Proceedings World Geothermal Congress 2000
Kyushu - Tohoku, Japan, May 28 - June 10, 2000

OPTIMIZING CASING DESIGNS OF SLIM HOLES FOR MAXIMUM DISCHARGE OF GEOTHERMAL FLUIDS FROM LIQUID FEEDZONES

Sabodh K. Garg[1], Jim Combs[2] and Billie Joe Livesay[3]

[1]Maxwell Technologies, Inc., 8888 Balboa Avenue, San Diego, California 92123, U.S.A.
[2]Geo Hills Associates, 2395 Catamaran Drive, Reno, Nevada 89509, U.S.A.
[3]Livesay Consultants, Inc., 126 Countrywood Lane, Encinitas, California 92024, U.S.A.

Key Words: Slim Holes, Liquid Feedzones, Casing Design, Off-Grid Geothermal Power Plants, Production Capacity

ABSTRACT

Because of their portability, low cost, and limited environmental impact, it is desirable to use diamond-bit coring (or small hybrid) rigs for drilling boreholes to supply geothermal fluid for small off-grid geothermal power plants. To-date, coring rigs have been principally used for drilling slim holes for geothermal exploration and reservoir assessment. Since these slim holes were not intended to serve as long-term production wells, little attention has been paid to optimizing casing design for obtaining maximum discharge of geothermal fluids. For example, many existing slim holes are completed with a 114 mm casing (~100 mm ID) and a 100 mm open hole (or 80 mm slotted liner in 100 mm open hole) below the cased interval. The latter design restricts the maximum discharge rate from boreholes with liquid feedzones to about 10 kg/s (~36 tons/hour). In this paper, alternate completion schemes for slim holes drilled by coring (or hybrid) rigs are examined. It is shown that with proper casing design, the discharge capacity of slim holes can be increased by as much as 200%.

1. INTRODUCTION

Approximately 2 billion inhabitants of the world do not have access to electricity and another 2 billion are underserved (Flavin and Dunn, 1999). Most of these people live in rural areas that are not connected to the national power grids. Because of the high cost of connecting remote areas to national power grids, a decentralized renewable-based electrical system may be advantageous for providing electrical needs of rural masses. In many areas of the world, for example in the countries around the Pacific Ocean, the so-called Ring of Fire, there exist considerable opportunities for the discovery and utilization of indigenous geothermal resources. Until recently, the common perception was that geothermally-generated electricity involved relatively large electrical power plants. Conventional geothermal power plants range in size from 10 MWe to 220 MWe (Combs et al., 1997). There is however a significant potential market for much smaller geothermal power generation units in the 100 kWe to 1 MWe capacity range. Such small geothermal generators have considerable potential for off-grid and village power applications.

The potential off-grid markets for geothermally-generated electricity present several challenges for geothermal developers. A key to the success of small-scale power generation is not to build a plant of oversized capacity compared to demand (Esaki, 1998). Also, it is critical to reduce exploration and wellfield development costs to a minimum. Since a conventional rotary-drilled geothermal well in a remote location can cost millions of dollars, it is likely that the costs of drilling and completing a typical large-diameter production well will dominate the economics of small (100 kWe to 1 MWe) geothermal power projects. If a slim hole, drilled by a minerals style diamond-bit coring or a small hybrid rig, could be used instead, substantial savings in drilling costs and hence a lower electricity price would be realized. Slimhole drilling costs are typically only a fraction of large-diameter rotary drilled wells (Finger, 1998; Goranson, 1998). The relative portability of the small rigs used to drill slim holes should prove economically advantageous in remote locations. Furthermore, the environmental impact and land-use requirements of the minerals style slimhole drilling operations are much less than for conventional rotary drilling.

To-date, wireline-cored and rotary drilled slim holes have been used primarily for geothermal exploration and reservoir assessment in many parts of the world. The Japanese geothermal industry in particular has had extensive experience in the use of slim holes for exploration drilling (Kato and Kizaki, 1993). Garg and his colleagues (Garg and Combs, 1997; Garg, et al., 1998) have analyzed discharge and injection data for both slim holes and large-diameter wells from four Japanese (Oguni, Sumikawa, Takigami and Kirishima) fields and one U.S. (Steamboat Hills) geothermal field. For boreholes producing from all-liquid feedzones, the productivity and injectivity indices are more or less equal. With a single exception (the Oguni Geothermal Field, Japan), the productivity and injectivity indices display no correlation with borehole diameter. Thus, the productivity index (or injectivity index in the absence of discharge test 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 (Garg and Combs, 1997). Pritchett (1995, 1998) has theoretically examined the capacity of boreholes with various uniform inside diameters to supply geothermal fluids for electric generation. According to Pritchett, boreholes with uniform inside diameter as small as 75 mm, and sufficient reservoir temperatures, can be used to supply the fuel requirements of a 100 kWe geothermal power plant.

