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ANALYSES OF MIXED-HYDROCARBON BINARY THERMODYNAMIC CYCLES FOR MODERATE-TEMPERATURE GEOTHERMAL RESOURCES USING REGENERATION TECHNIQUES

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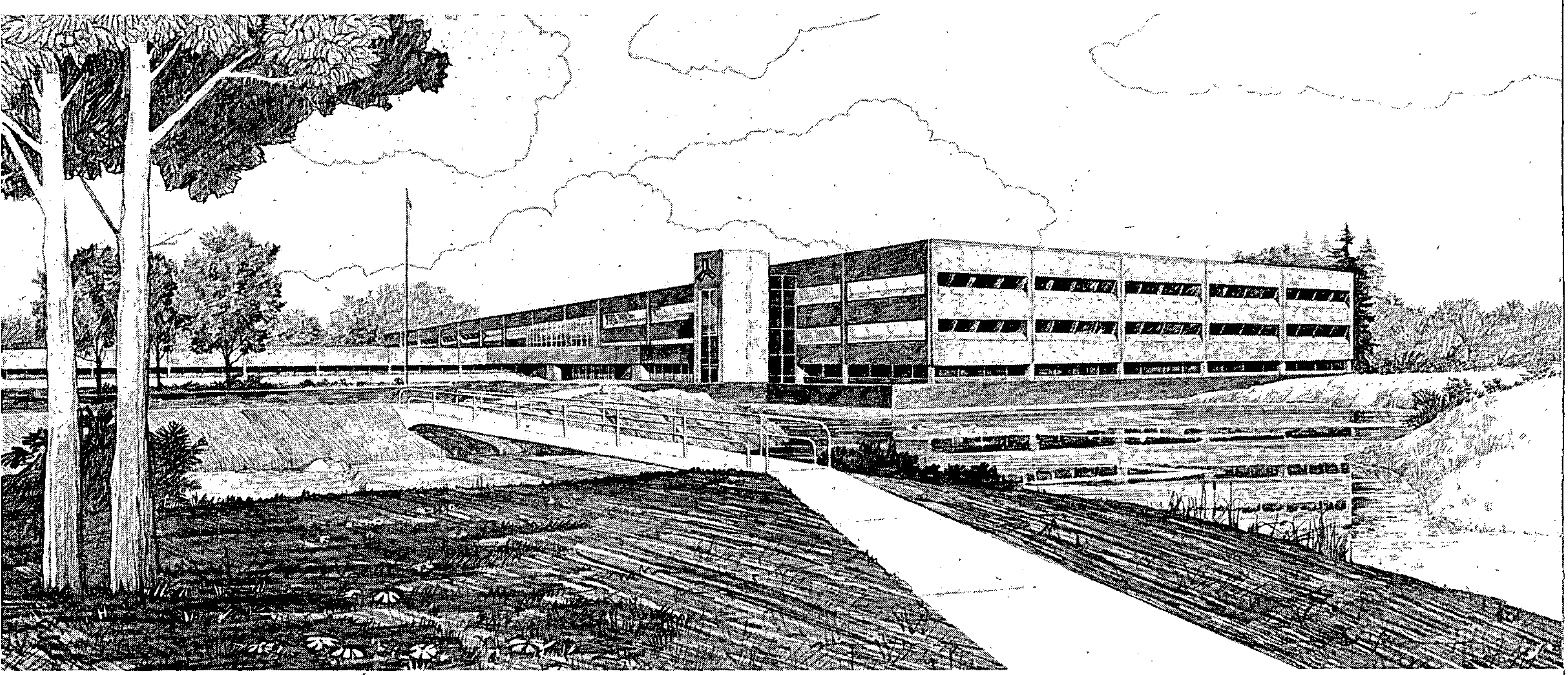

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MGW

ABSTRACT

Studies of basic binary geothermal cycles utilizing mixtures of hydrocarbons have shown better performance than for pure fluids for a moderate temperature (360°F) resource. However, a loss in net geofluid effectiveness (watt-hours net plant output/lbm geofluid) results when the geofluid outlet temperature is limited to temperatures in excess of 160°F to alleviate a silica precipitation problem.

This study examined three working fluids consisting of binary mixtures of hydrocarbons to see if use of regenerative preheating techniques such as turbine exhaust recuperation and/or turbine bleed could recover the loss in geofluid effectiveness for a 160°F geofluid outlet temperature. Results showed that with the most promising of the three working fluids a turbine exhaust recuperator alone is sufficient to recover all the lost effectiveness while maintaining the geofluid outlet temperature at 160°F. A brief study to investigate cold weather operation with that working fluid, and using the recuperator, showed no major detrimental response of the system; however, silica precipitation may present a problem in extremely cold weather, as the geofluid outlet temperature dropped below 160°F for the lowest wet bulb temperatures studied.

SUMMARY

A number of binary geothermal cycles utilizing three mixed hydrocarbon working fluids were analyzed for a moderate temperature (360°F) geothermal resource to evaluate the performance augmentation of regenerative preheating techniques such as turbine bleed and turbine exhaust recuperation. Working fluids considered include (by mass) 88% isobutane/12% isopentane, 96% isobutane/4% heptane, and 95% propane/5% hexane. Previous studies have shown these to be the better performing working fluids for the 360°F resource temperature.

Studies of the basic cycles without regenerative preheating show a loss in geofluid effectiveness (net plant power, watt-hr/lbm geofluid) of 7-14% when a geofluid outlet temperature of 160°F was maintained to prevent silica precipitation. Examination of the same cycles with recuperator and/or turbine bleed regenerative preheating of the working fluid shows that nearly all of the loss of performance can be regained by regeneration while maintaining the 160°F geofluid outlet temperature. The mixture judged to be the most promising of the three investigated, 96% isobutane/4% heptane, showed the same geofluid effectiveness for the regenerated case with the 160°F geofluid outlet temperature restriction, as for the non-restricted case without regeneration. An important added benefit of regeneration is the decrease in the amount of heat rejected in the cycle, thus decreasing the cooling tower size and cooling water makeup requirements by as much as 14%.

Comparing working fluids, the geofluid effectiveness for 96% isobutane/4% heptane with a recuperator alone was about 3% better than that for the 88% isobutane/12% isopentane mixture (the latter mixture was selected for use in the Heber plant). The 95% propane/5% hexane working fluid exhibited about 1% higher geofluid effectiveness but required more than twice the turbine inlet pressure relative to the isobutane/heptane mixture for a 160°F geofluid outlet temperature.

A brief probing study was made to investigate the recuperator/plant behavior during winter operation using 96% isobutane/4% heptane and assuming the same plant components as defined for summer operation at 600 psia turbine

inlet pressure (peak performance conditions). The study was intended to determine whether any unforeseen and/or detrimental operational characterisitics would be discovered for cold weather operation. No major problems were foreseen. The geofluid effectiveness increased by 28% as the ambient wet bulb temperature was decreased from 60°F to about 12°F while holding the working fluid flow constant. Whereas the geofluid flowrate changed insignificantly, the geofluid outlet temperature dropped from 160°F to 144°F. Therefore, at specific sites for which wet bulb temperatures reach sufficiently low values, silica precipitation may present a problem and a change in operating procedure (such as changing the working fluid flowrate or turbine inlet conditions) would be necessary at the coldest ambient temperatures.

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1. INTRODUCTION

A dual-boiling isobutane cycle was selected for the present 5-megawatt (5MW) Raft River Pilot Power Plant to utilize the lower temperature (near 300°F) geothermal resources. This study represents a continuation of earlier efforts directed toward the design of an improved binary geothermal electric plant suitable for utilization of both moderate and lower temperature resources. Earlier studies (Reference 1) have considered cycle improvements by way of introducing multiple-boiling and condensing, and employment of direct-contact heat exchangers. A small effort in Reference 1, directed toward the use of hydrocarbon mixtures as working fluids, showed that the mixtures showed promise. Reference 2 continued the study of hydrocarbon mixtures for 280°F and 360°F resource temperatures, and found that the highest geothermal effectiveness for the mixtures studied occurred for supercritical cycles.

The objectives of the present effort were to: (1) investigate the effect of turbine exhaust bleed and recuperation on geofluid effectiveness for three of the better performing binary mixtures with a geothermal resource temperature of 360°F, and (2) perform a short scoping study of the effect of off-nominal ambient wet bulb temperature on the performance of a recuperated system with the mixture judged to be best, overall.

This work was supported by the U. S. Department of Energy, Assistant Secretary for DOE Department of Geothermal Energy, under DOE Contract No. DE-AM07-76ID01570.

