43	Partially-drilled, hole depth = 603 m?
		?	05-16-83	600	0.25	Partially-drilled, hole depth = 656 m
		700	06-12-83	600	1.4	After well completion
S-4	159	1520	11-06-83	700	1.4	After well completion
			11-07-83	700	1.4	After well completion
			05-19-89	700	4.9	After 1989 injection
SA-1	216	1800	10-11-86	1057	1.5	After well completion
			04-16-89	1726	0.90	Before 1989 injection
			05-16-89	1726	2.0	After 1989 injection
SA-2	216	1450	09-22-87	968	1.0	After well completion
			09-22-87	968	1.2	After well completion
			04-16-89	1062	1.3	Before 1989 injection
			05-17-89	1061	1.7	After 1989 injection
SA-4	216	1240	05-30-88	1127	0.31	After well completion
			04-17-89	1262	0.88	Before 1989 injection
			05-18-89	1262	1.0	After 1989 injection
SB-1	216	1600	10-25-87	0	0.98	After well completion
			10-26-87	0	1.5	After well completion
			11-08-87	965	0.37	After well completion
			05-27-88	965	0.49	
			08-15-88	1665	0.44	
			05-28-89	1626	2.0	After 1989 injection
SB-2	216	1270	06-22-88	674	1.8	After well completion
			05-29-89	684	1.6	After 1989 injection
SB-3	216	880	08-05-88	678	0.41	After well completion
			05-30-89	678	1.5	After 1989 injection
SC-1	216	2310	11-15-87	2290	5.5	After well completion
			06-07-88	2329	4.9	
SD-1	216	?	09-04-86	387	2.7	Partially-drilled; hole depth = 396 m
		1550	10-12-86	700	0.65	After well completion
		1550	10-17-86	799	0.92	After well completion
52E-SM-1	79	730	09-30-78	0	0.002	After well completion
52E-SM-2	101	550	08-26-78	0	0.068	Partially-drilled; hole depth = 803 m
N59-SN-5	101	1600	11-12-85	0	0.068	After well completion

Notes: 1. After well completion ≡ within 1 month of drilling and well completion.
2. 1989 injection test: cold river water was injected into SA-1, SA-2, SA-4, S-4, SB-1, SB-2 and SB-3 during April and May 1989.

all liquid feedzones with little or no *in situ* boiling. Production from all the other Sumikawa boreholes is accompanied by *in situ* boiling. Slim hole S-1 and production wells SA-2 and SA-4 discharge only steam. A typical mass output curve for a Sumikawa borehole is shown in Figure 6. Interestingly, production from partially-drilled slim holes S-2 and 52E-SM-2 causes *in situ* boiling; final completions of these slim holes discharge fluid with an enthalpy equal to that of liquid water in the reservoir. In an attempt to stimulate well productivity, cold river water was injected into wells S-4, SA-1, SA-2, SA-4 and SB-1 in April and May 1989. Cold water injection was ineffective in raising the productivity of wells S-4 and SA-2. Production from well SA-1 nearly doubled and that from SA-4 increased by about 25 percent. In as much as SB-1 was not discharged prior to cold river water injection, it is impossible to evaluate the efficacy of cold water injection for this well.

Figure 6. Discharge rate versus wellhead pressure for production well S-4 (1984, 1985, 1986, and 1988).



The measured maximum mass discharge rates for the various Sumikawa boreholes are presented in Table 3. It is apparent from Table 3 that the maximum discharge for Sumikawa production wells varies over a wide range (from 28 tons/hour for SA-2 to 490 tons/hour for SC-1). Even for wells with liquid feeds and/or wells with limited *in situ* boiling, the discharge rate varies widely (from < 100 tons/hour for SD-1 to 490 tons/hour for SC-1). This large variation in discharge rates underscores the heterogeneous character of formation permeability at Sumikawa.

Table 3. Measured and predicted discharge rates for Sumikawa boreholes.

Borehole Name	Final Diameter (mm)	Measured Discharge Rate (tons/hour)	Area-Scaled Discharge* (tons/hour)	Scaled Maximum Discharge** (tons/hour)	Remarks
(A) Boreholes with liquid feeds and no *in situ* boiling					
52-E-SM-2	79	27	202	355	Final completion
S-2	101	52	238	364	Final completion
S-3	101	16	73	112	
SB-1	216	105			
SC-1	216	490			
(B) Boreholes with limited *in situ* boiling					
S-4	159	180	332	394	
SD-1	216	100			
(C) Boreholes with extensive *in situ* boiling					
52E-SM-2	101	5.1	23	36	Partially-drilled
S-2	101	4.1	19	29	Partially-drilled
S-1	143	35	80	101	
SA-1	216	62			
SA-2	216	28			
SA-4	216	30			