As already mentioned above, most existing slim holes drilled using coring rigs were used for geothermal exploration and reservoir assessment. Since these slim holes were not intended to serve as long-term production wells, little attention was devoted to optimizing casing design for obtaining maximum discharge of geothermal fluids. Many existing slim holes are completed with a 114 mm casing (~100 mm ID) and a 100 mm open hole (or 80 mm slotted liner in 100 mm open hole) below the cased interval. For self flowing boreholes producing from a liquid feedzone, the latter design restricts the maximum discharge rate to less than 10 kg/s (Garg and Combs, 1997). In this paper, alternate completion scenarios for slim holes are examined. We will show that with proper casing design, the discharge capacity of slim holes can be substantially increased.

2. CASING PROGRAM AND DISCHARGE CAPACITY

For purposes of the present discussion, it is assumed that a wireline coring rig (or an equivalent hybrid rig) will be used to drill the production well(s). The wireline coring rigs are by no means limited to drilling HQ (nominally 100 mm diameter hole) and NQ (nominally 78 mm diameter hole) size slim holes. As an example, the Boart-Longyear 602-type coring rig can be used to core a 159 mm diameter hole to about 1000 m. The hole can then be reamed to 219 mm diameter in order to cement in a 165 mm diameter production casing (Magee, 1998). The Japanese are known to have drilled 219 mm diameter holes, using coring rigs, to depths of around 1000 m. Thus, a coring rig may be utilized to drill and complete a borehole with the following casing program:

Rubble guard, 0–50 meters, 355 mm casing cemented in 445 mm hole

Surface casing, 0–300 meters, 244 mm casing cemented in 311 mm hole

Intermediate casing, 0–1000 meters, 165 mm casing cemented in 219 mm hole

Production interval, 1000–1500 meters, 100 mm hole with or without an uncemented liner.

The above casing program is illustrative of what can be done with wireline coring rigs. In the following, several different completion scenarios for the cased part of the hole will be considered. The diameter of the production interval however, has been assumed to be 100 mm in all cases.

The relationship between the discharge capacity and well completion can be most conveniently investigated by numerically simulating the flow through the wellbore. The wellbore computer simulation program WELBOR (Pritchett, 1985) was used to perform all of the numerical simulations in this study. The computer code treats the steady flow of liquid water and/or a two-phase water-steam mixture up a borehole. The user provides parameters describing the well geometry (inside diameter, well deviation), 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. In addition, values must also be specified for the flowing feedpoint pressure (or alternately stable feedpoint pressure and the productivity index) and temperature (or enthalpy for wells producing from a two-phase feedzone). This study is restricted to boreholes producing from liquid feedzones. In all of the cases, the frictional pressure gradient was treated using Dukler’s correlation (Dukler et al., 1964), and the relative slip between the liquid and gas phases was simulated employing the Hughmark liquid holdup correlation (Hughmark, 1962). There exist in the literature numerous empirical correlations for friction factor and liquid holdup. The use of Dukler and Hughmark correlations in the present work should not be construed to imply that the authors necessarily regard these correlations as more accurate than other available correlations.

2.1 Example A

To examine the effect of borehole diameter on the discharge capacity of wells producing from liquid feedzones, Pritchett (1993) carried out theoretical calculations for a variety of uniform inside diameter boreholes ranging from 50 mm to 350 mm. The feedzone depth, pressure, and temperature were assumed to be 1500 m, 80 bars, and 250°C, respectively. In addition, the pressure loss associated with flow in the reservoir rocks was taken to be negligible, which is tantamount to assuming that the productivity index is extremely large. Based on these computations, Pritchett concluded that the maximum discharge capacity scales with borehole diameter according to the relation:

$$M_{max} = M_O \left(\frac{d}{d_O} \right)^{2.56}$$

where M_{max} (M_O) is the discharge rate of a borehole with internal diameter $d(d_O)$.

To investigate the effects of the casing design (i.e., variation of inside wellbore diameter with depth) on the discharge capacity, it is convenient to examine the following four (4) well completions:

1) Uniform inside diameter of 100 mm over the entire depth interval (0–1500 m). This case is one of the several considered by Pritchett (1993).

