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Evaluation Of Hybrid Air-Cooled Flash/Binary Power Cycle

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Abstract:
Geothermal binary power plants reject a significant portion of the heat removed from the geothermal fluid. Because of the relatively low temperature of the heat source (geothermal fluid), the performance of these plants is quite sensitive to the sink temperature to which heat is rejected. This is particularly true of air-cooled binary plants. Recent efforts by the geothermal industry have examined the potential to evaporatively cool the air entering the air-cooled condensers during the hotter portions of a summer day. While the work has shown the benefit of this concept, air-cooled binary plants are typically located in regions that lack an adequate supply of clean water for use in this evaporative cooling. In the work presented, this water issue is addressed by pre-flashing the geothermal fluid to produce a clean condensate that can be utilized during the hotter portions of the year to evaporatively cool the air. This study examines both the impact of this pre-flash on the performance of the binary plant, and the increase in power output due to the ability to incorporate an evaporative component to the heat rejection process.

Key words: binary power cycle, flash-binary power cycles, air-cooled condensers, evaporative heat rejection

Introduction:
Geothermal resources are frequently found in semi-arid regions of the United States that lack an adequate supply of water for evaporative heat rejection systems. With a flash-steam conversion system, the condensed steam provides the required makeup water for an evaporative rejection system. When the geothermal resource temperature dictates the use of a binary power cycle, the lack of water typically necessitates that heat be rejected sensibly to the ambient. Because this sensible heat rejection is to the ambient dry-bulb temperature, the diurnal and seasonal variations in the ambient temperature can have a significant impact on the plant's power production. With a 300°F resource, an increase in the heat sink (ambient) temperature from 50° to 100°F decreases the brine's available energy (ideal work that can be done) by ~37%. The impact on a plant's power output is larger because conversion efficiencies tend to decrease for operation at off-design ambient conditions.

To mitigate this adverse impact on power output, work is being done to develop methods to evaporatively pre-cool the air before it passes through the condenser tube bundle. One such effort at a binary plant near Mammoth Lakes CA, has shown that shown the feasibility of this concept. Wider use of the concept has been limited by the availability of water. Unless there is another source of water, operators would have to use the cooled geothermal fluid for this evaporative cooling.

In the analytical study being reported, a model of a conventional binary plant was modified to include a geothermal fluid pre-flash to produce steam, which would subsequently be condensed and subcooled before being used in the evaporative air cooler. The plant configuration used to perform this condensation and subcooling is shown in Figure 1. In this configuration, the steam condenser and the binary cycle vaporizer are in parallel, while the condensate subcooler and the binary cycle preheater are in series. The configuration would allow the flash portion of the cycle to be isolated and placed in a stand-by mode during the winter, when the plant would operate as a conventional binary cycle.

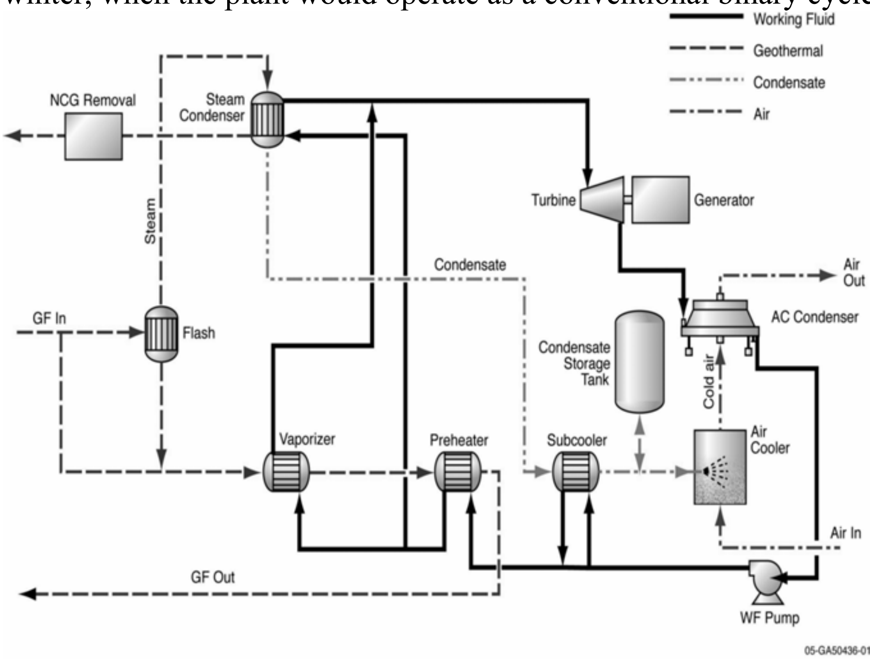

Figure 1: Schematic of the hybrid flash-binary cycle

The model of the binary portion of the power cycle was developed based upon the following assumptions.

