DISCLAIMER



# 2000Mw(t) HTGR-GT

# POWER CYCLE COOLING

# SYSTEM ALTERNATIVES

Performed for

**GAS-COOLED REACTOR ASSOCIATES**
**LA JOLLA, CALIFORNIA**

by

**united engineers**
& constructors inc.

**JUNE, 1980**

ABSTRACT

This power cycle cooling system study, prepared for Gas Cooled Reactor Associates by United Engineers & Constructors Inc. under Contract No. GCRA/AE/78-1, was a part of an overall effort to assess the economic potential of high temperature gas cooled reactor gas turbine (HTGR-GT) power plants. The cost, design and performance results obtained in the study for dry, wet/dry and wet tower systems designed for a 2000 MWt /800 MWe HTGR-GT plant are presented in this report. Similar cooling system results obtained in the study for 800 MWe pressurized water reactor and coal-fired steam cycle power plants are also presented for comparisons with the HTGR-GT plant. The results indicate that the total evaluated costs (capital costs plus operating penalty costs) of the cooling systems for the HTGR-GT plant, in the range from the all-dry system to the wet/dry system using about 50% of the water needed for the all-wet system, are much lower than the costs of the cooling systems for both the PWR and coal plants with the same water constraints as the HTGR-GT plant.

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## SECTION 1.0

## EXECUTIVE SUMMARY

### 1.1 INTRODUCTION

The objective of this power cycle cooling system study was to develop and compare design, cost and performance results for dry, wet/dry and wet tower systems designed for nominal 800 MWe high temperature gas cooled reactor gas turbine (HTGR-GT), pressurized water reactor (PWR), and coal-fired fossil power plants at Modesto, California, a hypothetical west coast site.

The high temperature waste heat rejection feature of HTGR-GT plants favors the application of dry cooling systems. In view of the existing and anticipated water shortage in many parts of the country[1], this characteristic may add to the economic incentive to the development of HTGR-GT plants.

In addition, there is considerable interest in determining the economic impact of using wet/dry cooling systems designed for water conservation in HTGR-GT plants. This interest has been spurred by the favorable results obtained in previous wet/dry cooling system studies [2,3] for fossil and nuclear steam cycle power plants, indicating considerable economic advantages for wet/dry cooling systems over dry cooling systems. A recent preliminary study of wet/dry cooling systems for HTGR-GT plants[4] has indicated that wet/dry cooling systems can substantially reduce the overall cooling system costs for these plants.

The present study addressed the cooling system cost advantages of HTGR-GT plants and was a part of an overall effort to assess the current economic potential of these plants.

## 1.2 SUMMARY AND CONCLUSION

The cooling system costs, which are presented as a function of water usage for the HTGR-GT, PWR, and fossil plants in Figures 1.1 to 1.3, include capital, operating penalty costs and the sums of these costs, i.e., total evaluated costs circa 1980. The comparison of the total evaluated costs for the three plants is shown in Figure 1.4. The capital costs include the direct costs for equipment purchase and installation and indirect costs for engineering and contingency. The penalty costs include the costs assessed to account for: 1) the loss of capacity at the peak ambient temperature and the loss of energy during a year if the plant cannot produce the rated capacity, 2) the power and energy required to operate the cooling system, 3) the cooling system maintenance required, and 4) the purchase, supply, treatment and make-up water required and blowdown disposal.

A sensitivity analysis was also performed to determine the effects of the changes of economic factors on the total evaluated cost characteristics of the alternate cooling systems.

The major conclusions are as follows:

1. The comparison of the 800 MWe HTGR-GT, PWR and fossil plants indicates that the total evaluated costs of the cooling systems for the HTGR-GT plant, in the range from all-dry to wet/dry using about 50% of the water needed for the all wet system, are much lower than the costs of the dry and wet/dry systems for the PWR and fossil plants with the same water usage constraints as the HTGR-GT plant. This basic conclusion remains valid even when substantial changes in the economic factors affecting the cooling system total evaluated costs occur.

2. For the HTGR-GT plant, a substantial reduction in total evaluated costs can be obtained by changing from an all-dry system to a wet/dry system of limited water usage, e.g., a water use of equivalent to 5% of the amount required by the all-wet tower system. Increasing the water usage beyond the 5% does not necessarily produce further cooling system cost reduction. In fact, the reverse is true for the wet/dry systems above 10% water usage; and the cost of the all-wet system is even higher than the all-dry system.

3. The cooling cost trend for the HTGR-GT plant indicated above is very sensitive to the changes in the economic factors. The cost trend indicated in (2) above may change due to changes in the economic factors.

4. For the PWR and fossil plants, the observed total evaluated cost trends of the dry, wet/dry and wet tower systems for both types of plants remain as expected from previous studies. The cost trend for the cooling systems of either plant is that the total evaluated cost decreases monotomically with increasing water usage from all-dry to all-wet.

5. The general trend of the cooling system total evaluated costs for the PWR or the fossil plant is relatively insensitive to the changes in the economic factors. The cost trend remains monotomically decreasing for a wide range of values of the economic factors.

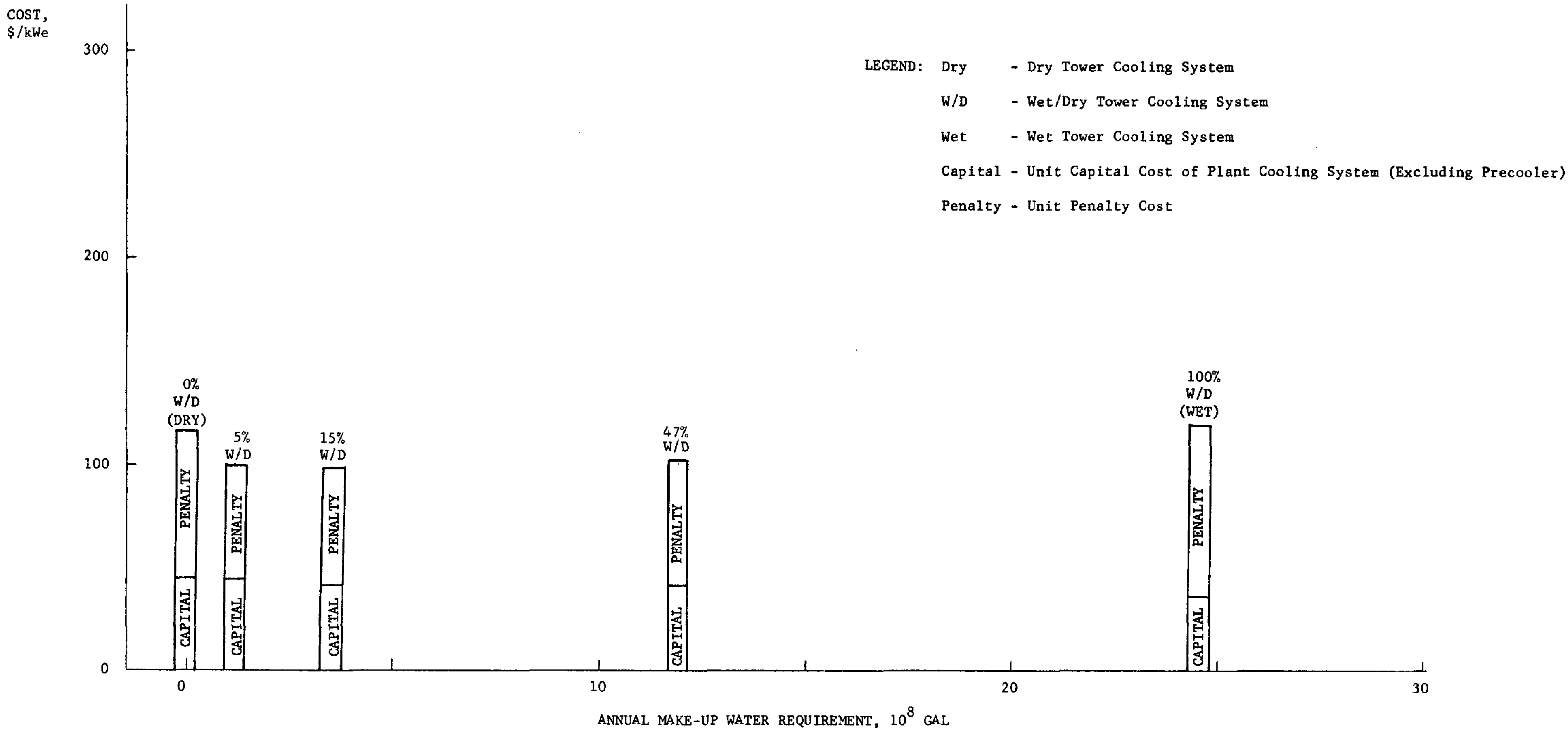


FIGURE 1.1

COST CHARACTERISTICS AS A FUNCTION OF MAKE-UP WATER REQUIREMENT
FOR COOLING SYSTEMS DESIGNED FOR AN 808 MWe HTGR-GT PLANT AT MODESTO, CALIFORNIA

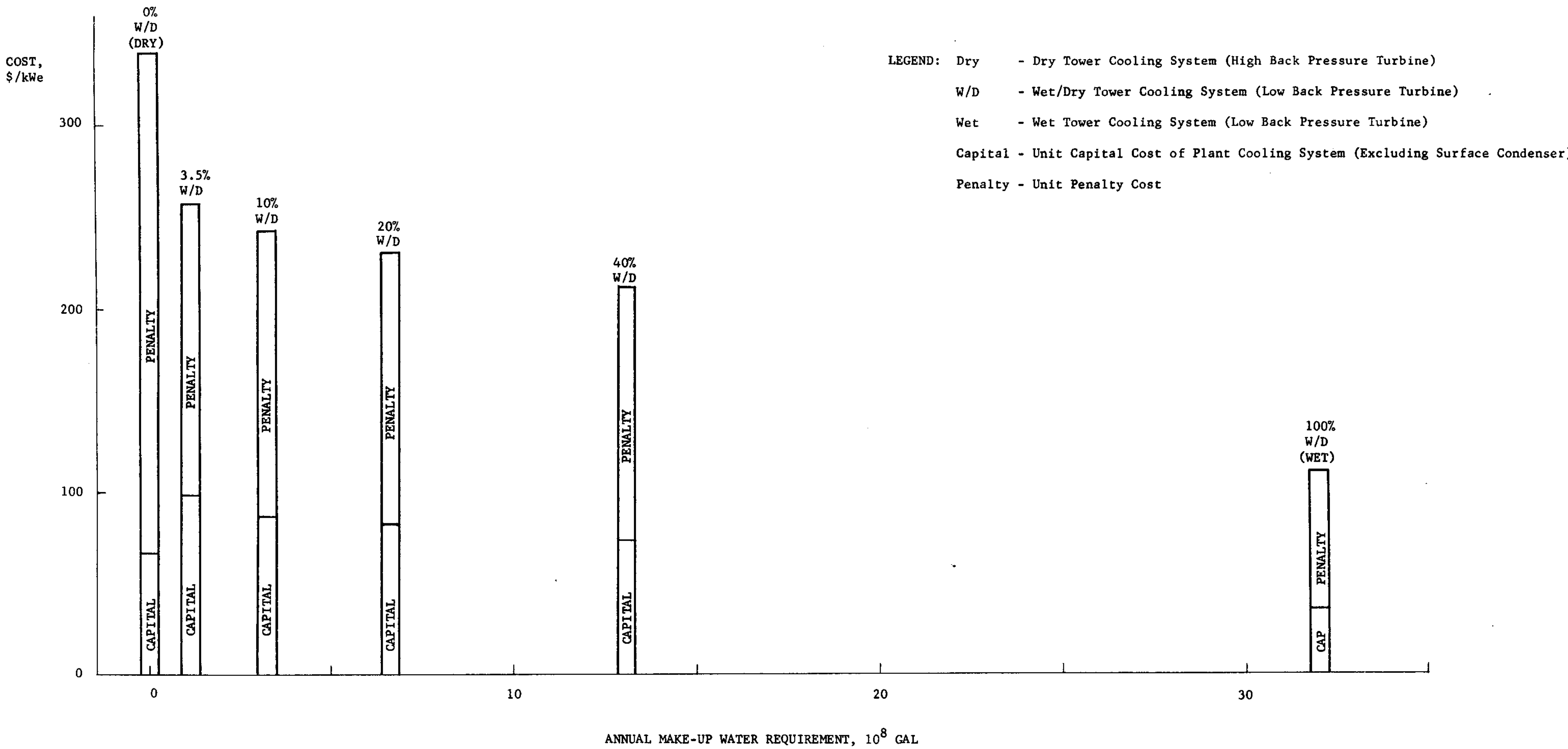


FIGURE 1.2

COST CHARACTERISTICS AS A FUNCTION OF MAKE-UP WATER REQUIREMENT
FOR COOLING SYSTEMS DESIGNED FOR AN 838 MWe PWR PLANT AT MODESTO, CALIFORNIA