2) Inside diameter of 104 mm from 0 to 1000 m, and 100 mm from 1000 m to 1500 m. This represents a typical existing slim hole completion.

3) Inside diameter of 154 mm from 0 to 500 m, 104 mm from 500 to 1000 m, and 100 mm from 1000 m to 1500 m. In this case, the typical existing slim hole completion is modified by using a 165 mm OD casing in the upper part of the hole.

4) Inside diameter of 154 mm from 0 to 1000 m, and 100 mm from 1000 m to 1500 m. This case represents perhaps the limit of what can be realistically done with the currently available wireline coring rigs.

Other than the borehole diameter, the various parameters (feedzone temperature and pressure, productivity index, stable formation temperature, effective thermal conductivity, etc.) required in the numerical calculations are the same as those used by Pritchett (1993). The effective thermal conductivity is assumed to be 4 W/m°C, and the stable formation temperature was approximated by the following temperature-depth distribution:

10 °C at 0 m
100 °C at 200 m
230 °C at 1000 m
250 °C at 1500 m

The computed discharge rate and wellhead enthalpy for the four (4) assumed well completions are displayed in Figure 1. It is apparent from the data displayed in Figure 1 that the discharge rate increases substantially with an increase in the inside diameter of the upper section of the wellbore. In addition, the wellhead discharge enthalpy generally increases with an increase in the diameter of the upper section; this is not really surprising as the heat loss per unit mass declines with an increase in the mass discharge rate. The maximum discharge rates for the four (4) completions are compared in Table 1.

For completions 2 and 4, the increase in the maximum discharge rate over the base case (i.e., completion 1) is comparable to that attainable by boreholes with uniform inside diameters of 104 mm and 154 mm respectively. Even for completion 3, an increase in the maximum discharge rate of over 90 % is obtained.

The computed downhole pressure profiles, corresponding to maximum discharge rates, for each of the four (4) completions are shown in Figure 2. With the exception of completion 3, the downhole pressure profiles are essentially the same. Single phase (liquid) conditions prevail below a depth of ~1000 m above which a transition to two-phase flow occurs. Except for completion 3, the inside diameter of the wellbore is uniform above the boiling point depth. The borehole diameter for completion 3 undergoes a change at 500 m which is directly responsible for the peculiar shape of the pressure profile for this completion.

2.2 Example B

The geothermal reservoir considered in the preceding example has a relatively low pressure (80 bars at 1500 m), and the transition from single-phase liquid to two-phase water-steam flow in the wellbore therefore occurs at considerable depth (~1000 m). The second example (Example B) is based on data obtained in the slim hole NE-5(i1) from the Takigami Geothermal Field, Kyushu, Japan (Garg, et al., 1996). The feedzone depth, pressure and temperature are 1080 m, ~67 bars, and ~210 °C, respectively. Based on the measured value of the injectivity index in NE-5(i1), and the fact that boreholes in the Takigami Geothermal Field have productivity indices that are essentially equal to the injectivity indices, the productivity index for NE-5(i1) is presumably quite large. Hence, for the present calculations, the productivity index is assumed to be infinite. As for Example A, the effective thermal conductivity is taken to be 4 W/m°C. The stable formation temperature is approximated by the following temperature-depth distribution.

15 °C at 0 m
50 °C at 500 m
185 °C at 900 m
210 °C at 1080 m

Although slim hole NE-5(i1) is slightly deviated, we have assumed that the borehole is vertical. The following three (3) well completions will be examined.

1) An inside diameter of 104 mm from 0 to 1000 m, and 100 mm from 1000 to 1080 m. This more or less represents the actual completion for slim hole NE-5(i1).

2) An inside diameter of 154 mm from 0 to 500 m, 104 mm from 500 to 1000 m, and 100 mm from 1000 to 1080 m.

3) An inside diameter of 154 mm from 0 to 1000 m, and 100 mm from 1000 to 1080 m.

The second and third completions correspond to the third and fourth completions of Example A.

The computed discharge rate and wellhead enthalpy values for the three (3) wellhead completions are plotted in Figure 3. Unlike for Example A, the computed wellhead characteristics for completions 2 and 3 (completions 3 and 4 of Example A) are not too different from each other. Once again, substantial increases in the maximum discharge rate and wellhead enthalpy for completions 2 and 3 are seen versus the base case (completion 1). The maximum discharge rates for the three (3) completions are compared in Table 2.