* Area Scaled Discharge Rate = Measured Discharge Rate × $(216/\text{well dia. in mm})^2$

** Scaled Maximum Discharge Rate = Measured Discharge Rate × $(216/\text{well dia. in mm})^{2.56}$

During the discharge tests of seven boreholes (slim hole S-2, partially-drilled slim hole S-2, large-diameter wells S-4, SA-1, SA-4, SC-1 and SD-1), pressure and temperature (or pressure, temperature and spinner) surveys were run. These pressure/temperature surveys were used to calculate the productivity indices for the Sumikawa boreholes. Productivity index, PI, is defined as follows:

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

where M is the mass discharge rate, P_{ns} is the stable (static) feedzone (or gauge depth) pressure, and P_{fp} is the flowing feedzone (or gauge depth) pressure. The static feedzone (or gauge depth) pressure was estimated from shutin pressure surveys. The pressure surveys in the discharging boreholes were used to obtain the flowing pressures.

As an example, consider production well SC-1. The well produces liquid water from several feedzones between 1950 m MD (temperature = 307°C) and 2320 m MD (temperature = 246°C). Over 60 percent of the production is derived from the feedzone at 2320 m MD (2310 m TVD). The stable pressure at 2310 m TVD is 149.0 bars. During a discharge test in November 1988, three downhole pressure/temperature/spinner surveys were run. Using the flowing pressures measured in the latter surveys, the productivity index for SC-1 is estimated to be 5.7 (±0.5) kg/s-bar. The productivity indices for individual Sumikawa wells are summarized in Table 4.

4. COMPARISON OF PRODUCTIVITY AND INJECTIVITY INDICES

Apart from transient effects associated with the initiation of production (or injection) from a borehole, the flow resistance (*i.e.*, pressure losses) of the reservoir rocks can be represented by the productivity (or injectivity) index. Injectivity indices are available for eighteen Sumikawa boreholes (see Table 2). Five of the boreholes listed in Table 2 (50-HM-3, O-5T, 52E-SM-1, 52E-SM-2, and N59-SN-5) are located outside the permeable zone of the Sumikawa field. Slim hole N60-KY-1 within the

Table 4. Productivity indices for Sumikawa boreholes.

Borehole Name	Final Diameter (mm)	Feedzone Depth (m TVD)	Test Date	Total Flow Rate (kg/s)	Static Pressure (bars)	Flowing Pressure (bars)	Productivity Index kg/s-bar)	Remarks
S-1	143	436	04-25-82 04-27-82 04-30-82	—	—	—	0.86	Produced dry-steam. PI estimated from mass flow rate and wellhead pressure (see text).
S-2	101	900	07-11-82	1.10	47.3*	7.26	0.027	Partially-drilled, hole depth = 904.6 m Two-phase feed
	101	940	11-10-82	13.4	51.0	40.5	1.3	Liquid feed
S-4	159	1520	10-04-84 10-31-84 10-12-85	37.5 39.1 35.1	93.0	51.3 49.4 58.2	0.90 0.90 1.01	Two-phase feed. Flowing pressure extrapolated from pressure surveys to 1050, 1050 and 1070 meters depth (see text).
SA-1	216	1800	09-21-89 09-22-89	13.6 13.7	114.0	26.5 34.6	0.16 0.17	Well produces mostly steam Two-Phase feed
SA-4	216	1240	09-23-89	8.06	81.0	10.8	0.11	Well produces dry steam from a two-phase feed
SC-1	216	2310	11-04-88 11-06-88 11-07-88	48.1 55.2 86.1	149.0	139.7 140.1 133.6	5.2 6.2 5.6	Liquid feeds (several entries)
SD-1	216	1200 (middle of permeable interval)	09-18-89 09-19-89	23.5 17.4	77.0	23.8 47.0	0.44 0.58	Several entries. Shallowest (800–900 m) two-phase; deeper entries liquid.

*Estimated from a fit to feedzone pressures for Sumikawa wells

Sumikawa field displays excellent pressure communication with several Sumikawa wells (S-4, SB-1, and SB-2); this slim hole has, however, very limited injectivity (see Table 2). Slim hole N60-KY-1 was injection tested only once (shortly after drilling); it is likely that the permeable fractures at the time of the test were laden with drilling mud and/or rock flour. In the following discussion, we will not further consider injectivity data for the aforementioned six boreholes. Of the remaining twelve boreholes (S-1, S-2, S-3, S-4, SA-1, SA-2, SA-4, SB-1, SB-2, SB-3, SC-1, SD-1), productivity indices (Table 4) are available for seven boreholes (S-1, S-2, S-4, SA-1, SA-4, SC-1, SD-1). The productivity and injectivity indices for the latter seven boreholes are compared in Table 5.

