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A STUDY OF ELECTRICAL GENERATING CAPACITIES OF SELF-DISCHARGING SLIM HOLES

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ABSTRACT

Theoretical calculations have been performed to estimate the electrical generating capacities of small-diameter geothermal wells for off-grid rural electrification using wellhead generators. In these applications, generating capacities of interest are typically in the range 100–1000 kWe. The approach amounted to (1) calculating the "wellhead discharge characteristics" (water/steam discharge rates as functions of wellhead pressure) for a variety of hypothetical well and reservoir descriptions, (2) employing a mathematical representation for the net generating capacity of a wellhead powerplant as a function of its operating inlet pressure and steam inlet rate, and (3) varying the wellhead (= turbine inlet) pressure to identify the "optimum" pressure value at which the net electrical power is maximized.

Calculations were carried out for well diameters from 75 mm to 300 mm, for well depths from 300 to 1200 meters, for reservoir temperatures from 100°C to 240°C, for piezometric surface depths (related to shut-in reservoir pressure) from zero to 250 meters, and for downhole productivity indices from 2 kg/s/bar to infinity. A few cases were also included in which the CO_2 content of the reservoir fluid was non-zero (up to 1% by mass in the brine). Both backpressure and condensing single-flash steam turbine powerplants were considered. The study was restricted to vertical wells of uniform inside diameter and to all-liquid in-situ reservoir fluids. Over fifteen thousand combinations of the above parameters were examined. The results indicate that slim holes as small as 100 mm inside diameter penetrating reservoirs with temperatures as low as 150°C can produce useful amounts of electrical power using condensing wellhead turbines (> 100 kWe). For higher reservoir temperatures, the electrical capacity of such a well can exceed one megawatt.

BACKGROUND

Remote-area mini-geothermal installations would typically consist of a single production well supplying a wellhead generator. An economic appraisal carried out by Entingh *et al.* (1994) concluded that such installations can compete favorably with existing off-grid electrification techniques (mainly diesel generators), and also with other proposed renewable energy sources (photovoltaic solar, wind, hybrids). But, for geothermal projects in the 100–1000 kWe range, the costs of drilling and completing the production well dominate the economics. Entingh et. al. assumed that conventional well completions would be employed (13-3/8 inch casing to 750 feet, 9-5/8 inch casing below that depth). If a slim hole could be used instead, 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 essential question is: can a slim hole deliver enough steam under practical conditions to generate economically significant quantities of electricity?

Last year, the author undertook a preliminary study of this question (Pritchett, 1995a), using theoretical techniques to mathematically model the fluid flow within geothermal wells of various diameters and to forecast their probable electrical generating capacity. This study was far from exhaustive, and employed several simplifying assumptions to render the problem tractable with minimum effort. The results indicated that, under reasonable conditions, slim holes can deliver sufficient fluid to be of considerable practical utility. These preliminary results encouraged the U. S. Department of Energy (DOE) to provide subsequent support for elaboration and extension of the feasibility study, relaxing a number of the more restrictive assumptions and approximations.

The first phase of the DOE study is now complete—it examines self-discharging wells driving single-flash steam turbogenerators. Other techniques (double-flash plants, binary plants, wells with downhole pumps, etc.) will be considered in the future. A rather voluminous report has been prepared for DOE (Pritchett, 1995b) containing a catalogue of computed results. The present paper summarizes the methodology employed and presents a few representative results.

APPROACH

As in the preliminary feasibility study, it was assumed that all wells are oriented vertically (no deviation), and that the inside diameter of each well is uniform from the feedpoint to the wellhead. Also, as before, only steady stable flowing conditions were considered. For the present study, two separate series of calculations were carried out. All "Series 1" calculations treated the reservoir fluid as consisting of pure H_2O. "Series 2" considered solutions of CO_2 gas in water (up to 1% CO_2 by mass). The CO_2-free "Series 1" calculations considered all combinations of the following values for the pertinent free parameters:

Borehole inside diameter: 6 values (75 millimeters, 100 mm, 125 mm, 150 mm, 200 mm and 300 mm).

Well feedpoint depth: 4 values (300 meters, 600 m, 900 m and 1200 m).

Well productivity index: 3 values (2 kg/s/bar, 4 kg/s/bar and infinity).

Reservoir temperature at feedpoint depth: 29 values (100°C, 105°C, 110°C, ..., 235°C and 240°C).

Depth of piezometric surface: 6 values (zero, 50 meters, 100 m, 150 m, 200 m and 250 m).

For "Series 2", the parameter values considered were:

Reservoir dissolved CO_2 content: 4 values (0.25%, 0.50%, 0.75% and 1% by mass).

Well feedpoint depth: only one value (600 meters)

Well productivity index: only one value (4 kg/s/bar).

Bore inside diameter, reservoir temperature and depth of piezometric surface; same as Series 1.

The "piezometric surface depth" is herein defined as follows:

$$Z = D_f - \frac{P_r - P_a}{\nabla P(T_r)}$$

where

D_f = well feedpoint depth
T_r = reservoir temperature at feedpoint depth
P_r = stable reservoir pressure at feedpoint depth
P_a = one standard atmosphere = 1.01325 bars
$\nabla P(T)$ = hydrostatic gradient for saturated liquid H_2O

In other words, the piezometric surface lies at the depth at which a reservoir-temperature hydrostatic pressure gradient, projected upward from the stable shut-in feedpoint pressure, would reach one atmosphere. The piezometric surface is usually slightly shallower than the stable standing water level in the well after a long period of shut-in.

