Title

FLOATING DRY COOLING, A COMPETITIVE ALTERNATIVE TO EVAPORATIVE COOLING IN A BINARY CYCLE GEO-THERMAL POWER PLANT

Permalink

https://escholarship.org/uc/item/7qk9k2bk

Authors

Pines, H.S.
Green, M.A.
Pope, W.L.
et al.

Publication Date

1978-07-01

DISCLAIMER

FLOATING DRY COOLING, A COMPETITIVE ALTERNATIVE TO EVAPORATIVE COOLING IN A BINARY CYCLE GEOTHERMAL POWER PLANT

H. S. Pines, M. A. Green, W. L. Pope, and P. A. Doyle
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

ABSTRACT

The application of the floating cooling concept to non-evaporative and evaporative atmospheric heat rejection systems is studied as a method of improving the performance of geothermal powerplants operating upon medium temperature hydrothermal resources. The LBL thermodynamic process computer code GEOTHM is used in the case study of a 50 MWe isobutane binary cycle power plant at Heber, California. It is shown that operating a fixed capacity plant in the floating cooling mode can generate significantly more electrical energy at a higher thermodynamic efficiency and reduced but bar cost for approximately the same capital investment. Floating cooling is shown to benefit a plant which is dry cooled to an even greater extent than the same plant operating with an evaporative heat rejection system. Results of the Heber case study indicate that a dry floating cooling geothermal binary cycle plant can produce energy at a bus bar cost which is competitive with the cost of energy associated with evaporatively cooled systems.

INTRODUCTION

The floating cooling concept refers to the off-design operation of an atmospheric cooled geothermal power plant rejecting heat to a forced-draft wet or dry cooling tower (1,2). The cooling system always operates at full capacity in response to a naturally varying wet or dry bulb sink temperature. The turbine back pressure (i.e., the condensing temperature) is periodically adjusted to generate the maximum available net power provided by the variable sink temperature. The net power output of the plant will float with the daily and seasonal atmospheric temperature fluctuations. A fixed cooling cycle, on the other hand, operates at a constant condensing temperature and delivers constant net power during the time of the year that the design wet or dry bulb temperature is not exceeded.

The practical thermodynamic advantages of floating cooling for medium temperature geothermal energy systems are twofold:

(1) Floating cooling can significantly increase the net power production of plants located in regions where the climatology exhibits large daily and seasonal wet and dry bulb temperature variations (3).

(2) The percentage increase in net power is greater for geothermal plants designed to operate at higher condensing temperatures, e.g., dry cooling systems. Floating cooling will counteract the adverse influence on plant performance inherent in the design of dry cooling systems operating at higher condensing temperatures than wet cooling systems.

Recent economic studies (4,5) have shown that medium and low temperature hydrothermal resources below 180°C favor organic fluid binary cycles over flash steam systems. The thermodynamic properties of these organic fluids (much higher vapor pressures and lower specific volumes than steam at similar condensing temperatures) allow turbines to be constructed whose efficiencies are less sensitive to the floating cooling operating mode than are steam turbines. These organic fluid expanders can

2b

operate over the range of exhaust pressures experienced with varying wet or dry bulb temperatures with minor variations in turbine efficiency. The design and cost of these machines for a floating cooling application are not radically different from machines built to operate at a fixed exhaust condition.

OBJECTIVE

The primary objective of this report is to establish and quantify the thermodynamic and cost benefits of the floating cooling concept in the operation of non-evaporative atmospherically-cooled geothermal systems operating upon medium temperature hydrothermal resources. This subject has recently been examined for evaporatively cooled geothermal systems (1). A binary cycle power plant utilizing the floating cooling heat rejection method is shown to generate significantly more electrical energy at a higher thermodynamic efficiency and reduced bus bar cost than the same plant operating in the conventional fixed condensing temperature mode, for approximately the same capital investment.

The thermodyamic and cost benefits of floating cooling are shown to be greater for a binary plant which is air-cooled rather than cooled evaporatively. Through a computer modelling case study of a commercial size binary plant at Heber, California, it is determined that energy produced by a dry floating cooling geothermal plant is cost competitive with evaporatively cooled plants.

