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PRELIMINARY ESTIMATES OF ELECTRICAL GENERATING CAPACITY OF SLIM HOLES— A THEORETICAL APPROACH

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ABSTRACT

The feasibility of using small geothermal generators (< 1 MWe) for off-grid electrical power in remote areas or for rural electrification in developing nations would be enhanced if drilling costs could be reduced. This paper examines the electrical generating capacity of fluids which can be produced from typical slim holes (six-inch diameter or less), both by binary techniques (with downhole pumps) and, for hotter reservoir fluids, by conventional spontaneous-discharge flash-steam methods. Depending mainly on reservoir temperature, electrical capacities from a few hundred kilowatts to over one megawatt per slim hole appear to be possible.

1. BACKGROUND

Small geothermal generators (from 100 to 1000 kilowatts capacity) have considerable promise for off-grid electrification around the world. Areas of particular interest include the more remote parts of Latin America, the Philippines and Indonesia, as well as numerous islands around the Pacific Rim. Entingh, *et. al.* (1994) examined the economic feasibility of such projects and concluded that small single-well plants of this type can compete favorably with existing off-grid electrification techniques in this capacity range (mainly diesel generators, which typically cost around one U.S. dollar per kilowatt-hour).

For projects in the 100–1000 kWe range, however, the costs of drilling and completing the production well dominate the economics. Entingh, *et. al.* assumed that the well would be drilled using conventional techniques (13-5/8 inch casing to 750 feet, 9-5/8 inch below that depth). If a slim hole could be used instead (herein defined as a well with inside diameter of six inches or less), considerable savings in drilling costs and final electricity price would be realized. Slim-hole drilling costs are typically only about one-third (per foot) of those of conventional drilling practice in the geothermal industry (Combs and Dunn, 1992).

The main drawbacks of using slim holes are (1) the capacity of a slim hole to produce fluid is substantially less than that of a conventional production well (Pritchett, 1993) and (2) if a downhole pump is required, small-diameter downhole pumps suitable for high-temperature operation are not presently commercially available. The absence of a suitable downhole pump mostly reflects lack of demand; no major technical obstacles exist in principle to scaling down designs for existing driveline pumps to fit into wells as small as four inches inside diameter (Gonzalez, 1994).

The remaining problem is to establish whether or not slim holes can deliver enough hot brine to the wellhead to be of practical interest for off-grid electrification projects. A preliminary examination of this question is presented in this paper. In view of the exploratory character of this study, numerous simplifying assumptions were made which could be relaxed in future work and examined in a properly funded sensitivity analysis. The main objective of the present study was simply to establish whether or not slim holes are practical for fueling small scale (< 1 MWe) geothermal power plants. Two situations were considered: (1) small backpressure and condensing steam-turbine geothermal plants powered by spontaneously discharging wells, and (2) small binary geothermal plants using wells with downhole pumps.

The present study is not exhaustive; in fact, only a single well feedpoint depth was considered (600 meters). The stable reservoir pressure at this depth was likewise fixed at 40 bars (absolute) for all cases considered. The reservoir fluid was treated as pure H_2O, even though substantial amounts of dissolved CO_2 gas are often present, which can have significant effects (both positive and negative) on power production. All wells considered have uniform inside diameter: either four inches (10.16 cm), five inches (12.70 cm) or six inches (15.24 cm). Three different values of borehole productivity index were likewise considered: 2 kg/second/bar, 4 kg/second/bar and infinity. Reservoir temperatures considered range from 100°C to 240°C. In all cases, the reservoir fluid is single-phase liquid.

2. FLASH-STEAM TURBOGENERATORS / UNPUMPED SLIM HOLES

Small backpressure steam turbines are the simplest geothermal generators available. Their main disadvantages are high steam consumption and potential air pollution problems. Skid-mounted backpressure units have been available commercially for many years, with capacities ranging from 200 kWe to 5,000 kWe. Typically, the inlet pressure for these units is about 50 psig (4.46 absolute bars). At that pressure, steam consumption ranges from 5 to 8 kilograms of 50 psig steam per second per megawatt of electricity generated. It was conservatively estimated, for modeling purposes, that a "typical" backpressure turbine requires 7 kg/s/MWe of steam at 50 psig.

