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DISCHARGE CAPABILITY AND GEOTHERMAL RESERVOIR ASSESSMENT USING DATA FROM SLIM HOLES

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ABSTRACT

Compared to conventional rotary-drilled large-diameter wells, the drilling costs for slim holes are relatively modest. Because of this cost differential, it is desirable to use slim holes for geothermal reservoir assessment. Production and injection data from slim holes and large-diameter wells at five geothermal fields (Oguni, Sumikawa, Takigami, and Kirishima, Japan; Steamboat Hills, U.S.A.) were examined to establish relationships (1) between productivity and injectivity indices, and (2) between discharge capacity of slim holes and large diameter wells. For boreholes with liquid feedzones, the productivity and injectivity indices are more or less equal, and the discharge rate of large-diameter wells can be predicted using either production or injection test data from slim holes. Analysis of injection and production data from boreholes for which discharge is accompanied by *in situ* boiling indicates that productivity index is about an order of magnitude smaller than the injectivity index. A wellbore simulator (WELBOR) was employed to investigate the effect of borehole diameter on the discharge capacity of boreholes with *in situ* boiling. Preliminary results imply that the discharge data from slim holes together with a wellbore simulator can be used to estimate the discharge capacity of large-diameter wells with two-phase feedzones.

1. INTRODUCTION

The utilization of slim holes in the exploration for and assessment of geothermal resources can drastically change the economics of a geothermal utilization project by lowering the initial cost associated with the project. A major impediment to the exploration for and assessment of new geothermal resource areas worldwide is the high cost of conventional rotary drilling. A conventional 1500-2000 m deep rotary-drilled geothermal well can cost millions of dollars. Compared to conventional geothermal wells, the drilling costs for slim holes (diameter < 150 mm) can be less than 60% of the total cost of a large-diameter well (Combs and Goranson, 1995). In addition, the success rate for geothermal exploration (wildcat) wells is only 25-40%. Because of the low success rate for geothermal wildcat wells and the aforementioned cost differential, in addition to the reduced environmental impact, it is desirable to use slim holes for geothermal exploration and reservoir assessment (Finger, et al, 1995; 1997).

In order to establish the utility of slim holes for definitive reservoir assessment, it is necessary to be able to predict the discharge characteristics of large-diameter wells based on discharge and/or injection tests on small-diameter boreholes. To compute the probable discharge characteristics of a large-diameter well, a relationship between the injectivity and/or productivity of slim holes and large-diameter production and/or injection wells is required. Since 1992, the U.S. Department of Energy (DOE), through Sandia National Laboratories (Sandia), has sponsored a research effort to demonstrate that slim holes can be used to provide reliable geothermal reservoir parameter estimates and to predict the production behavior of large-diameter wells (Combs and Dunn, 1992). To date, the DOE/Sandia slimhole research program has consisted of two primary elements, the first of which was the examination and analysis of slimhole and large-diameter well data from Japanese fields (Garg et al., 1995a, b; Garg and Combs, 1995; Garg and Combs, 1997; Garg, et al., 1998). The second element consisted of the drilling and testing of slim holes in several geothermal fields in the western U.S. to compare with offset large-diameter production wells. The first of these cost-shared tests, a 1220 m deep slim hole, was completed in mid-1993 at the Steamboat Hills Geothermal Field, Nevada (Finger, et al., 1994; Combs and Goranson, 1995). During 1995, two other deep slim holes were drilled, completed and tested at the Vale, Oregon and Newberry Crater, Oregon, geothermal prospects under the DOE/Sandia slimhole technology program (Finger, et al., 1996; 1997).

Analysis of the discharge and injection test data from both the slim holes and large-diameter production and injection wells performed under the DOE/Sandia slimhole technology program for four Japanese (Oguni, Sumikawa, Takigami, and Kirishima, and one U.S. (Steamboat Hills) geothermal field are summarized and discussed in this paper. Based on examination of production and injection data from these five geothermal fields, it is concluded that the performance of large-diameter geothermal wells with liquid or two-phase feedzones may be forecast using discharge and/or injection data from slim holes with liquid or two-phase feedzones.

2. ANALYSIS OF DOWNHOLE DATA

Garg and Combs (1993) presented a review of the publicly available Japanese data regarding slim holes. Slim holes had been successfully used in Japan 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 and/or discharge tests on small-diameter slim holes. When we initiated the DOE/Sandia sponsored slimhole data analysis project, there did 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 of large-diameter production and/or injection wells. However, based on the available proprietary Japanese and U.S. data that have been obtained and analyzed, we conclude that realistic prediction of discharge characteristics of large-diameter production wells can be made using test data from slim holes.