FLOATING COOLING IN THE IMPERIAL VALLEY--A CASE STUDY

The remainder of this report is devoted to computer modelling of the thermodynamic and cost benefits derived for floating cooling when applied to commercial-size geothermal isobutane binary cycle power plants located at Heber, CA. The resource and sink characteristics of the Heber site are typical of a number of medium temperature hydrothermal resources in California's Imperial Valley. Floating cooling is particularly suited to exploit the source and sink conditions characteristic of the Heber site for the following reasons:

(1) The local desert climate exhibits high maximum annual wet and dry bulb temperatures over relatively few degree days and large daily and seasonal wet and dry bulb temperature variations.

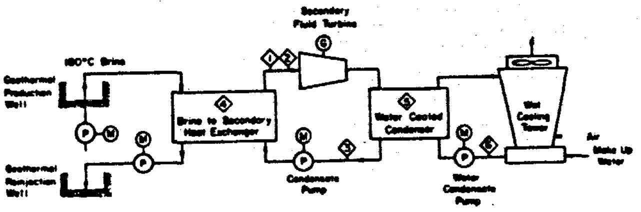
(2) The temperature of this resource (180°C) is best matched with an organic fluid binary cycle power plant (4).

(3) A suitable cooling water make-up supply cannot be guaranteed over the life of the plant according to preliminary design studies (4).

(4) The large additional capital and operating expenses incurred with a dry cooling system are offset by operating the plant in the floating cooling mode.

A FLOATING COOLING COMPUTER MODELLING SCENARIO USING PROGRAM GEOTHM

The computer model used in this study is the LBL-developed thermodynamic process computer code GEOTHM. The unique single-step optimization capability of the GEOTHM code is first employed in the design of two minimum energy cost 50 MWe net base load power plants. The first plant, illustrated in Figure 1, incorporates conventional evaporative heat rejection subsystem components, i.e., a water cooled condenser coupled to a forced draft wet cooling tower. The second plant, illustrated in Figure 2, is configurationally identical to the first plant except that a forced draft isobutane/air direct, dry-type cooling tower condensing system has replaced the evaporative heat rejection system. These are fixed 1% wet and dry bulb temperature designs, i.e., the plants will deliver 50 MWe constant net power during the 99% of the summer months (June through September) that the design wet and dry bulb temperatures are not exceeded. The program's off-design optimization routines then simulate the operation of these fixed capacity plants in the floating cooling mode, during daily and seasonal temperature variations, to maximize power production throughout the year. The floating cooling plants

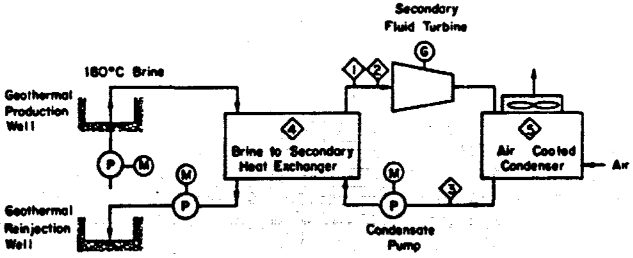


XBL 787-9838

OPTIMIZABLE PARAMETERS

1 *Turbine Inlet T*
2 *Turbine Inlet P*
3 *Condenser P*
4 *Pinch Point ΔT*
5 *Pinch Point ΔT*
6 *Approach ΔT*

Figure 1. A typical evaporative (wet) cooled binary geothermal power cycle with 180°C inlet brine.



XBL 787-9837

OPTIMIZABLE PARAMETERS

1 *Turbine Inlet T*
2 *Turbine Inlet P*
3 *Condenser P*
4 *Pinch Point ΔT*
5 *Pinch Point ΔT*

Figure 2. A typical dry air (dry) cooled binary geothermal power cycle with 180°C inlet brine.

will generate more than 50 MWe power during 99% of the summer months. Assuming that these are base-loaded plants, i.e., that all floating power can be sold at the same rate, the cost of energy for the floating cooling plants will be computed to include the revenues derived from the surplus energy sales. The cost of energy for both the floating and fixed operating modes are than compared.