2. BINARY GEOTHERMAL CYCLE DESCRIPTIONS

The working fluid in a binary geothermal electric plant undergoes the processes of a Rankine thermodynamic cycle. Figure 1, which is a schematic diagram of a simple binary geothermal cycle, illustrates these processes as well as the major components of the binary plant. Starting at the condensate storage tank, working fluid is pumped from the condenser to the heater pressure at nearly constant entropy. The working fluid is then heated and vaporized at

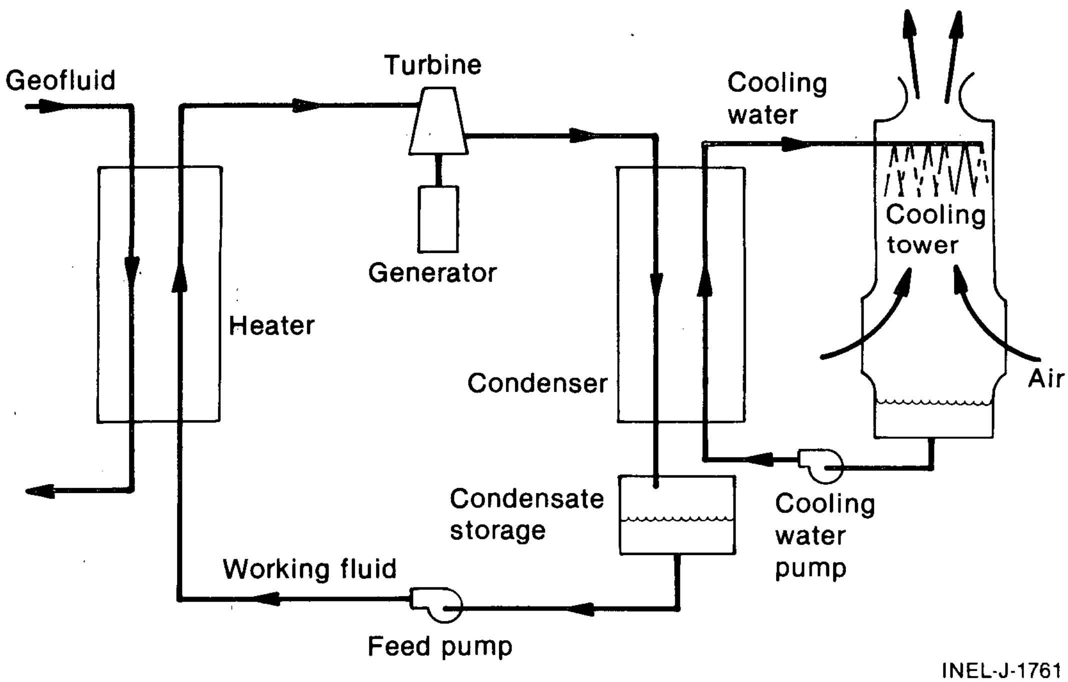

Figure 1: Simple Binary Geothermal Cycle

constant pressure in the heater as heat is transferred from the geothermal fluid. The working-fluid vapor expands through the turbine at nearly constant entropy, producing work on the turbine wheel. The turbine exhaust vapor is then condensed (following desuperheating if necessary) by rejecting heat to the cooling water in the condenser. This rejected heat, in turn, is transferred to the atmosphere in the cooling tower. The condensed working fluid finally passes into the condensate storage tank, and the cycle is repeated.

For a cycle which utilizes energy from a geothermal fluid at a given initial temperature and rejects heat to a given sink temperature, a theoretical maximum exists for the amount of work that can be produced by the cycle per unit mass of geofluid. This maximum corresponds to the change in thermodynamic availability (exergy) of the geothermal fluid between its initial state and its state corresponding to the heat sink temperature. Actual net work is less by the amount of the thermodynamic irreversibilities generated during each of the real processes in the cycle. Reference 1 investigated improvements to the simple cycle through use of multiple-boiling and condensing processes (refer to Figures 1 and 2 of Reference 1) to reduce the heat-addition and rejection irreversibilities. Reference 2 accomplishes much the same purpose through the use of mixtures of pure hydrocarbon working fluids. The approaches taken in this study extend the thermodynamic efficiency increase resulting from optimum use of mixtures of pure hydrocarbon fluids by using turbine bleed and/or recuperators to reduce thermodynamic irreversibilities in the heat addition and rejection portions of the cycle, to reduce the amount of heat added and rejected, and to increase the geofluid outlet temperature. Figure 2 shows a schematic diagram of the cycle when a recuperator is added. In simple terms the recuperator is used to preheat the working fluid with energy that would normally be provided by the geofluid and rejected to the cooling water.

Figure 3 shows a schematic diagram of the cycle with turbine bleed. The turbine bleed preheats the working fluid with low-pressure turbine bleed vapor which has little remaining useful work capability.

Figure 4 shows a schematic diagram of the cycle when both the turbine bleed and the recuperator are considered. In this mode of operation the recuperator