Small condensing steam turbines, while more complex and costly, produce substantially more power for a fixed steam supply and can be equipped to minimize air pollution. Unfortunately, such units are not yet readily available on a production-line basis at commercially acceptable terms. Condensing steam turbines can be designed to operate at much lower inlet pressures than backpressure units (sub-atmospheric inlet pressures are even possible), and thereby can exploit lower-temperature reservoirs. For the present study, however, it was assumed that a "typical" small condensing steam turbogenerator would also require a 50 psig steam supply, and that the specific steam consumption would be one-half of that of the backpressure turbine (3.5 kg/s/MWe). This estimate is probably conservative.

Although it is likely that the generating unit will be located very near the wellhead, a 0.5 bar pressure drop was assumed to occur between the wellhead and the turbine inlet. Thus, in all cases considered, the wellhead pressure was fixed at 4.96 bars (57.3 psig). A series of calculations was then carried out of the flow in uniform-diameter vertical wells to establish the total flow rate available as a function of hole diameter, productivity index, and reservoir temperature. The feedpoint depth was fixed at 600 meters where the assumed stable reservoir pressure is 40 bars. The vertical pressure gradient at a point in a flowing geothermal borehole consists of three components—hydrostatic head, an acceleration term which is small for single-phase flow but may be substantial in the two-phase region, and pipe friction. For friction, the formulation of Dukler, *et. al.* (1964) was employed. The general numerical approach is described by Pritchett (1985); for simplicity, a no-slip condition was assumed between the liquid and vapor phases in the two-phase region and lateral conductive heat losses to the formation through the casing were neglected.

Figure 1 shows the result of a typical calculation. In this case, the borehole diameter is five inches and the "intermediate" (4 kg/s/bar) productivity index was used. The reservoir temperature is 210°C. The stable reservoir pressure is 40 bars, but flow resistance in the formation (expressed by the productivity index) reduces the bottomhole flowing pressure to 35.8 bars. Below 400 meters depth the flow is essentially isothermal, but above that level the liquid boils and two-phase flow occurs. The total discharge rate is 16.8 kilograms of fluid per second which, if separated at 50 psig, yields 2.23 kg/s of steam. Note that, at 7 kg/s/MWe specific steam consumption, this borehole would produce steam capable of generating 320 kWe from a backpressure unit. At 3.5 kg/s/MWe, a condensing turbogenerator unit could deliver 640 kWe from this slim hole.

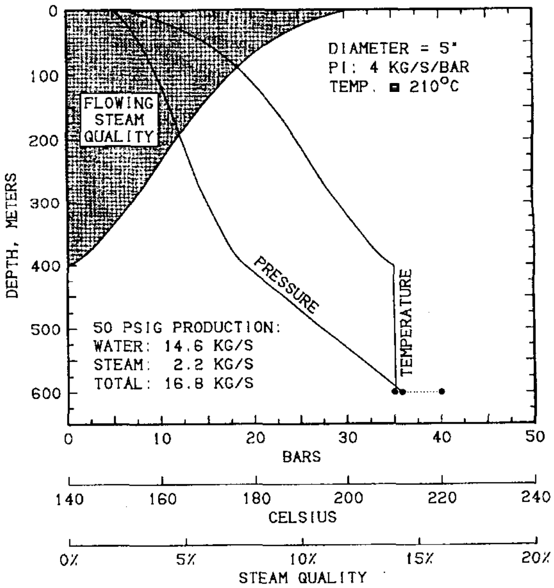

Figure 1. Computed downhole profiles in a discharging slim hole.

Calculations were carried out for 4", 5" and 6" inside diameter and for productivity indices of 2 kg/s/bar, 4 kg/s/bar, and infinity. Figure 2 summarizes the results in terms of mass flow rate of steam separated at 50 psig as a function of reservoir temperature, and also in terms of generating capacity from a small condensing turbogenerator operating at 3.5 kg/s/MWe. For a backpressure unit, these electrical capacity values should be reduced by a factor of two. Note that, at higher temperatures, capacities can significantly exceed 1000 kWe. The width of the shaded band for each hole diameter reflects the effect of varying the productivity index.