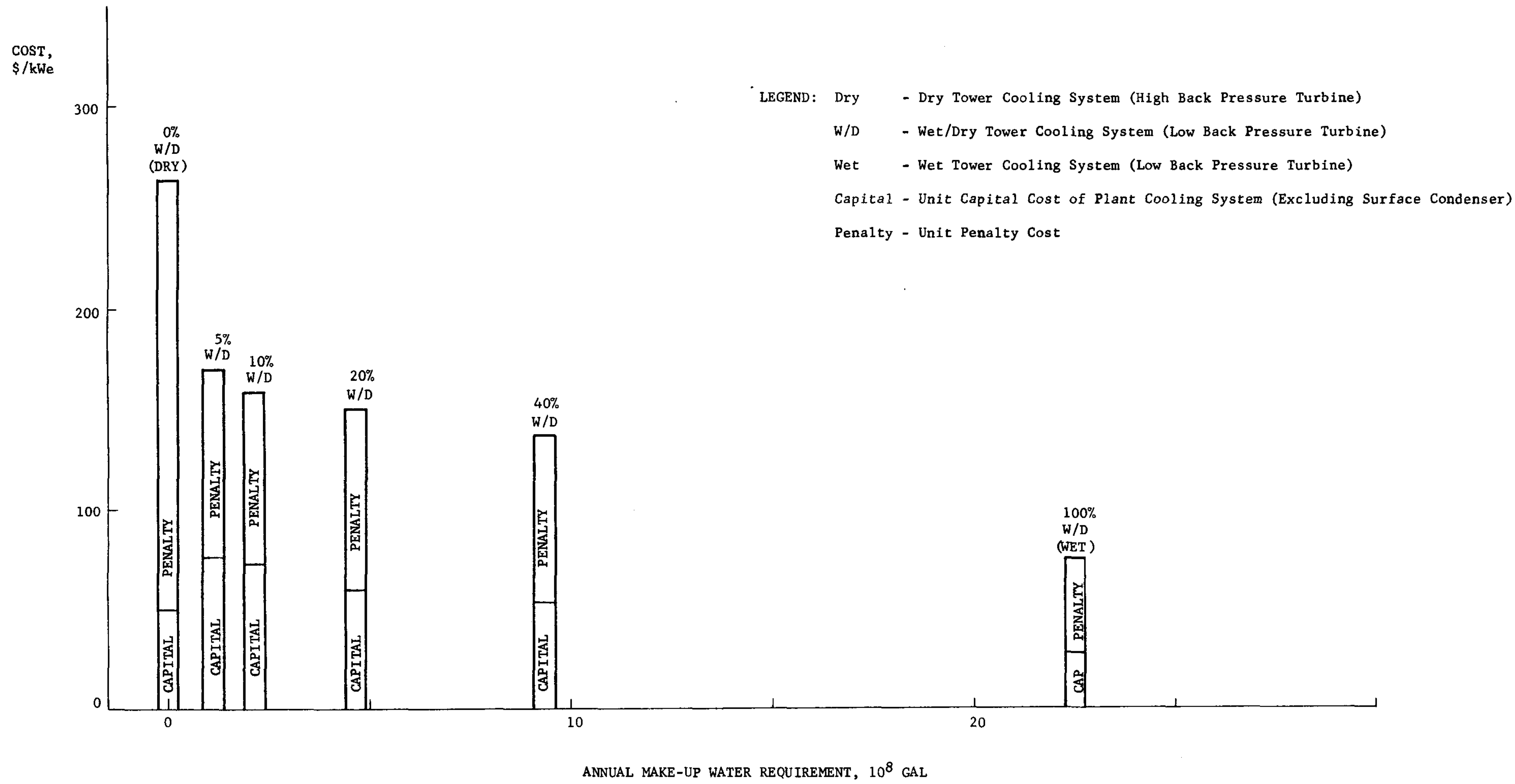


**FIGURE 1.3**

COST CHARACTERISTICS AS A FUNCTION OF MAKE-UP WATER REQUIREMENT
FOR COOLING SYSTEMS DESIGNED FOR AN 855 MWe FOSSIL PLANT AT MODESTO, CALIFORNIA

ECONOMIC FACTORS

| | |
|---|---|
| *Pricing Date* | January, 1980 |
| Average Plant Capacity Factor | 70% |
| Annual Fixed Charge Rate | 18% |
| Plant Life | 30 Years |
| Capacity Penalty Charge Rate | $621/kW |
| Replacement Energy Cost (Levelized) | 40.8 Mills/kWh |
| Water Cost (Levelized) | $1.0/1000 Gal |

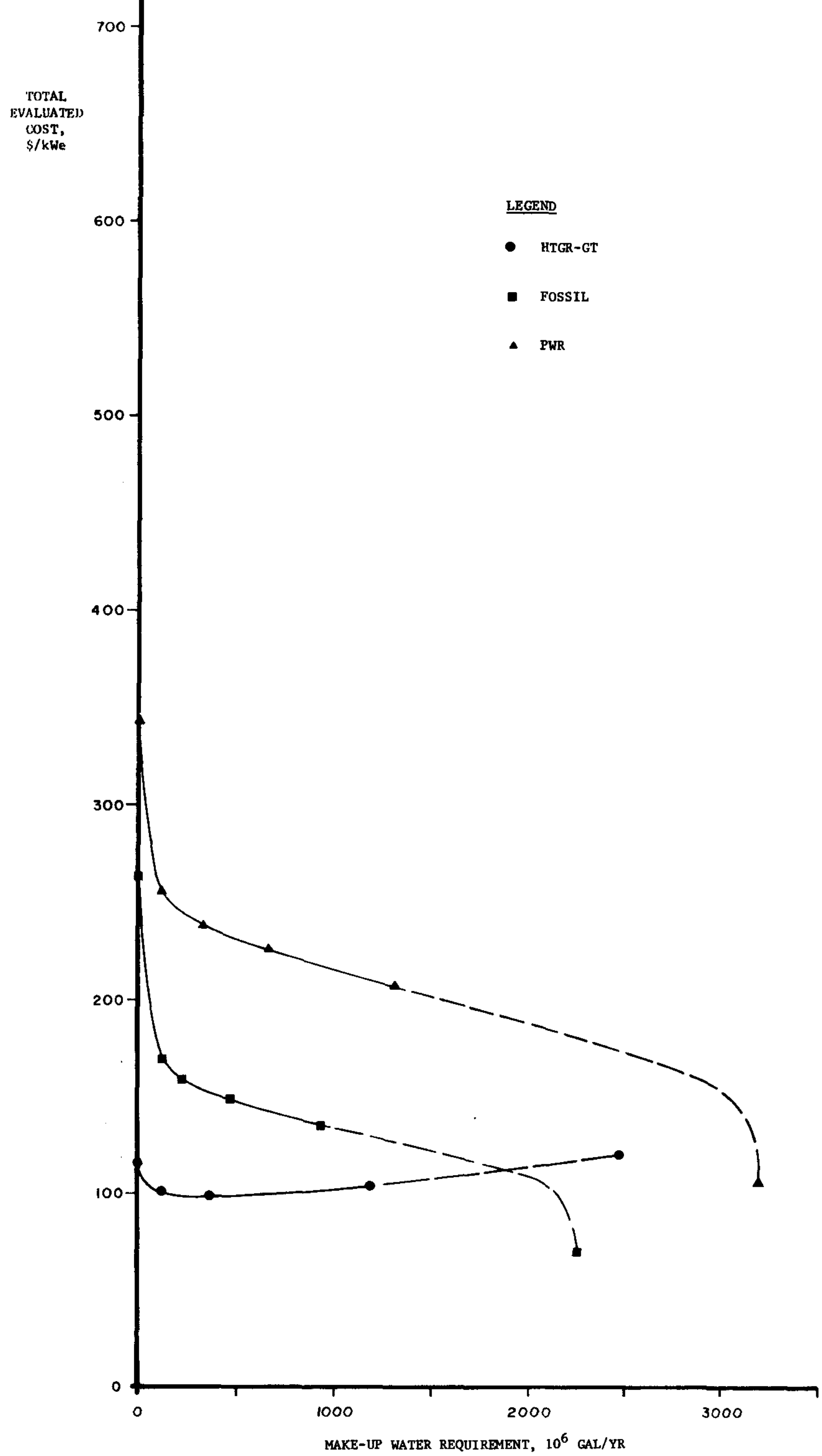


FIGURE 1.4

COMPARISON OF TOTAL EVALUATED COST CHARACTERISTICS OF 800 MWe (NOMINAL) POWER PLANTS AT MODESTO, CALIFORNIA

# SECTION 2.0

# METHOD OF ECONOMIC EVALUATION

## 2.1 GENERAL DESCRIPTION OF THE ECONOMIC METHOD

In order to assess alternate cooling systems on a common economic basis, several penalty costs should be included in the economic evaluation, in addition to the capital cost for the equipment and its installation. Common to all cooling system evaluations are the penalties incurred to account for: 1) the loss of plant performance (capacity loss at the peak ambient temperature and energy loss during a year), 2) the power and energy required to operate the cooling system, and 3) the cooling system maintenance requirements. Other penalties may be included under special circumstances. For instance, included in this evaluation is the cost incurred for the purchase of water and operating costs of the make-up water supply treatment and blowdown disposal systems because the cost of water is a primary concern.

The method used in this study for assessing the capacity and energy penalties is a fixed source-fixed demand method. A reference plant is assumed to be of fixed heat source, and there is a fixed demand for its output. It is against this fixed demand that the loss of plant performance for each cooling system is measured. Inability to meet this demand will be charged as a penalty cost which is capitalized and added to the capital cost of the cooling system. The sum of the penalty costs and capital cost of a cooling system is called the total evaluated cost (TEC). The nature of these costs is such that an optimum, i.e., minimum total evaluated cost system can be identified. The details of the penalty assessment, including maintenance and water cost penalties are given in this section.

## 2.2 TREATMENT OF LOSS OF PLANT PERFORMANCE

The economic penalty evaluation for the loss of plant performance depends on how the loss resulting from the cooling system performance deficiency is treated. As indicated in Section 2.1, the method used in this study assumes that the reference plant has a fixed size heat source and there is a fixed demand for the plant output. It is against this fixed demand that the loss of plant performance will be measured. Since the size of the plant heat source is fixed, the loss of plant performance will be provided by an outside source and not by adjusting the heat source of the reference plant. The treatment of the loss of plant performance is illustrated in Figure 2.1.

The figure shows the typical gross plant output of the reference power plant as a function of ambient temperature and time when the plant is operated with a cooling system. The ambient temperatures affect the plant output since the performance of a cooling system determines the lowest temperature of the thermodynamic cycle, and consequently, the plant output. The figure also shows the net plant output which is determined by deducting from the gross plant output the power required to run the cooling system auxiliary equipment.

The maximum plant capacity deficit with respect to the fixed demand occurs at the highest ambient temperature and represents the capacity replacement needed. This includes both the maximum loss of plant performance $(\Delta kW)_{max}$, and the coincidental auxiliary power requirement $(HP)_{aux}$. The shaded area represents the replacement energy required during the annual cycle. The area above the gross plant output curve represents the energy deficit caused by the changes in cooling system performance, whereas the shaded area between the gross plant output and the net plant output curves represents the energy requirements by the cooling system auxiliary equipment; e.g., pumps and fans.

## 2.3 ECONOMIC PENALTY EVALUATION

### 2.3.1 Capacity and Energy Penalties

The annual costs needed to provide the extra capacity and energy to compensate for the losses as discussed in the previous section are a part of the total penalty cost. In evaluating the penalties, it is assumed that the plant either operates at full capacity or is off-line and has an average capacity factor.

The equations used for evaluation of these penalty costs are given below:

Capacity Penalty ($P_1$):

$$P_1 = K \cdot afcr \cdot (\Delta kW)_{max} \quad (1)$$

Replacement Energy Penalty ($P_2$):

$$P_2 = cap \int_0^{8760} \left[ OAM + F \cdot HR\ (T) \right] \Delta kW(T)\ dt \quad (2)$$

Cooling System Auxiliary Power ($P_3$):

$$P_3 = K \cdot afcr \cdot (HP)_{aux} \quad (3)$$

Cooling System Auxiliary Energy ($P_4$):

$$P_4 = cap \int_0^{8760} \left[ OAM + F \cdot HR(T) \right] HP(T)\ dt \quad (4)$$

where $(\Delta kW)_{max}$, $\Delta kW(T)$, $(HP)_{aux}$, and HP(T) are shown in Figure 2.1 and:

afcr = annual fixed charge rate, %/100.

cap = average capacity factor of the plant, %/100.

F = fuel cost for the generating unit used to make up the loss of energy, \$/MBtu.

$(HP)_{aux}$ = cooling system auxiliary power requirement at $T_{max}$, kW.

HP(T) = cooling system auxiliary power requirement at ambient temperature T, kW.

HR(T) = heat rate as a function of ambient temperature for the generating unit used to make up the loss of energy, Btu/kWh.

K = capacity penalty charge rate, \$/kW.

$(\Delta kW)_{max}$ = maximum loss of capacity, kW.

$\Delta kW(T)$ = loss of capacity at ambient temperature T, kW.

OAM = operation and maintenance cost for the generating unit used, \$/kWh.

T = ambient temperature (T is a function of time), $^{o}F$.

$T_{max}$ = peak ambient temperature, $^{o}F$.

t = time, hr.

The capacity penalty, $P_1$, and auxiliary power penalty, $P_3$, (Equations (1) and (3)) are first cost penalties. They represent the capital expenditure of generating equipment needed to supply the extra power, either by the addition of peaking units, e.g., gas turbine or pump storage generating units, or by providing excess capacity from base load units in the utility system.

The replacement energy penalty, $P_2$, and the cooling system auxiliary energy, $P_4$, (Equations (2) and (4)) are the energy cost penalties which will accrue over the lifetime of the plant. They are evaluated by capitalizing the respective annual energy costs charged to the cooling system. These annual energy costs are evaluated by integrating the energy costs for a series of time periods which add up to a year. Each time period has a constant ambient dry bulb temperature and a coincident and constant wet bulb temperature.

### 2.3.2 Make-up Water Penalty

One of the disadvantages of wet cooling towers is the requirement of large amounts of make-up water to replenish the water evaporated and the water lost in blowdown. When wet cooling is used to augment dry cooling in wet/dry towers, the water requirement can be substantially reduced. In situations where the cost of supplying the make-up water is high, this penalty cost can be a significant factor in comparing dry, wet, and wet/dry towers.

The cost of supplying the make-up water to a plant consists of two components:

1. Pumping cost which includes both the capacity charge for the power required by the pumps and the energy charge for pumping the water.
2. Water purchases and treatment cost.

For specific power plants, these two component costs can be accurately estimated. However, since the site for this study is general in nature, a lumped charge for the make-up has been assumed in the form of dollars per unit quantity of make-up and the penalty was evaluated by the following equation:

$$P_5 = \text{make-up water penalty} \qquad (5)$$
$$= (C_m)(C_w)$$

where:

$C_m$ = annual make-up requirement, gal/year ($m^3$).

$C_w$ = cost for supplying make-up water, \$/1000 gal of water.

### 2.3.3 Cooling System Maintenance Cost Penalty

The cooling system maintenance penalty is the cost charged to a cooling system for services which include periodic maintenance, and replacement of parts. It is calculated on the basis of in-house engineering data, condenser tube cleaning costs and limited data supplied by cooling tower vendors.

Cooling tower maintenance mainly consists of:

1. lubrication and general inspection of the fan motors and gearboxes;
2. partial replacement of motors and gearboxes;
3. cleaning of the cold water basins of the wet towers; and,
4. partial replacement of finned tubes for the heat exchangers in the dry towers.

Condenser tube cleaning was assumed to be required yearly. The circulating water pumps, motors and associated equipment will require periodic maintenance. All of the maintenance costs were calculated, based on a percentage of the capital cost of the three components; pumps, condensers and cooling towers.

$$P_6 = \text{cooling system maintenance penalty} \quad (6)$$
$$= aC_c + bC_p + cC_T$$

where:

$C_c$ = capital cost of condensers.

$C_p$ = capital cost of pumps.

$C_T$ = capital cost of cooling towers.

a, b & c = coefficients for estimating the penalty cost for each component.

## 2.4 TOTAL EVALUATED COSTS

In summary, there are six penalties which are essential to the evaluation of cooling systems. These penalty costs are evaluated on an annual basis as shown in Equations 1 through 6. These penalty costs are then capitalized over the plant lifetime and added to the capital cost of the cooling system. The sum of the capital cost and the capitalized penalty cost is called the total evaluated cost and is expressed by the following equation:

$$C_t = C + \frac{1}{afcr} \sum_{j=1}^{6} P_j$$

where:

$C_t$ = total evaluated cost, \$.