Table 5. Comparison of productivity and injectivity indices for Sumikawa boreholes.

Borehole Name	Final Diameter (mm)	Feedzone Depth (m TVD)	Injectvity Index (kg/s-bar)	Productivity Index (kg/s-bar)	Remarks
S-1	143	436	1.3–6.8	0.86	Borehole produces dry steam. Injection and production depths are different.
S-2	101	900	0.76	0.027	Partially-drilled, hole depth = 904.6 m. *In situ* boiling on discharge.
	101	940	1.7	1.3	Liquid feed.
S-4	159	1520	1.4	0.94	*In situ* boiling on discharge; 1983 Injectivity Index
SA-1	216	1800	1.5	0.16	*In situ* boiling on discharge; 1989 Injectivity Index
SA-4	216	1240	0.94	0.11	1989 Injectivity Index; *in situ* boiling on discharge.
SC-1	216	2310	5.2	5.7	Liquid feeds.
SD-1	216	1200 (middle of permeable interval)	0.78	0.51	Shallowest feedzone two-phase; deeper feeds liquiid.

The injectivity indices for ten of the twelve boreholes (the two exceptions are S-1 and SC-1) are all of the order of unity. Injectivity index for SC-1 is significantly larger than that for other Sumikawa boreholes. Apparently, the injected fluid in S-1 enters the formation through a casing break at 70–100 meters; thus the injectivity index for S-1 is not representative of conditions at depth. The injectivity indices for Sumikawa boreholes do not depend in any systematic manner on the borehole diameter. This result is in agreement with theoretical results of Pritchett (1993) and of Hadgu, *et al.*, (1994). Both of these authors have suggested that apart from any differences associated with differences in wellbore skin (*i.e.*, near wellbore formation damage or stimulation), the productivity (or injectivity) should exhibit only a weak dependence on borehole diameter. The Sumikawa results are, however, at variance with results for the Oguni Geothermal Field (Garg, *et al.*, 1994). Both the productivity and injectivity indices for the Oguni wells display a strong dependence on borehole diameter. We suggest that the difference between the Oguni and Sumikawa results is due to the differences in drilling practice at the two fields. At Oguni, most of the slim holes were drilled with a complete loss of circulation; the drilling mud and/or rock flour apparently plugged some of the permeable fractures. In the case of Sumikawa slim holes, no blind drilling was necessary. Rotary drilling—employed to drill large-diameter holes in both the Sumikawa and Oguni Geothermal Fields—is rarely carried out with complete loss of circulation. Thus, it is likely that formation plugging is responsible for the apparent variation of productivity/injectivity indices with diameter at Oguni; apparently, formation plugging does not vary with diameter at Sumikawa. Data from other geothermal fields should be examined to determine the frequency of the occurrence of excess formation plugging with core drilling.

The injectivity indices for Sumikawa boreholes (~0(1)) are significantly smaller than productivity/injectivity indices for Oguni production wells (productivity indices for Oguni wells range from 4 kg/s-bar to 15 kg/s-bar). Liquid conditions prevail at the feedzone depth during production from Sumikawa boreholes S-2 (completed hole only) and SC-1; the productivity indices for these boreholes are more or less the same as the corresponding injectivity indices. The latter conclusions are in accord with results from the Oguni boreholes (Garg, *et al.*, 1994). Production from Sumikawa boreholes other than S-2 (completed hole only) and SC-1 is accompanied by *in situ* boiling. Low formation permeability and high formation temperatures (250°C < T < 320°C) are responsible for *in situ* boiling on discharge. The formation transmissivity for two-phase flow is always smaller than that for liquid flow. For Sumikawa boreholes with *in situ* boiling (S-1, S-4, SA-1, SA-4 and SD-1), the productivity index is, as expected, smaller than the corresponding injectivity index.

5. EFFECT OF BOREHOLE DIAMETER ON DISCHARGE RATE

Discharge characteristics of a geothermal borehole are principally controlled by (1) pressure losses associated with flow in reservoir rocks, and (2) pipe friction and heat losses in the wellbore. At Sumikawa, pressure losses in the reservoir constitute the bulk of pressure losses in boreholes for which discharge is accompanied by *in situ* boiling. Even for boreholes with liquid conditions at the feedzone depth, the pressure loss in the formation exceeds 10 bars (see Table 4 for boreholes S-2 and SC-1). This situation is quite different from that prevailing in the case of the Oguni Geothermal Field. At Oguni, the formation permeability is sufficiently high such that the pressure losses in the reservoir are insignificant compared to pressure losses in the borehole. The discharge behavior of an Oguni borehole is principally determined by pipe friction and heat losses in the wellbore. Pressure losses in the formation cannot, however, be neglected in the case of Sumikawa boreholes.