These results also indicate that reservoir temperatures of at least 180°C–190°C are required to

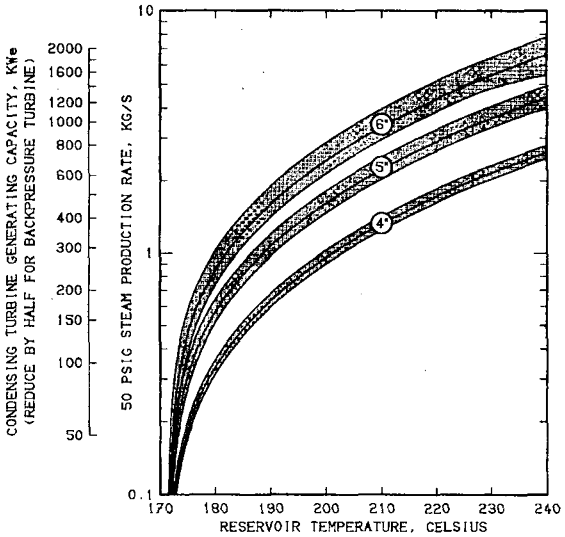

Figure 2. Steam production rate (separated at 50 psig) and available electrical generating capacity using flash-steam techniques from slim holes of various diameters as functions of reservoir temperature. Ranges are due to variations in downhole productivity index assumed.

produce useful amounts of power using these techniques. If, however, steam turbines with lower inlet pressures had been incorporated in the study (in addition to the 50 psig units), this temperature limitation would be less severe (at the cost of higher specific steam consumption). Using turbine entry pressure as an independent parameter and optimizing the system for maximum power production for each (reservoir temperature) / (productivity index) / (wellhead pressure) combination would increase the available power and extend the useful temperature range to lower values. In any event, it seems clear that if reservoir temperatures are sufficient, slim holes can provide enough steam for the desired applications using small conventional steam turbogenerators.

3. BINARY SYSTEMS / DOWNHOLE PUMPS

Binary generators have historically been the preferred technique for obtaining electricity from low- and moderate-temperature geothermal resources. Brine is brought to the surface with the help of a downhole pump, then circulated through a heat exchanger and reinjected. A low boiling-point secondary working fluid (such as isobutane or freon) flows in a closed loop from the heat exchanger (where it is vaporized) through a gas turbogenerator to a condenser, then back to the heat exchanger. The principal disadvantages of binary units are relatively high initial capital cost, mechanical complexity, and (for higher reservoir temperatures) reduced efficiency compared to condensing steam turbines.

Downhole pumps are required because reservoir temperatures are usually too low in typical binary applications for spontaneous discharge, and because it is important to maintain the geothermal brine in an all-liquid condition to maximize heat transfer and avoid scaling and corrosion in the heat exchanger (which is one of the most expensive components of the system). Conventional practice is to use driveline pumps, with an electric motor at the wellhead driving a multi-stage downhole pump through a gearbox by means of a long downhole vertical driveshaft. "Submersible" pumps (in which the electric motor is also downhole) have been under development for a number of years, but with limited success. For the present study, it was assumed that driveline pumps would be employed. One important limitation of driveline pumps is that the maximum practical pump depth is around 500 meters (Gonzalez, 1994).

The hot fluid requirements of binary generating systems depend upon numerous design parameters. For the present preliminary study, however, it was simply assumed that the amount of electrical power obtainable from such a power plant per kilogram of hot supply brine per second depends only on the plant inlet brine temperature (thereby neglecting differences in heat exchanger design, working fluid properties, *etc.*). Figure 3 shows the relationship between the plant efficiency (expressed as output

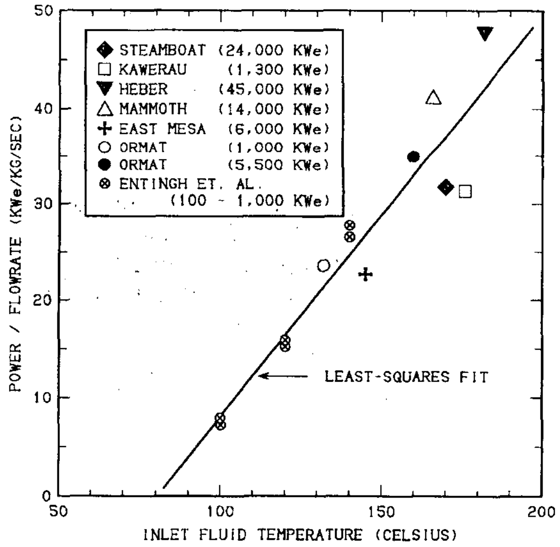

Figure 3. Gross electrical generating capacity (normalized to inlet brine mass flow rate) of various binary geothermal power stations as functions of brine inlet temperature.

electrical power relative to inlet brine flow rate) and plant inlet temperature for a variety of systems, including both actual field experience (Steamboat, Kawerau in New Zealand, Heber, Mammoth and the old East Mesa facility) and design estimates (Ormat, Entingh, *et. al.*). Somewhat surprisingly, despite variations in secondary loop fluid characteristics and other design parameters, all the data in Figure 3 are reasonably well represented by a simple linear function of inlet temperature:

$$\dot{E}_{gross} = 0.415\dot{M}(T - 80.6) \qquad (1)$$

where $\dot{E}_{gross}$ is the electrical power available from the generator, $\dot{M}$ is the inlet plant brine flow rate in kilograms per second and T is the brine inlet temperature (Celsius). A more detailed investigation would doubtless reveal important dependences upon other aspects of plant design, but for the present preliminary study the above correlation suffices.

