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Publication Date

1978-04-01

To be presented at the Geothermal Resources Council 1978 Annual Meeting, Hilo, Hawaii, July 25-28, 1978

LBL-7040

CONF-780708--19

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MASTER

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April 1978

Prepared for the U. S. Department of Energy under Contract No. W-7405-ENG-48

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LBL-7040

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LBL-7040

THE THERMODYNAMIC AND COST BENEFITS OF A FLOATING COOLING GEOTHERMAL BINARY CYCLE POWER PLANT AT HEBER, CALIFORNIA

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ABSTRACT

The application of the *floating cooling* concept to evaporative 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 bus bar cost for approximately the same capital investment. Floating cooling is also shown to minimize the adverse influence on plant performance due to a declining resource temperature.

INTRODUCTION

The development of medium temperature hydrothermal resources for the production of electrical energy has not proceeded at the pace hoped for by the geothermal community. This predicament is certainly influenced by the lower thermodynamic efficiency inherent in these resources and the associated higher costs of the thermal-mechanical energy conversion. This paper will show that application of the *floating cooling concept* to *evaporative heat rejection systems* can significantly increase the energy available from medium temperature hydrothermal resources. A binary cycle power plant utilizing the floating cooling heat rejection method can generate significantly more electrical energy at a higher thermodynamic efficiency and reduced bus bar cost than the same plant operating in the convential fixed condensing temperature mode, for approximately the same capital investment.

The *floating cooling concept** as defined in this study refers to the off-design operation of an atmospheric cooled geothermal power plant rejecting heat to a forced-draft wet cooling tower. The cooling system always operates at full capacity in response to a naturally varying wet 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 wet bulb 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 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 bulb temperature variations.

(2) The percentage increase in net power is greater at lower resource temperatures. Floating cooling systems will counteract the adverse influence on plant performance due to a declining resource temperature over time.

Recent economic studies[2,3] 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 operate over the range of exhaust pressures experienced with varying wet 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.

FLOATING COOLING IN THE IMPERIAL VALLEY - A CASE STUDY

The remainder of this report is devoted to com-

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*This concept has recently been examined for low temperature resources by INEL.[1]

puter modelling of the thermodynamic and cost benefits derived for floating cooling when applied to commerical-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 bulb temperatures over relatively few degree days and large daily and seasonal wet bulb temperature variations.

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

(3) As the reservoir is developed to a full generating capacity of say 200 MWe, the resource temperature is predicted to decline about 30°F over 25 years making the floating cooling binary cycle even more appropriate.

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 a *minimum energy cost* 50 MWe net base load power plant. This is a fixed 1% wet bulb temperature design, i.e., the plant will deliver 50 MWe constant net power during the 99% of the year that the design wet bulb temperature is not exceeded. The program's off-design optimization routines then simulate the operation of the fixed capacity plant in the floating cooling mode, during daily and seasonal wet bulb temperature variations, to *maximize power production* throughout the year. The floating cooling plant will generate more than 50 MWe net power during 99% of the year. Assuming that surplus floating power can be sold at the same rate as the base load power, the cost of energy for the floating cooling plant 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 then compared.

A) DESIGN AND OPTIMIZATION OF THE 50 MWe BASE LOAD PLANT

The binary cycle power plant modelled in this study is illustrated by the simplified schematic flow diagram, Figure 1. Brine downhole and reinjection pumps are not shown, but have been included in the model. In order to design and cost optimize this system, 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 cooling 50 MWe isobutane binary cycle design at Heber performed by Holt/Procon for EPRI.[2] Equipment design data included turbine and pump efficiency ratings, and heat exchanger and condenser heat transfer coefficients. For Holt's assumed values of 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. 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 plant to produce 50 MWe net power at minimum cost of energy for an 80°F 1% wet bulb temperature. GEOTHM adjusted the six optimizable cycle parameters to arrive at the minimum energy cost cycle illustrated on the T-Q plot in Figure 2, Case 1. The GEOTHM optimized design is in excellent agreement with Holt's. Case 1 cycle design information is summarized in column 1 of 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 Case 1 does.