Both completions 2 and 3 result in an increase in the maximum discharge rate of ~200 %. Contrary to results for Example A, very little is gained by the use of 154 mm ID casing below 500 m. The reason for the differing behavior observed in the two examples is related to the depth of the boiling point in the discharging well. The computed downhole pressure profiles corresponding to the maximum discharge rate for the three well completions of Example B are shown in Figure 4. All three downhole pressure profiles look similar, and transition from single-phase to two-phase flow occurs at or above 500 m. Stated somewhat differently, in Example B (completions 2 and 3) two-phase flow is confined to the 154 mm inside diameter section of the wellbore. By way of contrast, two-phase flow in completion 3 of Example A extends below the 154 mm diameter casing. These results clearly indicate that for maximum increase in the discharge rate, the transition to two-phase flow should occur in the upper larger diameter (i.e., 154 mm) section of the borehole.

3. CONCLUSIONS

Most existing wireline-cored, or rotary drilled, slim holes have been used for geothermal exploration and reservoir assessment. Because these slim holes were not intended to be used as production or injection wells, little effort was made to optimize casing design for obtaining maximum discharge of geothermal fluids. For self-flowing wells producing from a liquid geothermal reservoir, the usual slim hole completion (114 mm OD casing in the upper part and a 100 mm open hole in the production interval) restricts the maximum discharge rate to less than 10 kg/s (36 tons/hour). Wireline coring rigs are not limited to drilling HQ and NQ size slim holes. Currently available wireline coring rigs can be used to cement a 165 mm OD (154 mm ID) casing in a 219 mm diameter hole to a maximum depth of about 1000 m. The latter capability can be exploited to significantly increase the discharge capacity of slim holes.

Numerical computations presented in this paper show that the discharge capacity of a properly designed slim hole can be increased by a factor of about three or so by ensuring that the transition from single-phase to two-phase flow takes place in the 154 mm ID section of the wellbore. Significantly, increasing the borehole diameter (say from 100 mm to 154 mm) below the transition zone has little influence on the discharge capacity of the borehole. Thus, for obtaining maximum possible discharge of geothermal fluids from a slim hole at a minimum cost, the bottom of the 154 mm ID casing should be located somewhat below the expected interface between the single-phase and two-phase zones in the wellbore.

REFERENCES

Combs, J., Garg, S.K., and Pritchett, J.W. (1997). Geothermal Slim Holes for Small Off-Grid Power Projects. *Renewable Energy*, Vol. 10 (2/3), pp. 389-402.

Dukler, A. E., Wicks III, M., and Cleveland, R.G. (1964). Frictional pressure drop in two-phase flow – B. An Approach through similarity analysis. *A.I.Ch.E. Journal,* Vol. 10, pp. 44-51.

Esaki, Y. (1998). Small-Scale Geothermal Power Generation – Flash Cycles. *Proceedings Geothermal Off-Grid Power Workshop, Reno, Nevada, 2-4 December.* Geothermal Resources Council, Davis, California.

Finger, J. T. (1998). Update on Slimhole Drilling. *Proceedings Geothermal Off-Grid Power Workshop, Reno, Nevada, 2-4 December.* Geothermal Resources Council, Davis, California.

Flavin, C. and Dunn, S. (1999). Reinventing the Energy System. In: *State of the World 1999.* A Worldwatch Institute Report. W. W. Norton & Company, New York, pp. 22-40.

Garg, S.K. and Combs, J. (1997). Use of Slim Holes with Liquid Feedzones for Geothermal Reservoir Assessment. *Geothermics,* Vol. 26(2), pp. 153-178.

Garg, S.K., Combs, J., Ozawa, F. and Gotoh, H. (1996). A Study of Production/Injection Data from Slim Holes and Large-Diameter Wells at the Takigami Geothermal Field, Kyushu, Japan. *Geothermal Resources Council Transactions*, Vol. 20, pp. 491-502.

Garg, S. K., Combs, J., Kodama, M., and Gokou, K. (1998). Analysis of Production/Injection Data from Slim Holes and Large-Diameter Wells at the Kirishima Geothermal Field, Japan. *Proceedings Twenty-Third Workshop on Geothermal Reservoir Engineering, 26-28 January.* Stanford University, Stanford, California, pp. 64-76.

Goranson, C. (1998). Comparison of Drilling Costs and Logistics for Slim Holes versus Conventional Large-Diameter Wells. *Proceedings Geothermal Off-Grid Power Workshop, Reno, Nevada, 2-4 December.* Geothermal Resources Council, Davis, California.