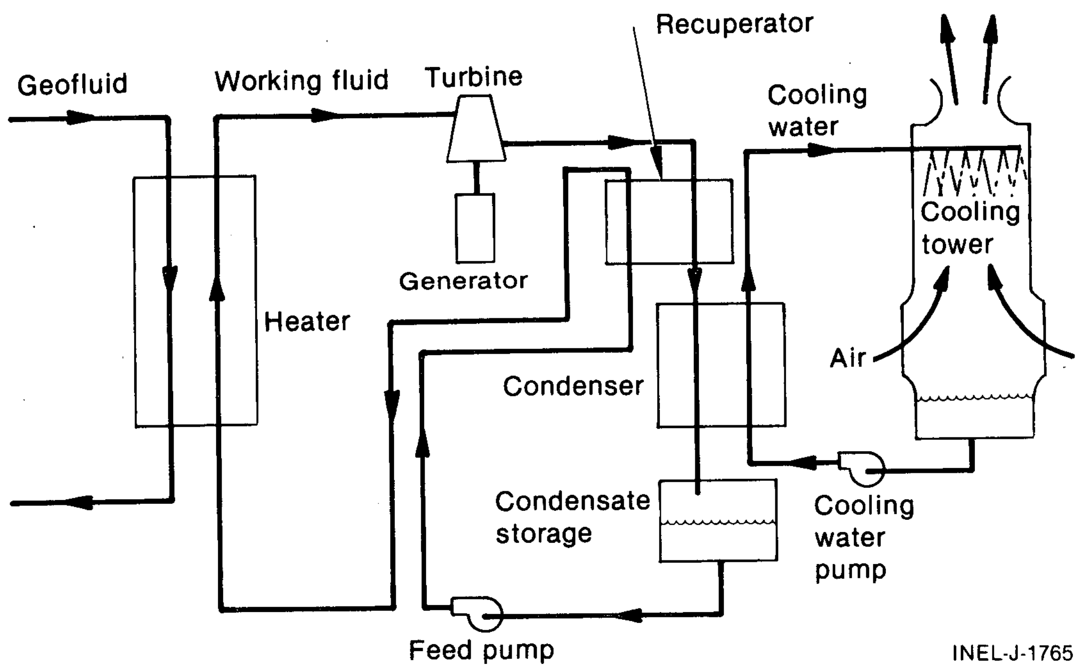

Figure 2: Binary Geothermal Cycle with Turbine Exhaust Recuperator

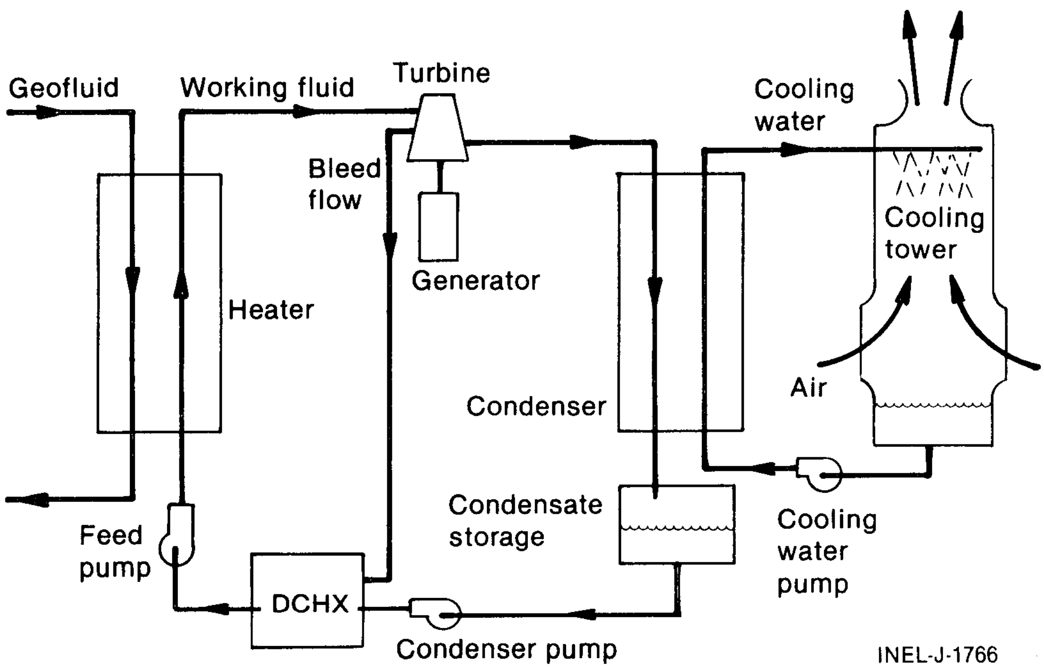

Figure 3: Binary Geothermal Cycle with Turbine Bleed

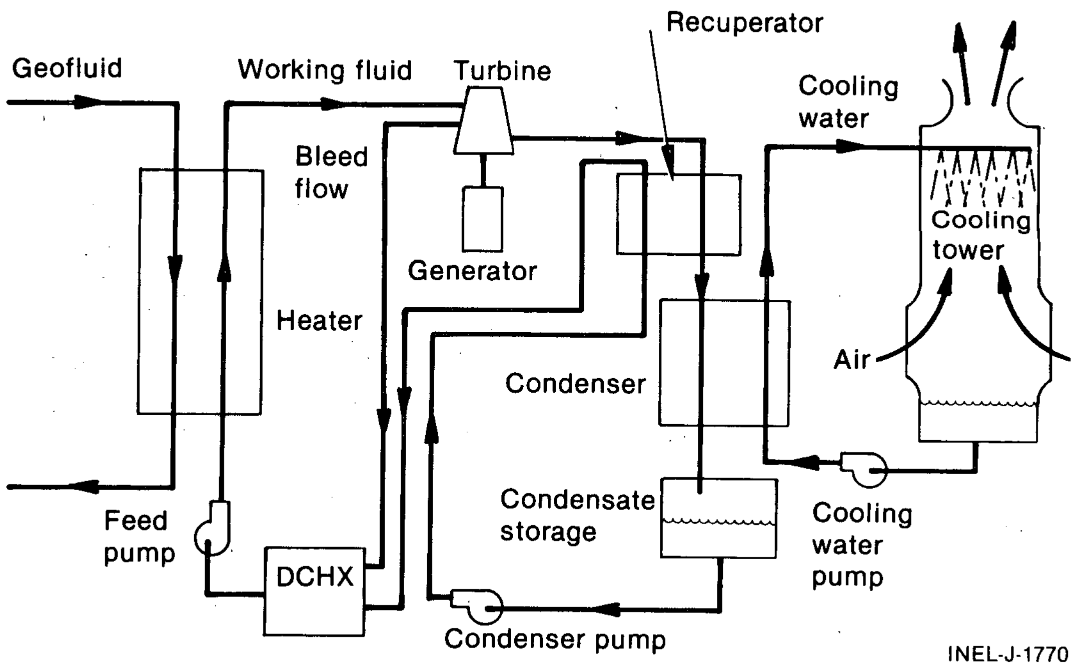

Figure 4: Binary Geothermal Cycle with Turbine Exhaust Recuperator and Turbine Bleed

is used to recover as much energy as possible within the constraints imposed by the turbine outlet and condensate bubble-point temperatures; the turbine bleed flow is sized to add just enough energy to maintain a 160°F geofluid outlet temperature while holding a specified pinch point temperature difference in the main working fluid heater.

Thermodynamically, one can recognize that the irreversibility generated in a heat exchange process is directly related to the total increase in entropy of the two fluids involved; it can be shown that the average difference in temperature between the two fluids during a heat exchange process is a measure of the thermodynamic irreversibility introduced. Counterflow heat exchangers help minimize this difference as does the utilization of the mixed hydrocarbon boiling and condensing characteristics as described in Reference 2. The non-isothermal boiling and condensing curves (temperature versus heat transferred) of a properly selected mixed working fluid follow the heating/cooling geofluid temperatures much more closely than the isothermal boiling and condensing curves of a pure fluid, thus also reducing the thermodynamic irreversibility. The recuperator and turbine bleed take some of the heat load from the heater working fluid inlet where the temperature difference is greatest, subsequently reducing the heat rejected to the cooling water (condenser). As a result the thermodynamic efficiency is increased, while the heater, condenser, and cooling tower sizes are reduced.

Quantitative estimates of the cycle efficiency increase, and of the resulting increase in geofluid effectiveness (while maintaining the 160°F geofluid outlet temperature), due to each of these changes are the primary considerations of this report.

3. CYCLE ANALYSIS METHODS

3.1 General

A number of single heating cycles were investigated with three mixed-hydrocarbon working fluids for a geothermal resource temperature of 360°F. Working fluids considered were 88% isobutane/12% isopentane (representative of the working fluid selected for the Heber plant), 96% isobutane/4% heptane (judged the most promising candidate from Reference 2), and 95% propane/5% hexane (the highest geofluid effectiveness from Reference 2, although at a very high turbine inlet pressure of 1,400 psia). Note that all compositions presented in this report are given in mass percents.

The general approach taken from each working fluid and system configuration investigated was to conduct cycle calculations which included determination of turbine power, working fluid pumping parasitic loss, and an estimate of the parasitic loss introduced by a wet cooling tower. The calculations were repeated for a number of turbine inlet (heater) pressures until a maximum net plant power was found. Optimum plant component sizes and state points were established for a nominal summer wet bulb temperature of 60°F during this process. The process was repeated for each working fluid, both with and without turbine bleed and/or recuperator. Cycle calculations were then conducted for off-design conditions at lower wet bulb temperatures. In these cases, the nominal, fixed, system configuration established in the design case was evaluated for changes in thermodynamic performance resulting from changes in ambient wet bulb temperature.

3.2 Assumptions

1. Shell-and-tube heaters, condensers, and recuperators were assumed. Turbine bleed cycles also used an auxiliary direct contact heat exchanger (DCHX).

2. Design pinch points (minimum approach temperature differences) in the heaters were 10°F for the nominal summer (60°F wet bulb) ambient condition.

3. Wet cooling towers were assumed which provide counterflow cooling water to the condenser at 70°F for the design case. (Cooling water inlet temperatures were lower for the off-design cases.) Counter-current cooling water flow was selected to maintain condensing approach temperature differences of 10°F for the nominal (60°F wet bulb) ambient conditions.

4. Pinch point temperature differences were kept at or above 9°F when establishing recuperator nominal designs.

5. Geofluid pumping requirements (at a given geofluid flowrate) were assumed the same for all cases, and those parasitic losses were not included.

6. Component and piping frictional pressure drops were neglected.

7. Pump and turbine efficiencies were assumed to be 80 and 85%, respectively, and electrical losses were not included.

8. Heater outlet state points were selected to avoid two-phase equilibrium conditions throughout the turbine expansion process and to minimize desuperheating of the turbine exhaust.

9. As in References 1 and 2 total cooling tower parasitic losses in in watts were estimated from earlier work as 0.077 times the cooling water flow in lbm/hr for a cooling water temperature rise (ΔT_{CW}) = 20°F. For $\Delta T_{CW} \neq$ 20°F small adjustments in this factor were made to account for changes in pumping power required for the modified cooling water flow.

10. Water properties were taken from the ASME steam tables (Reference 2). The mixed hydrocarbon fluid properties were obtained using computer program THERPP (Reference 4), which utilizes Starling's modified Benedict-Webb-Rubin equation of state.

11. For the turbine bleed study the working fluid exiting the DCHX is assumed to be at saturated liquid conditions, and the bleed flowrate adjusted to provide this.

An additional consideration resulted from the study of the 360°F geothermal resource. At this resource temperature sufficient silica is assumed to be dissolved in the geofluid that precipitation (possibly causing wellbore damage) may occur if untreated plant discharge geofluid is allowed to reach temperatures much less than 160°F. To incorporate this consideration, cycle performance was calculated for cases having plant geofluid outlet temperatures of 160°F as well as those which maintained 10°F pinch points in the heaters. For the off-design cases studied using 96% isobutane/4% heptane, normal plant operational strategy (i.e., choice of working fluid flow, heater pressure, geofluid flow, etc.) was predicted to result in the heater geofluid exiting at temperature somewhat lower than 160°F; different strategy could raise this temperature, but would impact plant performance to some extent during the coldest ambient conditions.