Pritchett (1993) employed numerical simulation to investigate the fluid-carrying capacity of boreholes of varying size. In the work by Pritchett (1993), the pressure losses in the formation were assumed to be negligible. Furthermore, the feedzone was assumed to contain single-phase liquid. Based on numerical simulations, Pritchett (1993) suggests that the maximum discharge rate $M_{\max}$ will increase at a rate somewhat greater than the square of borehole diameter.

$$M_{\max} = M_o \left(d/d_o \right)^{2+n}, \quad n > 0$$

where M_o is the actual borehole discharge rate, and d and d_o are the internal borehole diameters (mm). The exact value of n will most likely vary with feedzone conditions (depth, pressure, enthalpy, and gas content). For the conditions assumed by Pritchett (depth = 1500 m, pressure 80 bars, single phase liquid at 250°C, uniform borehole diameter), n is approximately equal to 0.56. The conditions assumed in Pritchett's work do not hold for Sumikawa boreholes. There is a need to extend Pritchett's work to investigate the effects of pressure losses in the reservoir and of *in situ* boiling on the flow capacity of geothermal boreholes.

The "area-scaled discharge rate" M^* is defined as follows:

$$M^* = M_o \left(d/d_o \right)^2$$

The "area scaled" and "scaled maximum (n = 0.56)" discharge rates for the Sumikawa slim holes are compared with measured discharge rates from large-diameter Sumikawa production wells in Table 3. The discharge rates for wells SB-1 (liquid feed) and SD-1 (limited boiling) are approximately equal to the scaled maximum discharge rate for slim hole S-3. The discharge rates for wells SB-1, SD-1 and S-3 (scaled maximum discharge rate) are unusually small for wells with liquid feedzones; the discharge rate in this case is limited by low formation permeability and not by pressure losses in the borehole. The scaled maximum discharge rates for slim holes S-2 and 52E-SM-2 (liquid feeds) provide an adequate prediction for discharge from well S-4 (limited *in situ* boiling). The measured discharge rate for well SC-1 (liquid feeds), however, exceeds the scaled maximum discharge rate for slim holes S-2 and 52E-SM-2 by about 25 percent. The maximum discharge (scaled to a nominal 216 mm diameter) rates for Sumikawa boreholes with little or no *in situ* boiling (52E-SM-2, S-2, S-3, SB-1, SC-1, S-4, SD-1) range from 100 tons/hour (well SD-1) to 490 tons/hour (well SC-1). The comparable range for Oguni wells extends from 227 ton/hour (slim hole GH-7) to 488 ton/hour (slim hole GH-8). The upper limit for the discharge rates is about the same for both the Sumikawa and Oguni boreholes. The Sumikawa boreholes do, however, display considerably more variability in discharge rates than the Oguni boreholes. In any event, the above-discussed data for Sumikawa boreholes taken in conjunction with Oguni data (Garg, *et al.*, 1994), imply that the "scaled-maximum discharge rate" provides a reasonable first prediction of the discharge performance of large-diameter geothermal wells (with little or no *in situ* boiling).

The measured maximum discharge rates for Sumikawa boreholes with extensive *in situ* boiling are substantially lower than for boreholes with liquid feedzones. The average scaled maximum discharge rate for slim holes 52E-SM-2, S-2, and S-1 is 55 tons/hour. By comparison, the average measured discharge rate for production wells SA-1, SA-2 and SA-4 is 40 tons/hour. The latter value for discharge rate (40 tons/hour) is not too different from that for Oguni well GH-15 (36 tons/hour). Oguni slim hole HH-2 has a scaled maximum discharge rate of 72 tons/hour. Based upon the available data from Oguni and Sumikawa boreholes (four slim holes, four large-diameter wells) with extensive *in situ* boiling, it appears that the "scaled maximum discharge rate" provides too high a prediction for the discharge rate of large-diameter wells. In all likelihood, the scaling rule ($n = 0.56$) derived for boreholes with liquid feeds and with little or no pressure loss in the formation, is not applicable to boreholes with two-phase feeds. Additional theoretical work is needed to examine the scalability (or lack thereof) of discharge data from slim holes to predict the performance of large-diameter wells.

The Sumikawa and Oguni borehole data (especially for boreholes with liquid feeds) provide support for the premise that the discharge performance of large-diameter production wells may be forecast using production/injection data from slim holes. The utility (and applicability) of any prediction scheme can only be established by examining actual discharge data from a statistically significant number of slim holes and production wells from several geothermal fields. The set of geothermal fields should include both single and two-phase reservoirs. A wide range of permeabilities is also needed to delineate the effect of pressure losses in the reservoir on the discharge performance of boreholes.

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