Both the original feasibility study (Pritchett, 1995a) and the present work consider only single-phase-liquid reservoirs. Certain of the above combinations of (feedpoint depth / reservoir temperature / reservoir CO_2 content / piezometric surface depth) result in reservoir pressures which are below the bubble-point pressure for the local conditions. These combinations were eliminated, leaving 15,018 combinations of reservoir CO_2 content, reservoir pressure, reservoir temperature, feedpoint depth, productivity index and well diameter to be examined.

For each of these 15,018 cases, the "wellhead characteristics" (relationships among discharge rate, discharge enthalpy and flowing wellhead pressure) were determined; typically, this required between 50 and 100 individual integrations of the governing conservation equations up the borehole to characterize these functional relationships. As a result, more than one million individual borehole-flow calculations (each for a specific value of the total fluid discharge rate together with one of the 15,018 parameter combinations) were carried out, which occupied the full attention of a modern scientific workstation for about three weeks. For each case, these calculations yielded the relationship between flowing wellhead pressure and the discharge rates of water and of steam at that pressure, as well as the wellhead temperature and the composition (CO_2 mass fraction) of the water and of the steam.

The next step, for each value of the wellhead pressure, was to determine the electrical generating capacity implicit in the predicted well steam output (and composition) for both "backpressure" and "condensing" single-flash steam turbine designs. It was assumed that wellhead generating units would be employed, so the turbine inlet pressure was taken to be the same as the flowing wellhead pressure, and the turbine inlet receives saturated vapor (no liquid, no superheat). For each design, the particular value of the wellhead pressure which produces the maximum amount of net electrical power was identified. The value of the "optimum" wellhead pressure (and the net maximum generating capacity) was thereby established for each combination of parameters (well diameter, feedpoint depth, reservoir pressure, reservoir temperature, productivity index, and reservoir CO_2 content). These results (for each of the 15,018 cases considered) are incorporated in the DOE report (Pritchett, 1995b).

MODELING FLOW IN THE FORMATION

For purposes of the present study, flowing bottomhole conditions (pressure, enthalpy, composition) were obtained from "reservoir" conditions (pressure, temperature, CO_2 content) using a modified productivity index approach. Define a "critical flow rate" ($\dot{M}_c$) by:

$$\dot{M}_c = I(P_r - P_b) \qquad (2)$$

where I is the productivity index, P_r is the reservoir pressure, and P_b is the bubble-point pressure associated with the reservoir enthalpy and CO_2 content. So long as the well discharge rate ($\dot{M}$) is less than the critical rate ($\dot{M}_c$), the reservoir will remain single-phase liquid and the flowing feedpoint pressure (P_f) is given by:

$$P_f = P_r - \frac{\dot{M}}{I} \quad (3)$$

If, however, $\dot{M} > \dot{M}_c$, the following alternate form is adopted:

$$P_f = P_b + F \times \left[(P_r - P_b) - \frac{\dot{M}}{I} \right] \quad (4)$$

Here, F represents the factor by which flow resistance in the two-phase region exceeds that of the corresponding single-phase liquid situation. The proper value for F is likely to be site-specific, and to depend upon the relative permeability functions appropriate for the reservoir and the detailed geometry of the fracture network supplying the well. For present purposes, the relatively conservative value $F = 8$ was selected, which results in substantially increased flow resistance if extensive two-phase flow occurs in the formation. The occurrence of two-phase flow in the reservoir was the exception rather than the rule in the present calculational suite (< 8% of the cases considered), mainly confined to conditions of low reservoir pressure, high reservoir temperature, large well diameter, shallow feedpoint depth, low productivity index, and/or high reservoir CO_2 content.

MODELING FLOW UP THE BOREHOLE

Calculations of flow up the well from the feedpoint to the wellhead were carried out using computational modules of the WELBOR borehole-flow simulator (Pritchett, 1985). Figure 1 illustrates one of the one-million-plus computed profiles of conditions within discharging wells which were generated in the course of this study. In this particular case, the inside diameter of the well is 150 mm and the feedpoint depth is 600 meters. No CO_2 is present and, at 600 meters depth, the reservoir temperature is 200°C and the stable shutin pressure is 43.4 bars (corresponding to a piezometric surface depth of 100 meters). This particular profile corresponds to a flowing wellhead pressure of 3.00 bars, which results in wellhead discharges of 23.7 kilograms per second of liquid and 3.5 kg/s of steam (27.2 kg/s total wellhead discharge).

The pressure gradient within the well (Figure 1A) consists of the sum of three terms (Pritchett, 1985); hydrostatic pressure, pipe friction, and a fluid acceleration term. Pipe friction is represented in these calculations using the method of Dukler, Wicks and Cleveland (1964). In the single-phase region below 353 meters depth in the well, hydrostatic effects dominate, frictional effects play a very minor role, and the acceleration term is negligible. At 353 meters depth, the rising fluid reaches its bubble-point pressure and begins to boil. Within the two-phase region, all three terms in the momentum equation (hydrostatic pressure, pipe friction, and fluid acceleration) play significant roles. In the upper part of the well, most of the wellbore volume is filled with steam; near the wellhead, the liquid phase occupies only 7.4% of the well's cross-section area. The upflow rate of liquid water below 353 meters depth is essentially constant and modest (Figure 1B), but once boiling begins both phases accelerate, with the upward velocity of the vapor phase exceeding that of the liquid phase due to buoyancy. These calculations treat interphase "slip" using Hughmark's (1962) empirical correlation.