Both the New Energy and Industrial Technology Organization (NEDO) and the Japanese geothermal operators, have drilled and tested small-diameter coreholes (i.e., slim holes) and large-diameter geothermal wells. We have analyzed the available drilling and testing data from boreholes in four Japanese (Oguni, Sumikawa, Takigami, and Kirishima) and one U.S. (Steamboat Hills) geothermal field which amounts to a total of 159 boreholes, including 68 slim holes and 91 large-diameter wells (see Table 1.)

The drilling data from the boreholes included location, surface elevation, total depth, circulation loss data, borehole completions (e.g., hole sizes, casing sizes and depth intervals, deviation surveys) and geologic data (e.g., stratigraphy, rock type, formation depth intervals). The downhole data after completion of the boreholes and during injection and discharge testing includes PTS (i.e., pressure, temperature and spinner) surveys to obtain feedzone depths, pressures and temperatures.

3. INJECTION TESTS

It is a common practice in Japan to conduct a short term (i.e., a few hours) injection test soon after the drilling and completion of a borehole. The 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 are placed either near or above the principal feedzone. Because of wellbore cooling due to the injection of cold fluid, the measured change in pressure at the gauge depth will underestimate the change in pressure at the feedzone depth; however, the decrepancy will decline with continued injection. After the injection of a few wellbore volumes, the temperature in the depth interval between the gauge and feedzone depths should approach a stable value; hence, the rates of pressure change at the two depths will be similar.

The Injectivity Index (II), calculated from data obtained during the injection tests, is defined as follows:

$$II = M/(P_{flowing} - P_{static})$$

where M is the mass injection rate (single rate test), $P_{flowing}$ is the flowing pressure (at the gauge depth) during cold water injection, and P_{static} is the shut-in pressure at the gauge depth. For multi-rate injection tests, the equation becomes

$$II = \Delta M/\Delta P$$

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

From the data obtained from the four Japanese geothermal fields, injection tests were performed on thirty-nine (39) slim holes and forty-six (46) large-diameter wells (see Table 2). The borehole data from Steamboat Hills provided another four (4) slim holes and four (4) large-diameter wells.

4. DISCHARGE TESTS

A borehole must be discharged to ascertain its productive capacity. During most of the discharge tests, pressure and temperature (or pressure, temperature and spinner) surveys were run. These pressure/temperature surveys were used to calculate the productivity indices for the boreholes. The Productivity Index, PI, is defined as follows:

$$PI = M/(P_{static} - P_{flowing})$$

where M is the discharge (i.e., mass production) rate, P_{static} is the stable (static) feedzone (or gauge depth) pressure, and $P_{flowing}$ is the flowing feedzone (or gauge depth) pressure. For some of the boreholes that were analyzed, multi-rate discharge tests were performed, and pressures were recorded downhole with Kuster gauges or capillary tube type gauges. These pressure data can be used to determine the productivity index as follows:

$$PI = \Delta M/\Delta P$$

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

As part of the discharge tests of the Japanese boreholes, the characteristic output curves (i.e., mass and enthalpy versus wellhead pressure) were also obtained.

From the data obtained from the four Japanese geothermal fields, discharge tests were performed on twenty-nine (29) slim holes and thirty-eight (38) large-diameter wells (see Table 3). The boreholes at Steamboat Hills provided data from another four (4) slim holes and four (4) large-diameter wells.

5. PRODUCTIVITY AND INJECTIVITY INDICES

Discharge capacity of a geothermal borehole is principally determined by pressure losses associated with flow (1) in the reservoir rocks, and (2) in the wellbore. Ignoring pressure transient effects, the flow resistance (i.e., pressure losses) of the reservoir rocks can be represented by the productivity index. Prediction of the mass output of a large-diameter well based on discharge data from a slim hole requires, among other things, a relationship between productivity index and borehole diameter.

Because of the increased importance of frictional and heat losses in small-diameter boreholes, it is often difficult to discharge slim holes. There is, however, no problem with performing injection tests and determining the injectivity index of slim holes. If a relationship can be established between injectivity and productivity indices, then it should be possible to use injection tests on slim holes to predict the probable discharge characteristics of large-diameter wells.