$C$ = capital cost of cooling system, \$.

afcr = annual fixed charge rate, %/100.

$P_j$ = economic penalties, \$.

This total evaluated cost represents an effective capital cost of the cooling system.

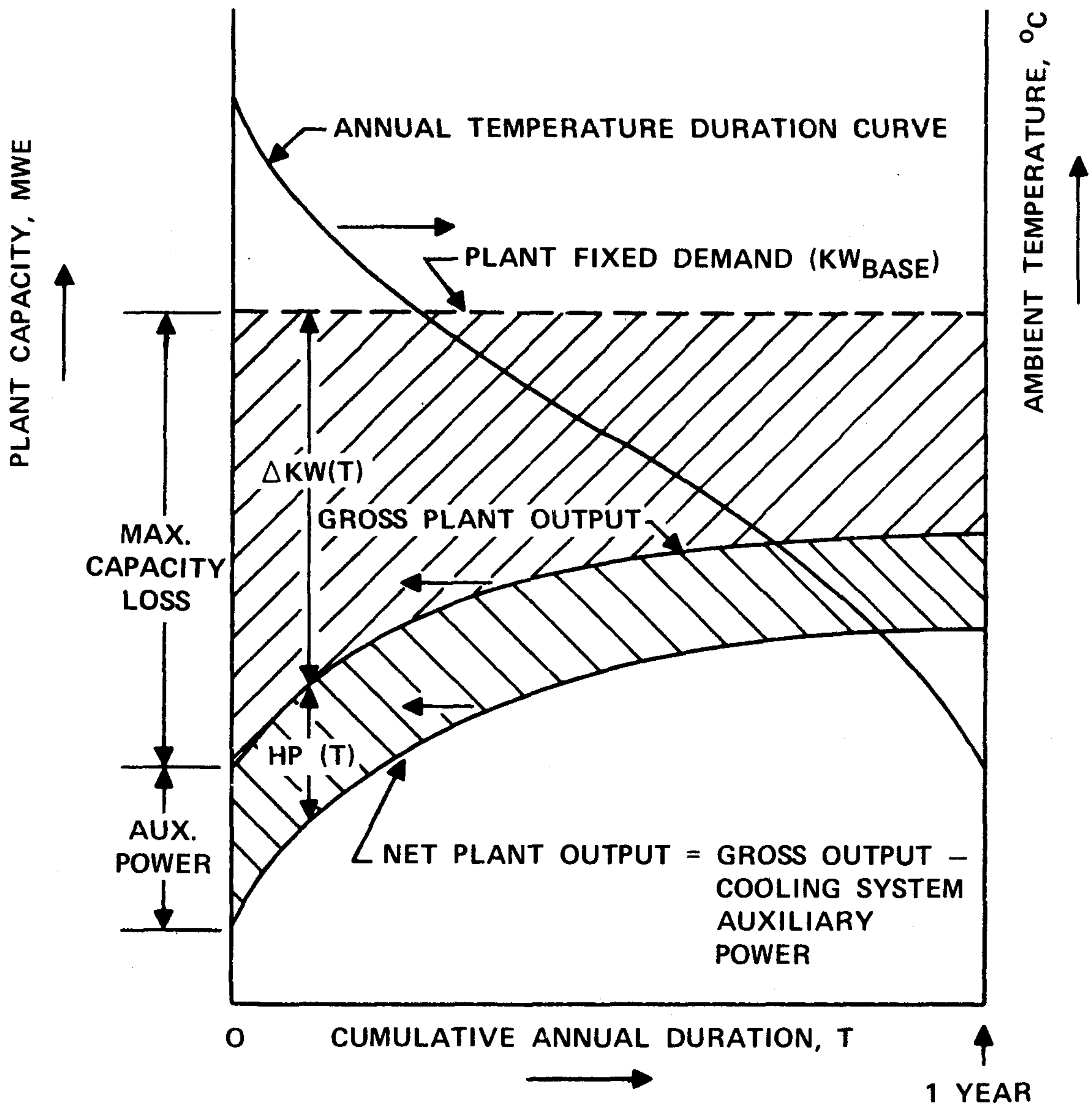


Figure 2.1 Ambient Temperature Duration And Corresponding Plant Performance

# SECTION 3.0

## DESCRIPTION OF COOLING SYSTEMS AND PARAMETERS REQUIRED FOR ECONOMIC EVALUATION

### 3.1 DESCRIPTION OF COOLING SYSTEMS

The cooling systems evaluated include those using wet towers, dry towers, and wet/dry towers designed for water conservation. A brief description of these cooling systems follows, the major tower design features are given in Table 3.1.

For the PWR and fossil power plants, both the wet and dry towers are modular type mechanical draft towers. A schematic diagram of a wet tower cooling system is shown in Figure 3.1 for a PWR plant. The schematic diagram of a dry tower system is similar to that for the wet tower except that the make-up and blowdown systems are not required.

The wet/dry cooling tower system investigated is shown schematically in Figure 3.2. It is a cooling system in which separate mechanical draft wet and dry cooling towers are connected in series on the cooling water side. The system can be operated in either a wet/dry mode or an all-dry mode. When it is operated in a wet/dry mode, the cooling water is pumped through the steam condenser and then to the dry tower. After being partially cooled in the dry tower, the cooling water is then pumped through the wet tower before returning to the condenser. Depending on the heat load to be shared by the wet tower, only a portion of total water flow may need to be cooled by the wet tower, the remaining flow is bypassed and is rejoined with the water leaving the wet tower.

Several different modes of wet/dry operations can be utilized for a wet/dry system. For instance, two distinct modes were analyzed in the ERDA and EPA wet/dry tower studies[2,3] for nuclear and fossil steam-electric plants. It was determined in these studies that the so-called "S-1" mode in which the wet tower is operated as little as possible, is the preferred mode of operation for both PWR and fossil plants because it is more water conservative and more economical than the so-called "S-2" mode. The wet/dry tower systems evaluated in this study for the PWR and fossil plants are designed to operate on the S1 mode. These two operational modes are described below in terms of turbine back pressures for PWR and fossil steam electric plants. When these two operational modes are applied to HTGR-GT plants, the same descriptions apply when the key parameter is replaced by precooler inlet water temperature.

Mode S1 - The main objective of this mode is to operate the wet helper tower as little as practically possible. The back pressure variations of a typical steam turbine operating in this mode and the concurrent ambient temperature variation are schematically presented in Figure 3.3. At the peak summer ambient temperature, both the wet and dry towers are operated at full capacity and the back pressure is at point 1. As the ambient temperature falls, the wet cells are turned off in succession when the back pressure can be maintained at or slightly below a specified design value. Each time when a wet cell is taken out of service as the ambient temperature falls, the back pressure would rise sharply and then gradually decrease again, creating a saw-tooth shape curve between point 1-8. When point 8 is reached, all the wet cells are turned off and the dry tower rejects the entire heat load. As the ambient temperature continues to fall, the back pressure first rises stepwise to point 9 and gradually decreases to point 10. Between points 9-10, the cooling system is operated in the all-dry mode.

Mode S2 - The second mode of operation represents a system operating with much less control of the wet tower. The back pressure variation of a typical steam turbine operating in S2 mode and the concurrent ambient temperature variations in this mode are shown in Figure 3.4. As the ambient temperature falls from the peak to the point which corresponds to the design ambient for the dry tower, both the wet and dry towers are operated at full capacity, and the back pressure follows the path 1-2. At point 2, the entire wet tower is turned off and the dry tower can reject the entire heat load. As the cooling system starts to operate in all-dry mode, the back pressure rises sharply to point 3 and then gradually drops off to point 4.

For HTGR-GT power plants, the schematic diagrams of the cooling system alternatives evaluated are shown in Figures 3.5 through 3.7. For the wet/dry tower and wet tower systems, intermediate heat exchangers have to be used to step down from the pressurized precooler water loop. The dry towers in the dry tower and wet/dry tower cooling systems are natural draft dry towers with hyperbolic reinforced concrete shells. The finned-tube heat exchanger modules are located at base of tower and are oriented vertically. The wet towers are multi-celled induced mechanical draft type with concrete structures, identical to those used in the steam cycle PWR and fossil plants.

The wet/dry towers for the HTGR-GT plants are designed to operate in the S2 mode described previously. An analysis of the S1 and S2 modes has indicated that for the HTGR-GT plants, S2 mode is preferrable.

## 3.2 PARAMETERS FOR ECONOMIC EVALUATION

### 3.2.1 Site Ambient Temperatures - Modesto, California

The most important site parameter for cooling tower system design and operation is the site ambient temperature. The performance of dry towers is a function of ambient dry bulb temperature whereas the performance of the wet towers is affected primarily by the ambient wet bulb temperature. The ambient dry bulb and wet bulb temperature characteristics during a typical year at Modesto, California is shown in Figure 3.8.

The entire range of ambient temperatures and the annual average ambient temperature at a site affect the annual electric generation and the replacement energy requirement of the plants. The maximum ambient temperature determines the peaking capacity requirement. The annual average and maximum dry bulb/wet bulb temperatures at Modesto, California are $64^{o}F/55^{o}F$ and $105^{o}F/75^{o}F$ respectively.

### 3.2.2 Reference Power Plant Characteristics

The cooling systems are designed for three reference power plants with identical rated electric output, i.e., 800 MWe (nominal).

The high temperature gas cooled reactor-gas turbine reference power plant (HTGR-GT) has a fixed heat source of 2000 MWt (megawatts thermal). At a precooler temperature of $70^{o}F$, the plant delivers a gross output of 808 MWe. The plant output performance as a function of precooler temperatures is shown in Figure 3.9.

The pressurized water reactor (PWR) steam cycle reference power plant has thermal rating of 2397 MWt. This heat source may be coupled with either a conventional turbine or a high back pressure turbine, the latter is needed for all-dry cooling systems. The plant delivers the rated electric output of 838 MWe (gross) at a back pressure of 2 in HgA (50.8 mm-HgA) when it is coupled with a conventional low back pressure turbine. The performance characteristics of the plant with a conventional turbine and a high back pressure turbine are shown in Figures 3.10 and 3.11 respectively. It should be mentioned that the high back pressure turbine is currently not available for this application.

For the fossil fueled reference plant, the thermal and electric ratings are 1953 MWt and 855 MWe respectively. The output performance characteristics of the plant with a conventional low back pressure turbine and a high back pressure turbine are given in Figure 3.12 and 3.13 respectively.

### 3.2.3 Economic Factors

The economic factors used in this evaluation are given in Table 3.2. The capacity charge rate and replacement energy charge rate are based on data given in Reference 3 for base loaded power plants. In addition, it was assumed that the capacity and energy replacement will be provided by a system mix of 80% coal-fired fossil plants and 20% light water reactor nuclear plants. The estimated replacement energy charge rate includes only the fuel and O&M costs. The cooling system capital costs are based on Eastern Pennsylvania delivery and labor rates.

TABLE 3.1

MAJOR DESIGN FEATURES OF COOLING TOWERS

| | |
|---|---|
| Natural Draft Dry Towers for HTGR-GT Plants | Each natural draft dry tower has a hyperbolic concrete shell with a maximum base diameter of 500 feet and a minimum shell thickness of 6 inches. The fin-tube heat exchanger modules are arranged vertically around the tower base. Each module has 489 tubes in 10 flow passes. The tubes are 1-inch outside diameter, 0.085 inch walls and are carbon steel. The fins are continuously extruded aluminum with 2¼-inch O.D. and 10 fins per inch. |
| Mechanical Draft Dry Towers for PWR and Fossil Plants | The mechanical draft dry towers consist of rectangular modules arranged back-to-back. Each module has 776 circular finned tubes in two flow passes and it is equipped with a 200-HP motor and a 28-foot diameter fan at the top of the module. The module dimensions are 45 feet wide, 44 feet long and 66 feet high. The finned tubes are of 1-inch outside bare tube diameter, 0.06 inch walls and are made of admiralty. The fins are made of aluminum, the fin pitch and fin height are 10 fins/inch and 0.625 inches respectively. |
| Mechanical Draft Wet Towers for All Plants | The mechanical draft wet towers in both the all-wet towers and wet/dry towers consist of modules arranged in single lines. One module design is used for all the towers. The module is the induced draft, cross-flow type with concrete structure. The module dimensions are 71 feet wide, 36 feet long, and 54 feet high. Its fill height is 41 feet. Each module has a 28-foot diameter fan located on the top of the module and driven by a 200 HP motor. |

TABLE 3.2

ECONOMIC FACTORS

| | |
|---|---|
| Pricing Date | January, 1980 |
| Average Plant Capacity Factor | 70% |
| Annual Fixed Charge Rate | 18% |
| Plant Life | 30 Years |
| Capacity Penalty Charge Rate | $621/kW |
| Replacement Energy Charge Rate (Levelized) | 40.8 Mills/kWh |
| Water Cost (Levelized) | $1.0/1000 Gal |

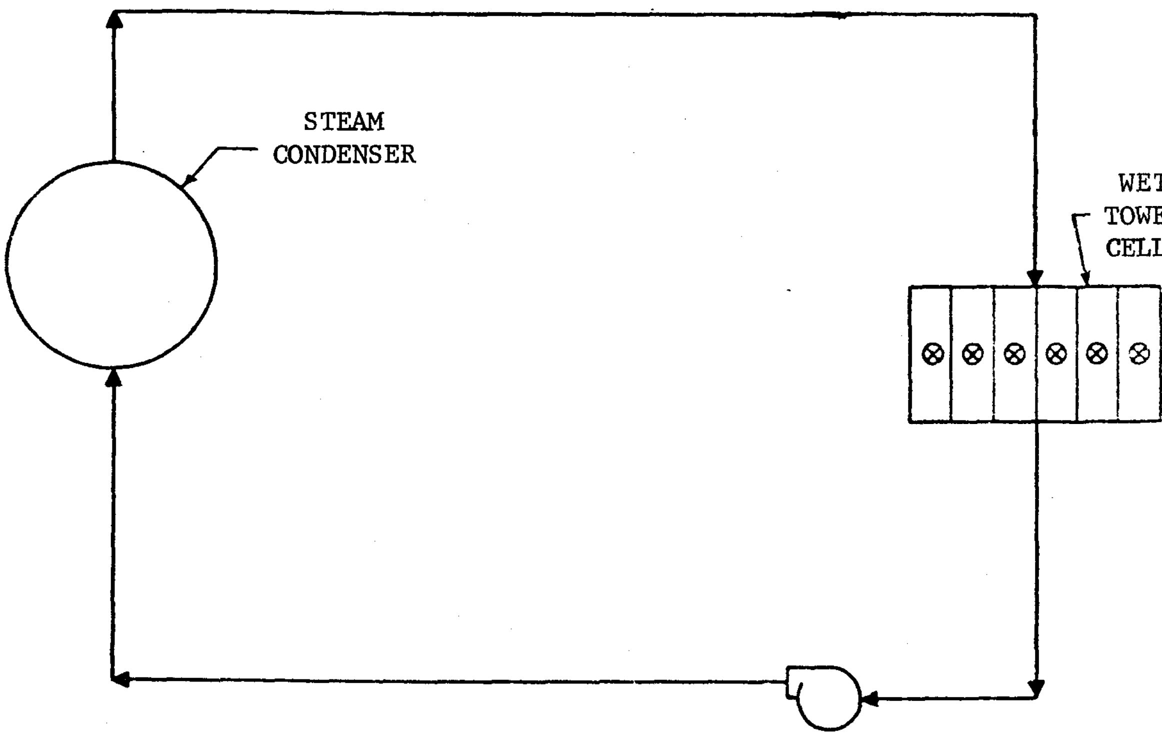


Figure 3.1 Schematic Diagram of a Wet Tower Cooling System for Rankine Cycle Power Plants