- 300°F geothermal fluid
- 10 MW net (exclusive of geothermal fluid pumping requirements)
- isobutane working fluid
- air design conditions of 50°F, 14.7 psia and 50% relative humidity
- working fluid to air flow ratio of 0.04 (corresponding air temperature range of ~22°F)
- rotating equipment efficiency of 80% (pump and turbine)
- fan efficiency of 55%
- heat exchangers sized for 10°F pinch points at design conditions
- turbine inlet superheat of 1°F
- design pressure drops of 30 psi for the working fluid and 0.25-inch of water for the air

The baseline plant (no pre-flash or evaporative cooling) was sized to produce the indicated 10 MW at the design ambient and resource temperatures. The geothermal fluid flow rate and the heat exchanger, pump, fan, and turbine sizes were determined based on this plant output. In projecting plant output at different ambient conditions, equipment sizes and geothermal flow were held constant. At off-design conditions, working fluid and air flow rates were determined by assuming pump or fan power was constant and that the fluid pressure drop varied with the change in fluid velocity (flow rate divided by density) raised to an appropriate power. When the geothermal fluid pre-flash and evaporative air cooling system were incorporated into the plant model, the following assumptions were made:

- pre-flash pressure > 14.7 psia
- no power parasitic associated with the evaporative air cooling system

An analysis was performed to determine the impact of a range of ambient conditions on the plant output. The ambient conditions were representative of those expected for a location in the western United States. At the selected "summer" condition, the air temperature was 90°F, and the wet bulb temperature was 60°F. This summer condition and the design ambient condition were used to project the moisture content of the air at other ambient temperatures. At this "summer" condition the air has a low relative humidity (~15%), which would allow for significant cooling of the air, provided sufficient water is available.

Results:
Baseline Binary Plant Performance: The performance of the baseline binary plant (without the pre-flash or air cooling) is shown in Figure 2 as a function of the higher ambient temperatures. Two performance curves are shown in this figure; in one the turbine inlet pressure is fixed and in the other the turbine inlet pressure is varied to match the pump discharge pressure (less the working fluid pressure drop). This flexibility requires a turbine with a variable nozzle geometry, and the associated control system. At the higher ambient temperatures, this ability to vary the turbine inlet pressure (and not throttle working fluid flow) allows up to 25% more power to be produced.