As will be seen, the electrical power demands of the downhole pump have a major influence upon the net generating capacity of the binary systems considered in this study. Essentially, a downhole pump is a device for raising the flowing pressure of the upflowing fluid as it passes through the pump. The hydraulic power delivered by the pump is given simply by:

$$\dot{E}_{hyd} = \Delta P \times \dot{V} \qquad (2)$$

where ΔP is the pressure increase induced by the operation of the pump and $\dot{V}$ is the volumetric flow rate of the liquid through the pump. The hydraulic power $\dot{E}_{hyd}$ is related to the mechanical power delivered to the downhole pump by the driveline $\left(\dot{E}_{mech}\right)$ by the "mechanical/hydraulic efficiency", which depends upon a variety of factors including pump design, diameter, and flow rate. The mechanical power $\dot{E}_{mech}$ is related in turn to the electrical power consumed by the wellhead motor $\left(\dot{E}_{motor}\right)$ by the "electrical/mechanical efficiency" which incorporates losses in the motor, the gearbox, the downhole shaft bearings, etc. In the present study, it was assumed that the "electrical/mechanical efficiency" is 85 percent, based on informal discussions with various field operators:

$$\dot{E}_{mech} / \dot{E}_{motor} = 0.85 \qquad (3)$$

The "mechanical/hydraulic efficiency" $\left(\dot{E}_{hyd} / \dot{E}_{mech}\right)$ depends, for a particular pump, on the volumetric flow rate passing through the pump. The efficiency is zero at zero flow rate, but increases with increasing flow rate to a maximum value, then decreases again with further flow rate increase. For typical geothermal driveline pumps, the maximum efficiency is around 70 percent to 80 percent. Smaller diameter pumps exhibit similar behavior, but the maximum efficiency will usually be somewhat lower and will be realized at a much lower flow rate.

Figure 4 shows measured mechanical/hydraulic efficiency data for several downhole pumps, including four different pumps of 33 cm diameter and one of only 9 cm diameter (the 9 cm diameter pump is similar in basic design to the 33 cm geothermal pumps, but was not intended for high-temperature applications). In Figure 4, the efficiency data are plotted as functions of volumetric flow rate per unit cross-section area (of the smallest pipe within which the pump will fit), which amounts to the average upward fluid velocity just below the pump. Evidently, maximum efficiency is achieved when this average velocity is around 0.8 to 1.0 meters per second for pumps of this type. As shown, these data are adequately represented by the following expression:

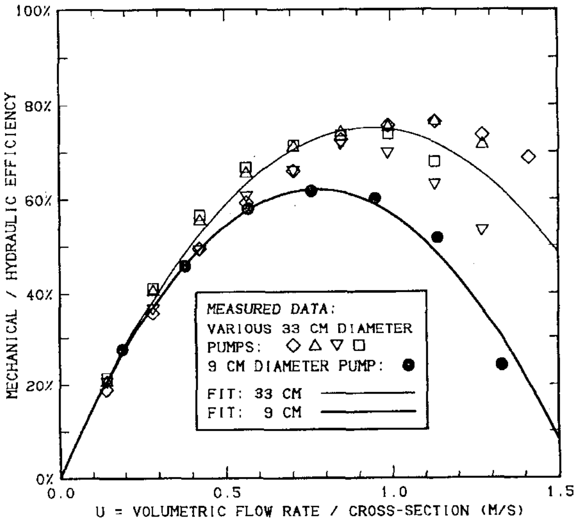

Figure 4. Mechanical/hydraulic efficiency of various driveline-type downhole pumps.