In general, the specific enthalpy of an element of fluid entering the well at the feedpoint and flowing upward within the hole will decrease due to three causes: (1) increase in the fluid kinetic energy (Figure 1B), which takes place at the expense of the fluid enthalpy, (2) work done against the force of gravity, and (3) lateral heat losses through the casing to the surrounding reservoir. Lateral heat losses from the well to the surrounding formation through the casing were taken into account in these calculations by (a) assuming a particular quadratic distribution with depth of temperature in the rock formation adjacent to (but a few meters away from) the well, and (b) employing a heat transfer coefficient derivable from the thermal boundary layer analysis presented by Minkowycz and Cheng (1976). As shown by Pritchett (1981; 1993), the effective heat transfer coefficient, based on the Minkowycz-Cheng results, may be expressed by:

$$U = 0.6\frac{K}{d} \quad (5)$$

where d is the borehole diameter and K is the "effective formation thermal conductivity", taken for the present purposes to be 3 watts/m/°C. As shown in Figure 1C, the temperature within the well is usually greater than that in the formation outside, so that the fluid within the well loses heat to the formation. The net effect on flowing enthalpy within the well is illustrated in Figure 1D; the most important reason for the enthalpy decline is usually lateral heat loss, particularly for small diameter wells (Pritchett, 1993).

MODELING THE POWER PLANT

The theoretical maximum power that may be obtained from the wellhead steam is equal to the total work done by adiabatic expansion from inlet conditions (saturated H_2O/CO_2 vapor at wellhead pressure) to outlet conditions (to one atmosphere for backpressure turbines; to

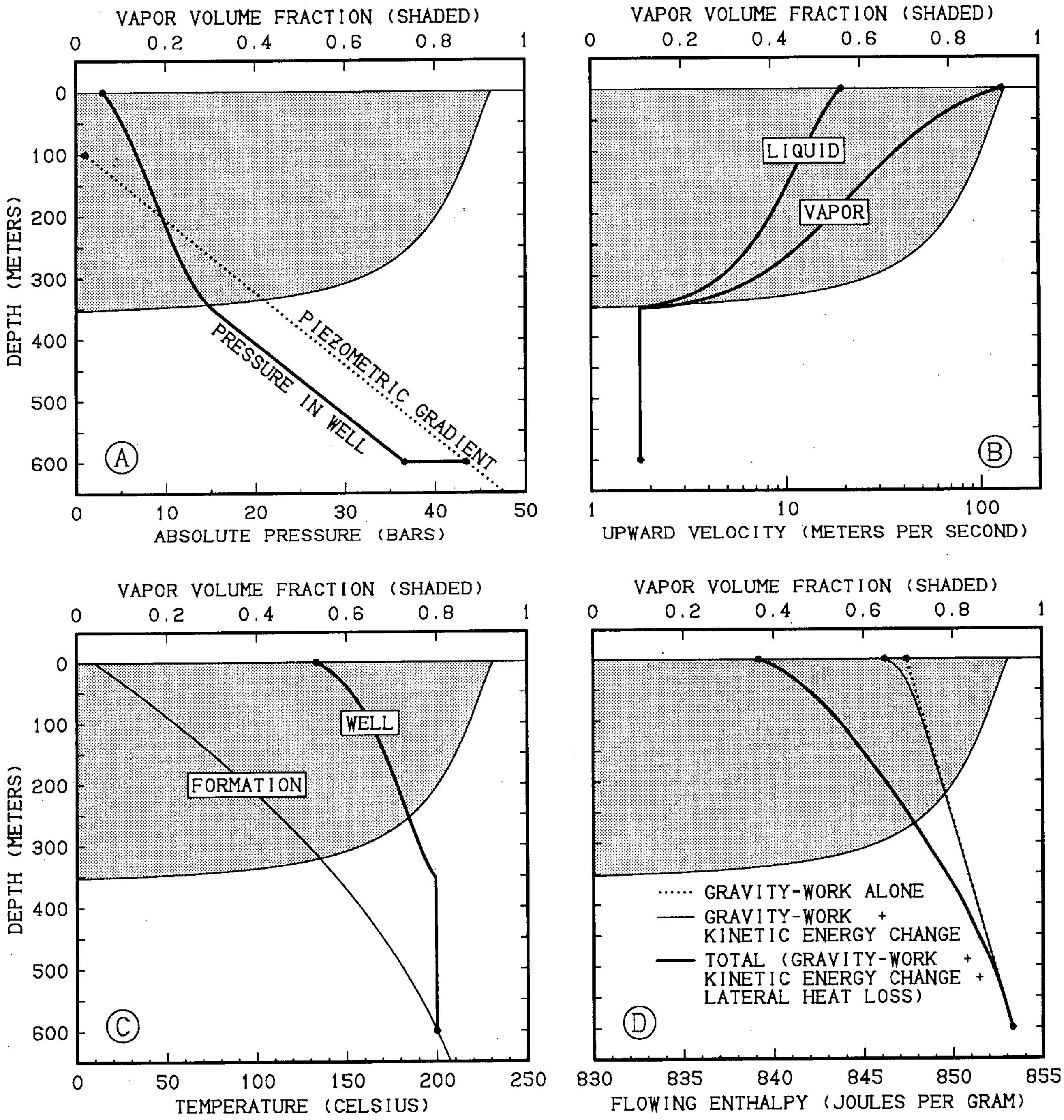

Figure 1. Typical computed downhole conditions. Reservoir temperature = 200°C, piezometric surface depth = 100 m, well feedpoint depth = 600 m, well inside diameter = 150 mm, no reservoir CO_2, productivity index = 4 kg/s/bar, flowing wellhead pressure = 3 bars. Discharge: 23.7 kg/s liquid, 3.5 kg/s steam.

condenser temperature for condensing turbines). Adiabatic expansion of a 10% CO_2 vapor (by mass) from saturated conditions at three bars is illustrated in Figure 2. Adiabatic expansion is governed by:

$$dE + PdV = 0 \quad (6)$$

and the mechanical work done (against the turbine blades in this case) is:

$$dW = -dE \quad (7)$$

where P is pressure, V is specific volume, E is fluid specific internal energy, and W is mechanical work. The pressure-volume relationship during the expansion is shown in Figure 2A; Figure 2B shows the corresponding change in temperature. For present purposes, it was assumed that the condenser would be maintained at 39°C (Forsha, 1994; Nichols, 1995). Figure 2C illustrates the total work done (integral of Figure 2A); in this case, the available work for the condensing case exceeds that of the backpressure case by a factor of three. Since the expansion begins with a saturated system, upon expansion a liquid mist will appear in the turbine; in the backpressure case around 6% of the inlet steam mass will have condensed at the outlet, whereas for the condensing case around 15% of the steam condenses within the turbine (Figure 2D).