3.3 Summary of Analytical Procedure

In general, hand calculations, supplemented by a simplified computer code to aid in the iterative calculations of the heat exchanger performance, were used to generate the state points throughout the system. Without detailing each of the many cycle calculations, a brief summary of the calculational procedure will be given for two representative types of cycles from which calculation procedures for the other types can be derived. The two types presented below include: (1) the recuperator cycle, and (2) the turbine bleed cycle.

3.3.1 Recuperator Cycle

Reference will be made to the calculations for the 96% isobutane/4% heptane cycle at 600 psia turbine inlet pressure because this cycle was studied for both design and off-design ambient wet bulb conditions. Figure 2 and Figures 9 through 11 show flow diagrams of this cycle.

The first step in any of the calculations is to obtain fluid properties (References 3 and 4) over the temperature and pressure range of interest. The cycle calculations are begun by selecting a turbine inlet pressure, thus establishing the working fluid pressure level in the high pressure side of the loop. The turbine inlet entropy is then selected so that the turbine expansion process does not go through the two-phase region. Now, from these two properties (pressure and entropy), all other properties at the turbine inlet can be obtained. The condenser bubble-point temperature is specified; thus the pressure on the low pressure side of the loop is known. The remaining exit properties can then be obtained since the exit pressure and turbine efficiency are known.

Now, the recuperator can be isolated. The pump inlet conditions are those at the condenser outlet (bubble point). The pump outlet pressure (assumed to equal the heater pressure) is known, together with its efficiency, so that the state points on both sides of the pump can be obtained. The recuperator cold side inlet conditions are thus defined. (Note that if the pump ΔP is extremely high, the temperature increase across the pump may result in recuperator cold side temperatures being too high for satisfactory recuperator performance. In this case a dual-stage pumping procedure is used in which the first pump raises the recuperator inlet pressure only high enough to keep the working fluid saturated as it is heated in the recuperator, and then a second pump downstream of the recuperator raises the pressure to the turbine inlet pressure.) Since the two recuperator inlet temperatures are known, an iterative procedure can be implemented to solve for the two outlet temperatures with the constraint that the minimum temperature approach (pinch point) be a selected value (9°F in these cases). For the 96% isobutane/4% heptane cycle, it was found that desuperheating and some condensing took place in the recuperator; these conditions resulted in the pinch point occurring at the working fluid dew point. Recuperator temperature distributions can now be calculated, together with an overall heat exchanger UA (product of heat transfer surface area and coefficient) for sizing the recuperator. (This UA was used in the off-design studies.)

The condenser working fluid inlet and outlet state points are now known. For the summer design case, a cooling water inlet temperature was specified to represent a dew point of 60°F. This allowed calculation (again iteratively) of the condenser flow rate ratio to result in a pinch point of 10°F, and obtain an overall UA for the condenser. Inlet and outlet conditions on both sides of the condenser are thus known. For the study of a winter cycle, a lower condenser outlet bubble point temperature was selected, and then the cooling water inlet temperature and pinch point were allowed to float while constraining the cooling-water-to-working-fluid flow ratio and overall UA to the design values.

The remaining unit to be studied is the heater. The working fluid inlet and outlet temperatures are known, as is the geofluid inlet temperature. For the design case the heater was sized so as to give approximately a 160°F geofluid outlet temperature. This resulted in a ratio of working fluid to geofluid flow , and an overall UA for a 10°F pinch point. For the study of the off-design case, the flow ratio, pinch point, and geofluid outlet temperature were allowed to float while the overall UA and working fluid outlet conditions were kept the same as for the design cycle. The result of this approach is that the geofluid outlet temperature decreases somewhat as the wet bulb temperature is decreased.

3.3.2 Turbine Bleed Cycle

Most of the cycle calculations for the turbine bleed operation are the same as those discussed in 3.3.1 above. Only the differences are presented below. Figures 3 and 4 show the schematic diagrams of the turbine bleed options.

The first difference is that an additional pump is required, with a different system pressure to be calculated between the pumps. The intermediate pressure is specified by the assumption that saturated liquid exits the direct contact heat exchanger.

The heater is studied first to obtain the working fluid inlet conditions in the same manner as previously discussed (fix working fluid outlet, pinch point, geofluid inlet and outlet conditions to obtain working fluid inlet, flow ratio, and overall UA). Then calculate the enthalpy change (Δh) across the feed pump to obtain properties (saturated liquid) at DCHX outlet. Once the intermediate pressure is known, the condenser pump conditions can be evaluated as before. Caculation of the recuperator performance follows (if there is one), and the state points and flows for the condenser are determined as previously described.

The last calculation is to define the amount of turbine bleed that will combine with the condenser flow and produce saturated liquid out of the DCHX. The bleed flow is obtained by a simple enthalpy balance on the DCHX since all state points are known. Note that the bleed flow must be accounted for in the power calculations since some working fluid bypasses part of the turbine as well as the condenser and condenser pump.

4. RESULTS

4.1 Baseline Cycles

Results of cycle analyses for a 360°F geothermal resource temperature, and a 60°F wet bulb temperature, without a recuperator or turbine bleed, are shown in Figure 5 to provide baseline performance values. This figure shows values of net plant power (geofluid effectiveness) versus the turbine inlet temperature for each of the three mixtures studied. The Raft River 5MW plant working fluid, isobutane, is shown for comparison. The solid lines correspond to cases in which the heater outlet geofluid temperature was held at 160°F (to prevent silica precipitation), and the dashed lines represent cases in which the geofluid outlet temperature was allowed to fall below 160°F while maintaining a 10°F pinch point in the heater. The two different constraints result in different values of maximum performance which occur, in general, at different values of turbine inlet temperature for a given working fluid system.

Baseline performance comparisons (Figure 5) indicate the following:

1. All three candidate binary working fluids show performances 6-14% greater than for pure isobutane. This improvement is an indication of the reduced irreversibilities produced by a properly selected mixture in the heating and condensing processes.

2. Most significant in the figure is the large loss in performance of each fluid when the geofluid exit temperature is restricted to 160°F by silica precipitation considerations. If the performance lost by this restriction could be recovered, the geofluid effectiveness could be increase by as much as 7% for the 96% isobutane/4% heptane mixture and 14% for the 95% propane/5% hexane mixture. This possibility is pursued in the next section.

3. In general, the 95% propane/5% hexane mixture displayed the highest geofluid effectiveness but at the penalty of an extremely high turbine inlet (heater) pressure of 1,400-1,800 psia versus 600 psia for the 96% isobutane/4% heptane mixture.