Design and Optimization of the 50 MWe Fixed Capacity Plants

The binary cycle power plants modelled in this study are illustrated by the simplified schematic flow diagrams, Figures 1 and 2. In order to design and cost optimize these systems, the GEOTHM equipment and cost models require that the user input reasonable equipment efficiency and cost data applicable to the particular plant to be modelled. The data for this paper was obtained from a comprehensive feasibility study for a fixed capacity evaporative cooling 50 MWe isobutane binary cycle design at Heber performed by Holt-Procon for EPRI (4). Equipment design data included turbine and pump efficiency ratings, and heat exchanger and condenser heat transfer coefficients. For Holt's assumed values for the six system state parameters listed in Figure 1, GEOTHM verified Holt's baseline design, i.e., his fluid mass flows, component sizes, and parasitic power calculations. Scaling factors built into GEOTHM's component costing routines were then adjusted so that component costs computed by GEOTHM were normalized to match Holt's vendor quotations. Heat transfer coefficients and component unit area costs for the dry cooling tower system were obtained from vendor design quotations supplied directly to LBL (6).

The brine cost ($/btu) was normalized to Holt's for the same flow rate and primary heat exchanger duty. Direct and indirect cost factors were similarly scaled so that total plant and field capital cost, and cost of energy were in agreement. Finally, GEOTHM's non-linear optimization routines were used to design the plants to produce 50 MWe net power at minimum cost of energy for a 26.7°C (80°F) 1% wet bulb temperature and a 43.9°C (111°F) 1% dry bulb temperature, respectively. The GEOTHM adjusted the optimizable cycle parameters to arrive at the minimum energy cost cycles illustrated on the T-Q plot in Figure 3. The GEOTHM optimized wet cooling design is in excellent agreement with Holt's. Figure 3 cycle design information is summarized in columns 1 and 2 in Table 1. It is important to note that Holt's 50 MWe (net) design did not include the approximately 5 MWe of brine production and injection pumping power, whereas these parasitic power requirements are included in the GEOTHM studies.

The two minimum energy cost designs depicted in Figure 3 are a striking contrast in many respects. The higher condensing temperature imposed by the dry cooling heat rejection system reduces the energy available in the turbine expansion process, even though the optimizer has increased turbine inlet temperature in comparison with the wet cooling cycle. Therefore, there is a large increase in all fluid mass flows, which when coupled with the large parasitic fan power requirement, results in a much greater total heat load upon the cycle. Note there is a much larger mean temperature difference across the air cooled condenser in comparison with the water cooled condenser. This is an attempt by the optimizer to minimize the area of this relatively expensive finned-tube heat exchanger. Note the brine reinjection temperature is higher for the dry cooled plant.

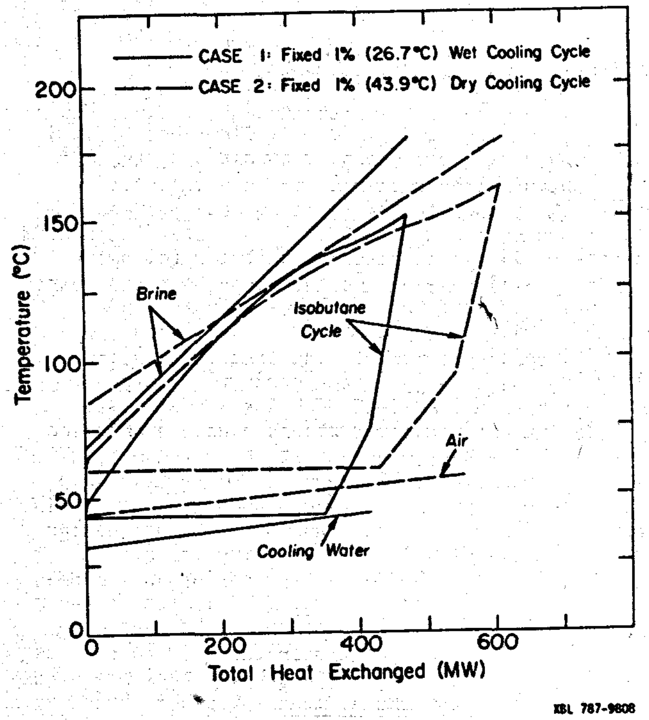


Figure 3. A temperature heat flow plot comparing an evaporative (wet) cooled cycle with a dry cooled cycle at the 1% design condition.

Table 1. Power plant parameters for fixed and floating wet and dry cooled binary plants at Heber, California.

