# ISOBUTANE GEOTHERMAL BINARY CYCLE SENSITIVITY ANALYSIS

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**Presented are sensitivity analysis calculations to determine operating conditions for an isobutane geothermal binary cycle. For the design basis and cost formulas used, it is found that a subcritical pressure cycle is lower in cost than a supercritical pressure cycle which has a higher thermodynamic efficiency.**

## INTRODUCTION

Presented herein is a summary of sensitivity analysis calculations for an isobutane geothermal binary cycle performed using a computer simulator described elsewhere (1). The geothermal binary cycle, for which a schematic diagram is also presented elsewhere (1), is a Rankine-type power cycle in which the working fluid receives thermal energy by heat transfer from the geothermal brine. Geothermal binary cycle thermodynamics, equipment design, costing, and simulation are summarized elsewhere (1, 2); more detailed information is presented in reports available from the National Technical Information Service (3, 4).

### Design Basis

To focus attention on cycle operating conditions, a design basis with fixed working fluid composition, equipment parameters, resource temperature and net power output is used herein, although these fixed parameters also could be varied in sensitivity analysis. Based on preliminary sensitivity studies, the selected design basis consisted of the following conditions: isobutane was the working fluid; the heat exchangers were of the countercurrent flow shell-and-tube type with 1-inch outside diameter tubes and 1 13/32-inch triangular pitch (tube center-to-center spacing); the brine and cooling water velocities were 7 ft/sec; the working fluid shell side fouling factor was 0.0001; the brine and cooling water tube side fouling factors were 0.0005 (a value typically selected for pure water because the brine was assumed to be of low salinity and to have the properties of pure water); the cooling water condenser inlet and outlet temperatures were 80°F and 100°F; the brine inlet temperature was 400°F; the axial flow turbine had a specific speed of 80 and an isentropic efficiency of 0.86; the net power output was 25 MW; the well system contained an equal number of production and reinjection wells with 8-inch casings, depths of 3925 ft, and flow rates of 109 lb/sec; the well gathering system piping was 5000 ft long.

### Sensitivity Studies

Sensitivity analysis calculations for cycle operating conditions were focused on turbine inlet and exit conditions and heat exchanger LMTD's (log mean temperature differences). These factors are affected by the simulator input data for the turbine inlet temperature and pressure and the approach temperatures for the brine heat exchanger and the condenser. A quantity referred to herein as the capital cost index is used for evaluation of the sensitivity of capital cost to variations in the parameters studied. The capital cost index is simply the ratio of the calculated capital cost to an arbitrarily defined design basis capital cost.

On the basis of previous work on geothermal binary cycles, the turbine inlet pressure and temperature were initially chosen to be 500 psia and 380°F. It was observed that the brine heat exchanger and condenser heat transfer surface areas as well as the shell side and tube side pressure drops were much higher than expected. This was due mainly to the large amount of superheat at the brine heat exchanger outlet and condenser inlet. It was decided to begin sensitivity analysis for a supercritical cycle; hence, a higher turbine inlet pressure of 1000 psia was selected. To avoid excessive superheat at the condenser inlet, and to obtain a near maximum enthalpy