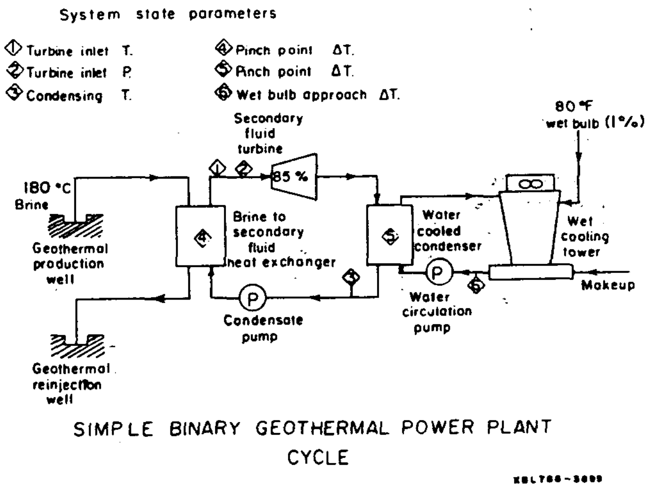

FIGURE 1 Simple geothermal binary cycle power plant schematic. The six system state parameters are optimized with program GEOTHM for a minimum energy cost design objective.

B) OFF-DESIGN FLOATING COOLING MODELLING

Once the plant has been designed, i.e. equipment sizes, costs, and fluid mass flows established at the GEOTHM minimum energy cost design, the off-design optimization routines can be invoked to *operate* the plant in the floating cooling mode. In addition to fixing the brine flow rate, the GEOTHM floating cooling model assumes that the

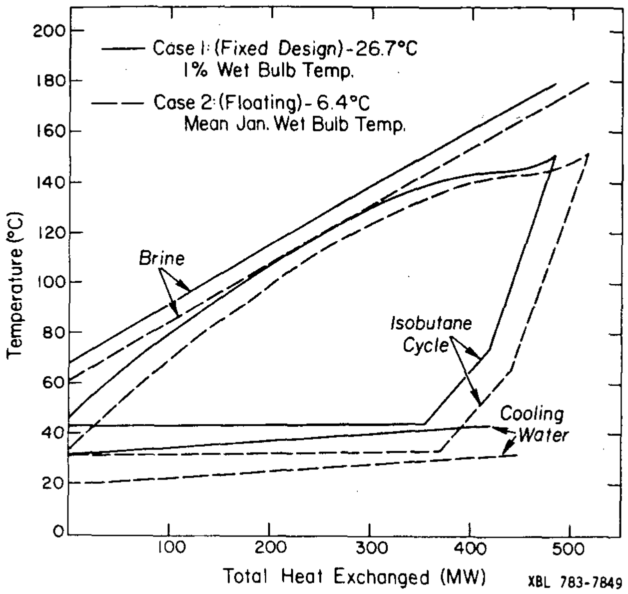

FIGURE 2 T-Q plots illustrating the adjusted floating cooling power plant operating conditions so that plant can generate maximum net power at the stated wet bulb temperatures. Note particularly the 10°C shifts in condensing and cooling water temperatures.

following six 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 and, (6) cooling water flow rate. Coupling the six constraints with the six system state variables mathematically dictates a unique solution for the turbine back pressure at any given wet bulb temperature. The one-to-one relationship linking turbine back pressure with wet bulb temperature is plotted in Figure 3. The off-design turbine efficiency will vary with turbine back pressure according to the turbine performance model shown in Figure 3. In order to maximize the off-design production of floating power, the turbine has been designed to operate at its peak efficiency for a turbine back pressure corresponding to the *annual mean* wet bulb temperature.

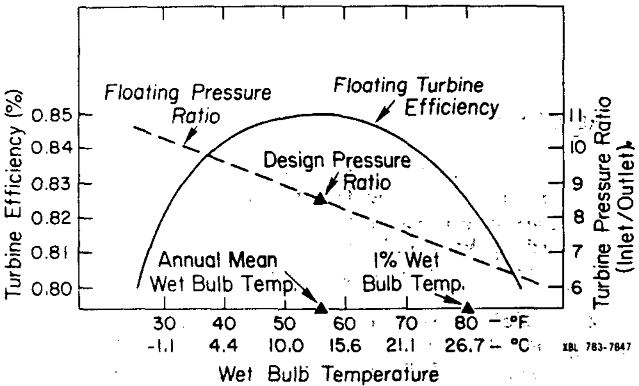

FIGURE 3 Turbine performance chart[5] (axial-flow organic fluid machine). Plots of turbine operating conditions (efficiency and pressure ratio) required by floating cooling wet bulb temperature variations. Peak efficiency design point corresponds to annual mean wet bulb temperature.