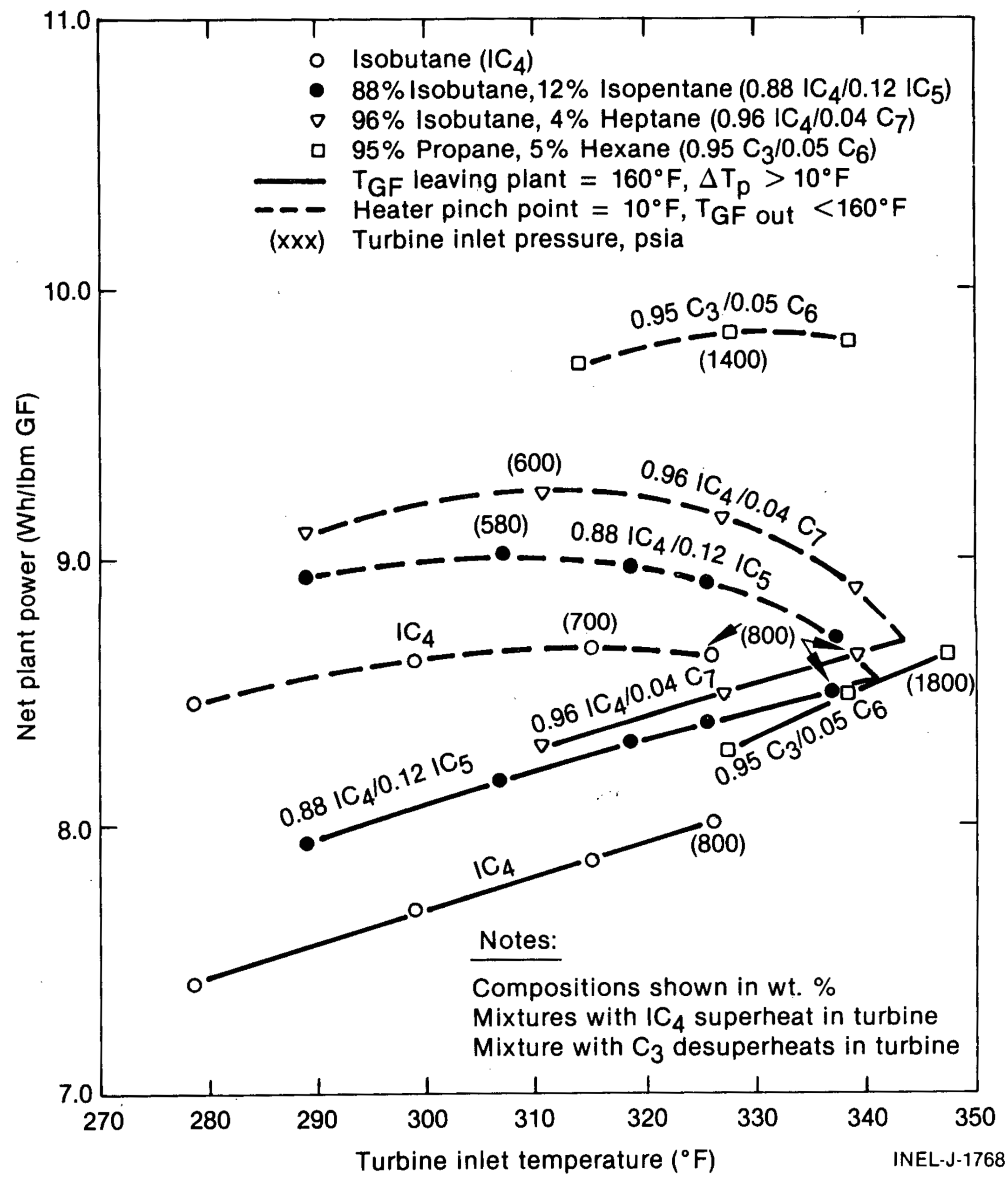

Figure 5: Net Plant Power without Turbine Exhaust Recuperator or Turbine Bleed, T_{GF} = 360°F, $T_{Wet\ Bulb}$ = 60°F

4.2 Regenerated Cycles, Summer Design Points

The next phase of this study was to investigate methods of recovering part or all of the cycle performance lost by introducing the 160°F geofluid outlet constraint. This recovery was accomplished through use of turbine bleed and/or recuperation for the same 360°F geothermal resource with a 60°F wet bulb temperature. Cases were run for each of the three mixtures; the results are presented in Figures 6 through 8. The results for each fluid will be discussed below.

4.2.1 88% Isobutane/12% Isopentane (Heber Fluid)

Figure 6 shows the results of the study of the Heber plant working fluid utilizing a recuperator and a recuperator plus turbine bleed to reduce the thermodynamic irreversibilities. It is seen that if a recuperator is used, even with the geofluid exit temperature restriction of 160°F, the performance is comparable to the non-recuperated case without a geofluid outlet temperature restriction. Adding turbine bleed does very little to the recuperated cycle alone.

4.2.2 96% Isobutane/4% Heptane

Figure 7 shows the results of the study for the isobutane/heptane mixture, the most promising of the three working fluids, utilizing a recuperator and a recuperator plus turbine bleed for energy recovery. Here, again, the recuperator alone can maintain the 160°F geofluid outlet temperature and enhance the cycle performance to the level of an unrecuperated cycle without the 160°F geofluid exit temperature limit. Adding turbine bleed did not improve the geofluid effectiveness. The recuperated cycle at 600 psia turbine inlet pressure shows the most promising performance of those investigated. At these conditions, the net plant power of 9.28 watt-hr/lbm geofluid is derived from the components of 11.53 watt-hr/lbm geofluid power output from the turbine, 1.29 watt-hr/lbm geofluid parasitic loss for the pump, and 0.96 watt-hr/lbm geofluid parasitic loss for the wet cooling tower.

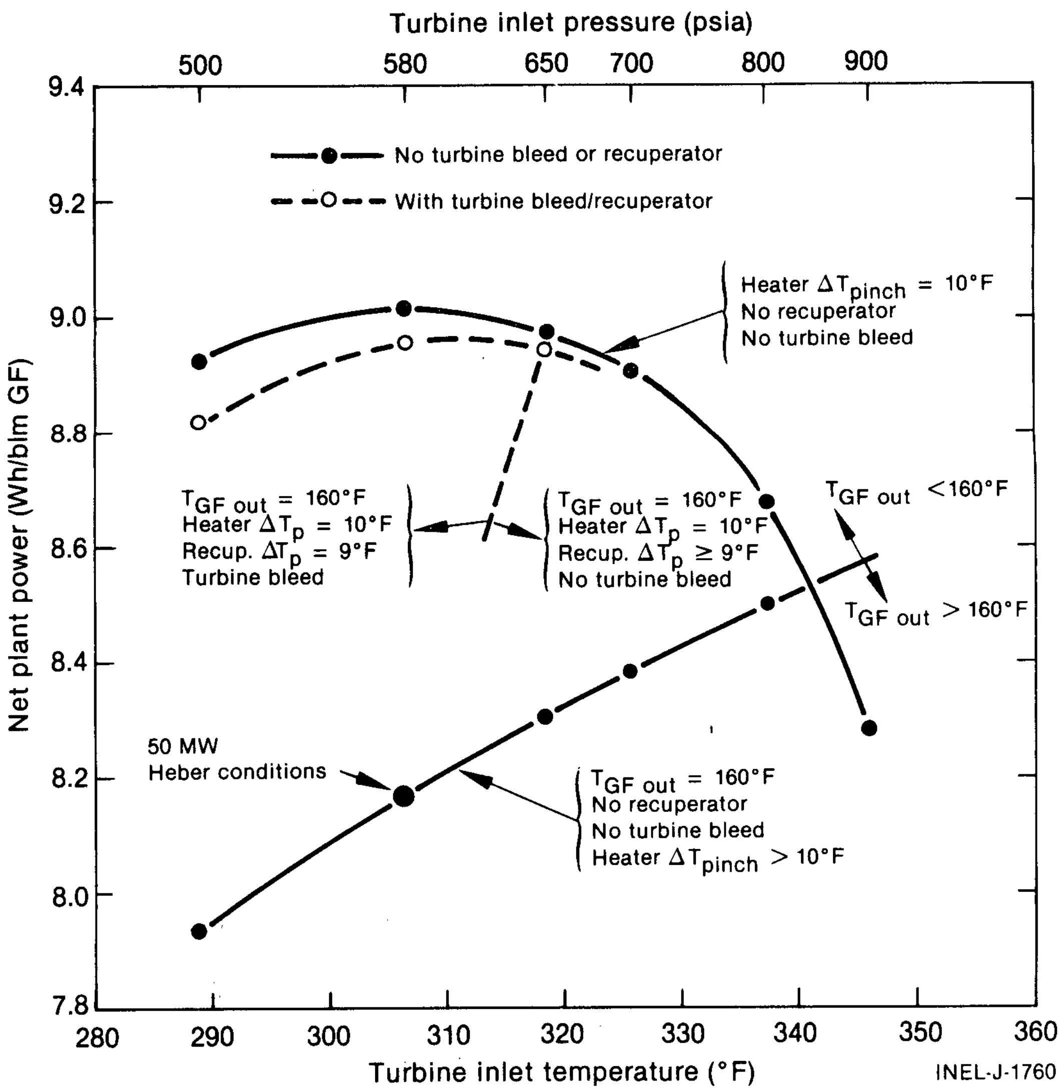

Figure 6: Effects of Turbine Exhaust Recuperator and Turbine Bleed on Net Plant Power, 88% Isobutane/12% Isopentane, T_{GF} = 360°F, $T_{Wet\ Bulb}$ = 60°F