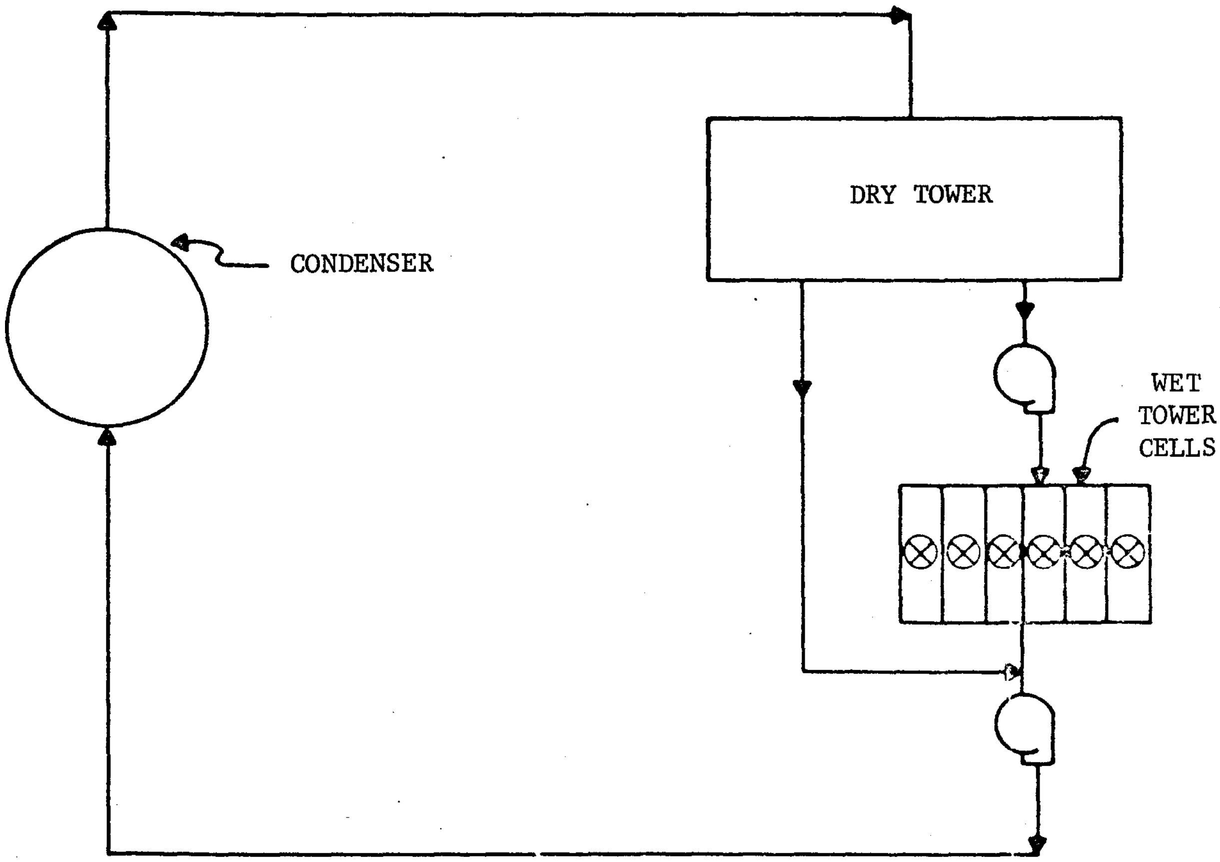


Figure 3.2 Schematic Diagram of a Series-Water Flow Wet/Dry Tower Cooling System for Rankine Cycle Power Plants

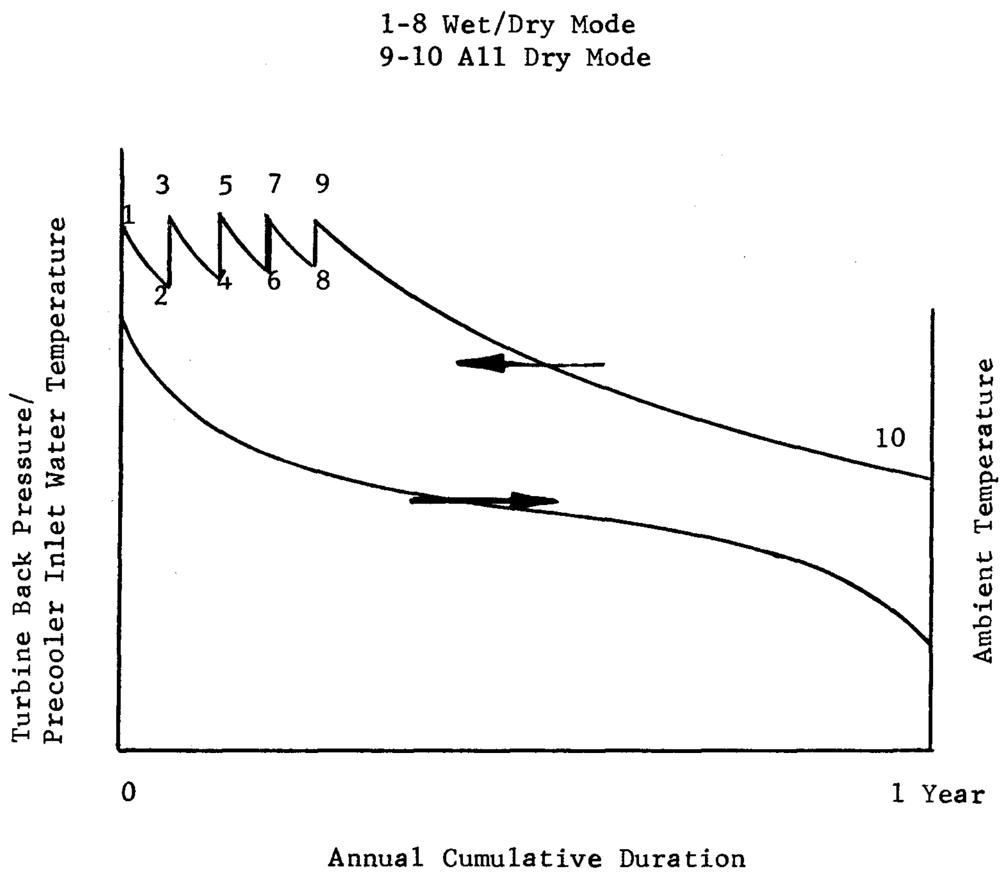


Figure 3.3 S1 Mode Operational Characteristics for Series-Flow Wet/Dry Tower Cooling Systems

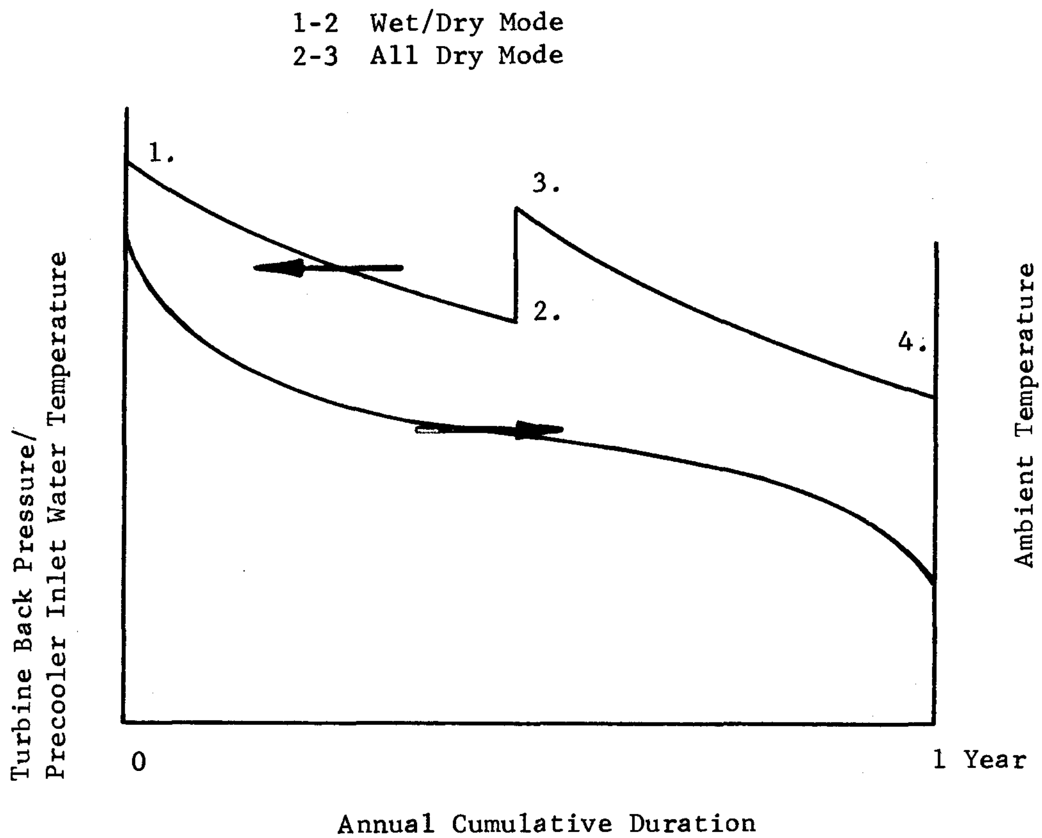


Figure 3.4 S2 Mode Operational Characteristics for Series-Flow Wet/Dry Tower Cooling System

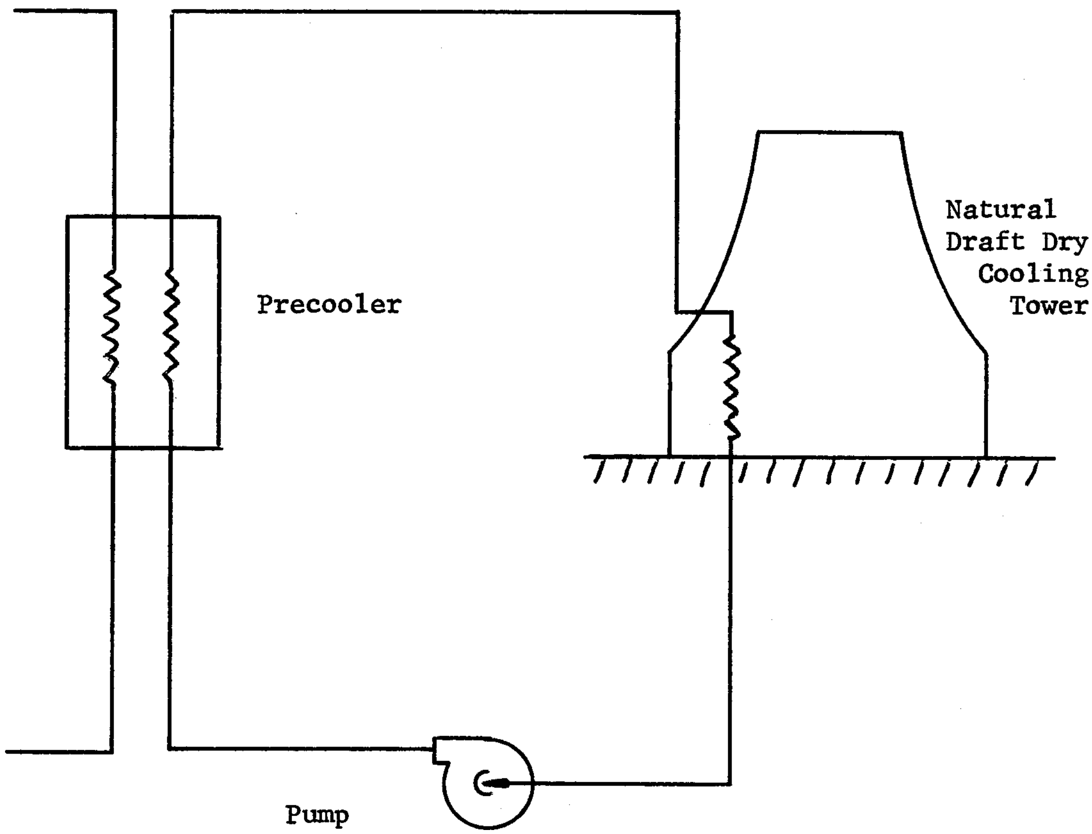


Figure 3.5 Schematic Diagram of Dry Cooling Tower System for HTGR-GT Power Plants

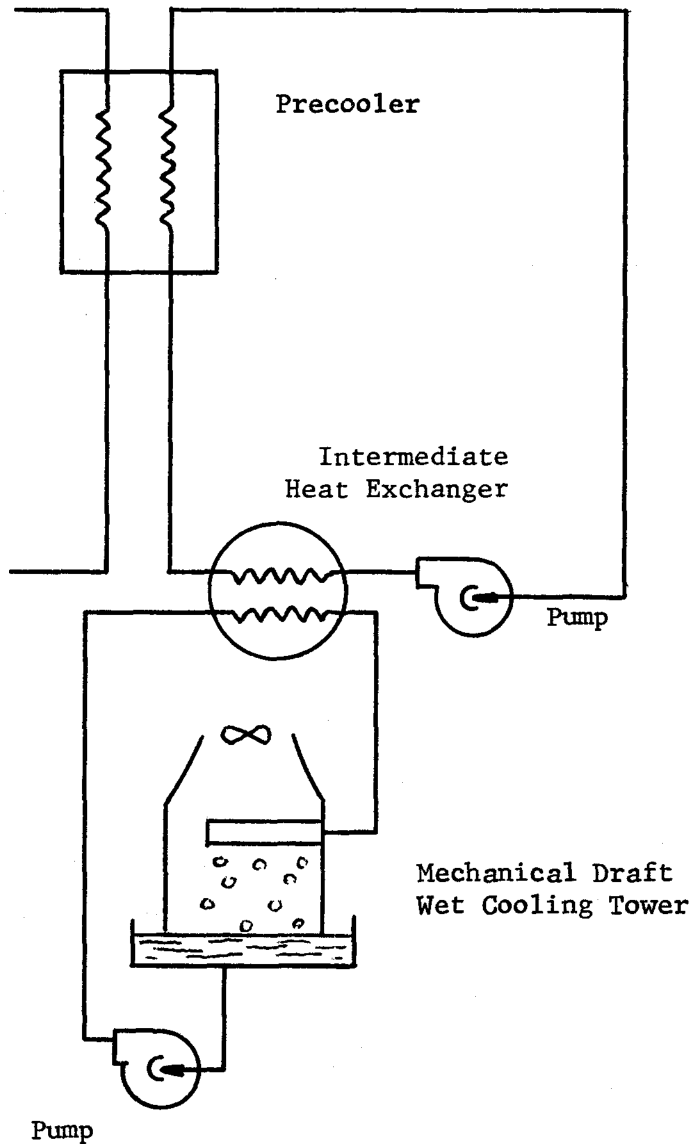


Figure 3.6 Schematic Diagram of a Wet Tower Cooling System for HTGR-GT Power Plants with an Intermediate Heat Exchanger