Of course, the actual electrical generating capacity is significantly lower than the theoretical work rate of expansion. For a backpressure turbine, the net electrical power may be represented by:

$$\dot{E}_{net} = \dot{M}_v W_{bp} e_t e_b e_g \quad (8)$$

where

$\dot{M}_v$ = mass flow rate through turbine,
W_{bp} = specific work done by expansion to 1.01325 bars,
e_t = turbine efficiency,
e_b = gearbox efficiency, and
e_g = generator efficiency.

For condensing turbines, the available work of expansion is greater, but parasitic loads associated with operating the condenser/cooling system must be supplied:

$$\dot{E}_{net} = \dot{M}_v \times \left(W_{cn} e_t e_b e_g - L\right) \quad (9)$$

where

W_{cn} = specific work done by expansion to 39°C, and
L = parasitic load.

Based on design studies for small steam turbogenerators reported by Forsha (1994), and after consultation with Nichols (1995), the following efficiency values were selected for use in this study (for both backpressure and condensing designs):

e_t (turbine efficiency) = 0.75
e_b (gearbox efficiency) = 0.98
e_g (generator efficiency) = 0.96

and the parasitic loads for the condensing case were estimated as follows:

Condensate pumps:	8 kWe/kg/second
Cooling tower fans:	5 kWe/kg/second
NCG vacuum pump:	3 kWe/kg/second
Total parasitic load:	16 kWe/kg/second

The resulting computed electrical generating capacities for both backpressure and condensing single-flash turbogenerators (as functions of saturated steam inlet pressure and CO_2 content) are illustrated in Figure 3. Note that the CO_2 mass fraction in the separated steam will be substantially greater than that dissolved in the reservoir brine.

A TYPICAL CASE

The general procedure followed for each of the 15,018 cases considered in this study is illustrated in Figure 4 (for the particular case with reservoir temperature = 200°C, piezometric surface depth = 100 meters, casing I.D. = 150 mm, feedpoint depth = 600 m, I = 4 kg/s/bar and no reservoir CO_2). The effect of fluid discharge rate on flowing wellhead pressure is shown in Figure 4A; the maximum possible discharge rate is 28 kg/s (water plus steam). Note that the wellhead pressure passes through a maximum value (6.9 bars); at low flowrates, wellhead pressure declines with declining flowrate due to heat loss effects. In some cases, the maximum possible flowing wellhead pressure does not reach one atmosphere; such cases were eliminated from further consideration since it would probably be impossible to induce the wells to discharge in practice. The flowing wellhead enthalpy tends to increase with increasing flowrate (Figure 4B), owing mainly to the decline in importance of lateral heat losses with increasing discharge rate (reduction in residence time).

Combining the data from Figures 4A and 4B permits the forecasting of the wellhead steam discharge rate as a function of wellhead pressure (Figure 4C); combining this relationship with the electrical generating capacity data (Figure 3) permits predictions to be made of the electrical generating capacity of this well as a function of wellhead pressure, for both condensing and