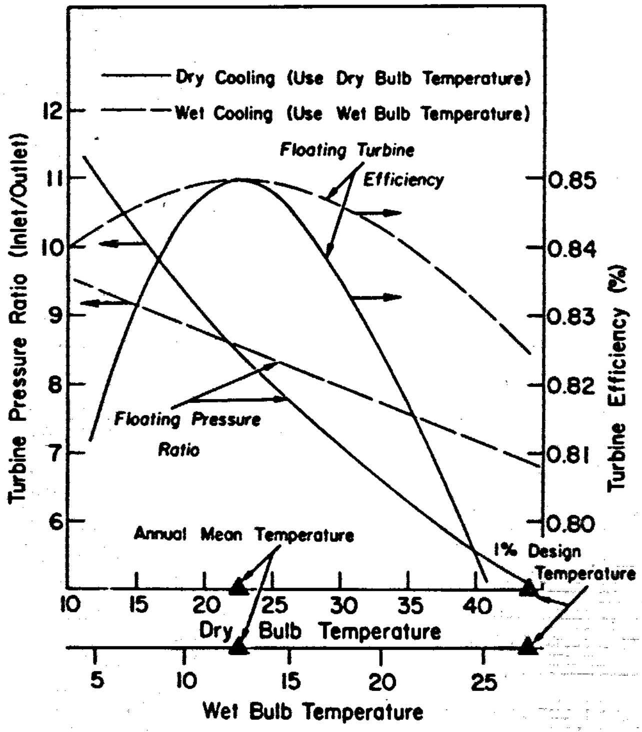
Process Design Parameters	Fixed Capacity Plants		Floating Cooling Plants	
	Wet	Dry	Wet	Dry
Avg. Net Power (MWe)	50.0	50.0	60.5	81.3
Avg. Gross Power (MWe)	70.9	82.8	82.4	114.1
Avg. Cycle Efficiency (%)	11.0	8.6	12.0	11.8
Brine Flow Rate (kg/sec)	950	1427	992	1492
Avg. Plant Yield (kwhr per metric ton of brine)	14.6	9.7	16.9	15.1
Heat Rejection System Power Requirement (MWe)	4.3	9.4	4.3	9.5
Annual Brine Cost (M$)	6.8	10.2	7.1	10.6
Plant Capital Cost (M$)	30.8	43.7	32.0	46.6
Plant Capital Cost Per kW of Average Net Power ($)	616	874	529	573
Bus Bar Energy Cost* (mills/kwhr)	37.8	54.2	32.6	35.2

*Eighty-five percent plant availability is assumed.

Off-Design Floating Cooling Modelling

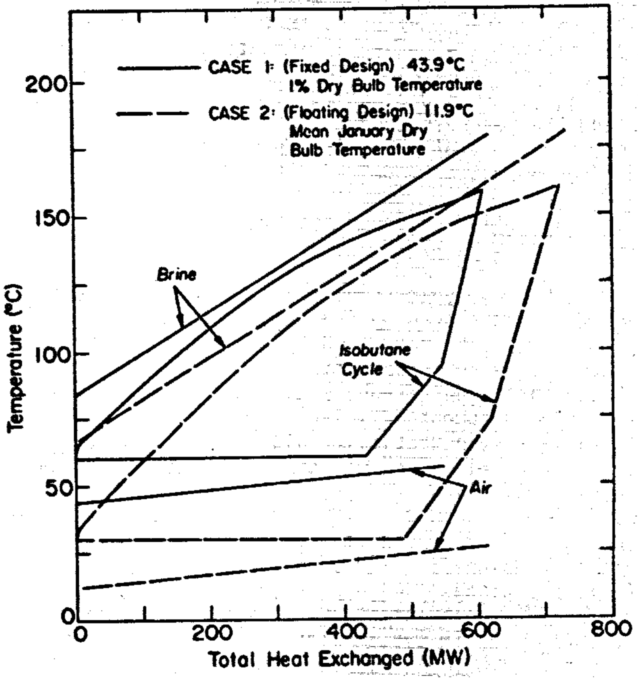
Once the plants have been designed, i.e., equipment sizes, costs, and fluid mass flows established at the GEOTHM minimum energy cost designs, the off-design optimization routines can be invoked to operate the plants in the floating cooling mode. In addition to fixing the brine flow rate, the GEOTHM floating cooling model assumes that the following conditions will remain constant throughout the year: (1) turbine inlet temperature, (2) turbine inlet pressure, (3) heat exchanger area, (4) condenser area, (5) cooling tower packing area (wet system only) and, (6) cooling water or air flow rate. Coupling these constraints with the system state variables mathematically dictates a unique solution for the turbine back pressure at any given wet or dry bulb temperature. The one-to-one relationship linking turbine pressure ratio with wet and dry bulb temperature is plotted in Figure 4. The off-design turbine efficiency will vary with turbine back pressure according to the turbine performance models shown in Figure 4. In order to maximize the off-design production of floating power, the turbines for each of the plants have been designed to operate at their peak efficiency for a turbine back pressure corresponding to the annual mean wet or dry bulb temperature, respectively.