Hughmark, G.A. (1962). Holdup in gas-liquid flow. *Chemical Engineering Progress,* Vol. 53, pp. 62-65.

Kato, H., and Kizaki, Y. (1993). Utilization of Slim Holes in Geothermal Resource Exploration in Japan: Experience of the NEDO Geothermal Development Promotion Survey Project. *Geothermal Resources Council Transactions,* Vol. 17, pp. 431-435.

Magee, R. (1998). Personal Communication to Jim Combs on December 17.

Pritchett, J.W. (1985). *WELBOR:* a computer program for calculating flow in a producing geothermal well. Report No. SSS-R-85-7283, Maxwell Technologies (formerly S-Cubed), San Diego, California.

Pritchett, J. W. (1993). Preliminary Study of Discharge Characteristics of Slim Holes Compared to Production Wells in Liquid-Dominated Geothermal Reservoirs. *Proceedings Eighteenth Workshop on Geothermal Reservoir Engineering, 26-28 January.* Stanford University, Stanford, California, pp. 181-187.

Pritchett, J. W. (1995). Preliminary Estimates of Electrical Generating Capacity of Slim Holes – A Theoretical Approach. *Proceedings Twentieth Workshop on Geothermal Reservoir Engineering, 24-26 January.* Stanford University, Stanford, California, pp. 41-46.

Pritchett, J.W. (1998), Theoretical Examination of Natural Discharge and Pumped Slim Holes for Off-Grid Power Applications. *Proceedings Geothermal Off-Grid Power Workshop, Reno, Nevada, 2-4 December.* Geothermal Resources Council, Davis, California.

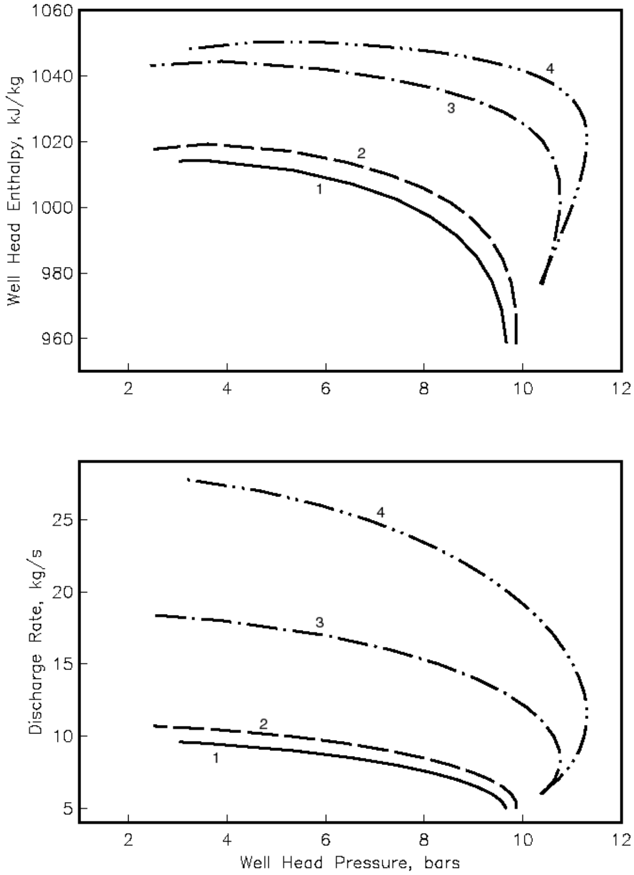

Figure 1: Computed mass discharge rate and wellhead enthalpy for the four (4) well completions of Example A (see text).

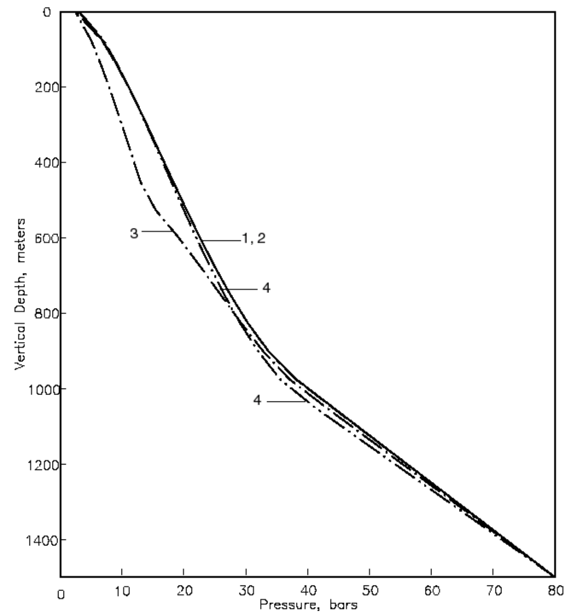

Figure 2: Downhole pressure profiles corresponding to maximum discharge rates for each of the four (4) well completions of Example A.