Based on theoretical considerations, Pritchett (1993) and Hadgu, et al. (1994) have suggested that apart from any differences associated with variations 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. With the exception of Oguni boreholes, the productivity and injectivity data indicate that indeed theory does match observed data. Both the productivity and injectivity indices for Oguni boreholes display a systematic dependence on borehole diameter which is most likely due to the interaction of the drilling fluids and the fracture characteristics in the subsurface. Garg, et al. (1995) had ascribed the apparent variation of productivity/injectivity indices with borehole diameter to differences in drilling techniques (i.e., core drilling versus rotary drilling); however, the injectivity and productivity index data for Takigami, Sumikawa, and Kirishima boreholes indicate that core drilling (with complete circulation loss) did not result in any impairment of borehole injectivity/productivity.

Both productivity and injectivity indices were derived for twelve (12) slim holes and fifteen (15) large-diameter wells of the Japanese boreholes that discharge from liquid feedzones. Injectivity and productivity indices for Oguni, Sumikawa, Takigami, and Kirishima boreholes with liquid feedzones are displayed in Figure 1. The injectivity and productivity indices for these boreholes with liquid feedzones are equal to first order. Based upon the amount of data and the four orders of magnitude variation of the injectivity and productivity indices (i.e., from ~0.08 kg/s-bar to ~50 kg/s-bar) displayed in Figure 1, it is reasonable to conclude that, in the absence of discharge testing, the injectivity index may be used to compute the flow resistance of naturally fractured geothermal formations to liquid production.

The data from about seven (7) boreholes (i.e., three (3) slim holes and four (4) large-diameter wells) from the Oguni, Sumikawa, and Kirishima Geothermal Fields are characterized by two-phase feedzones, i.e., in these boreholes there is *in situ* boiling in the geothermal reservoir. The measured maximum discharge rates for boreholes with extensive *in situ* boiling are substantially lower than for boreholes with liquid feedzones. Based on the data obtained to date, the productivity index for a borehole with *in situ* boiling is much smaller that the injectivity index. Because of the relative permeability effects, the flow resistance of reservoir rocks is much greater for two-phase flow than single-phase liquid transport.

The injectivity and productivity index data for the Oguni, Sumikawa, and Kirishima boreholes with two-phase feedzones are exhibited in Figure 2. The data in Figure 2 suggest that the productivity index for two-phase transport is approximately one-tenth of the corresponding injectivity index. Because of the sparseness of the data set, the latter conclusion must be regarded as somewhat tentative. Additional studies are required to draw firm conclusions regarding the relationship between injectivity index and two-phase productivity index. Data from high-temperature geothermal fields spanning a wide range of transmissivities are needed for these studies.

6. MATHEMATICAL MODELING OF FLUID FLOW IN BOREHOLES

To investigate the relationship between the discharge capacity of slim holes and large-diameter wells with liquid or two-phase feedzones, a wellbore simulator may be employed to numerically model the discharge characteristics of boreholes with different diameters. The numerical parameters derived from a fit to actual production data can then be used to investigate the effect of borehole diameter on the discharge rate.

In order to determine the fluid carrying capacity of geothermal boreholes of varying diameters, Pritchett (1993) conducted numerical simulations assuming that (1) boreholes are of uniform size, (2) pressure losses in the formation are negligible, and (3) boreholes produce from a liquid feedzone. Based on these numerical simulations, Pritchett (1993) found that the maximum discharge rate of a borehole increases at a rate somewhat greater that the square of the borehole diameter (i.e., $2 + n$, $n>0$). For the conditions assumed by Pritchett (feedzone depth = 1500 m, pressure = 80 bars, single phase liquid at 250°C, uniform borehole diameter), n is approximately equal to 0.56. In a similar theoretical study, Hadgu, et al. (1994) have considered single-phase (liquid) adiabatic flow (no heat loss) up a wellbore and suggest that n equals 0.62.

Most large-diameter wells at Oguni and at Sumikawa Geothermal Fields are completed with a 9-5/8 inch (internal diameter 224 mm) cemented casing and a 8-1/2 inch (= 216 mm) open hole; however, in some cases, the open hole is lined with a 7 inch uncemented liner. Thus, most Oguni and Sumikawa large-diameter wells have a more or less uniform internal diameter (= 22 cm), and satisfy one of the key assumptions (i.e., uniform wellbore diameter) made by Pritchett (1993) in his theoretical analysis. We have documented that test data from slim holes with liquid feedzones can be used to predict the discharge characteristics of large-diameter "Oguni-Sumikawa type" wells with liquid feedzones (Garg and Combs, 1995; Garg, et al., 1995a).