The T-Q plot in Figure 5 shows how the dry cooling cycle has been adjusted to accommodate a seasonal shift in the dry bulb temperature. Case 2 represents the adjusted floating cooling thermodynamic operating condition of a plant experiencing the increased cooling potential afforded by the mean January dry bulb temperature (11.9°C) for Heber, CA. Case 2 is a significant departure from the Case 1, the fixed 1% dry bulb temperature (43.9°C) design for the following reasons:



XBL 787-9807

Figure 4. Turbine pressure ratio and turbine efficiency vs wet or dry bulb temperature for wet and dry floating cooling power cycles.



XBL 787-9809

Figure 5. A temperature heat flow plot comparing dry cooled cycles at the 1% design dry bulb temperature (43.9 C) and the mean January dry bulb temperature (11.9 C).

(1) The isobutane condensing temperature is about 30°C lower!

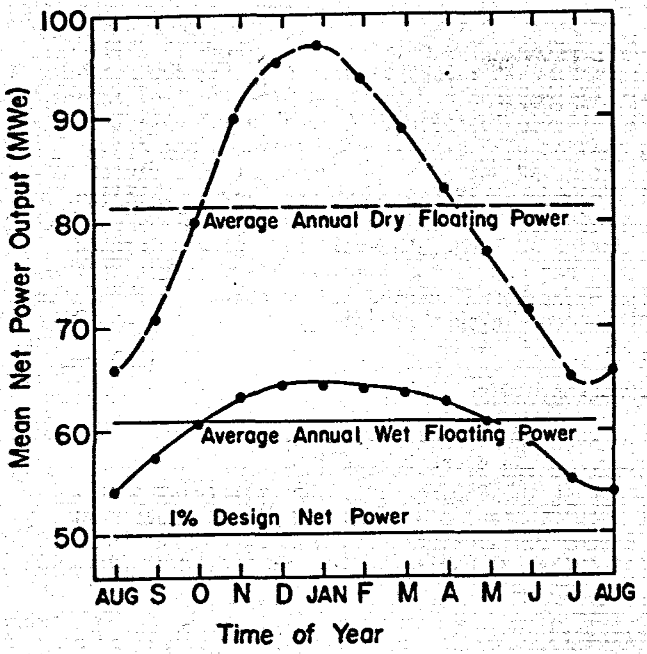
(2) The reduced condensing temperature, and consequently the reduced turbine back pressure, allows the turbine to extend its expansion process to produce more useful work. This plot shows the extended turbine expansion line, resulting in a 93% increase in net power!

(3) The increase in available energy at the lower dry bulb temperature shows up as an increase in the heat transferred across the heat exchanger and condenser and as a nearly 20°C decrease in the brine reinjection temperature.

(4) The greater heat transfer load imposed upon the constant area exchanger and condenser is compensated by an increase in the mean temperature difference across these devices.

Seasonal Floating Power Output for Heber Power Plants

The monthly mean net power generated by a floating cooling power plant for the 180°C Heber resource is computed using published monthly mean climatological data (7). Figure 6 is a plot of the monthly mean floating net power output for both the wet and dry cooling plants. Note that the mean net power production during all months exceeds the 50 MWe fixed capacity rating, since the mean monthly wet or dry bulb temperatures are always less than the 1% design temperatures. These seasonally varying float-



XBL 787-9805

Figure 6. Floating net power as a function of the month of the year for floating evaporative and dry cooled plants which generate 50 MWe at the 1% design condition.

ing power curves can be normalized to average annual floating values by integrating the area beneath each curve. Figure 6 shows that operation as a floating cooling plant can increase the output of a 50 MWe fixed cooling plant to an average annual floating net power of 60.5 MWe for wet cooling or 81.3 MWe for dry cooling. This is a 21% and a 63% increase respectively, provided that the generator is designed to accommodate the largest anticipated floating power output (85 MWe electricity gross, wet; 129 MWe gross, dry). The average cycle efficiency is also improved from 11% to 12% for the wet cooling plant and from 8.6% to 11.8% for the dry cooling plant.