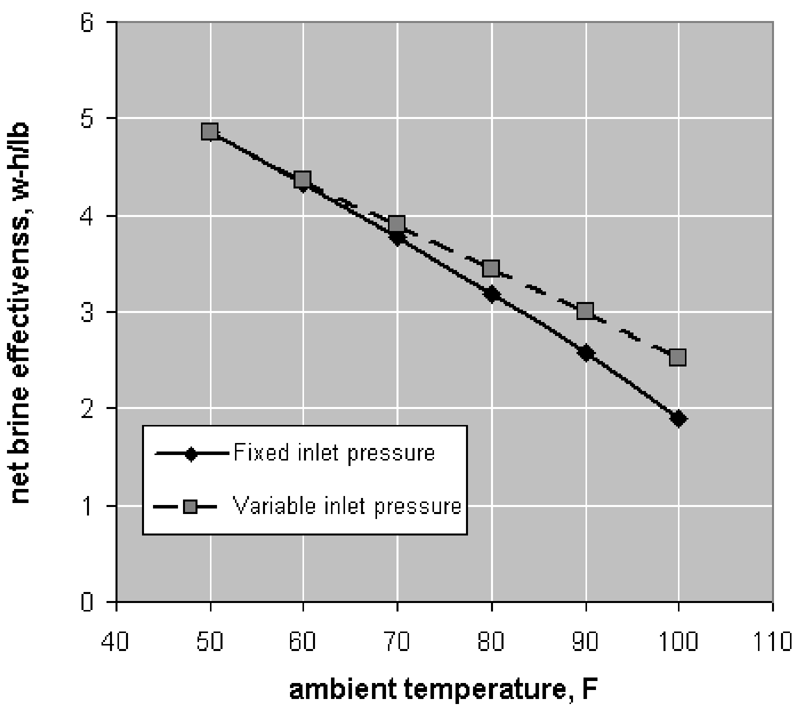

Figure 2: Binary plant performance without evaporative enhancement

Use of Condensate for Continuous Cooling of the Air: Once the baseline plant performance was established, the pre-flash, steam condenser and subcooler, and evaporative air-cooling system were incorporated into the plant model. The first scenario considered was the continuous use of the condensate produced from the pre-flash to cool the air entering the condenser. In Figure 3, the degree to which the air can be cooled is shown as a function of the flash pressure for two different air temperatures. These results show that while there is a limit to the amount cooling that can be done at the lower ambient temperatures, at the higher air temperatures the flash process will not produce sufficient steam condensate to approach the upper limit placed on the relative humidity.

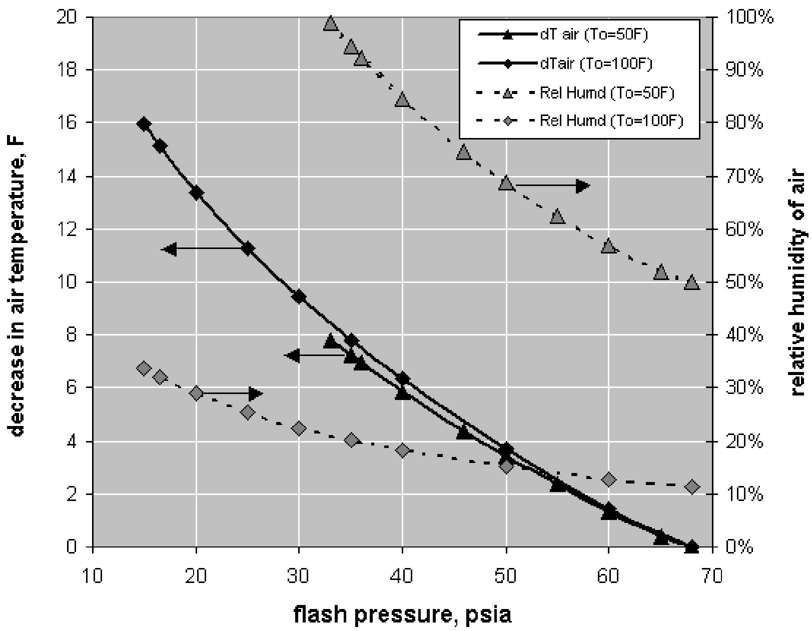

Figure 3: Effect of pre-flash pressure on air conditions entering the condenser

The relative impact of continuous air cooling on plant output is shown in Figure 4 (fixed turbine inlet pressure) and Figure 5 (variable turbine inlet pressure). These results indicate that at higher ambient temperatures, there is a larger impact on the plant performance if the turbine inlet pressure is fixed (representative of a fixed nozzle geometry). This result is primarily due to the greater impact the ambient temperature has on the plant output if the inlet pressure is fixed (see Figure 2). It does not indicate more power will be produced with the fixed inlet pressure (typically the variable inlet pressure will result in more power). Note that at the lower ambient temperatures, the fixed working fluid pumping power limits the degree to which the geothermal fluid can be flashed and continuously used for cooling the air.