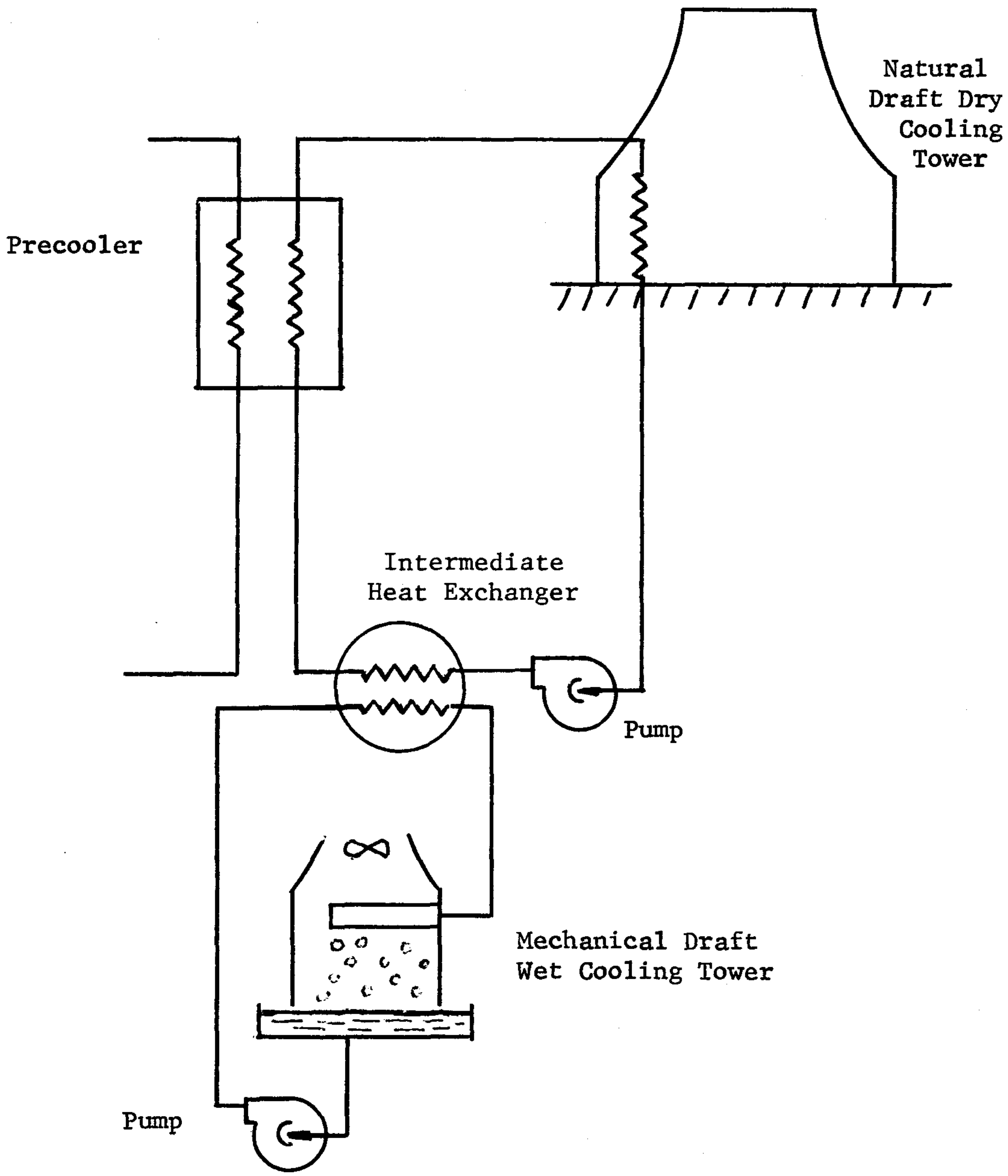


Figure 3.7 Schematic Diagram of a Wet/Dry Tower Cooling System for HTGR-GT Power Plants with an Intermediate Heat Exchanger

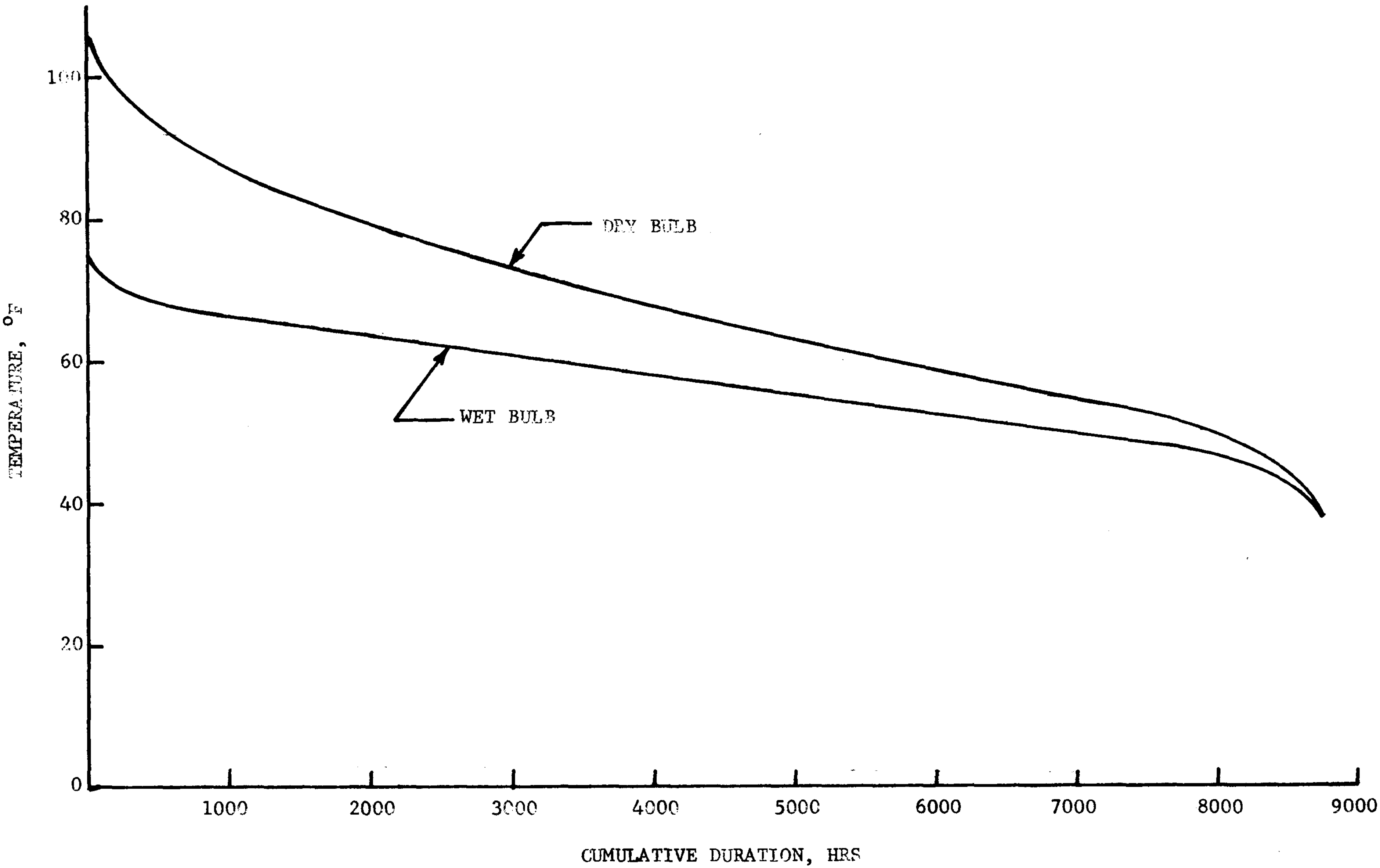


FIGURE 3.8 TEMPERATURE DURATION CURVE - MODESTO, CALIFORNIA

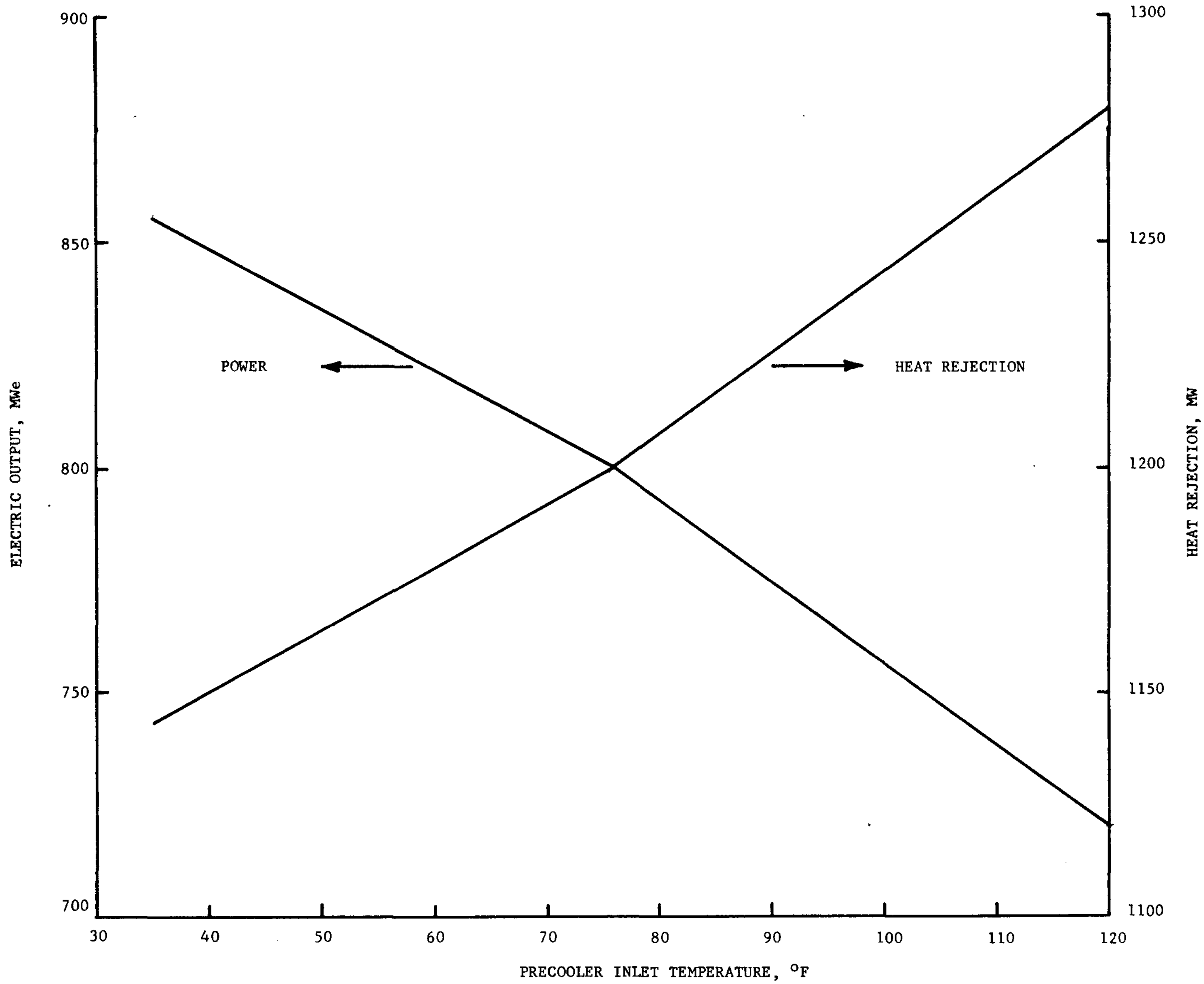


Figure 3.9 Plant Output Performance and Heat Rejection Rates Versus Precooler Inlet Water Temperature of a HTGR-GT Plant