COST BENEFITS OF FLOATING COOLING

The results of these power plant case studies for the optimized fixed and floating, wet and dry designs are summarized in Table 1. Modification of the fixed capacity plants to operate in the floating cooling mode requires only a minor increase in plant capital investment. Nevertheless, revenues derived from the sale of surplus floating power substantially reduces the cost of energy produced compared to the same plant operated at fixed capacity. This energy cost reduction is particularly dramatic in the case of the dry cooling plant. Whereas energy produced by the fixed capacity dry cooling plant costs 43% more than for its (fixed capacity) wet cooling counterpart, the energy cost of the dry floating plant exceeds the wet floating energy cost by only 8%. Clearly, the incremental thermodynamic advantages afforded the dry floating cycle over the wet floating cycle translates into significant cost benefits. It is interesting to note that the cost of energy for the dry floating plant is less than that for the fixed capacity evaporatively cooled system (1).

An initial inspection of Table 1 indicates the seemingly attractive prospect of producing energy from a dry floating cooling plant at costs competitive with wet cooling systems. This pleasantly suprising result must be examined with the following qualifications:

(1) The dry cooled plant which produces 50 MWe at the 1% design condition requires about 50% more plant capital investment expenditures than a comparable evaporatively cooled plant.

(2) The net power output of the floating cooling plants fluctuate significantly with daily and seasonal atmospheric temperature variations. Maximum daily power production occurs during late evening and early morning hours. Maximum seasonal power production occurs during the winter months (see Figure 6). These times are usually considered off-peak demand periods by utilities.

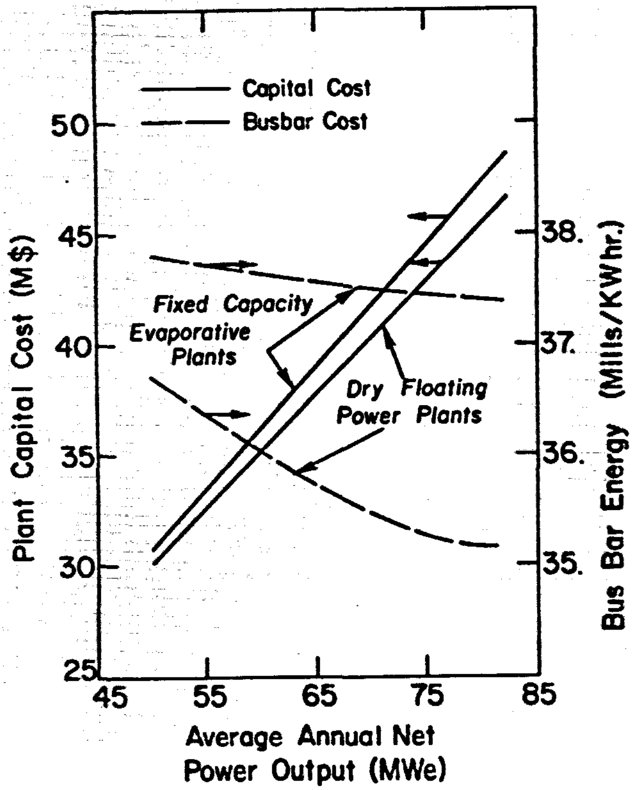
(3) This report assumes that all energy produced by a floating cooling power plant can be sold at the same rate. This assumption may be subject to adjustment to reflect a utility's attitudes toward the seasonal and daily power production schedual.

(4) The cost of brine paid to the producer is charged on a dollars per pound basis for a floating plant operating at a constant year-round brine flow requirement, even though the brine reinjection temperature fluctuates with the sink temperature variation. The validity of this brine cost assumption for floating plant operations must await actual contractual negotiations between field producer and utility.