The T-Q plot in Figure 2 shows how the cycle has adjusted to accomodate a seasonal shift in the wet 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 wet bulb temperature (6.4°C) for Heber, Calif. Case 2 is a significant departure from the Case 1 fixed 1% wet bulb temperature (26.7°C) design for the following reasons:

(1) The isobutane condensing temperature and the cooling water inlet temperature are both about 10°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 14 MWe (28%) increase in net power!

(3) The increase in available energy at the lower wet bulb temperature shows up as an increase in the heat transferred across the heat exchanger and condenser and as a 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.

C) SEASONAL FLOATING POWER OUTPUT FOR A HEBER POWER PLANT

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.[4] Figure 4 is a plot of the monthly mean floating net power output and monthly mean floating cycle efficiency (cycle efficiency ≡ Net Power/Total Heat In). These seasonally varying floating power and efficiency curves can be normalized to *average annual floating* values by integrating the area beneath each curve. Figure 4 shows that operation as a floating cooling plant can increase the output of a 50 MWe fixed cooling plant to 61 MWe average annual floating net power, a 22% increase, provided that the generator is designed to accommodate the largest anticipated floating power output (85 MWe gross). The average cycle efficiency is also improved from 10.9% to 12.1%.

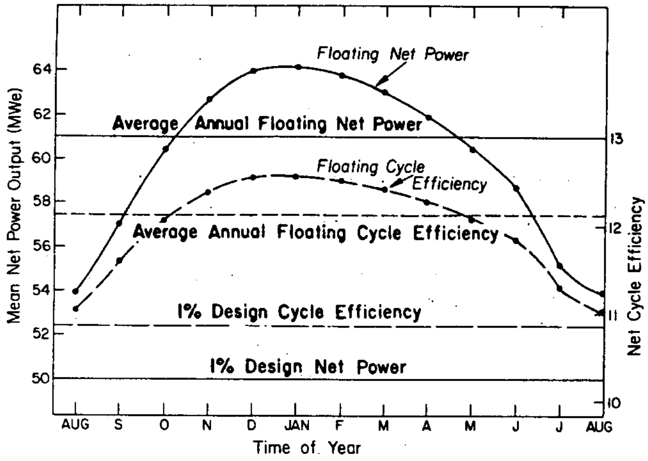

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FIGURE 4 Seasonally varying *monthly mean* floating net power output and floating cycle efficiency for 50 MWe (1%) floating cooling power plant, 180°C resource temperature. The floating performance curves are normalized to *average annual floating* values for comparison with the fixed capacity plant design.

D) DECLINING RESOURCE TEMPERATURE SCENARIO

In order to illustrate the increasing benefits of floating cooling at lower resource temperatures, a modelling scenario for the development of the Heber resource has been devised. This scenario assumes that a 50 MWe net (1% wet bulb design) binary cycle power plant is to be constructed every 7 years for a total of 4 plants or 200 MWe net generating capacity. In compliance with reservoir engineering estimates of a declining resource temperature at Heber, these plants are designed to operate over their assumed 25 year lifetimes at different average resource temperatures: 180°C, 175°C, 170°C, and 165°C respectively. Each plant is designed for minimum cost of energy (assuming constant 1976 dollars).

Each plant is then modelled to float with the seasonally varying wet bulb temperature. The seasonal variation of the monthly mean floating net power for 50 MWe (1%) plants designed to operate at different average resource temperatures is shown in the 3-D isometric plot, Figure 5. As predicted, *the mean floating net power is seen to increase for plants designed to operate at lower resource temperatures.*

COST BENEFITS OF FLOATING COOLING

The results of these four power plant case studies are summarized in Table 1. Modification of a fixed capacity plant to operate in the floating cooling mode requires only a *minor increase* in the plant and field capital investments. Nevertheless, revenues derived from the sale of surplus floating power *substantially reduces* the cost of energy produced compared to same plant operated at fixed capacity. The bus bar cost of energy for each plant operating in both the fixed and floating modes is plotted in Figure 6. As the cost of energy increases with decreasing resource temperature, floating cooling is seen to mitigate this cost increase by as much as 14%. The increasing *thermodynamic benefits* of floating cooling, as the resource temperature declines, translates into *greater percentage energy cost reductions*, ΔCost.