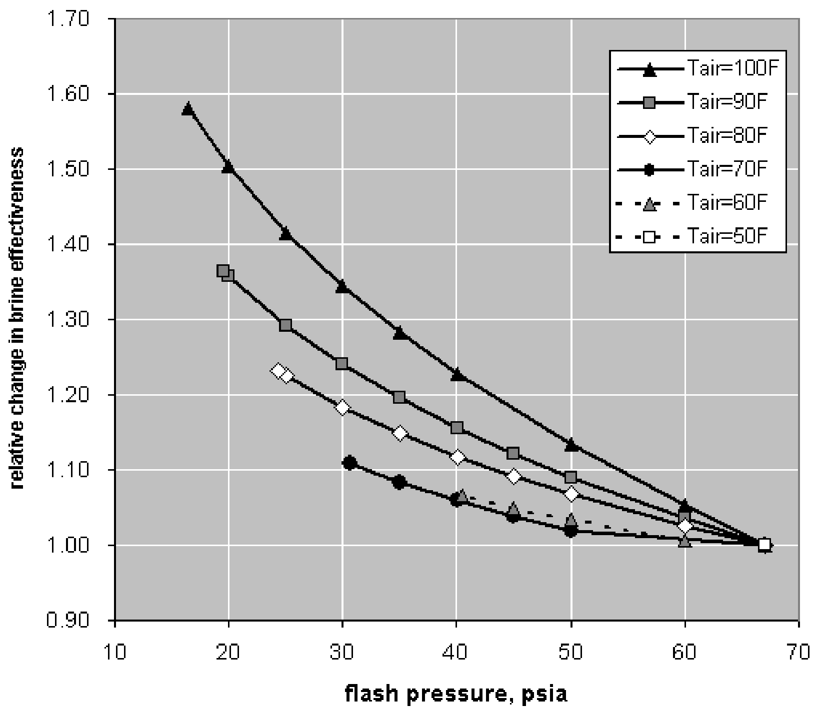

Figure 4: Impact of continuous cooling on plant performance with fixed turbine inlet pressure

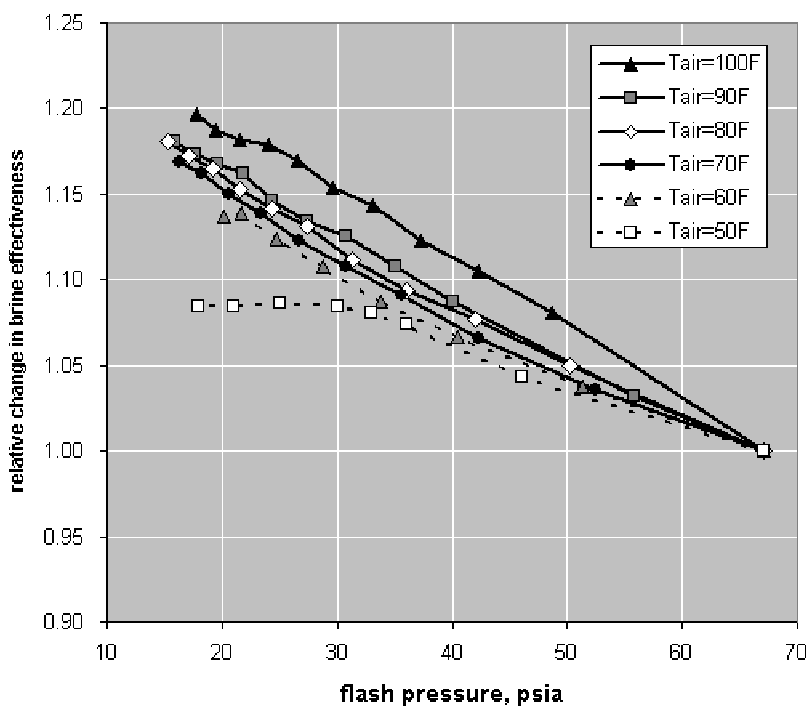

Figure 5: Impact of continuous cooling on plant performance with variable turbine inlet pressures

<u>Selective Use of Condensate for Air Cooling</u> In lieu of continuously cooling the air, the condensate produced can be stored during the cooler portions of the day and used to augment the cooling during the hotter periods of the day when there is significant potential for further cooling of the air (as suggested in Figure 3). While this scenario allows additional power to be produced during the hotter portions of the day, the flashing process impacts plant performance when the produced condensate is being stored. The impact of the flash process on plant performance (with variable turbine inlet pressure) is shown in Figure 6. Results indicate that there is minimal impact on performance at flash pressures above ~35 psia, and that this impact decreases with the ambient temperature. Because the hybrid plant will only operate in this mode during the cooler portions of the day, the indicated adverse effect of the ambient temperature on performance is not expected to be large. A similar evaluation where the turbine inlet pressure was fixed indicated the flashing would have even less impact on plant output.