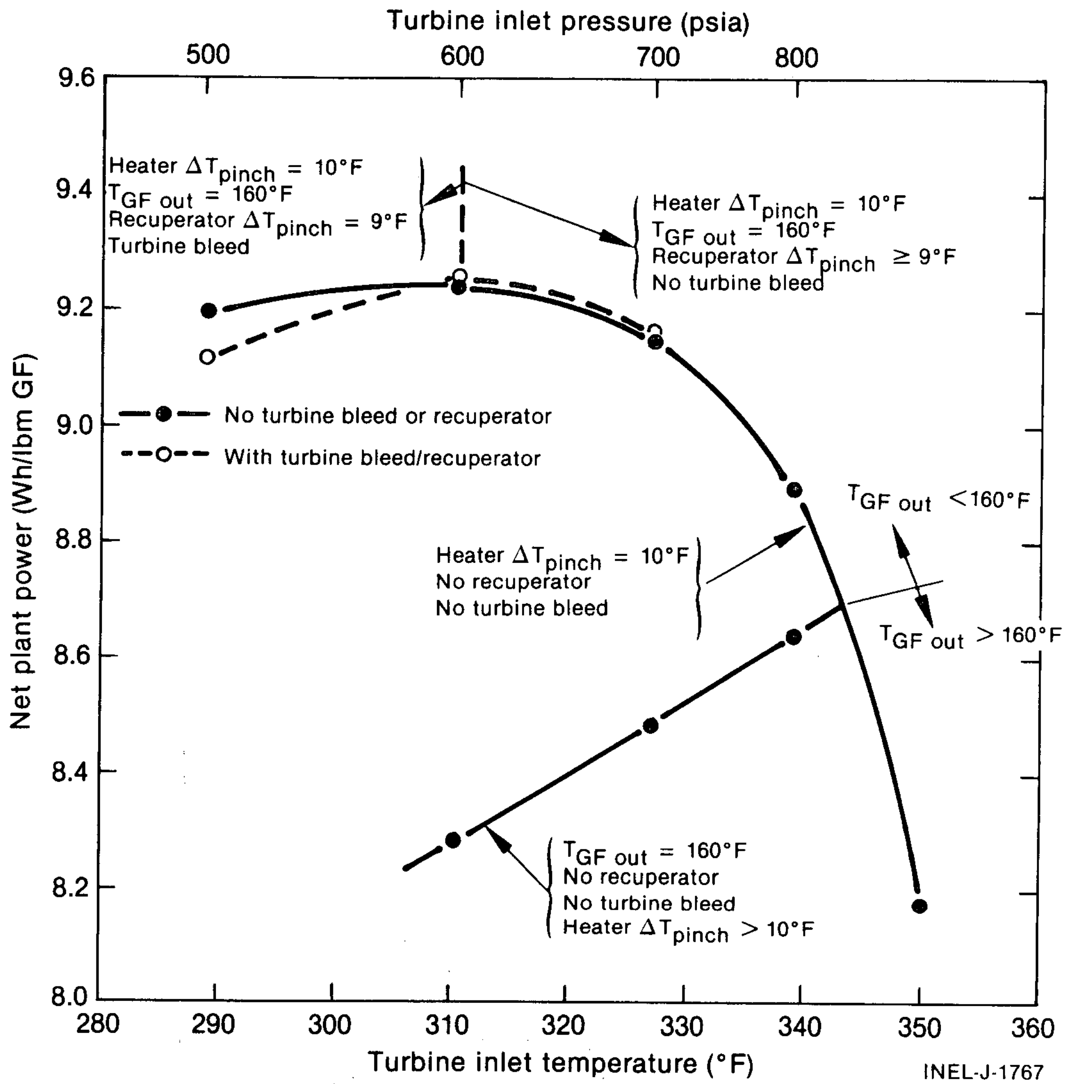

Figure 7: Effects of Turbine Exhaust Recuperator and Turbine Bleed on Net Plant Power, 96% Isobutane/4% Heptane, T_{GF} = 360°F, $T_{Wet\ Bulb}$ = 60°F

4.2.3 95% Propane/5% Hexane

Figure 8 shows the results of the study for this fluid utilizing turbine bleed and recuperator. This working fluid performs considerably better than the others if the geofluid outlet temperature is allowed to go below 160°F. If, however, the outlet temperature is held at 160°F, the performance with turbine bleed and recuperator is very close to that for 96% isobutane/4% heptane, but at a much higher heater pressure. The recuperator is not nearly as effective for this working fluid as for the other two mixtures because the working fluid exhausts from the the turbine in a saturated vapor state.

4.2.4 Comparison of Fluids

This study suggests that the most promising working fluid of those studied is the 96% isobutane/4% heptane mixture utilized in a cycle with a turbine exhaust recuperator. The optimum turbine inlet pressure is found to be 600 psia. This cycle, operated with a 160°F lower limit on the geofluid outlet temperature, will produce as high a geofluid effectiveness as the unrecuperated 96% isobutane/4% heptane cycle without the temperature restriction; its geofluid effectiveness is about the same as for the recuperated 95% propane/5% hexane mixture but without the high pressure requirements.

4.3 Off-Design Operation

4.3.1 Assumptions

This portion of the study was performed to investigate the performance of the most promising cycle in off-design or winter ambient conditions. Basically, the system configuration selected included:

1. Working fluid is 96% isobutane/4% heptane.

2. Heater pressure = 600 psia.

3. Recuperator operation with 9°F pinch point.

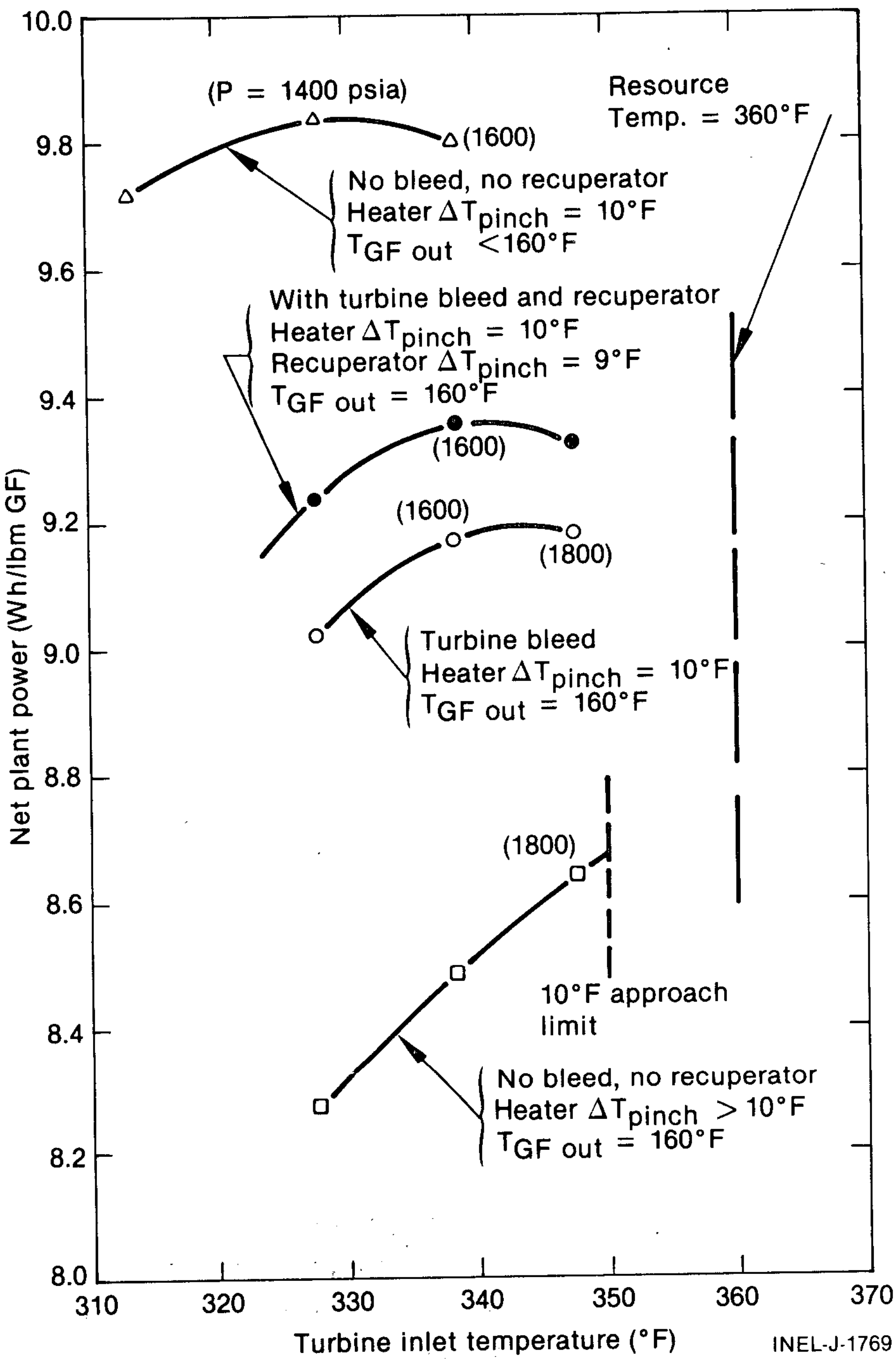

Figure 8: Effects of Turbine Exhaust Recuperator and Turbine Bleed on Net Plant Power, 95% Propane/5% Hexane, T_{GF} = 360°F, $T_{Wet\ Bulb}$ = 60°F

4. Heater and condenser with 10°F pinch points.

5. Heat exchanger sizing was same as for the summer design case.

In addition, an operation strategy had to be selected to be able to obtain a solution since many ways of operating the plant could be considered. First, it was decided to maintain the turbine inlet conditions fixed at the design values, including temperature, pressure, entropy and flowrate. This allowed the use of the same fixed geometry turbine. However, as a result of this restriction, the geofluid outlet temperature and fluid flowrate ratio in the heater were required to float. The UA of the heater was kept the same.