To model the flow characteristics of boreholes with both uniform and non-uniform diameter, the wellbore computer simulation program WELBOR (Pritchett, 1985) was utilized. The WELBOR code treats the steady flow of water and/or steam up a borehole. The user provides parameters describing the well geometry (inside diameter and angle of deviation with respect to vertical along the hole length), a stable formation temperature distribution with depth, and an "effective thermal conductivity" representing the effects of conductive heat transfer between the fluid in the wellbore and the surrounding rock formation. Values must also be specified for the flowing feedpoint pressure (or alternatively, stable feedpoint pressure and productivity index) and enthalpy (or alternately, temperature for wells producing from a single-phase liquid zone.) For the borehole calculations made in the present studies, the frictional pressure gradient was treated using Dukler's correlation (Dukler, et al., 1964) and a user prescribed roughness factor. The relative slip between the liquid and gas phases was simulated using the Hughmark liquid holdup correlation (Hughmark, 1962).

Given the downhole (usually at feedzone depth) values for mass flow, pressure and temperature, the WELBOR code was used to compute the conditions along the wellbore and at the wellhead (pressure, flowing enthalpy, etc.). The principal parameters that were varied to match the measured conditions in the wellbore and at the wellhead are (1) effective thermal conductivity and (2) interior roughness factor. For both the slim holes and large-diameter production wells, WELBOR was used to match the downhole pressure/temperature profiles and the results of characteristic tests.

To illustrate the computational procedure, it is instructive to consider the large-diameter well TT-7 at the Takigami Geothermal Field. The upper section of TT-7 has the largest diameter (ID = 38.13 cm) of all the Takigami production wells. The large-diameter of the upper section is directly responsible for TT-7 being the most prolific production well at Takigami. To assess the effect of the diameter of the upper section on the discharge behavior of the non-uniform large-diameter production well TT-7, two calculations were made assuming that the inside diameter of the upper section equals (1) 31.79 cm and (2) 22.44 cm. Most of the Takigami production wells are completed with a 31.79 cm upper section. The upper section diameter of 22.44 cm defines the hypothetical "Oguni-Sumikawa type" well (Garg, et al, 1996). The computed discharge characteristics for these two cases are shown in Figure 3. It is apparent from Figure 3 that the discharge rate is a strong function of the upper section diameter of the well. For the 31.79 cm case, the maximum discharge rate is ~338 tons/hour. The maximum discharge rate for the hypothetical "Oguni-Sumikawa type" well is only ~144 tons/hour. By way of contrast, the measured maximum discharge rate for TT-7 is almost 500 tons/hour.

To investigate the relationship between the discharge capacity of slim holes and large-diameter wells with two-phase feedzones, WELBOR was used to numerically model the discharge characteristics of boreholes with different diameters. The numerical parameters derived from a fit to actual production data can then be used to investigate the effect of borehole diameter on the discharge rate. We have modeled boreholes from the Oguni, Sumikawa, and Kirishima Geothermal Fields with two-phase feedzones. For both slim holes and large-diameter wells with two-phase feedzones, WELBOR was used to match the downhole pressure/temperature profiles. The model parameters (roughness factor, holdup parameter) derived from fits to downhole data were then employed to match the results of characteristic tests by varying feedzone pressure and enthalpy. Finally, the discharge characteristics of a "standard" large-diameter well were predicted using model parameters (roughness factor, holdup parameter, productivity index) for slim holes.

Kirishima slim hole KE1-6 discharged a mixture of water and steam with wellhead enthalpies ranging from 937 kJ/kg to 1009 kJ/kg, implying that the discharge from KE1-6 was accompanied by *in situ* boiling. The downhole pressure profile in KE1-6 was simulated (Garg et al, 1998) to obtain a set of model parameters (roughness factor, holdup parameters, productivity index) that would match the measured characteristic discharge data. The downhole pressure profile was matched with a discharge rate of 9.0 tons/hour together with a feedzone pressure of 16.54 bars yielding a productivity index of 0.044 kg/s-bar compared to the value of ~0.05 kg/s-bar obtained from test measurements. With the calculated model parameters from slim hole KE1-6, the maximum discharge rate for a typical large-diameter geothermal well (224 mm ID cased interval, 159 mm ID uncemented liner in 216 mm open hole) was computed to be 14.8 tons/hour. The calculated maximum discharge rate for the large-diameter well with two-phase feedzones is not much greater than that for slim hole KE1-6. Because of the very small productivity index, most of the pressure drop takes place in the formation. Thus, as far as the maximum discharge rate is concerned, the formation (and not the well diameter) is the limiting factor. Increasing the well diameter does not result in a commensurate increase in the discharge rate. Slim hole KE1-6 has a productivity index (~0.05 kg/s-bar) similar to that for large-diameter well KE1-21. The maximum discharge rate for KE1-21 was measured as ~13.5 tons/hour.