$$\dot{E}_{hyd} / \dot{E}_{mech} = 1.60\,U - \left(0.784 + \frac{2.22}{D}\right) U^2 \qquad (4)$$

where U is the above average velocity (m/s) and D is the pump (pipe) diameter in centimeters. This expression was used to estimate the pump efficiency available from the (hypothetical) downhole pumps in the slim holes considered in this study. For various inside diameters of interest, the fit yields for the maximum efficiency and the corresponding volumetric flow rate:

Diameter	Maximum Efficiency	Corresponding Velocity	Corresponding Flow Rate
4" (10.16 cm)	63.9%	0.798 m/s	0.0065 m^3/s
5" (12.70 cm)	66.8%	0.834 m/s	0.0106 m^3/s
6" (15.24 cm)	68.8%	0.860 m/s	0.0157 m^3/s
13" (33.00 cm)	75.2%	0.939 m/s	0.0803 m^3/s

These pumps are only effective for single-phase liquid flow. To avoid pump cavitation, the minimum pump depth was required to be 20 meters below that depth within the well where the fluid would otherwise begin to boil.

Since all flow within the well for these binary cases is by definition single-phase, the calculation of the flow within the well is somewhat simplified as compared to the flash-steam cases. In the binary case, however, lateral heat losses to the formation were taken into account using a heat loss formulation (see Pritchett, 1985) derivable from the work of Minkowycz and Cheng (1976), assuming a fairly high average formation thermal conductivity (3 W/m/°C) and that the formation temperature distribution is linear with depth between 10°C at the ground surface and reservoir temperature at the feedpoint (600 meters). This will usually overestimate heat losses somewhat. The Dukler, *et. al.* (1964) friction correlation was also employed in the binary cases.

The general approach is as follows. For specified values of reservoir temperature, well diameter and productivity index, at any particular mass flow rate the pump is placed 20 meters below the bubble-point depth, and the pump-induced pressure increase (ΔP) is adjusted so as to just maintain single-phase liquid conditions at the wellhead. As a practical matter, the necessary number of downhole pump stages is dictated by the above value of ΔP. The volumetric flow rate at the pump is computed based on the pipe diameter, the specified mass flow rate, and the steam-table density of water at the local temperature. This permits the calculation of the hydraulic power required (Eqn. 2) and the power required by the electric motor (using Eqns. 3 and 4). The gross electric power available from the generator is given by Eqn. 1 (where T is the computed wellhead brine temperature); the net exportable electrical power available from the system is therefore:

$$\dot{E}_{net} = \dot{E}_{gross} - \dot{E}_{motor} \qquad (5)$$

This procedure is repeated for various assumed mass flow rates until a value is found which maximizes $\dot{E}_{net}$ (the maximum power available from the binary system for the selected values of well diameter, productivity index, and reservoir temperature).

Figure 5 (upper) shows the ratio $\dot{E}_{motor} / \dot{E}_{gross}$ as a function of reservoir temperature for these calculations; the width of the band reflects the variability due to variations in well diameter (4" to 6") and productivity index (2 kg/s/bar to infinity). At low temperatures, the downhole pumping burden can consume over half the gross electricity generated. Even at high temperatures, the burden exceeds 20%. The reservoir considered in these calculations is relatively low-pressure (40 bars at 600 meters depth), which contributes to the high pumping power requirements. The lower part of Figure 5 similarly shows the range of "minimum pump depth" as a function of reservoir temperature for these calculations. At 200°C, required pump depths are approaching 500 meters, which is the probable practical depth limit for driveline pumps. For this reason, calculations were not carried out for higher reservoir temperatures.

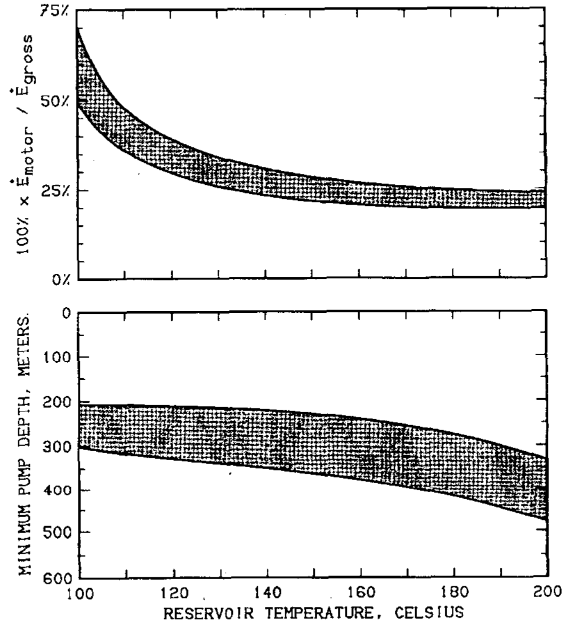

Figure 5. Electrical burden imposed by downhole pump (upper) and minimum permissible pump depth (lower) as functions of reservoir temperature. Ranges due to variations in well diameter (4" to 6") and productivity index assumed (2 kg/s/bar to infinity).