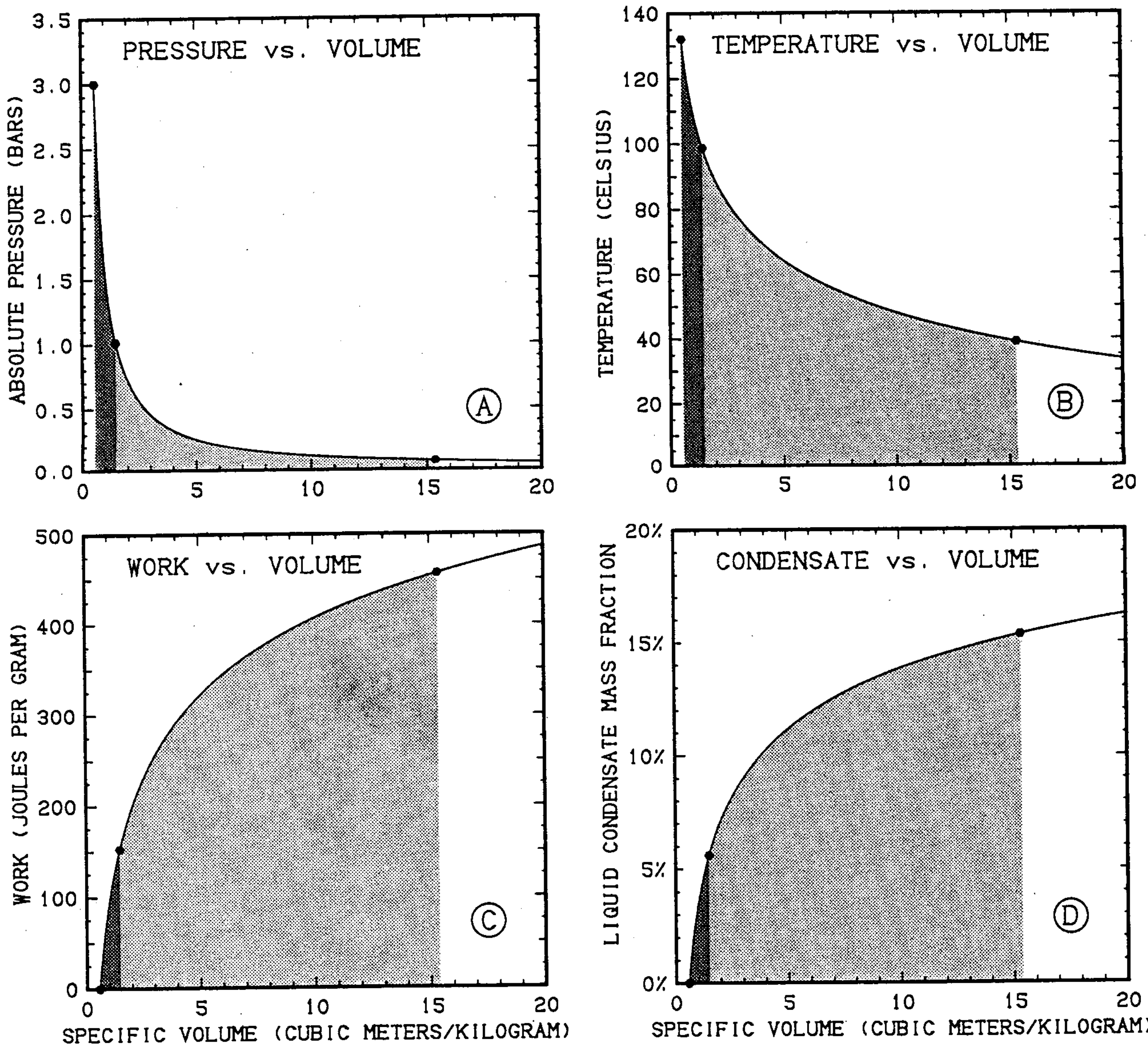

Figure 2. Adiabatic expression of saturated (CO_2 / H_2O) vapor (10% / 90% by mass) separated at 3 bars pressure.

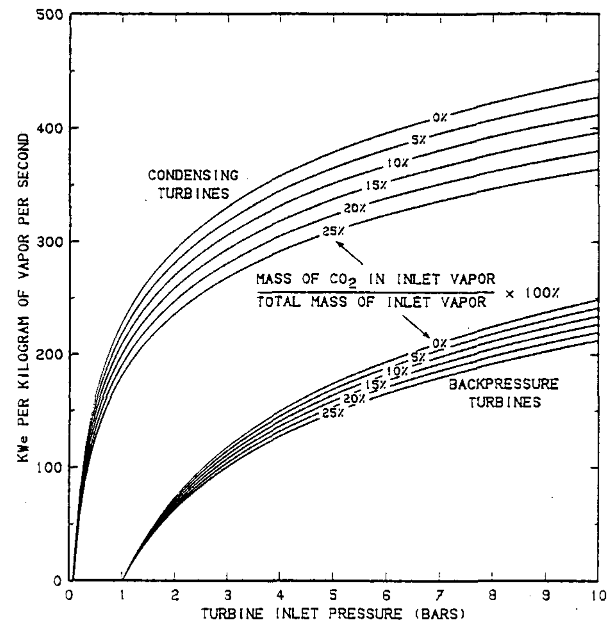

Figure 3. Net electrical power generated per unit inlet saturated vapor phase flow rate for both condensing and backpressure turbines with various values of inlet vapor-phase CO_2 mass fraction.

backpressure single-flash turbine designs (Figure 4D). For each design, an "optimum" value of the operating wellhead pressure may thereby be identified, at which the electrical generating capacity takes on a maximum value. For this particular case, the backpressure design is optimized at 3.61 bars wellhead pressure (427 kWe capacity); the condensing turbine will be optimized at a lower operating pressure (1.75 bars) and will produce almost three times as much power (1245 kWe).

INFLUENCE OF PARAMETER VARIATIONS

Calculations such as those illustrated in Figure 4 were carried out for all 15,018 parameter combinations considered in this study, and values of optimum operating pressure and corresponding maximum electrical generating capacity were obtained for each case for each power station design (backpressure and condensing turbine). The most important parameters influencing generating capacity are the well diameter and the reservoir temperature. Results for typical values of the remaining parameters (piezometric surface depth = 100 m, feedpoint depth = 600 m, productivity index = 4 kg/s/bar and no reservoir CO_2) are shown in Figure 5. Figures 5A and 5B indicate results (maximum electrical capacity and optimum operating pressure respectively) for backpressure turbines for the various borehole diameters considered as functions of temperature. Figures 5C and 5D provide corresponding values for the condensing case.

Clearly, electrical generating capacity tends to increase with increasing well diameter, and usually with increasing reservoir temperature. For large well diameters and high temperatures, however, electrical capacity can actually decrease as reservoir temperature increases. This is because two-phase flow is taking place in the formation, increasing the flow resistance (see Eqn. 4). If two-phase flow becomes sufficiently pervasive, reservoir resistance becomes the main limiting factor on steam production and electrical capacity can become almost independent of well diameter. Optimum operating wellhead pressure increases with increasing reservoir temperature. For condensing turbogenerators, electrical capacities are significantly higher than for backpressure systems, and electricity may be produced from lower-temperature reservoirs. Also, optimum operating pressures are substantially lower for condensing turbines than for backpressure units; for reservoir temperatures below 170°C or so, optimum condensing turbine inlet pressures are sub-atmospheric.