7. CONCLUSIONS

Production and injection test data from boreholes with liquid feedzones imply that (1) productivity and injectivity indices are more or less equal, and (2) discharge rate of large-diameter wells with liquid feedzones may be predicted based on test data from slim holes with liquid feedzones. Based on the amount of data and the range of values for the indices from the Oguni, Sumikawa, Takigami, and Kirishima Geothermal Fields, it can be concluded that in the absence of discharge testing, the injectivity index may be used to characterize the flow resistance of naturally fractured geothermal reservoir rocks to liquid production. The productivity/injectivity indices for slim holes provide a lower bound on the corresponding indices for large-diameter wells. Thus, the productivity index (or more importantly, injectivity index in the absence of discharge data) from a slim hole with a liquid feedzone can be used to provide a first estimate of the probable discharge capacity of a large-diameter geothermal production well.

A wellbore simulator, WELBOR, was used to model the discharge characteristics of both slim holes and large-diameter wells at Takigami. The model parameters were used to calculate the probable discharge characteristics of "Oguni-Sumikawa type" wells (Garg, et al., 1996). The predicted average maximum discharge rate (for "Oguni-Sumikawa type" wells) using Takigami slim hole data is identical with that obtained from measurements from large-diameter production wells at Takigami. Thus, the Takigami data from non-uniform diameter wells imply that the discharge characteristics of large-diameter wells with liquid feedzones may be predicted based on test data from slim holes with liquid feedzones.

Modeling of large-diameter Takigami wells also suggests that using large-diameter casing in the two-phase section of a well has a large beneficial effect on the discharge capacity of geothermal wells with liquid feedzones and moderate to good productivity indices. By way of contrast, increasing well diameter in the liquid portion of the well has little influence on the discharge capacity. Additionally, for wells with low productivity indices, the discharge rate is largely independent of well diameter. These results suggest the importance of well design. For optimum production, the well design should include consideration of fluid state (pressure, temperature, gas content, etc.) and formation characteristics (e.g., productivity index).

Analysis of injection and production data from boreholes with two-phase feedzones from the Oguni, Sumikawa, and Kirishima Geothermal Fields indicates that the two-phase productivity index is about an order of magnitude smaller than the injectivity index. Because of the sparseness of the data set, this conclusion should be confirmed by additional data. Simulation of characteristic data from large-diameter wells shows that both the productivity index and feedzone enthalpy undergo changes with variations in feedzone pressure and discharge rate. Lowering the feedzone pressure results in enhanced boiling and hence greater steam phase mobility. The variations in productivity index and feedzone enthalpy are, however, modest (~ 10 percent), and suggest that the productivity index and feedzone enthalpy corresponding to maximum discharge rate (and lowest feedzone pressure) from slim holes should be used to estimate the discharge capacity of large-diameter wells.

For boreholes with poor productivity indices, almost all of the pressure drop takes place in the formation, and increasing borehole diameter has little or no influence on the discharge capacity of the boreholes. The discharge capacity for these boreholes is limited by the formation characteristics, and not by the borehole diameter. From the data analyzed to date, it appears that a productivity index of the order of 0.3 kg/s-bar is needed to obtain economically significant discharge rates from a geothermal well. Data from slim hole KE1-6 and large-diameter well KE1-21 in the Kirishima Geothermal Field suggest that barring variations in the productivity index with borehole diameter, it should be possible to deduce the discharge characteristics of large-diameter wells using test data from slim holes with two-phase feedzones.

This latter conclusion must, of course, be confirmed by data from a statistically significant number of boreholes with two-phase feedzones. Additional studies are required to better understand relationships (1) between injectivity index and two-phase productivity index, (2) between borehole diameter and two-phase productivity index, and (3) between well completion (i.e., diameter) and the discharge capacity of boreholes with two-phase feedzones. Data from a set of high-temperature geothermal fields spanning a wide range of transmissivities are needed for these later studies.