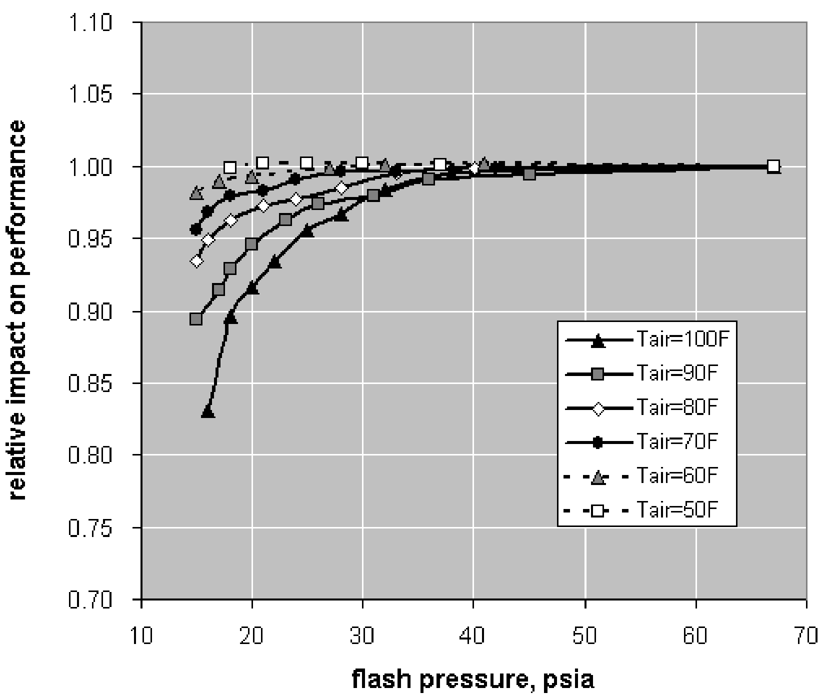

Figure 6: Impact on performance when condensate is being stored and air is not cooled

The potential impact of being able to cool air is showing in Figure 7 as a function of the both ambient temperature and the relative humidity of the cooled air. If the air was cooled continuously with condensate produced from a 20 psia flash pressure, then at a 100°F ambient temperature ~18% more power would be produced (see Figure 5). As shown in Figure 7, if sufficient water were available to cool the air at this temperature to a relative humidity of 75%, power output could be increased by ~55% (relative to the baseline plant). These results illustrate the impact that the selective use of the condensate could have during those periods when the ambient temperatures are highest.

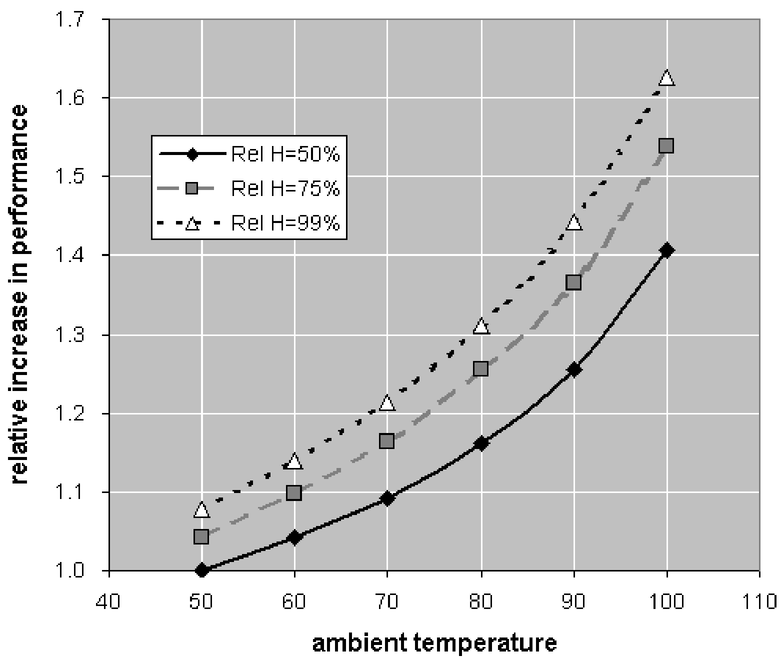

Figure 7: Impact of air cooling of plant output

<u>Effect on Plant Power Production:</u> In evaluating the impact of the hybrid binary/flash cycle on power production, it was assumed that the pre-flash and evaporative cooling system for the air would be used during the period between May 15th and October 15th. Using an hourly temperature data base for Reno NV (1995), it was projected that on hotter days up to 7,000,000 lbs. of water would be required to cool the air to a 99% relative humidity on a continuous basis. Generating this amount of water would require pre-flash pressures lower than the assumed lower limit of 14.7 psia on the flash process. If the evaporative air cooling system were used only during the 8 hour period between 10 am and 6 pm, the daily water requirement decreased to ~3,000,000 lbs, which could be provided with flash pressures between 25 and 30 psia.