Figure 6 shows how the maximum value of the net export power $\dot{E}_{net}$ varies with reservoir temperature for each well diameter considered (4", 5" and 6"). The width of each band reflects the effects of varying the productivity index. Even for the smallest hole diameter considered (4"), 100 kWe or more can be generated so long as the reservoir temperature exceeds 125°C or so, and for higher temperatures the capacity of a six-inch slim hole approaches 1000 kWe.

4. SUMMARY AND CONCLUSIONS

Substantial improvements are obviously required to transform the present preliminary "quick-look" into a comprehensive study of the generating capacity of slim hole completions. These include increasing the sophistication of the powerplant models employed (both flash-steam and binary), improving the characterization of the downhole pump (and perhaps considering alternatives to driveline pumps), and improving the borehole brine flow description (in particular, incorporating liquid/vapor slip and lateral heat losses in the flash-plant model). Consideration should also be given to varying the inlet turbine pressure for the condensing flash-steam case to optimize performance. For low inlet pressures and low reservoir temperatures, downhole pumps may be required in the flash-steam case as well. Furthermore, the effects of varying the borehole feedpoint depth (fixed at 600 meters in the present work) and the reservoir pressure relative to depth (40 bars at 600 meters herein), as well as possible effects of non-condensables such as CO_2 need to be taken into account.

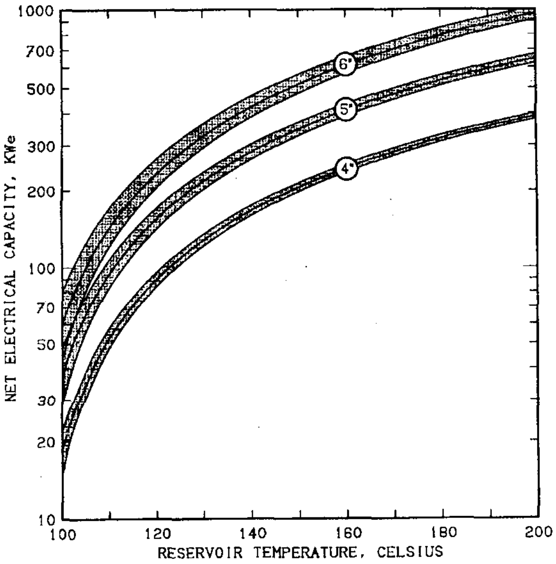

Figure 6. Net electrical generating capacity using binary techniques available from slim holes of various diameters as functions of reservoir temperature. Ranges are due to variations in downhole productivity index.

Despite these limitations, the present study clearly demonstrates that slim-hole completions have considerable potential for satisfying the brine requirements of small off-grid power stations in the 100–1000 kilowatt range. The initial capital cost savings available using slim-hole drilling techniques could substantially reduce the final cost per kilowatt-hour of such geothermal projects.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Combs, J. and J. C. Dunn (1992), "Geothermal Exploration and Reservoir Assessment: The Need for a U. S. Department of Energy Slim-Hole Drilling R&D Program in the 1990's", Geothermal Resources Council Bulletin, v. 21, No. 10, pp. 329-337.

Dukler, A. E., M. Wicks III and R. G. Cleveland (1964), "Frictional Pressure Drop in Two-Phase Flow — B. An Approach Through Similarity Analysis", A. I. Ch. E. J., v. 10, p. 44.

Entingh, D. J., E. Easwaran and L. McLarty (1994), "Small Geothermal Electric Systems for Remote Powering", Geothermal Program Review XII: Geothermal Energy and the President's Climate Change Action Plan, U. S. Department of Energy, San Francisco.

Gonzalez, J. (1994), Johnston Pump Co., personal communication.

Minkowycz, W. J. and P. Cheng (1976), "Free Convection about a Circular Cylinder Embedded in a Porous Medium", Int. J. Heat and Mass Transfer, v. 19, p. 805.

Pritchett, J. W. (1985), "WELBOR: A Computer Program for Calculating Flow in a Producing Geothermal Well", S-Cubed Report Number SSS-R-85-7283.

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