In the condenser, both the UA and the fluid flowrate ratio were maintained at the design values. Working fluid outlet temperatures were selected at bubble points of 85°F (design value), 70°F and 55°F; these bubble point temperatures then fixed the working fluid pressure on the low pressure side of the system. From typical Marley wet cooling tower performance data, an ambient wet bulb temperature was estimated which would provide the cooling water flowrate and inlet temperature required. This approach, rather than specifying a wet bulb temperature beforehand, simplified the calculations and still produced the desired relationship of performance versus ambient wet bulb temperature.

For the recuperator the UA was maintained at the design value.

4.3.2 Results (Off Design Ambient Conditions)

Calculations were performed for wet bulb temperatures of 60°F (summer design), 37.6°F, and 11.7°F. The performance was found to increase with a decrease in wet bulb temperature as shown in Table 1 below. Results of this portion of the study in terms of state points, flows, and power balances for the three wet bulb temperatures are shown in Figures 9 through 11.

TABLE 1. RESULTS OF OFF-DESIGN PERFORMANCE STUDY, 360°F RESOURCE, 96% ISOBUTANE/4% HEPTANE, 600 PSIA TURBINE INLET, RECUPERATOR

Wet-Bulb Temperature (°F)	Net Plant Power (watt-hr/lbm GF)	Condenser Bubble Point (°F)	Condenser Coolant Inlet (°F)	Geofluid Outlet (°F)
60.0	9.28	85	70.0	159.2
37.6	10.55 (+13%)	70	54.3	151.4
11.7	11.86 (+28%)	55	38.8	143.8

In general, no problems with the cycles were encountered in operating this fixed system at the lower wet bulb temperatures. The geofluid flow rate in the heater changed negligibly so differences in well pump parasitics could be ignored. Note, however, that the geofluid outlet temperature decreased considerably at the lowest wet bulb temperatures. The extent of operational problems resulting from the relationship between wet bulb and geofluid outlet temperature (Table 1 above) is clearly site specific. It has been estimated that for the 360°F resource temperature, actual precipitation will not occur above a geofluid temperature of about 145°F. If plant outlet piping were well insulated, for example, wet bulb temperatures above, say 20°F, may not result in silica precipitation; therefore, precipitation may not be a problem for many sites. At sites for which silica precipitation would be expected during the colder periods, plant operational strategy could be modified, perhaps by running less working fluid through the cycle at a reduced turbine inlet pressure with a resulting performance penalty incurred during a small part of the year. Selection of a modified operation and prediction of the resulting performance was not undertaken in this preliminary investigation.

Table 1 shows that performance gains of up to 28% could be obtained during cold weather operation in the mode selected. A year-round average can be obtained from wet bulb data for a specific site by integrating the short term performance data shown.

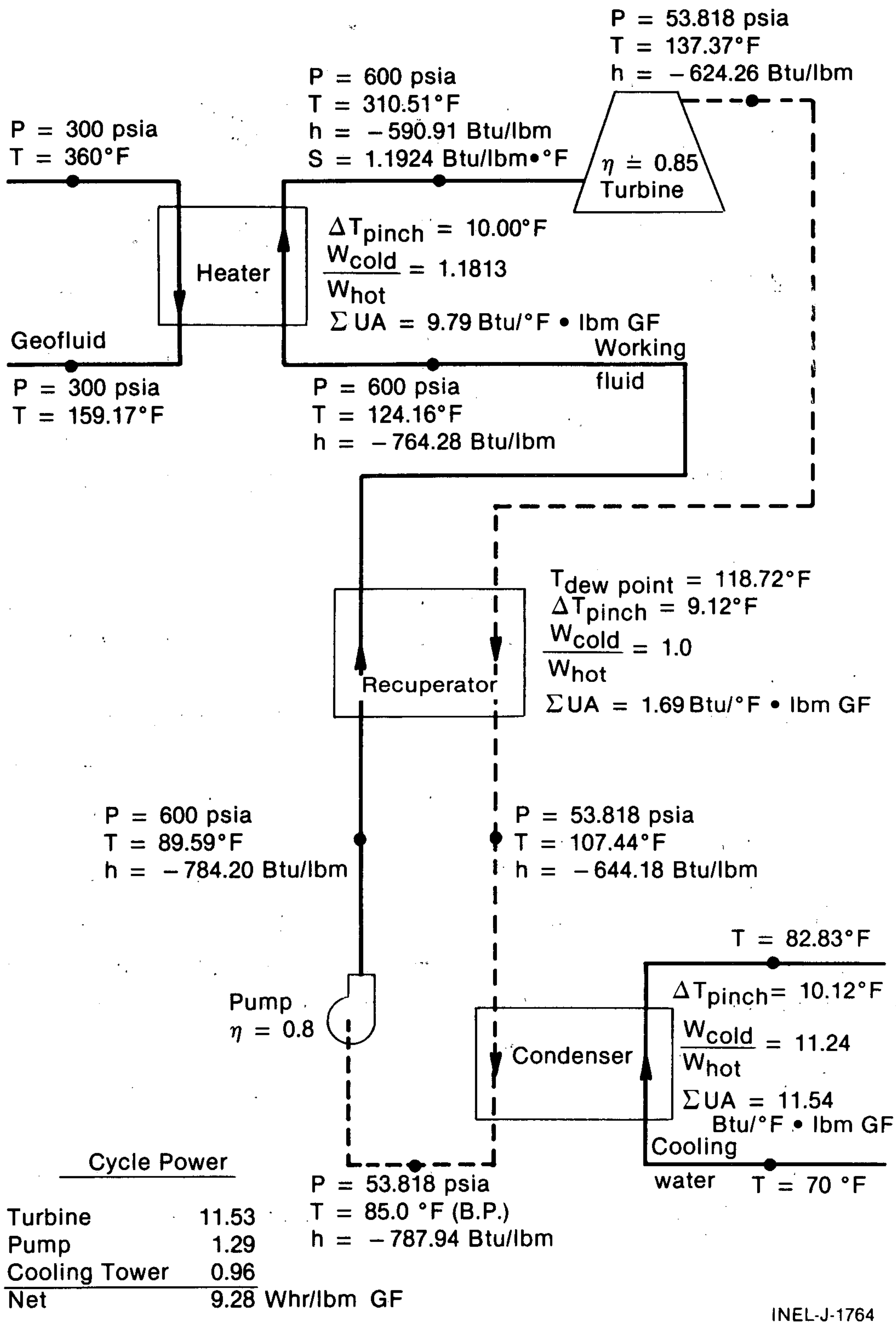

Figure 9: State Point Diagram, 96% Isobutane/4% Heptane, 600 psia Turbine Inlet, T_{GF} = 360°F, $T_{Wet\ Bulb}$ = 60°F (summer design)