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Table 1. Geothermal Borehole Data Sets

Geothermal Field	Number of Slim Holes	Number of Large-Diameter Wells	Total Number of Boreholes
Oguni, Kyushu	15	10	25
Sumikawa, Honshu	15	11	26
Takagami, Kyushu	11	27	38
Kirishima, Kyushu	23	31	54
Steamboat Hills, NV	4	12	16
Totals	**68**	**91**	**159**

Table 2. Geothermal Borehole Injection Test Data

Geothermal Field	Number of Slim Holes	Number of Large-Diameter Wells	Total Number of Boreholes
Oguni, Kyushu	5	10	15
Sumikawa, Honshu	9	9	18
Takagami, Kyushu	7	16	23
Kirishima, Kyushu	18	11	29
Steamboat Hills, NV	4	4	8
Totals	**43**	**50**	**93**

Table 3. Geothermal Borehole Discharge Test Data

Geothermal Field	Number of Slim Holes	Number of Large-Diameter Wells	Total Number of Boreholes
Oguni, Kyushu	8	6	14
Sumikawa, Honshu	4	7	11
Takagami, Kyushu	7	9	16
Kirishima, Kyushu	10	16	26
Steamboat Hills, NV	4	4	8
Totals	**33**	**42**	**75**

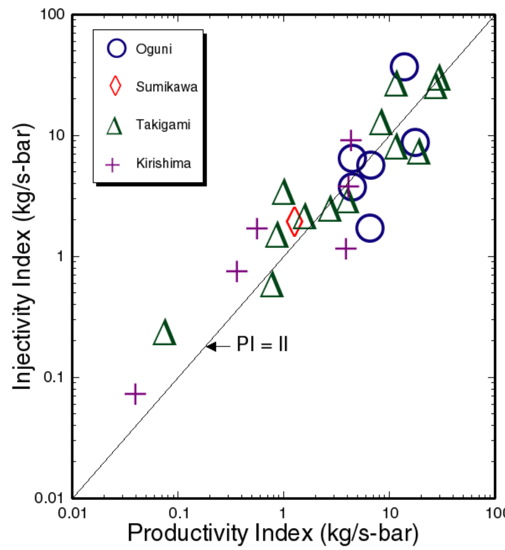

Figure 1. Injectivity Index (II) versus Productivity Index (PI) for Oguni, Sumikawa, Takigami, and Kirishima Boreholes with Liquid Feedzones.

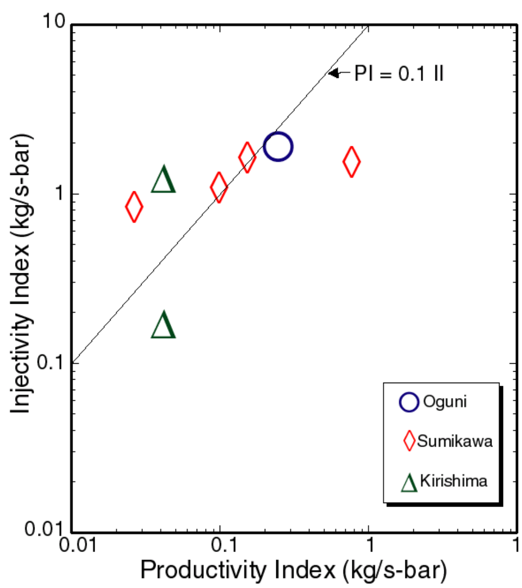

Figure 2. Injectivity Index (II) versus Productivity Index (PI) for Oguni, Sumikawa, and Kirishima Boreholes with Two-Phase Feedzones.

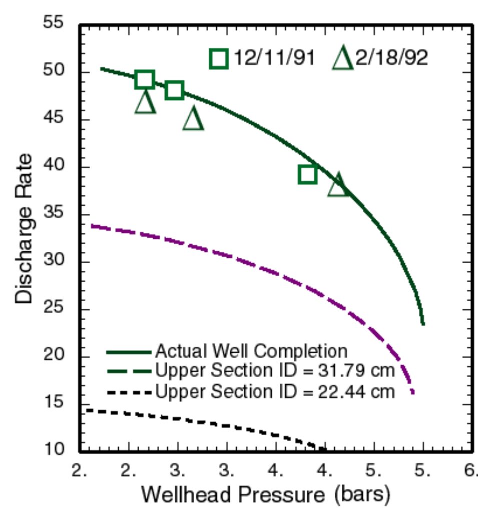

Figure 3. Discharge rate versus wellhead pressure for large-diameter production well TT-7 recorded during the long term production test (November 1991-February 1992). The solid line represents the computed characteristic curve for TT-7. The dashed and dotted lines denote the computed characteristic curves for two hypothetical well completions (see text; adapted from Garg, et al., 1996).