Different operating scenarios for both the usage and generation of the steam condensate were evaluated. A baseline performance was established where there was no pre-flash of the geothermal fluid and no cooling of the air. A scenario was then evaluated where the condensate produced from a pre-flash of 20 psia was used to continuously cool the air. Scenarios were also considered where the condensate produced by pre-flash pressures of 25, 30 and 35 psia was stored, and then only used during the hottest 8 hours of the day. The effect on the power produced during the period from May 15th to October 15th is shown in Figure 8. In this figure the total power produced during this period is plotted as a function of the hour of the day for each of the scenarios considered. These results (which assume a variable turbine inlet pressure) show there is minimal penalty in power output during the period when condensate is stored (consistent with the results in Figure 6). With these operating scenarios one has the option of producing ~13% more power continuously, or ~29% more power during the hotter portions of the day.

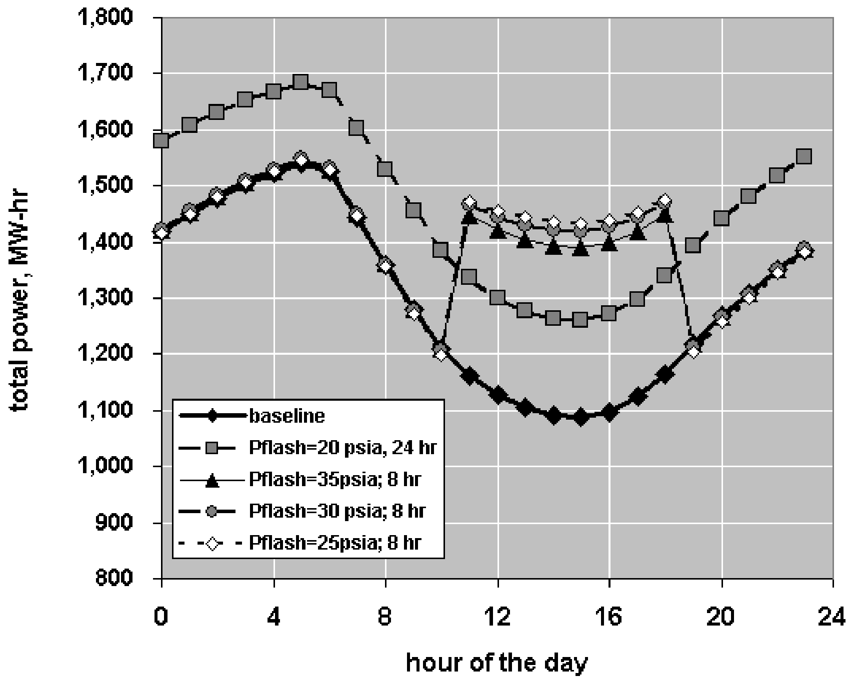

Figure 8: Impact of condensate generation and usage to cool air on plant output during the summer

Cost: In addition to the equipment associated with the conventional binary power plant, the proposed hybrid system will include the flash vessel, heat exchangers for condensing and cooling the steam produced, the evaporative air cooling system, and depending upon the operation scenario selected, a storage tank and delivery pump. Preliminary estimates indicate that the capital cost of this equipment, exclusive of the evaporative cooling system for the air, will vary from $1,050 to $2,900 per kW of additional power produced (based on the continual cooling of the air). This is effectively the cost of the water for the evaporative cooling system. The minimum cost would occur at a pre-flash pressure between 35 and 50 psi. The heat exchanger required to condense the steam represents a significant portion of the capital cost. Its size increases as the flash pressure decreases (due both to the increased production of steam and the decreasing temperature differences in the condenser). Kutscher's[1] evaluation of evaporative cooling systems indicated their costs could vary from ~$38 to $185 per kW for a nominal 1 MW plant. Using a lower value of $40 per kW, the evaporative cooling system would add ~$400K to the total cost (this assumes that this evaporative system cost is fixed and does not vary with the amount of air cooling accomplished).