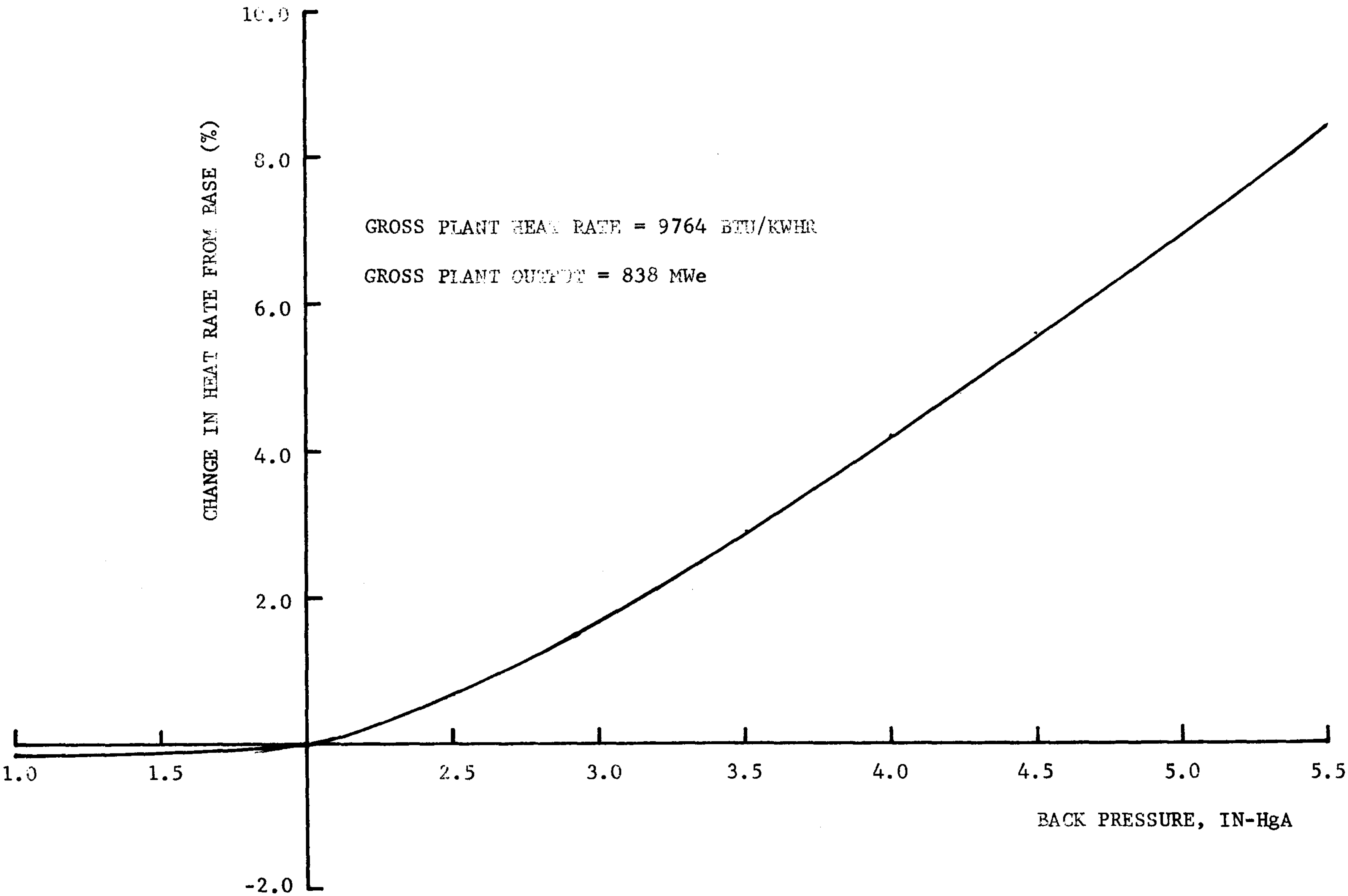


Figure 3.10 Heat Rate Correction Curve for a PWR Plant with a Conventional Turbine

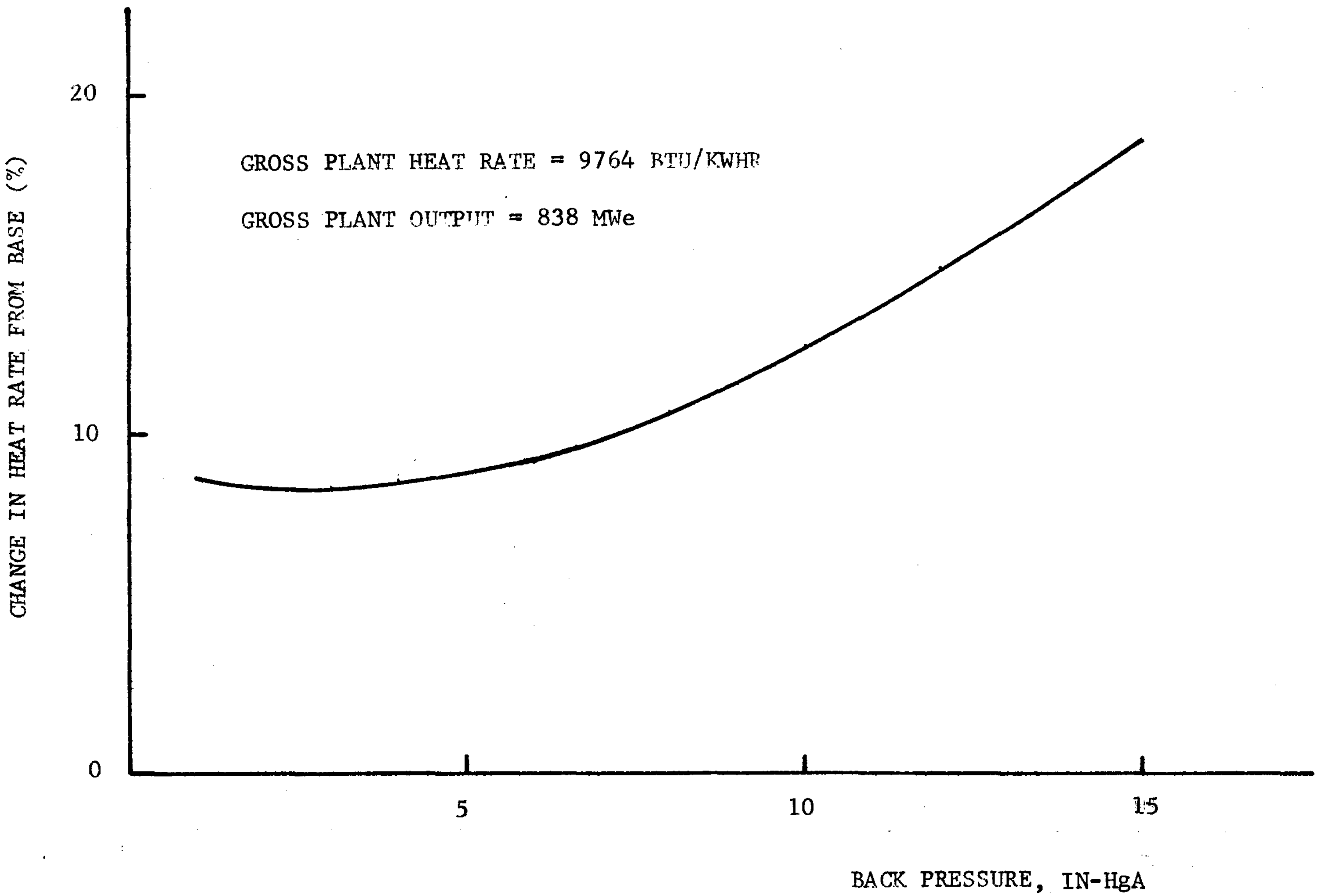


Figure 3.11 Heat Rate Correction Curve for a PWR Plant with a High Back Pressure Turbine

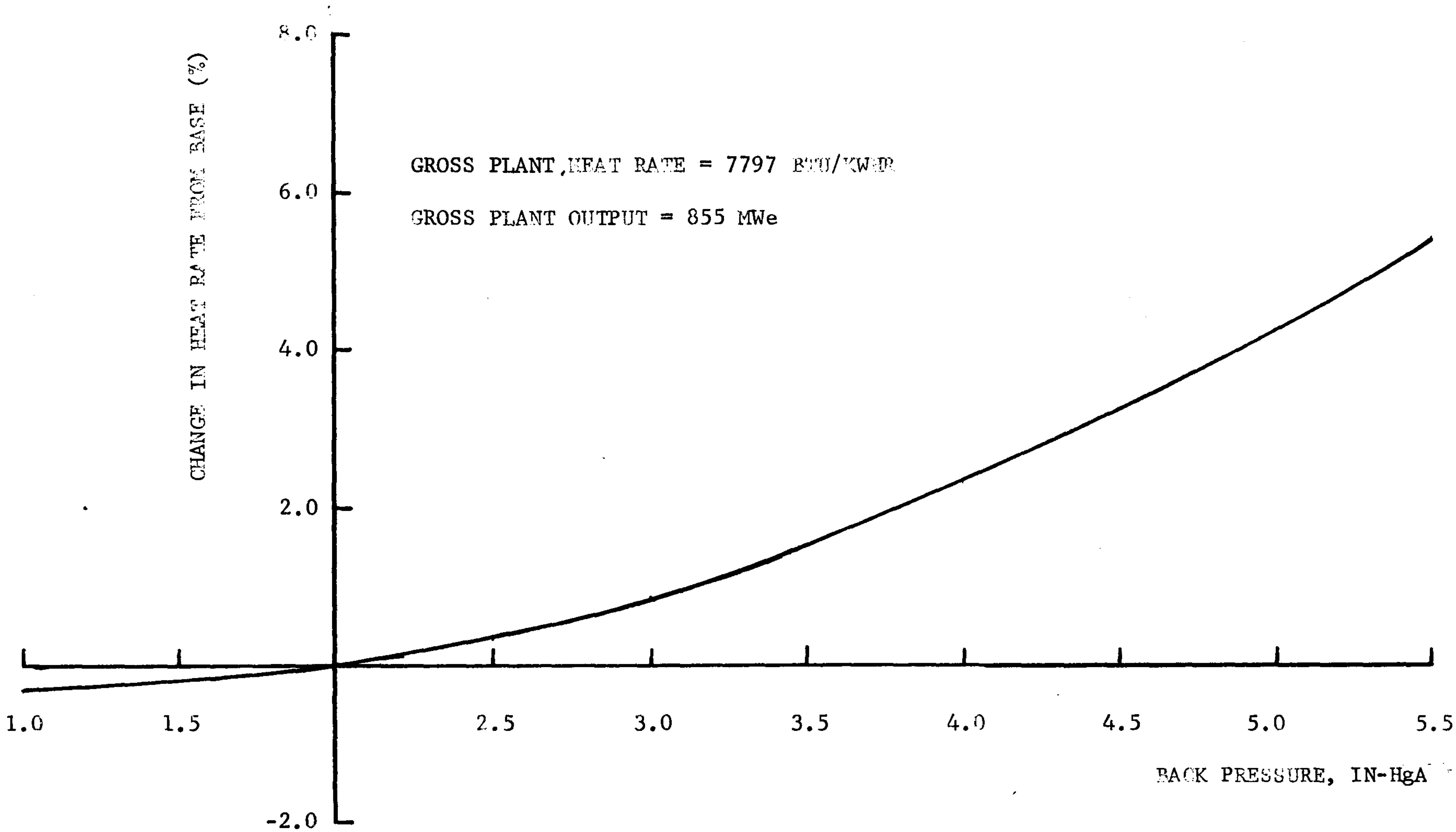


Figure 3.12 Heat Rate Correction Curve for a Fossil Plant with a Conventional Turbine

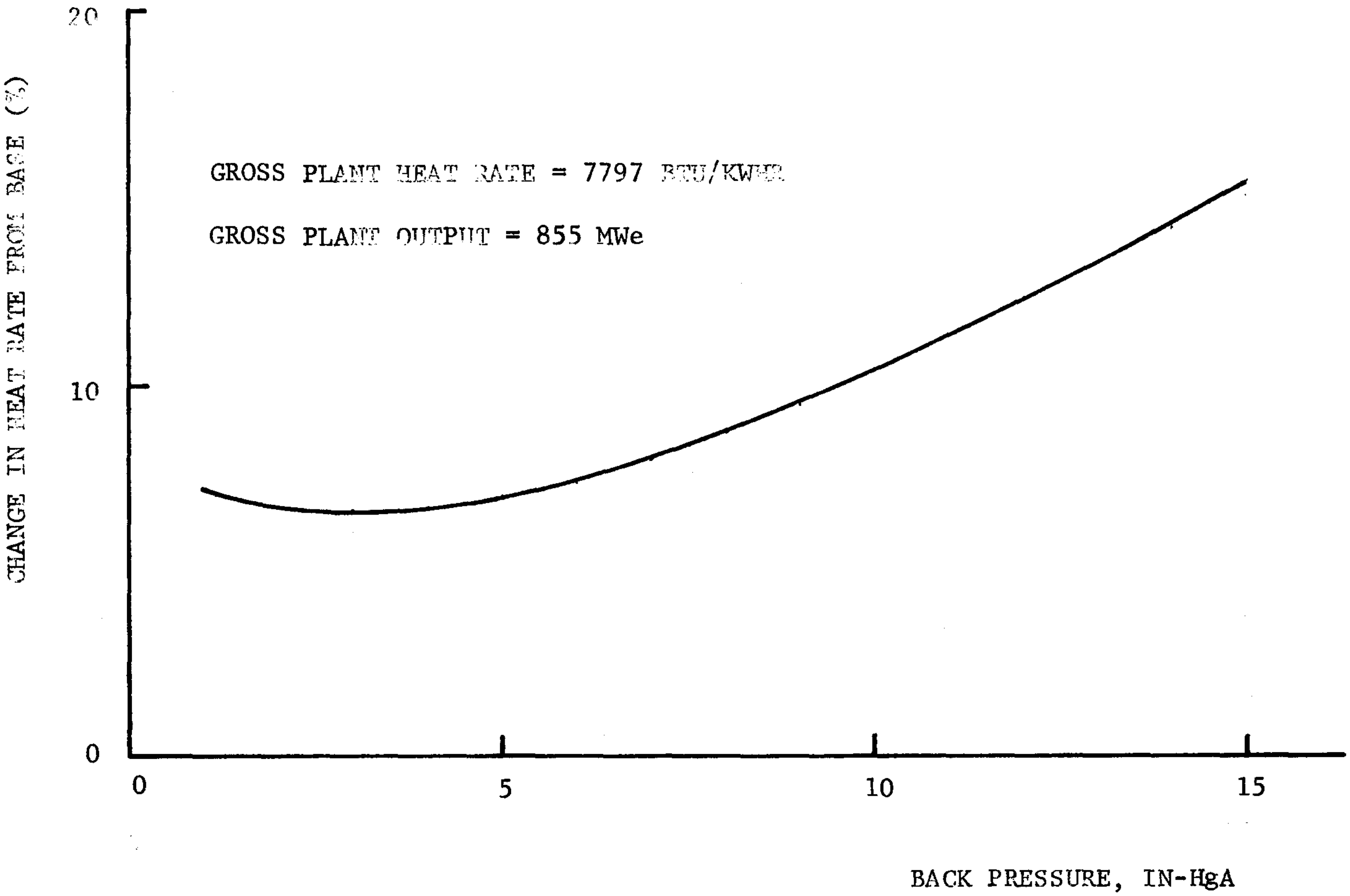


Figure 3.13 Heat Rate Correction Curve for a Fossil Plant with a High Back Pressure Turbine

## SECTION 4.0

## RESULTS OF EVALUATION

### 4.1 COOLING SYSTEM SELECTION

The selection of cooling systems for economic comparisons normally involves the following process: for each type of cooling system a series of designs are determined by changing pertinent design parameters. For each cooling system designed, its thermal performance, water consumption, auxiliary power and energy needs and other requirements are evaluated during a typical annual cycle. The capital and operating penalty costs of the cooling system are then estimated using the sizing and performance information obtained, and the economic parameters and penalty assessment method selected. The total capital cost is added to the total capitalized penalty cost to obtain the total evaluated cost of the system. From the series of cooling systems, the system with the lowest total evaluated cost is chosen as the "optimized cooling system" for economic comparison. For wet/dry cooling systems designed for water conservation, an optimum system is normally chosen for a specific water usage.