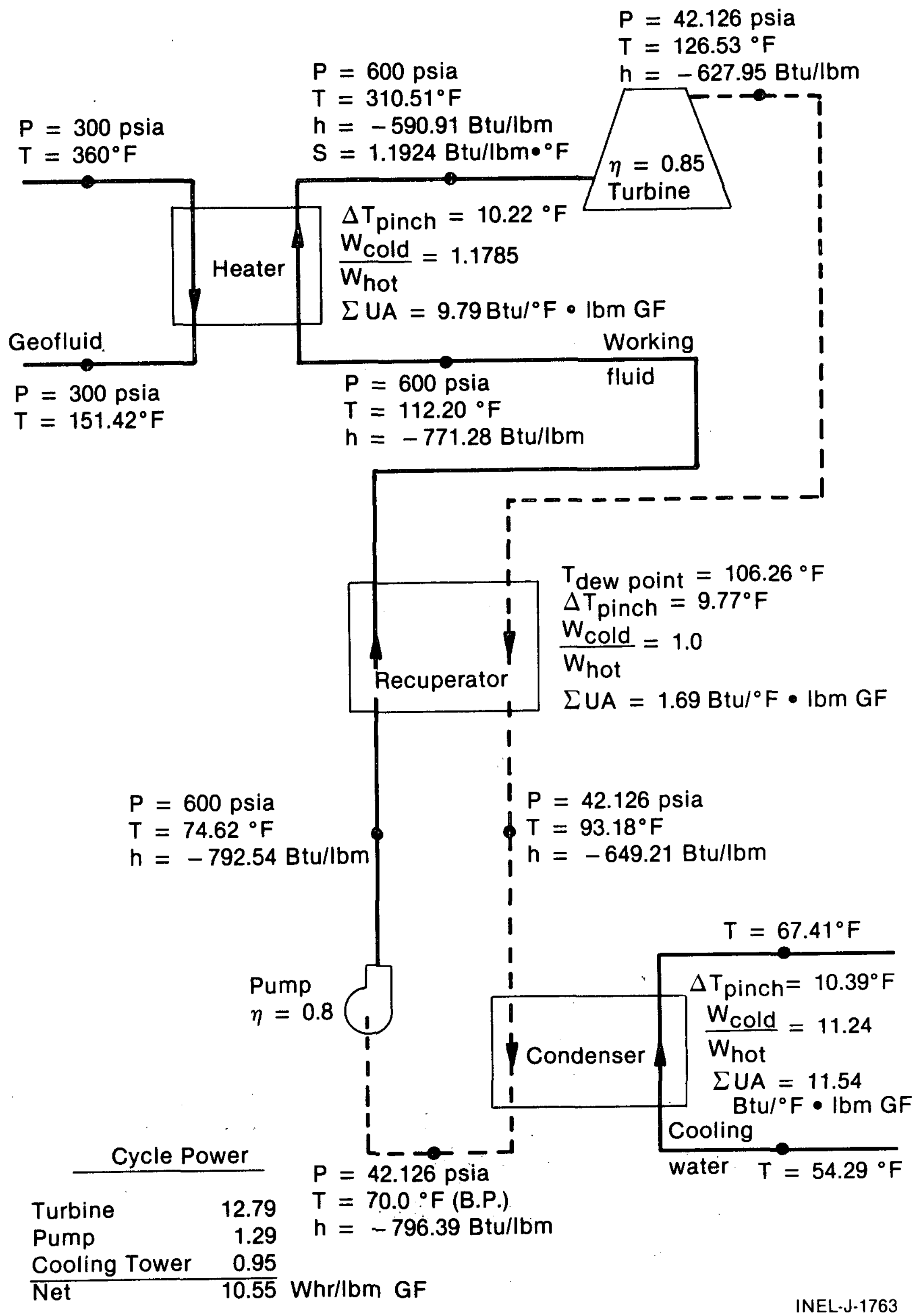

Figure 10: State Point Diagram, 96% Isobutane/4% Heptane, 600 psia Turbine Inlet, T_{GF} = 360°F, $T_{Wet\ Bulb}$ = 37.6°F

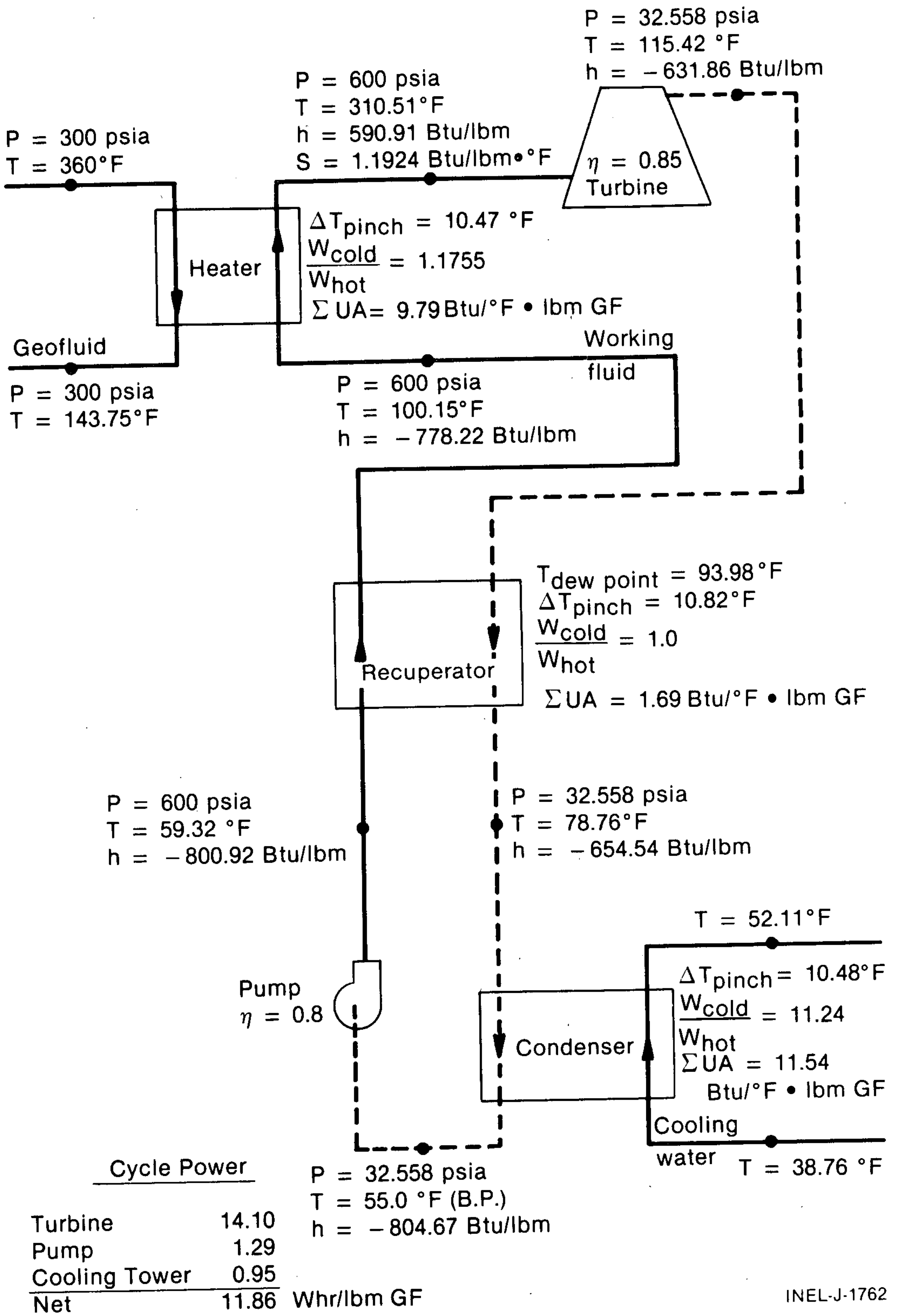

Figure 11: State Point Diagram, 96% Isobutane/4% Heptane, 600 psia Turbine Inlet, T_{GF} = 360°F, $T_{Wet\ Bulb}$ = 11.7°F

5. CONCLUSIONS

Results and conclusions of the several portions of the study are summarized below:

1. For the 360°F geothermal resource studied herein, the maximum unregenerated geofluid effectiveness occurred for a 95% propane/5% hexane working fluid at a heater pressure of 1,400 psia. In this case the geofluid outlet temperature fell below 160°F (indicating potential silica precipitation problems).

2. For a geofluid outlet temperature maintained at 160°F, the same working fluid at 1,600 psia heater pressure provided the highest geofluid effectiveness of the three investigated. However, the recuperated 96% isobutane/4% heptane working fluid had an effectiveness only about 1% lower at a heater pressure of 600 psia, a more conventional pressure level. The latter cycle was judged to be the better, overall.

3. For the 96% isobutane/4% heptane cycle, imposing a lower limit of 160°F on the geofluid outlet temperature penalized the net geofluid effectiveness by about 7%.

4. For that mixture a recuperator alone can recover the entire increment of geofluid effectiveness lost by imposing the 160°F lower limit on the geofluid outlet temperature, and at the same time reduce the cooling tower size and makeup water by about 14%.

5. Recuperated winter operation shows no general operational difficulty, and results in a considerable increase in geofluid effectiveness. The lowest wet bulb temperature considered, 11.7°F, showed an effectiveness increase of 28%. The geofluid outlet temperature fell below 160°F for the lowest wet bulb temperature. The possibility of resulting silica precipitation must be examined on a site specific basis.

6. Mixed hydrocarbon working fluids utilizing turbine exhaust recuperation appear promising, and warrant experimental evaluation.

6. REFERENCES

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