The remaining parameters, although less important than well diameter and reservoir temperature, also play important roles in determining electrical capacity. The effects of perturbing these parameters (one at a time) are illustrated in Figure 6. Results are displayed for maximum generating capacity using condensing single-flash turbines for well diameters of 75, 150 and 300 mm as functions of temperature; results are qualitatively similar for backpressure units, but electrical output is lower and the curves are shifted somewhat towards higher temperatures. The "base case" around which parameters are perturbed in Figure 6 involves 600 meters feedpoint depth, 100 meters piezometric surface depth, 4 kg/s/bar productivity index, and no reservoir CO_2.

The effect of varying the stable reservoir pressure (piezometric surface depth) is illustrated in Figure 6A. Unsurprisingly, increasing the reservoir pressure (while holding all other parameters constant) results in increased electrical capacity under all conditions. Furthermore, if reservoir pressures are higher, the minimum reservoir temperature required for practical power generation declines.

Increasing the feedpoint depth (Figure 6B) usually causes a decline in electrical output (except for those cases in which substantial two-phase flow is taking place in the formation), but the relative importance of this parameter depends on wellbore diameter. The reason is the relative effect of lateral heat losses from the wellbore to the surrounding formation. As well depth increases, a greater surface area is exposed through which heat losses may occur, so that wellhead enthalpy declines with increasing well depth. This effect is more important for small-diameter wells than for large-diameter wells because of the decreasing area/volume ratio with well diameter.

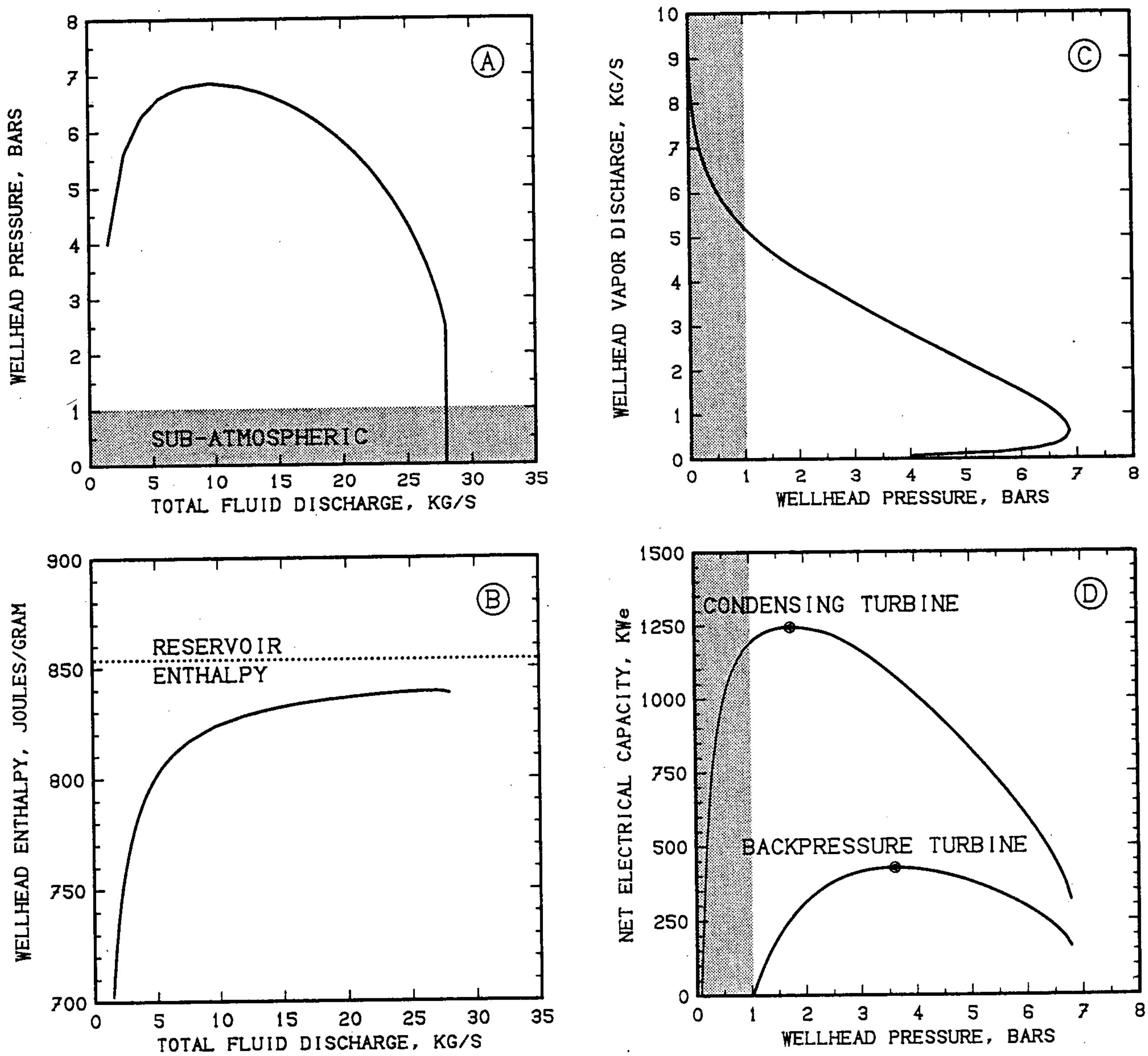

Figure 4. Wellhead characteristics for 600 meter deep 150 mm I.D. well with piezometric surface depth at 100 meters, reservoir temperature = 200°C, productivity index = 4 kg/s/bar, and no CO_2 in the reservoir. A: Wellhead pressure as a function of total discharge rate. B: Discharge enthalpy as a function of total discharge rate. C: Wellhead steam discharge rate as a function of wellhead pressure. D: Electrical generating capacity as a function of wellhead pressure.