Figure 6 also shows that floating cooling can generate power from a 167°C resource for the same cost of energy (for a slightly greater capital investment) as a fixed capacity plant operating from a 180°C resource. From an equivalent cost of energy standpoint, *floating cooling has the effect of increasing the Heber resource temperature* (ΔT_{EQ}) *by 12.8°C or about 23°F.* This *temperature-cost equivalence effect* suggests that floating cooling may allow geothermal binary cycles to:

1) Maintain general economic attractiveness to lower resource temperatures than previously believed.

2) Compete more effectively with flashed steam cycles at higher resource temperatures.

CONCLUSIONS

A computer modelling case study of the thermodynamic and cost benefits of a floating cooling geothermal binary cycle power plant at Heber, California has been described. The operation of a 50 MWe (net) fixed capacity plant in the floating cooling mode increases net power production by 22% and reduces the cost of energy by 12.5%, for approximately the same capital investment. Floating cooling can also minimize the adverse influence on plant performance due to the predicted temperature decline of the Heber resource.

The potential thermodynamic and cost benefits of the floating cooling operating mode should serve to stimulate the development of medium temperature hydrothermal resources in areas where the climatology exhibits large daily and seasonal temperature variations.

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ACKNOWLEDGMENT

We gratefully acknowledge the support of DOE/DGE for LBL Cycle studies and GEOTHM development.