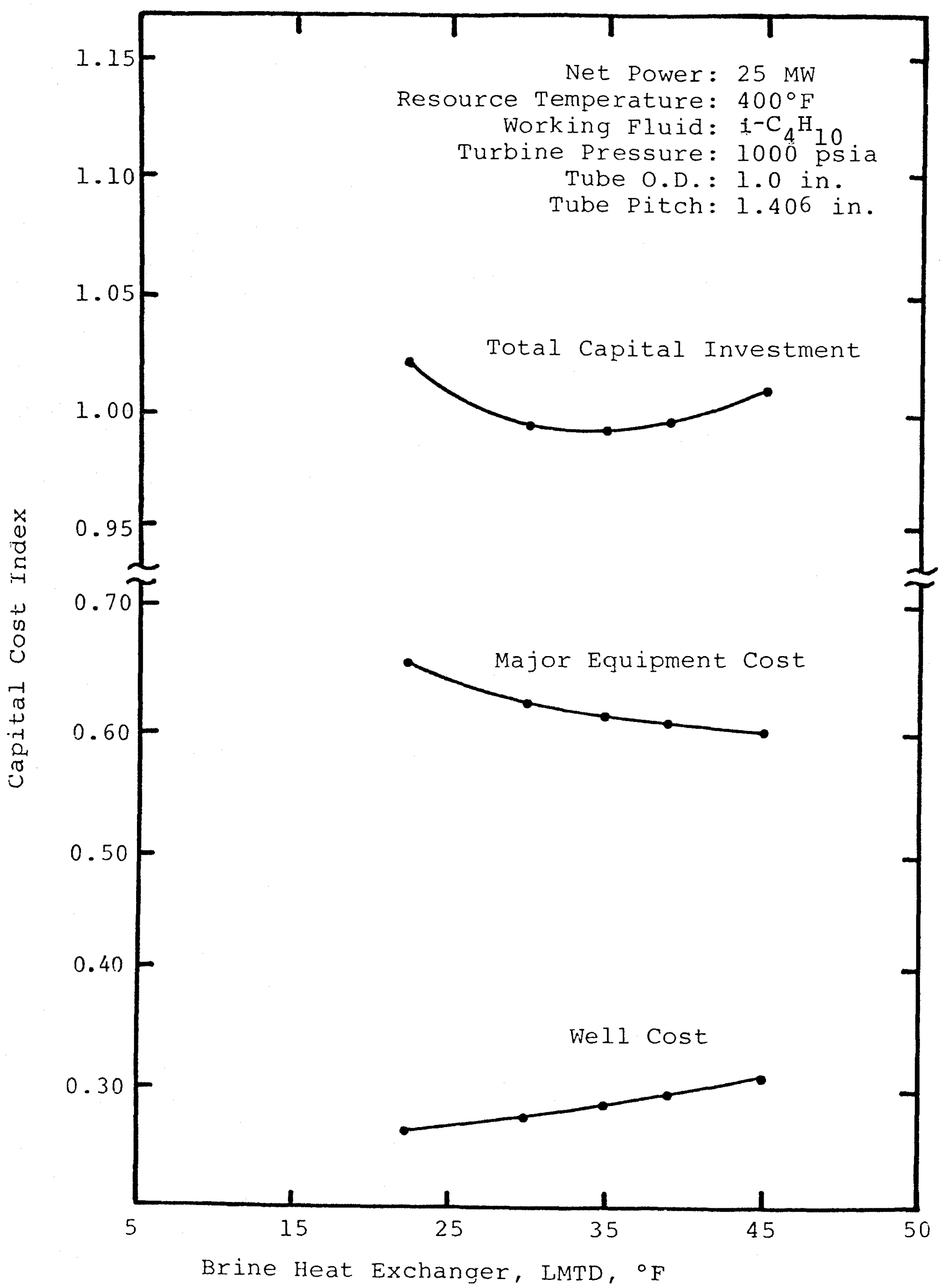


FIGURE 1. Capital Cost of Major Equipment and Wells as a Function of Heat Exchanger LMTD