For both the nuclear and fossil Rankine-cycle power plants, United Engineers has developed a proprietary computer code for optimizing all conventional cooling systems (once-through cooling, wet towers, dry towers, cooling ponds and power spray canals) and wet/dry tower systems using the procedure described above. This code was used to evaluate the cooling systems of the 800 MWe (nominal) PWR and fossil power plants in this study. Such a computer code is not available for optimizing cooling systems of HTGR-GT power plants. The results of the cooling systems for the 800 MWe (nominal) HTGR-GT plant were obtained mainly with hand calculations and without comprehensive optimization. Instead, after carefully selecting a set of design parameters for a cooling system, its equipment size, performance, capital, penalty and total evaluated costs were determined. The results were examined. If it was determined that substantial reduction in capital or penalty costs could be obtained with a different choice of design parameters or operational mode, another case was evaluated. This approach was considered a reasonable alternative to a comprehensive optimization on the basis of experience obtained in previous cooling system optimization studies[2,3,5]. The results of the studies indicate that total evaluated cost curves as a function of design parameters are generally relatively flat near the optimum point. Therefore, if a proper set of design parameters is chosen, the total evaluated cost of the system should be only a few percent higher than that for the optimum system even though the best balance between the capital and penalty cost may not have been obtained.

## 4.2 RESULTS OF EVALUATION

The cooling systems were evaluated for three nominal 800 MWe plants (HTGR-GT, PWR and fossil) at Modesto, California. The site ambient temperatures are shown in Figure 3.8 and are characterized by maximum and annual average dry bulb/wet bulb temperatures of 105°F/75°F and 64°F/55°F respectively. The costs were based on the economic factors given in Table 3.2.

### 4.2.1 Design and Costs of Cooling Systems for the 800 (Nominal) HTGR-GT Power Plant

The costs and design data for the cooling systems designed for the HTGR-GT plant are given in Tables 4.1 through 4.4. The cooling systems include a dry tower system, a wet tower system and three wet/dry tower systems requiring about 5 percent, 15 percent and 47 percent respectively of the water usage of the wet tower system.

The summary capital costs, individual and summary penalty costs, and total evaluated costs of the selected cooling systems are given in Table 4.1. The capital cost breakdown and design data of these cooling systems are given in

Tables 4.2 through 4.4. The cooling system total evaluated costs given in Table 4.1 are graphically depicted in Figure 4.1 to show the cost trend. Table 4.1 and Figure 4.1 show that there is a sharp reduction of about 15 percent in total evaluated cost from the dry tower system to the 5 percent water usage wet/dry tower system. The wet/dry tower systems with water usages greater than about 5 percent provide very little or no economic advantage. In fact, the all-wet system is even more costly than the all-dry system.

This cost trend may be explained as follows:

1. The site, Modesto, California, has a high peak ambient dry bulb temperature of 105°F and a modest annual average ambient dry bulb temperature of 64°F. Since the HTGR-GT plant performance (electric output) is very sensitive to precooler inlet temperature which is directly affected by ambient temperature change, the dry system performs poorly at the peak ambient temperature and suffers a large capacity loss. On the other hand, the cooling system performs well during the rest of the year and requires only a small amount of energy replacement. Thus, the dry system has a high capacity penalty cost and a low replacement energy cost.
2. By shaving the dry tower heat load mainly at the maximum and elevated ambient temperatures with a wet tower, that is, by using a wet/dry system with peak-shaving capacity and requiring only a small amount of water consumption, the capacity penalty is sharply reduced. Although the replacement energy penalty is also increased substantially and a small amount of water penalty cost is added, the net effect is that the total evaluated cost of the 5 percent water usage system is about 15 percent lower than the dry system.

3. For the wet/dry tower systems with water usage greater than about 5 percent, the increases in water and pumping penalty costs as a result of increased water usage and larger quantity of circulating water to be pumped as indicated in Table 4.4 combine to offset the reductions in the capital and capacity penalty costs. Consequently, very little or no gain is achieved for wet/dry systems with water usage higher than about 5 to 10 percent. In fact, the wet/dry system with 48 percent water usage has a higher total evaluated cost than the 15 percent wet/dry system.
4. For the all-wet system, because the precooler loop cannot be eliminated, the capital cost of the wet system is only slightly lower than those for the dry and wet/dry system. However, the much higher pumping penalty cost, which includes the pumping penalty costs for the precooler loop and the wet tower loop, and the high water penalty cost combine to push the total penalty cost for the wet system higher than that for the dry and wet/dry systems. The net result is that the wet system has the highest total evaluated cost.

### 4.2.2 Design and Costs of Cooling Systems for the 800 MWe (Nominal) PWR and Fossil Power Plants

The cost and design data of the optimized cooling systems for the PWR and fossil plants are given in Tables 4.5 through 4.8 and Tables 4.9 through 4.12 respectively. The total evaluated costs of the cooling systems for both the PWR and fossil plants are also plotted in Figure 4.1 to show the cost trends. The cooling systems for each plant include a dry tower system, a wet tower system and four wet/dry tower systems with varying amounts of annual water usages up to about 40 percent of the water usage of the wet tower system for the plant. The dry tower systems are designed for high back pressure turbines whereas the wet/dry and wet tower systems are designed for conventional low back pressure turbines with a maximum operating limit of 5 in-HgA (127 mm-HgA).

With respect to the total evaluated costs, the observed cost trends for PWR and fossil plants from previous studies (e.g., ERDA wet/dry tower study for nuclear plants[(2)] and EPA wet/dry tower study for fossil plants[(3)]) remain as expected. These are:

1. The total evaluated cost trends for PWR and fossil plants are similar.
2. The cost of dry cooling is considerably higher than that of wet cooling. For the cooling systems evaluated, the cost of the dry tower system is about three times that of the wet tower system for both the PWR and fossil plants.
3. Peak shaving the dry tower heat load at the maximum and elevated ambient temperatures with a wet tower will sharply reduce the cost. In other words, a wet/dry system requiring only a small amount of water consumption can reduce the total evaluated cost significantly as compared to the dry tower system.
4. The addition of more wet towers to shave the dry tower load and to operate for longer duration both at the maximum and lower ambient temperatures will continue to reduce the cost, but the reduction is at lower rate.

#### 4.2.3 Comparison of the Cooling System Costs for the 800-MW(e) (Nominal) HTGR-GT, PWR and Fossil Power Plants

The comparison of unit total evaluated costs ($/kW) for the cooling systems designed for the three 800 MWe (nominal) HTGR-GT, PWR and fossil plants at Modesto, California is given in Figure 4.1. The economic factors used to generate the costs are shown on this figure. These costs are plotted against annual water consumption (gal/yr) requirements of various cooling systems.

Figure 4.1 shows that generally under the same constraints the total evaluated costs for fossil plants are considerably lower than those for PWR plant and the total evaluated costs of the HTGR-GT plant are in turn considerably lower than those for fossil plant. It is of particular interest to this study to note that the total evaluated costs of the coolings systems for the HTGR-GT plant from the all-dry system to the wet/dry system using about 50% of the water needed for the all wet system are much lower than the costs of the dry and wet/dry systems for the PWR and fossil plants with the same water usage constraints as the HTGR-GT plant.

The differences between the cooling systems costs for the PWR and the fossil (coal) plant are caused by the difference in heat rejection rates of the two plants. For the same MWe rating, a PWR plant normally has about one and one half times the heat rejection rate of a fossil plant.

The differences in total evaluated costs between the HTGR-GT and both the PWR and fossil plants are mainly due to the differences in turbine exhaust conditions, plant performance characteristics and plant design constraints. The high turbine exhaust temperature conditions of HTGR plants favor the design and operation of the dry tower system, resulting in much lower capital, penalty and total evaluated costs as compared to the costs of dry tower systems for the comparable PWR and fossil plants.

## 4.3 ECONOMIC SENSITIVITY ANALYSIS

An economic sensitivity analysis was performed on the following economic factors: capacity charge rate, replacement energy charge rate, and water cost. The objectives were: 1) to determine the effects of these economic factors on the total evaluated cost trend of the wet/dry cooling systems for each of the three plants investigated, and 2) to determine if the changes of the economic factors would affect the relative cost differentials of the cooling systems for the three plants.

In performing the analysis, these economic factors were varied from the base values as indicated in Table 3-2 both individually and collectively. The penalty costs of the alternate cooling systems were then adjusted and added to the capital costs to obtain the new total evaluated costs for each new set of the economic factors. The new total evaluated cost curves for all three plants are shown in Figures 4.2 to 4.15. In addition, on each of these figures, the total evaluated cost curves obtained with the base values of the economic factors are also presented to facilitate cost trend comparisons.

Figures 4.2 to 4.4 show the effects on the total evaluated costs by changing the capacity charge rate; Figures 4.6 to 4.8 the effects by changing the replacement energy charge rate; Figures 4.9 to 4.11 the effects by changing the unit water cost; Figures 4.11 to 4.13 the effects by changing both the replacement energy charge rate and the unit water cost; Figures 4.14 to 4.15 the effects of changing all those factors simultaneously.

These results indicate that for the moderate changes of the economic factors, the basic cost trends of the wet/dry cooling systems remain unchanged for both the PWR and fossil plants. Only when unusually high changes occur, e.g., water costs of $8.00/1000 gal. would the cost characteristic change drastically. The cost trend of the wet/dry cooling system for the HTGR-GT plant, however, is more sensitive to the changes in capacity and replacement energy charge

rates as shown in Figures 4.11 and 4.15. For example, when the charge rate for energy replacement is doubled, the dry cooling system becomes the most economic cooling system for HTGR-GT plant as indicated in Figure 4.3.
The results also show that the relative cost differentials of the wet/dry cooling systems for the three plants are not substantially affected by the variation of the economic factors.

## 4.4 PLANT OUTPUT PERFORMANCE WITH THE OPTIMIZED COOLING SYSTEMS

The performance of each of the three plants are shown in Tables 4.13 through 4.15 in terms of: 1) time duration that a plant with an alternate cooling system would produce its rated output, 2) the average output and the corresponding deficit with respect to its rated output, and 3) the lowest output and the corresponding maximum capacity deficit at the peak ambient temperature of the site.

The results show that HTGR-GT plants with a dry system and a 5 percent water usage wet/dry system can generate rated output or higher than rated output in 57 percent and 40 percent of the time respectively. On the other hand, the HTGR-GT plants with the two wet/dry systems requiring 15% and 47% of the wet tower water use cannot generate rated output during any time during a year. Also, the same plant with the all-wet does not perform well, generating rated output only 3% of time during a year.

The performance of the PWR and fossil plants, in terms of the annual percentage of time that a plant can generate its rated output, are similar as shown in Tables 4.14 and 4.15.

The explanations for the aforementioned performance in terms of percentage of time the plant can produce the rated output for the HTGR-GT plant is as follows:

1. The good performance of the HTGR-GT plant with the all-dry system is due to the combined effect of good cooling system performance of dry systems at low ambient dry bulb temperatures and the favorable plant performance characteristics as shown in Figure 3.9. Figure 3.9 shows that the HTGR plant output increases rapidly as the precooler inlet temperature decreases. Good cooling system performance at low dry bulb temperatures produces low precooler inlet temperatures and high plant outputs. Although the site maximum dry bulb temperature is very high (105°F), the annual average dry bulb temperature is relatively modest (64°F). As a result, the plant can generate rated output 57% of time during a year.
2. The plant with the 5% water usage wet/dry system also performs very well because the cooling system has a large dry tower and operates in all-dry mode during most of the year.
3. The poor performance of the HTGR-GT plant with the all-wet system is also caused by the existence of the temperature difference in the intermediate heat exchangers. For a given tower performance, the precooler water inlet temperature is increased by an amount equal to this temperature difference. As a result, the plant performance is penalized and the plant can generate rated output only 3 percent of the time.

4. The 15% and 47% water usage wet/dry systems operate mostly in wet/dry mode. Since a terminal temperature difference must exist in the intermediate heat exchangers, the plant performance is penalized. Therefore, the plants with these wet/dry systems cannot generate the rated output at any time during a year.

The aforementioned performance trends for the PWR and fossil plants can be explained as follows:

1. The rated outputs of these plants are based on low back pressure turbines. Since the all-dry systems are designed for high back pressure turbines which can be operated at back pressure up to 15" HgA but produce significantly lower outputs at all back pressures. Therefore, the plants with dry systems can not generate rated outputs at any time.
2. The very low water usage wet/dry systems have relatively large dry towers and operate in all-dry mode during large portions of a year when the ambient temperatures are low. Since the dry systems perform well at low ambient temperatures, the plants are able to generate output during substantial portions of a year.
3. The optimum wet/dry systems are designed to operate in S1 mode which sacrifices plant performance in favor of water conservation. The turbine back pressure is kept essentially constant at a specified value by gradually turning off portions of the wet helper tower until the dry tower can handle the

load while maintaining the back pressure below the specified value. At high water usages, an optimum wet/dry system generally has a dry tower insufficient to handle the entire heat load without exceeding the design back pressure which is generally higher than that for the rated output. Therefore, the wet/dry systems operate all year in wet/dry mode and the turbine back pressure is kept at a value higher than that for the rated output. Consequently, both the PWR and fossil plants with high water usage wet/dry systems cannot generate rate output at any time during a year.

4. The poor performance of the plants with the wet tower system are the result of economic trade-offs between the capital costs and various penalty costs. Although the tower systems for both the PWR and fossil plants can be sized with sufficient cooling capabilities so that these plants can generate rated outputs during most of the time in a year or even all year around, the economic analysis performed indicates that these systems would not be the optimum choice. In other words, the increases in capital costs and decreases in penalty costs would be such that the total evaluated costs of these cooling systems are higher than those of the systems selected.