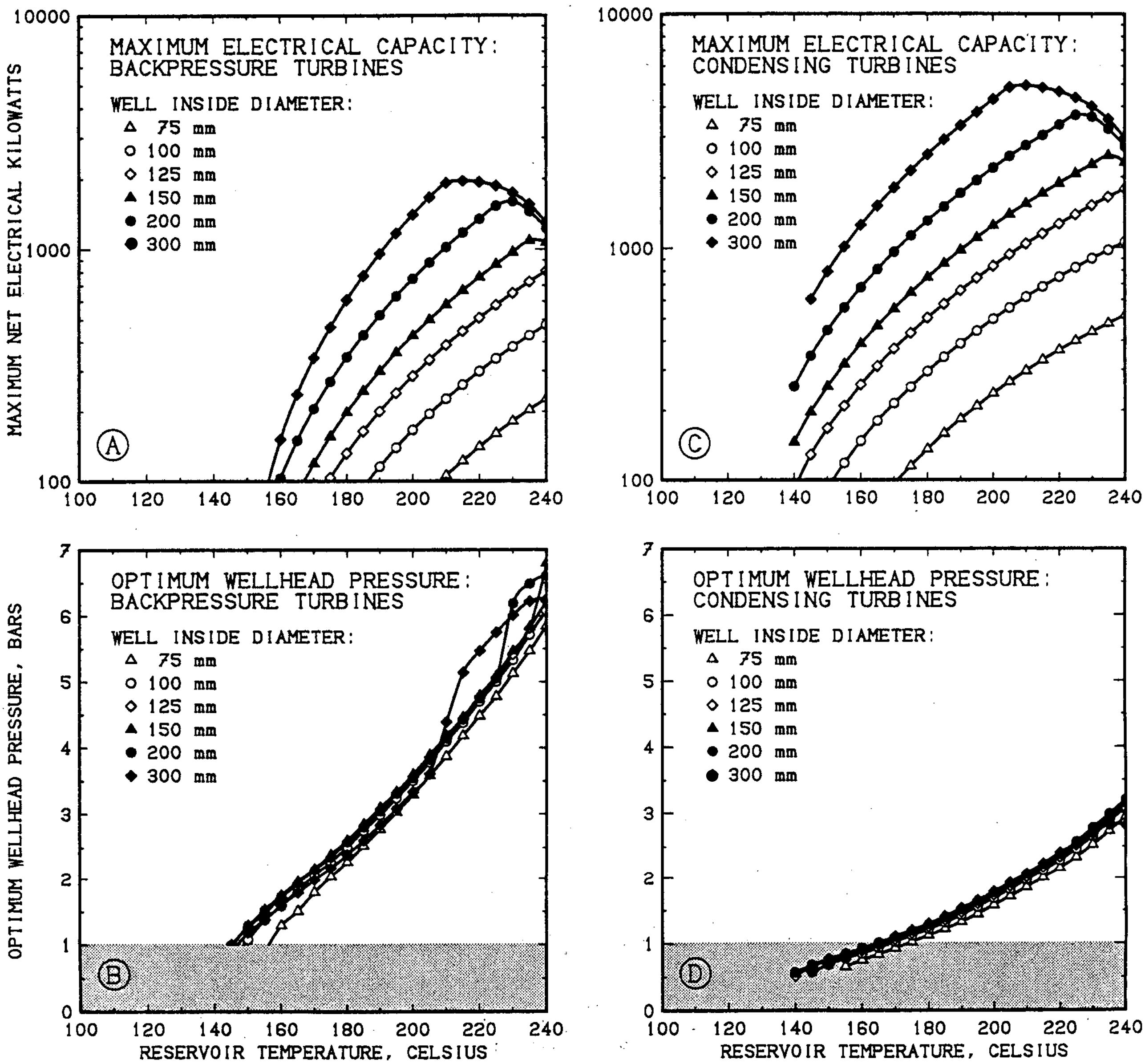

Figure 5. Maximum electrical capacity (A, C) and optimum operating pressure (B, D) for backpressure (A, B) and condensing (C, D) turbines, as functions of well inside diameter and reservoir temperature. Feedpoint depth = 600 m; piezometric surface depth = 100 m; productivity index = 4 kg/s/bar; no reservoir CO_2.