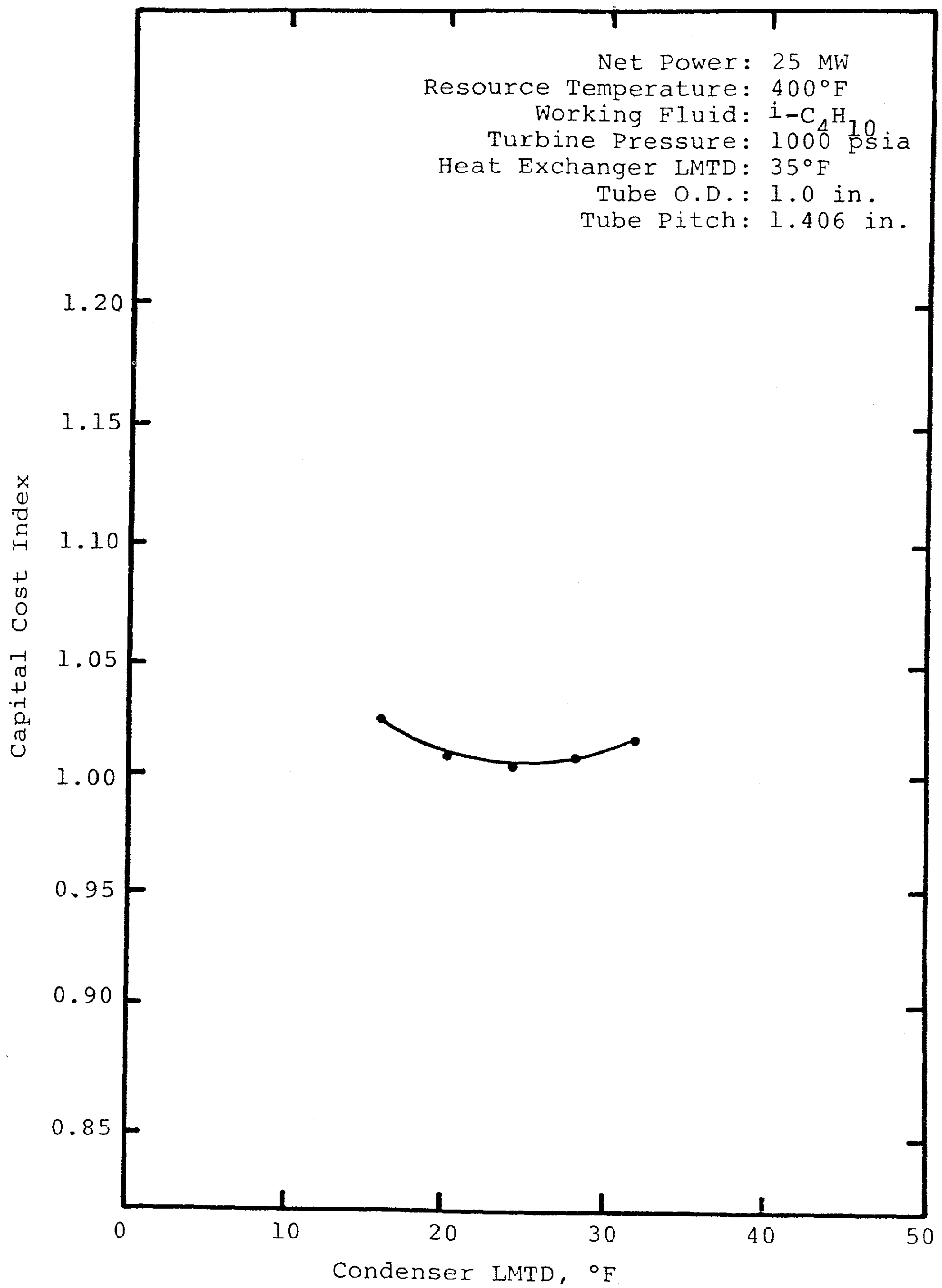


FIGURE 2. Capital Cost Index as a Function of Condenser LMTD