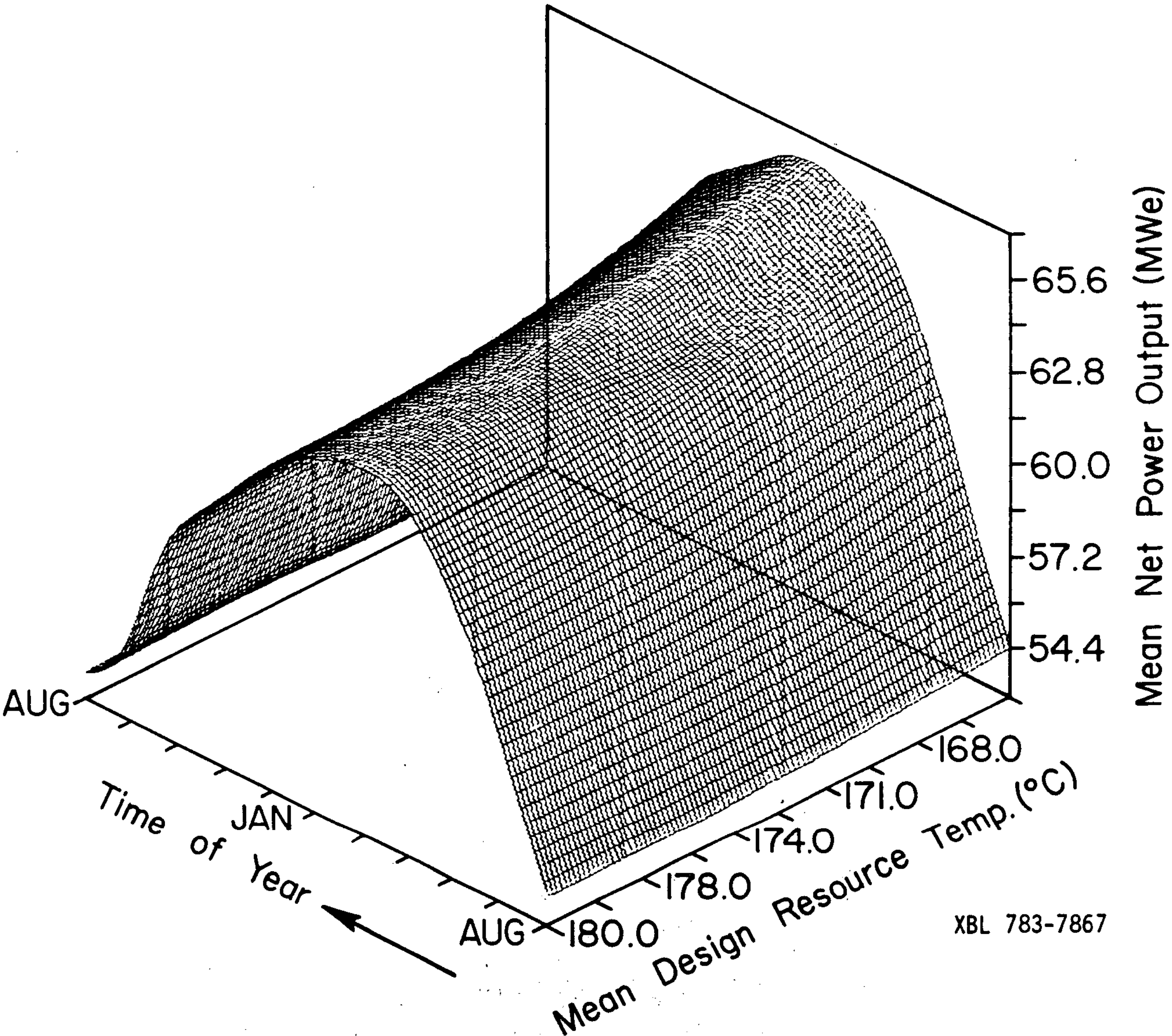

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FIGURE 5 Seasonally varying monthly mean floating net power output for 50 MWe (1%) plants designed to operate at different average resource temperatures. The mean floating net power *increases* for plants designed to operate at lower resource temperatures.

PROCESS DESIGN PARAMETERS	MEAN DESIGN RESOURCE TEMPERATURE (°C)							
	180+	180*	175+	175*	170+	170*	165+	165*
Avg. Net Power (MWe)	50.0	61.0	50.0	61.2	50.0	61.7	50.0	62.4
Avg. Gross Power (MWe)	69.8	81.3	70.2	82.0	70.7	83.1	71.9	85.4
Avg. Cycle Efficiency (%)	10.9	12.1	10.7	12.0	10.4	11.7	9.9	11.1
Brine Flow Rate (kg/sec)	966	1009	1055	1095	1140	1189	1240	1267
Annual Fuel Requirement (MWhrx10^3)**	3462	3770	3520	3836	3622	3965	3803	4211
Brine Unit Cost ($/MWhr)**	1.99	1.99	2.13	2.13	2.24	2.24	2.31	2.26
Plant Capital Cost (M$)	31.04	32.35	31.65	33.18	32.95	34.42	34.46	36.79
Bus bar Energy Cost (Mills/kWhr) (85% plant availability)	38.3	33.5	40.4	35.3	42.9	37.2	45.7	39.3

● floating cooling design
** thermal megawatts
+ 50 MWe fixed 1% wet bulb design

TABLE 1 Process design and cost data for four 50 MWe (1%) binary cycle power plants designed to operate at different mean resource temperatures. This table lists process data for each plant operating in both a fixed capacity mode and a floating cooling mode.

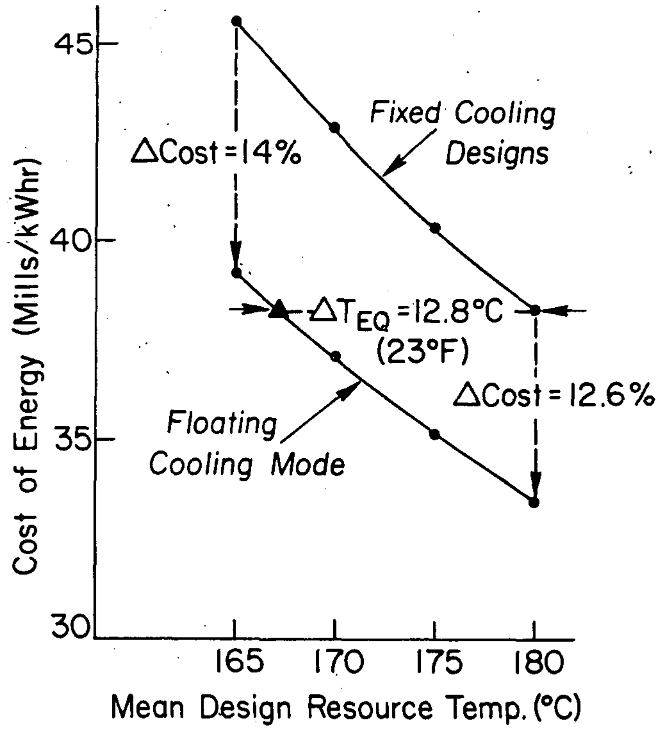

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FIGURE 6 Bus bar cost of energy for 50 MWe (1%) plants operating in both fixed and floating modes for different mean design resource temperatures.

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