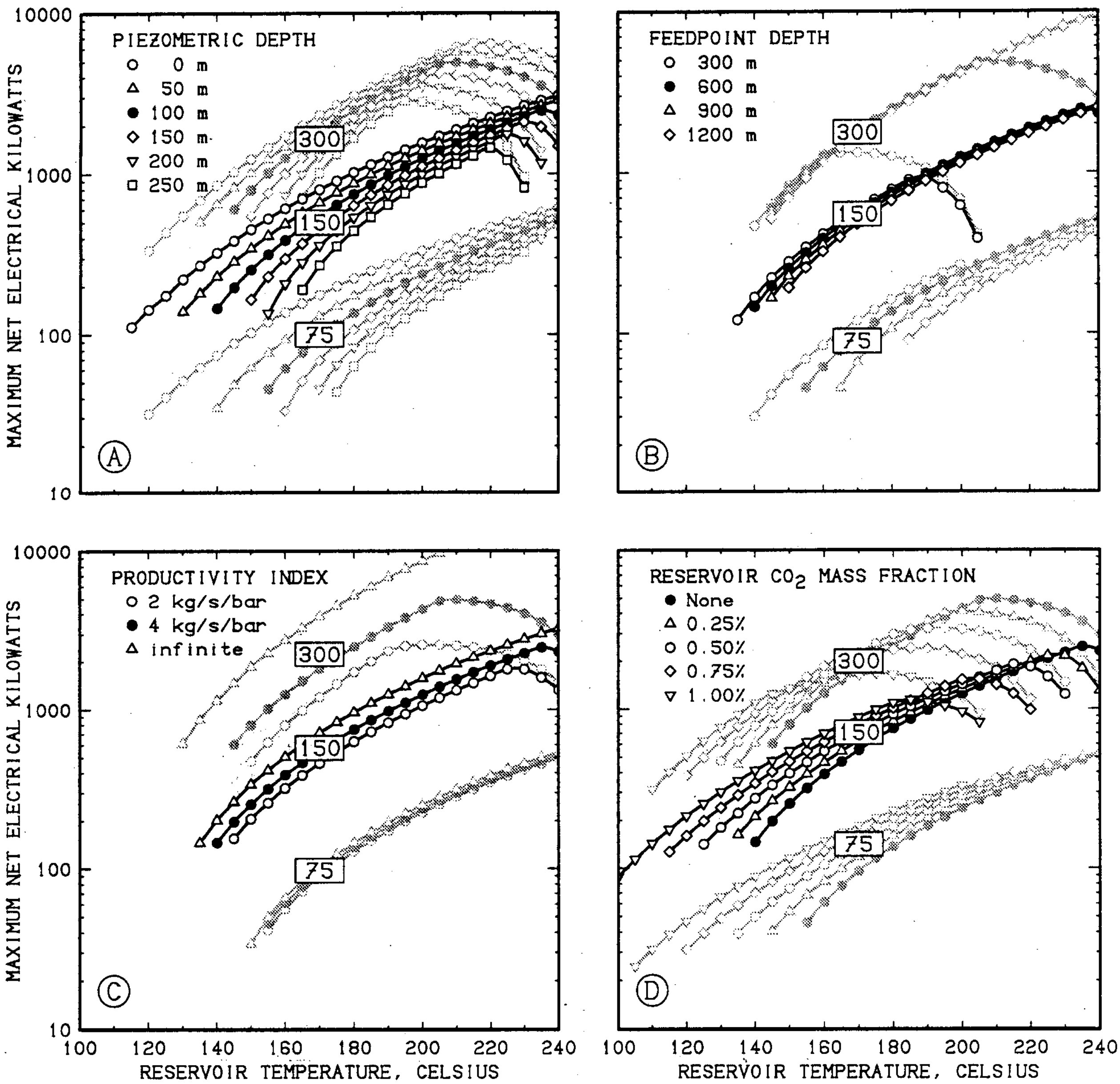

Figure 6. Effects of parameter variations upon electrical generating capacity using condensing turbines for 75, 150 and 300 mm I.D. wells around "base case" conditions: 100 m piezometric depth, 600 m feedpoint depth, 4 kg/s/bar productivity index, and no reservoir CO_2.

As one might expect, increasing the well productivity index increases the electrical generating capacity (Figure 6C), but the effect is most pronounced for large-diameter wells and is relatively unimportant for slim holes. For small-diameter wells, most of the overall frictional resistance to flow (from the reservoir to the wellhead) consists of pipe friction whereas reservoir resistance dominates for large-diameter wells. Accordingly, the importance of the exact value of the reservoir flow resistance increases with increasing well diameter.

Finally, if the CO_2 content of the reservoir increases (all other parameters being held constant), the general tendency is for electrical capacity to increase for lower reservoir temperatures but to be relatively unaffected or even to decrease at high reservoir temperatures, particularly for large-diameter wells (Figure 6D). This results from a combination of three effects. As noted earlier, increasing reservoir CO_2 has the effect of increasing the CO_2 content of the separated steam by a much larger factor, which reduces the electrical capacity of the plant (per kilogram of steam consumed); see Figure 3. Furthermore, increasing the reservoir CO_2 content also decreases the in-situ bubble-point pressure, causing two-phase flow to occur in the reservoir (and reduce electrical output by increased flow resistance) at lower temperatures, particularly for large-diameter wells. On the other hand, by reducing the bubble-point pressure, adding CO_2 causes two-phase flow to begin within the well at a greater depth, increasing gas-lift and permitting self-discharge of the well at lower reservoir temperatures.

CONCLUDING REMARKS

These results clearly indicate that slim holes have considerable promise for supplying small off-grid steam turbogenerators. At 240°C, wells of 100 mm inside diameter can produce over one megawatt of electricity. Electricity output of 100 kWe is possible with 100 mm holes for reservoir temperatures as low as 150°C or so, using low-pressure condensing turbines. Backpressure turbogenerators, while cheaper and simpler, are much less efficient than condensing turbines, and will usually produce less than half the electricity from the same well. They are also frequently unacceptable from an environmental standpoint, and require higher reservoir temperatures to be useful at all.

The next step is to examine even more sophisticated powerplant designs driven by self-discharging wells. The single-flash designs examined in the present study simply waste the heat in the separated wellhead liquid. To capture some of this energy and improve efficiency, double-flash steam turbogenerating plants and flash/binary hybrids (in which the separated liquid passes through a heat exchanger and powers a secondary closed loop containing low boiling point working fluid) could be employed. In future work, we plan to evaluate the efficiency improvements that could be obtained using these techniques.

It is reasonably clear, however, that to obtain electrical power from lower temperature reservoirs (100°C–120°C range), downhole pumps will be required. At these reservoir temperatures, insufficient gas-lift is available to permit self-discharge under most practical conditions. Therefore, we plan to develop mathematical representations for mass and heat flow in wells containing downhole pumps. These models will then be coupled with powerplant models of various types, including single- and double-flash steam turbogenerators, flash/binary hybrids, and pure binary plants.

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