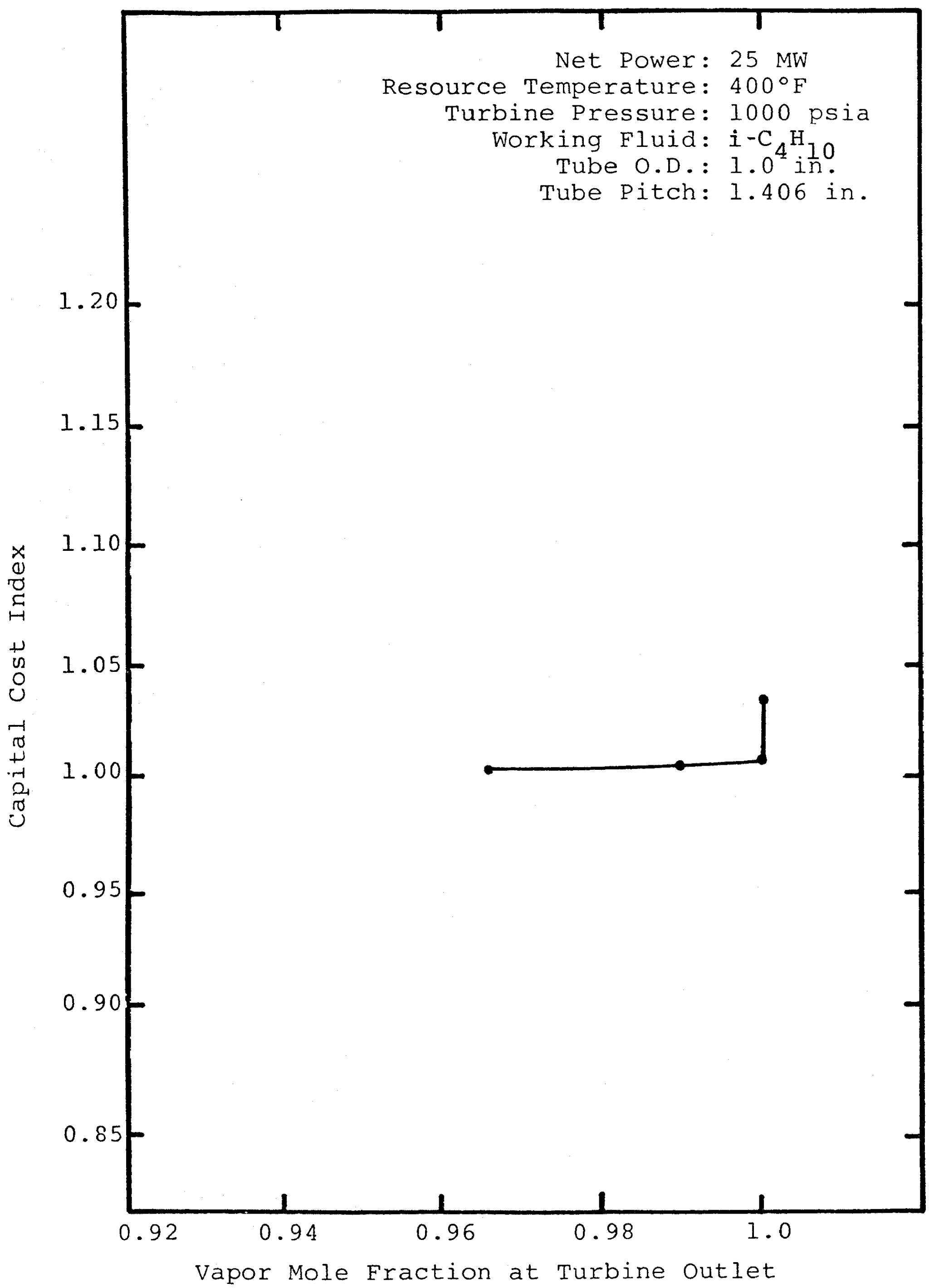


FIGURE 3. Effect of Vapor Mole Fraction at Turbine Outlet on the Capital Cost index