At a pre-flash pressure of 35 psia, the 10 MW plant's annual power output could be increased by ~2,700 MW-hr at a capital cost of ~$770K; this corresponds to an installed cost of ~$2,500 per kW. While the power output would increase with a lower flash pressure, the cost for the added area in the steam condenser increases the installed cost in terms of dollars per additional kW generated. The installed cost of $2,500 per kW for the additional capacity is above the probable binary plant cost, but because output capacity is being added without additional well field development costs, this hybrid system will is likely lower the total project cost in terms of dollars per kW. These cost estimates are based upon the continuous usage of the condensate produced. If the condensate is selectively used, the costs will increase both due to the addition of a condensate storage tank and to the lower increase in the annual power generation. This evaluation did not include any assessment of the added operating and maintenance (O&M) costs that would be expected with the evaporative cooling system and the pre-flash unit.

Issues: The evaluation of the hybrid flash/binary system included assumptions that both simplified the analysis and attempted to not penalize the potential benefit from the concept. Included were assumptions made relative to the flash process and the steam condensation that will impact both performance and cost.

The chemistry of the geothermal fluid may ultimately dictate the feasibility of using the pre-flash to generate steam condensate. The flashing process will concentrate dissolved solids in the unflashed fluid that subsequently flows through the binary plant heat exchangers. This concentration of solids can increase the potential for scaling of these heat exchange surfaces and increase any minimum temperature limits imposed on the effluent geothermal fluid. For the lower temperature resources, concerns relative to the solubility of amorphous silica will likely not be an issue. (Using the solubility curves in Ellis and Mahon[2] (1977) for quartz and amorphous silica, the temperature solubility of amorphous silica raised from ~100°F for the 300°F to ~110°F in the concentrated, unflashed liquid.) Other species, such as antimony sulfide, may also impose a temperature limit; these were not examined in this evaluation.

Flashing of the geothermal fluid will increase the potential for the precipitation of calcite on downstream piping and heat exchange surfaces. Scale inhibitors are commonly used to prevent calcite precipitation in wells having two-phase flow. It is probable that these same scale inhibitors could be used to control calcite precipitation in this application. The cost of these inhibitors would be an O&M cost that was not included in this evaluation.

The non-condensable gases produced during the flashing of the geothermal fluid will have to be continually removed from the steam condenser. The partial pressure that they are allowed to build up to before removal will affect both the size of the steam condenser and the amount of steam that is vented with the non-condensables; a higher partial pressure will increase the condenser size and decrease the amount of steam that is vented. A portion of the steam that is vented in the noncondensables can be recovered with a secondary condenser. The condensation of this vent steam could be accomplished by rejecting the latent heat to a portion of the fluid leaving the binary cycle working fluid feed pump. Although the determination of the optimum sizing of the noncondenable removal system is not being reported here, an assessment of this removal system on both performance and cost will be done as part of this study.

It should be noted that while the geothermal fluid chemistry may impact both equipment and operating costs for the hybrid system, it may also preclude or limit the use of the geothermal fluid as a source of water for the evaporative air cooling.

Summary:

The concept of using the condensate from a pre-flash of the geothermal fluid entering a binary plant to evaporatively cool the air entering an air-cooled condenser has the potential to increase power production by up to ~13% over the summer, or up to ~29% during the hotter portions of the day. Although on an annual basis, the total increase in power is modest (3 to 5%), it is attainable without increasing resource production, and is achieved during the period when there may a premium received for additional power produced.

Preliminary estimates of the cost of the additional equipment suggest that the additional generation capacity will have a cost ($ per kW) roughly equivalent to the stand-alone binary plant. The economic merit of this concept will depend upon the cost of the evaporative cooling system for the air, the cost of alternative sources of water for this cooling, and the chemistry of the geothermal fluid at the candidate site. Because of the high quality of the water produced by condensing the steam, it is probable that a less expensive evaporative cooling system could be used that will also have lower O&M costs (relative to lower quality, alternative sources of water). However, it is probable that the binary plant's other O&M costs would increase due to issues associated with the flashing of the geothermal fluid. In addition the level of non-condensable gases in the geothermal fluid will dictate the size of the heat exchangers both to condense the steam and to recover steam from the vented non-condensable gas stream.

If there are no cost effective alternatives for providing the water for the evaporative cooling, this concept can be viable, particularly if there is a premium for power produced during the hotter periods of the year.

Acknowledgement:

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