Table 1: Maximum discharge rates for the four(4) completions of Example A.

Completion	Maximum Discharge Rate (kg/s)	Discharge Rate Ratio †	$(d/100)^{2.56}$††
1	9.6	1.00	1.00
2	10.7	1.11	1.11
3	18.4	1.92	3.02
4	27.8	2.90	3.02

† Maximum discharge rate / 9.6
†† Here d denotes the diameter (mm) of the uppermost section.

Table 2: Maximum discharge rates for the three (3) completions of Example B.

Completion	Maximum Discharge Rate (kg/s)	Discharge Rate ratio †
1	8.1	1.00
2	23.2	2.86
3	24.4	3.01

† Maximum Discharge Rate/8.1

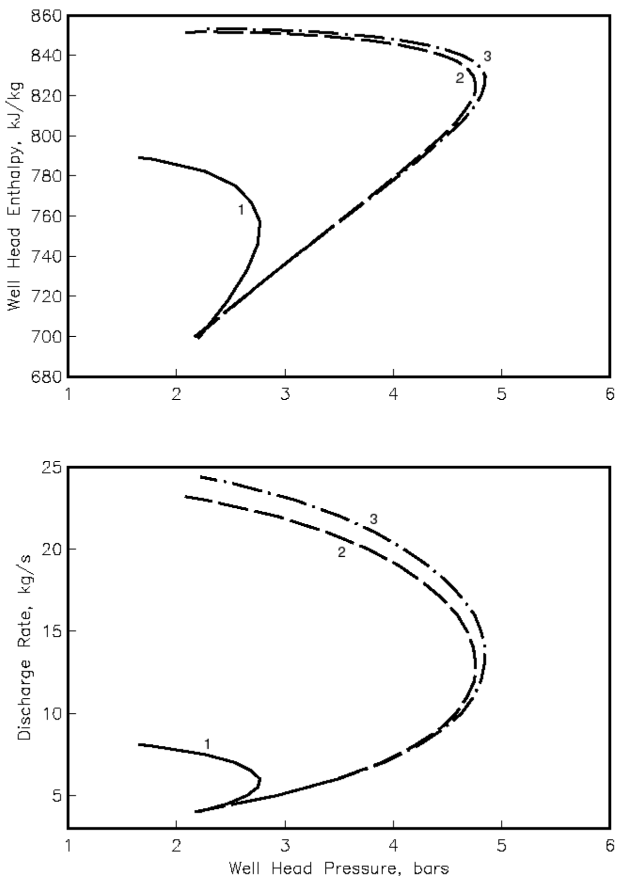

Figure 3: Computed mass discharge rate and wellhead enthalpy for the three(3) well completions (see text) of Example B.

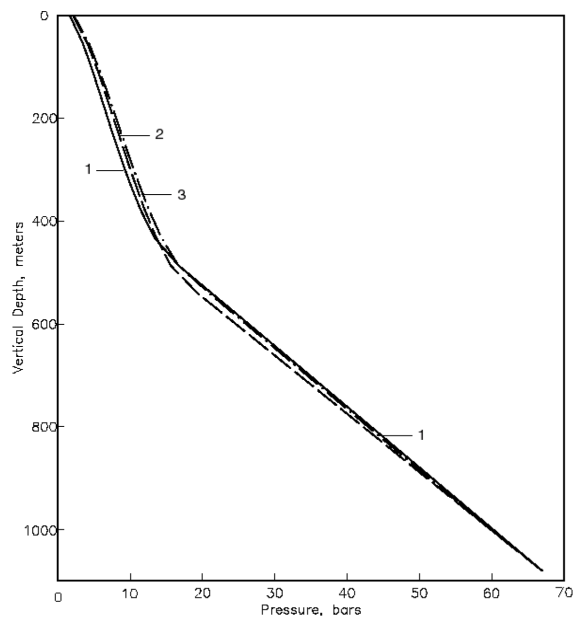

Figure 4: Downhole pressure profiles corresponding to maximum discharge rates for each of the three (3) well completions of Example B.