CAPITAL INVESTMENT--POWER OUTPUT--ENERGY COST TRADE-OFF STUDY FOR DRY FLOATING COOLING PLANTS

Although dry floating cooling geothermal systems appear to be energy cost competitive with wet cooling systems, they are more expensive from a plant capital investment standpoint. Depending upon a utility's ability to obtain capital, it may be desirable to build a floating cooling plant which is less expensive than a 1% dry bulb design. Such a floating plant would generate less than 50 MWe during a greater portion of the year than for the 1% design case. The average annual floating net power output of these plants will be less than 50 MWe during a greater portion of the year than for the 1% design case.

To illustrate this capital investment--net power output--energy cost relationship, the following computer modelling scenario was devised. Four dry floating cooling plants, each designed to generate more than 50 MWe net power for dry bulb temperatures less than 43.9°C (1%), 37.8°C (15%), 33.9°C (50%), and 22.5°C (mean annual dry bulb temperature) respectively, are optimized by GEOTHM for minimum bus bar energy cost. The average annual floating net power for these plants is 81.3 MWe, 68.9 MWe, 62.4 MWe, and 49.2 MWe respectively. The plant capital costs and bus bar energy costs for these plants are plotted in Figure 7. The GEOTHM then designed four minimum energy cost 1% fixed capacity wet cooling plants to deliver constant net power corresponding to the average annual power output of the dry



XBL 787-9806

Figure 7. Plant capital cost and bus bar energy cost as a function of average annual net power output from fixed wet cooled plants and floating dry cooled plants.

floating cooling plants. The plant capital investments and energy costs for each of these fixed capacity plants are also plotted in Figure 7.

Comparison of the cost curves in Figure 7 shows that a dry floating cooling plant can deliver the same amount of average annual power as a fixed capacity wet cooling plant for a slightly lower plant capital cost requirement and at a lower cost of energy!

CONCLUSION

Floating cooling is best used in power cycles employing the binary or secondary working fluid concept. Dry air cooling systems are particularly well suited to the binary cycles because the secondary working fluid entering the condenser from the turbine has a lower specific volume, this reduces the size of the air cooled condenser.

Bus bar energy cost from a geothermal power plant employing floating dry cooling is competitive with the cost of energy from an evaporatively cooled system. The capital cost (given in dollars per average net kilowatt) of a floating dry cooled plant is comparable with the capital cost of an evaporatively cooled plant. A power plant with floating cooling will exhibit wide seasonal and daily variations of net power production. This variation will be greater if the plant uses dry air cooling. As a result, the use of floating dry cooling should be considered for geothermal power plants located in arid regions of the American West. (Most of the known hydrothermal geothermal resources in the United States occur in such regions.)

ACKNOWLEDGEMENTS

The authors acknowledge the efforts of L. F. Silvester, and R. L. Fulton for their role in developing the GEOTHM code. We gratefully acknowledge the support of the United States Department of Energy Division of Geothermal Energy for their support for LBL cycle studies and GEOTHM development.

REFERENCES

1 Pines, H. S., et al., "The Thermodynamic and Cost Benefits of a Floating Cooling Geothermal Binary Cycle Power Plant at Heber, California," presented at the Geothermal Resources Council 1978 Annual Meeting, Hilo, Hawaii, July 25-28, 1978, LBL-7040, April 1978.

2 Shaffer, C. J., "Floating Power Optimization Studies for the Cooling System of a Geothermal Power Plant," TREE-1164 EG&G Idaho, Inc., Idaho National Engineering Laboratory, Idaho Falls, August 1977.

3 Ezzat Khalifa, H., "Effect of Seasonal Variations of Ambient Temperature on the Performance of Low Temperature Power Cycles," Division of Engineering Report of Brown University COO/4051-10, Providence, RI, June 1978.

4 Roberts, Vasel W. (Project Manager), "Geothermal Energy Conversion and Economics-Case Studies: EPRI-301, Project 580," prepared by Holt/ Procon, Ben Holt and Edward L. Ghormley (principal investigators), Electric Power Research Institute, Palo Alto, CA, November 1976.

5 Bloomster, C. H., and Knutsen, C. A., "The Economics of Geothermal Electricity Generation from Hydrothermal Resources," BNWL-1989, Battelle Pacific Northwest Labs., Richland, Washington.

6 Eugene Eno of LBL, private communication on various vendor quotes.

7 Imperial Irrigation District, "Imperial Valley Annual Weather Summary 1977--Monthly High, Low and Mean Temperatures and Rainfall, 1914-1977," from Records of Watermaster.