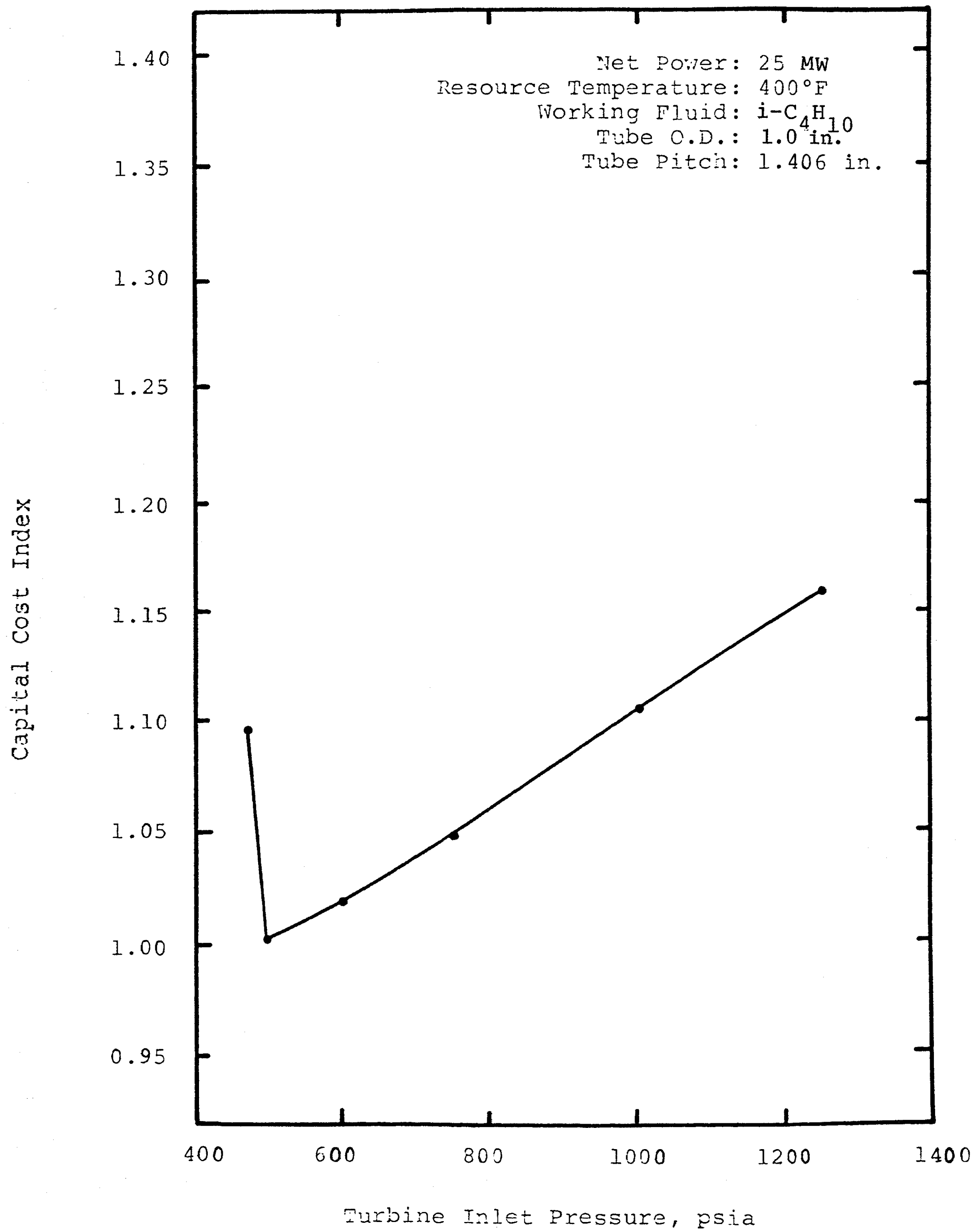


FIGURE 4. Effect of Turbine Inlet Pressure on the Capital Cost Index

change through the turbine, a turbine inlet temperature of 325°F then was chosen.

**Brine Heat Exchanger LMTD**

Figure 1 shows a minimum capital cost index for a brine heat exchanger LMTD of 35°F. The LMTD for the brine heat exchanger was varied by adjusting the allowable approach temperature between the working fluid and brine at the brine exit.

The parameter which critically affects the brine heat exchanger LMTD is the pinch point Δ T. For this calculation, the minimum allowable pinch point Δ T was kept at 10°F. The interesting thing to note is that as the brine heat exchanger allowable approach temperature is increased, the brine flow rate increases, the brine heat exchanger LMTD increases, and the brine heat exchanger required surface area decreases, as expected, whereas the condenser duty and surface area increase slightly with a corresponding increase in the cooling water flow rate. The condenser duty is increased because of the increase in working fluid flow rate needed to make up for the parasitic power due to the increase in brine pumping required. As the brine heat exchanger LMTD is increased, the major equipment total capital cost decreases, while the well capital cost increases. At small LMTD's equipment cost dominates, while at large LMTD's well cost dominates, as can be seen from the shape of the curves shown in Figure 1. From the general shape of Figure 1, it can be stated that the optimum brine heat exchanger LMTD lies between 30°F and 37°F for the conditions specified.

**Condenser LMTD**

Figure 2 shows the effect of varying the condenser LMTD on the capital cost index. The brine heat exchanger LMTD of 35° was used for these calculations, which indicate the optimum condenser LMTD to be between 22 and 26°F. As shown by the behavior represented in Figure 2, as condenser LMTD increases, the required condenser surface area decreases, and so does the major equipment capital cost; but the brine heat exchanger duty increases because of decreased thermal efficiency and the resulting increase in working fluid flow rate. Hence, an optimum condenser LMTD exists which balances these opposing cost factors.

**Turbine Outlet Vapor Mole Fraction**

The results of the analysis performed to determine the optimum vapor mole fraction at the turbine outlet are shown in Figure 3. Brine heat exchanger and condenser LMTD's of 35°F and 24°F were utilized for all the data points. The important points can be noted. (a) The cost suddenly increases with increasing vapor mole fraction at a vapor mole fraction of 1.0 (100% quality) even though the amount of superheat is not more than 0.1°F. (b) The capital cost index is almost constant for vapor mole fractions less than 1.0, which is probably because the decrease in turbine efficiency corresponding to the amount of liquid present at the turbine outline has not been accounted for in the calculations. The capital cost would increase with increased liquid at the turbine exit if the decrease in turbine efficiency were considered. (c) The brine heat exchanger and condenser surface areas decrease as the vapor mole fraction decreases; the brine flow rate also decreases. (d) The major equipment capital cost decreases as the amount of superheat is decreased. For vapor mole fractions less than 1.0, the cost starts increasing as the vapor mole fraction is further decreased. It was concluded that a vapor mole fraction between 0.99 and 1.0 is optimal.

**Turbine Inlet Pressure**

In the sensitivity calculations discussed above, a turbine inlet pressure of 1000 psia was utilized. In order to evaluate the effect of turbine inlet pressure on capital cost, calculations at a number of pressures were carried out (with the turbine inlet temperature chosen to achieve a saturated vapor condition at the turbine outlet). The resulting calculations indicated a turbine inlet condition of 500 psia and 271°F to be optimal for the isobutane cycle under these conditions. Figure 4 shows a plot of turbine inlet pressure versus capital cost index. The following points can be noted. (a) The capital cost index decreases almost linearly as the turbine inlet pressure is decreased (owing mainly to decreasing brine heat exchanger cost) down to a pressure of 500 psia. (b) The capital cost index suddenly jumps from 1.0 at 500 psia to 1.1 at 470 psia as the turbine inlet pressure is decreased below 500 psia. (c) The increase in the total plant cost below 500 psia is due mainly to the amount of superheat at the condenser inlet, which in turn has the following effects. i) The brine heat exchanger duty, size and brine flow rate increase because of the decrease in cycle efficiency caused by superheat at the condenser inlet, resulting in a larger working fluid flow rate. The increase in working fluid flow rate increases the cooling water flow rate required. ii) The condenser cost increases because of the increase in the heat transfer surface area due to the desuperheating region. iii) The cooling water pumping requirements also increase because of the increased flow rate of cooling water, increasing the parasitic power requirement.

## CONCLUSIONS

Sensitivity analysis calculations summarized herein demonstrate the use of a geothermal binary cycle simulator for determination of near optimal operating conditions for an isobutane cycle. For the case of a 400°F geothermal fluid resource, it is shown that for isobutane, which has a critical pressure of 529.1 psia, a subcritical pressure cycle with turbine inlet pressure of 500 psia is lower in capital cost than supercritical pressure cycles, which are known to yield more work per pound of brine (3). The simulator also can be utilized for sensitivity analysis of capital cost with respect to equipment parameters, geothermal fluid resource temperature, plant net power, and working fluid composition. In addition, the simulator can be used as a subprogram for an optimization executive program to determine optimal values of parameters of interest in geothermal binary cycle power plant design. The user should note, however, that the simulator is not intended for use as a detailed plant design program and that any information peculiar to a specific geothermal site would have to be incorporated into the algorithm.

## ACKNOWLEDGMENT

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