TABLE 4.1

CAPITAL AND PENALTY COST+ SUMMARY FOR VARIOUS COOLING SYSTEMS DESIGNED FOR 808 MWe HTGR-GT PLANT AT MODESTO, CALIFORNIA

| Cooling System | Dry Tower | Wet/Dry Tower | | | Wet Tower |
|---|---|---|---|---|---|
| Annual Water Usage ($10^6$ gal/% of Wet Tower) | 0/0 | 112/4.5 | 358/14.5 | 1182/48.0 | 2465/100.0 |
| CAPITAL COST ($\$10^3$): | | | | | |
| Plant Cooling System Direct Cost Excluding Precooler | 28,222 | 27,977 | 26,774 | 25,268 | 23,258 |
| Indirect Cost* | 7,056 | 6,994 | 6,694 | 6,317 | 5,815 |
| Total Capital Cost | 35,278 | 34,971 | 33,468 | 31,585 | 29,073 |
| PENALTY COST ($\$10^3$): | | | | | |
| Capacity | 50,612 | 22,356 | 20,804 | 20,493 | 18,929 |
| Auxiliary Power | 831 | 2,403 | 2,644 | 3,159 | 5,663 |
| Replacement Energy | 3,486 | 13,782 | 13,684 | 13,899 | 15,006 |
| Auxiliary Energy | 1,870 | 4,420 | 5,533 | 7,071 | 12,561 |
| Make-up Water | | 623 | 1,988 | 6,567 | 13,694 |
| Cooling System Maintenance | 1,037 | 1,378 | 1,340 | 1,351 | 1,632 |
| Total Penalty | 57,836 | 44,962 | 45,993 | 52,540 | 67,485 |
| TOTAL EVALUATED COST: | | | | | |
| Total Cost ($\$10^3$) | 93,114 | 79,933 | 79,461 | 84,125 | 96,558 |
| Unit Cost ($/kW) | 115 | 99 | 98 | 100 | 120 |

* 25% of Direct Cost
\+ January, 1980 Price

TABLE 4.2

CAPITAL COST BREAKDOWN FOR VARIOUS COOLING SYSTEMS DESIGNED FOR 808 MWe HTGR-GT PLANT AT MODESTO, CALIFORNIA

| Cooling System | | Dry Tower | Wet/Dry Tower | | | Wet Tower |
|---|---|---|---|---|---|---|
| Annual Water Usage ($10^6$ gal/% of Wet Tower) | | 0/0 | 112/4.5 | 358/14.5 | 1182/48.0 | 2465/100.0 |
| Account No. | Account Description | Capital Cost+ ($$10^6$) | | | | |
| 261. | Structure | 354 | 993 | 1,357 | 1,101 | 1,944 |
| 262. | Mechanical Equipment | | | | | |
| 262.1 | Heat Rejection System | | | | | |
| 262.11 | Water Intake Equipment | | 55 | 78 | 111 | 121 |
| 262.12 | Circulating Water System | 2,459 | 3,505 | 3,552 | 3,715 | 4,255 |
| 262.13 | Cooling Towers | 25,601 | 19,270 | 16,642 | 14,366 | 10,735 |
| 262.14 | Intermediate Heat Exchanger | | 3,237 | 3,534 | 3,920 | 3,428 |
| 262.15 | Make-up & Blowdown System | | 559 | 788 | 1,113 | 1,217 |
| | Sub-Total 262. | 28,060 | 26,626 | 24,594 | 23,225 | 19,756 |
| 26. | Main Condenser Heat Rejection System | 28,414 | 27,619 | 25,951 | 24,326 | 21,700 |
| | Cooling System Electric Equipment* | 356 | 785 | 823 | 942 | 1,558 |
| | Total (Account 26, and Electric Equipment) | 28,770 | 28,404 | 26,774 | 25,268 | 23,258 |

* This is the electric equipment cost attributed to the complete cooling system and included in the plant electric equipment cost account (Account 24).

\+ January, 1980 Price.

TABLE 4.3

SUMMARY OF DESIGN DATA FOR THE DRY AND WET TOWER COOLING SYSTEMS DESIGNED FOR AN 808 MWe HTGR-GT PLANT AT MODESTO, CA.

| Variable | Natural Dry | Mechanical Wet |
|---|---|---|
| General Design Data | | |
| Design Temperatures, $^oF$ | | |
| Dry Bulb | 102 | 102 |
| Wet Bulb | 71 | 71 |
| Cold Water | 112 | 81 |
| Cooling Range | 216 | 45 |
| ITD (Dry Tower) or Approach (Wet Tower) | 226 | 10 |
| Design Precooler Inlet Temperature, $^oF$ | 112 | 86 |
| Maximum Precooler Inlet Temperature, $^oF$ | 117 | 89 |
| Design Heat Load, $10^9$ Btu/hr | 4.321 | 4.182 |
| Plant Capacity at Cooling System Design Point, MWe | 734 | 775 |
| Annual Make-up Water Usage, $10^6$ gal. | 0 | 2,465 |

TABLE 4.3 (cont'd)

SUMMARY OF DESIGN DATA FOR THE DRY AND WET TOWER COOLING SYSTEMS DESIGNED FOR AN 808 MWe HTGR-GT PLANT AT MODESTO, CA.

| Variable | Natural Dry | Mechanical Wet |
|---|---|---|
| Intermediate Heat Exchange | | |
| Surface Area, $10^3$ $ft^2$ | --- | 209,000 |
| Circulating Water Flow & Pump, Precooler Loop/Cooling Tower Loop | | |
| Circulating Water Flow Rate, $10^3$ gpm | 41 | 40/91 |
| Number of Pumps | 2 | 2/2 |
| Pumping Head, ft of Water | 151 | 108/91 |
| Motor Rating, hp per pump | 1100 | 800/3000 |
| Motor Brake Horsepower, hp per pump | 942 | 647/2385 |
| Cooling Tower | | |
| Natural Dry (Dia. x Height), ft | 381 x 455 | ---- |
| Mechanical Wet Tower (Number of Cells) | --- | 27 |

TABLE 4.4

DESIGN DATA FOR WET/DRY COOLING SYSTEMS DESIGNED FOR 808 MWe HTGR-GT PLANT AT MODESTO, CA.

| Variable | Annual Make-up Water Usage, % of Wet Tower | | |
|---|---|---|---|
| | 4.5 | 14.5 | 48.0 |
| General Design Data | | | |
| Mode of Wet/Dry Tower Operation | S2 | S2 | S2 |
| Design Parameters for Dry Towers: | | | |
| Dry Bulb/Wet Bulb Temperatures, $^{o}F$ | 105/75 | 105/75 | 105/75 |
| Cold Water Temperature, $^{o}F$ | 123.6 | 154 | 186 |
| Cooling Range, $^{o}F$ | 179.4 | 149 | 117 |
| Tower ITD, $^{o}F$ | 198 | 198 | 198 |
| Heat Load, $10^9$ Btu/hr | 3.554 | 2.928 | 2.299 |
| Design Parameters for Wet Helper Tower: | | | |
| Dry Bulb/Wet Bulb Temperatures, $^{o}F$ | 105/75 | 105/75 | 105/75 |
| Tower Approach Temperature, $^{o}F$ | 12 | 10 | 10 |
| Cooling Range, $^{o}F$ | 25 | 30 | 40 |
| Design and Maximum Precooler Inlet Temperature, $^{o}F$ | 92 | 90 | 90 |
| Heat Load, $10^9$ Btu/hr | 0.629 | 1.255 | 1.881 |
| Heat Load Distribution at Design Point - Wet Tower/Dry Tower, % | 15/85 | 30/70 | 45/55 |
| Annual Make-up Water Usage, $10^6$ gal | 112 | 358 | 1,182 |

TABLE 4.4 (cont'd)

DESIGN DATA FOR WET/DRY COOLING SYSTEMS DESIGNED FOR 808 MWe HTGR-GT PLANT AT MODESTO, CA.

| Variable | Annual Make-up Water Usage, % of Wet Tower | | |
|---|---|---|---|
| | 4.5 | 14.5 | 48.0 |
| Intermediate Heat Exchanger | | | |
| Surface Area, $ft^2$ | 197,000 | 217,000 | 240,000 |
| Precooler Loop Circulating Water Flow & Pumps | | | |
| Circulating Water Flow Rate, $10^3$ gpm | 40.5 | 40.5 | 40.5 |
| Number of Pumps | 2 | 2 | 2 |
| Pumping Heat, ft of Water | 151 | 151 | 151 |
| Motor Rating, hp of Water | 1,100 | 1,100 | 1,100 |
| Motor Brake Horsepower, hp per pump | 942 | 942 | 942 |
| Cooling Tower Loop Circulating Water Flow & Pumps | | | |
| Circulating Water Flow Rate, $10^3$ gpm | 50 | 84 | 96 |
| Number of Pumps | 2 | 2 | 2 |
| Pumping Heat, ft of Water | 80 | 83 | 85 |
| Motor Rating, hp per Pump | 700 | 1,250 | 1,500 |
| Motor Brake Horsepower, hp per Pump | 567 | 990 | 1,162 |
| Cooling Tower | | | |
| Natural Draft Dry (Dia. x Height), ft | 305 x 375 | 244 x 307 | 201 x 258 |
| Wet Tower (Number of Cells) | 5 | 9 | 12 |

TABLE 4.5

CAPITAL AND PENALTY COST+ SUMMARY FOR VARIOUS COOLING SYSTEMS DESIGNED FOR 838 MWe PWR PLANT AT MODESTO, CALIFORNIA

| Cooling System | Dry Tower** | Wet/Dry Tower | | | | Wet Tower |
|---|---|---|---|---|---|---|
| Annual Water Usage ($10^6$ gal/% of Wet Tower) | 0/0 | 114/3.6 | 326/10.1 | 662/20.7 | 1308/40.9 | 3200/100.0 |
| CAPITAL COST ($\$10^3$): | | | | | | |
| Plant Cooling System Direct Cost Excluding Condenser | 44,820 | 66,095 | 58,498 | 55,397 | 49,098 | 23,761 |
| Indirect Cost* | 11,205 | 16,524 | 14,624 | 13,849 | 12,274 | 5,940 |
| Total Capital Cost | 56,025 | 82,619 | 73,122 | 69,246 | 61,372 | 29,701 |
| PENALTY COST ($\$10^3$): | | | | | | |
| Capacity | 81,518 | 33,589 | 27,363 | 20,976 | 17,179 | 9,628 |
| Auxiliary Power | 14,056 | 22,503 | 20,233 | 18,112 | 16,008 | 9,042 |
| Replacement Energy | 100,539 | 25,621 | 36,778 | 41,214 | 38,468 | 5,333 |
| Auxiliary Energy | 30,271 | 47,111 | 41,082 | 36,634 | 33,820 | 20,130 |
| Make-up Water | | 635 | 2,808 | 3,680 | 7,268 | 17,783 |
| Cooling System Maintenance | 2,150 | 3,625 | 3,384 | 3,156 | 3,053 | 1,982 |
| Total Penalty | 228,534 | 133,084 | 130,648 | 123,772 | 115,796 | 63,898 |
| TOTAL EVALUATED COST: | | | | | | |
| Total Cost ($\$10^3$) | 284,559 | 215,703 | 203,770 | 193,018 | 177,168 | 93,599 |
| Unit Cost ($/kW) | 340 | 257 | 243 | 230 | 211 | 112 |

* 25% of Direct Cost
** High Back Pressure Turbine
\+ January, 1980 Price

TABLE 4.6

CAPITAL COST BREAKDOWN FOR VARIOUS COOLING SYSTEMS DESIGNED FOR 838 MWe PWR PLANT AT MODESTO, CALIFORNIA

| Cooling System | | Dry Tower** | Wet/Dry Tower | | | | Wet Tower |
|---|---|---|---|---|---|---|---|
| Annual Water Usage ($10^6$ gal/% of Wet Tower) | | 0/0 | 114/3.6 | 326/10.1 | 663/20.7 | 1308/40.9 | 3200/100.0 |
| Account No. | Account Description | Capital Cost+ ($\$10^6$) | | | | | |
| 233.121 | Surface Condenser | 6,854 | 8,275 | 7,358 | 6,869 | 6,524 | 7,367 |
| 261. | Cooling System Structure | 1,185 | 1,734 | 1,713 | 1,701 | 1,708 | 2,345 |
| 262.11 | Water Intake Equipment | | 135 | 171 | 195 | 215 | 245 |
| 262.12 | Circulating Water System | 4,353 | 9,372 | 8,298 | 7,527 | 7,308 | 5,215 |
| 262.13 | Cooling Towers | 35,103 | 46,379 | 40,496 | 38,462 | 33,117 | 12,211 |
| 262.15 | Make-up and Blowdown Equipment | | 1,175 | 1,494 | 1,705 | 1,874 | 2,140 |
| | Sub-Total 262. | 39,456 | 57,061 | 50,459 | 47,889 | 42,514 | 19,811 |
| 26. | Main Condenser Heat Rejection System | 40,641 | 58,804 | 52,172 | 49,590 | 44,222 | 22,156 |
| | Cooling System Electric Equipment* | 4,179 | 7,291 | 6,326 | 5,807 | 4,876 | 1,605 |
| | Total (Account 233.121, Account 26, and Electric Equipment | 51,674 | 74,370 | 65,856 | 62,266 | 55,622 | 31,128 |

* This is the electric equipment cost attributed to the complete cooling system and included in the plant electric equipment cost account (Account 24).

** High Back Pressure Turbine.

\+ January, 1980 Price.

TABLE 4.7

SUMMARY OF DESIGN DATA FOR THE DRY AND WET TOWER COOLING SYSTEMS DESIGNED FOR AN 838 MWe PWR PLANT AT MODESTO, CA.

| Variable | Mechanical Dry Tower (High BP Turbine) | Mechanical Wet Tower (Low BP Turbine) |
|---|---|---|
| General Design Data | | |
| Design Temperatures, $^{o}F$ | | |
| Dry Bulb | 102 | 102 |
| Wet Bulb | 71 | 71 |
| Cold Water | 142 | 87 |
| Cooling Range | 28 | 22 |
| ITD (Dry Tower) or Approach (Wet Tower) | 68 | 16 |
| Design Turbine Back Pressure, in-HgA | 13.73 | 2.92 |
| Maximum Operating Back Pressure, in-HgA | 14.79 | 3.10 |
| Design Heat Load, $10^9$ Btu/hr | 5.74 | 5.36 |
| Plant Capacity at Cooling System Design Point, MWe | 715.3 | 826.0 |
| Annual Make-up Water Usage, $10^6$ gal. | 0 | 3,200 |

TABLE 4.7 (cont'd)

SUMMARY OF DESIGN DATA FOR THE DRY AND WET TOWER COOLING SYSTEMS DESIGNED FOR AN 833 MWe PWR PLANT AT MODESTO, CA.

| Variable | Mechanical Dry Tower (High BP Turbine) | Mechanical Wet Tower (Low BP Turbine) |
|---|---|---|
| Condenser | | |
| Surface Area, $10^3$ $ft^2$ | 627 | 678 |
| Number of Tubes | 53,300 | 63,400 |
| Tube Length, ft | 44.9 | 40.8 |
| Circulating Water Flow & Pump | | |
| Circulating Water Flow Rate, $10^3$ gpm | 410 | 488 |
| Number of Pumps | 3 | 3 |
| Pumping Head, ft of Water | 52 | 85 |
| Motor Rating, hp per pump | 2,500 | 4,500 |
| Motor Brake Horsepower, hp per pump | 2,000 | 3,940 |
| Cooling Tower | | |
| Number of Cells | 125 | 31 |

TABLE 4.8

DESIGN DATA FOR WET/DRY COOLING SYSTEMS DESIGNED FOR 838 MWe PWR PLANT AT MODESTO, CA.

| Variable | Annual Make-up Water Usage, % of Wet Tower | | | |
|---|---|---|---|---|
| | 3.6 | 10.1 | 20.7 | 40.9 |
| **General Design Data** | | | | |
| Mode of Wet/Dry Tower Operation | S1 | S1 | S1 | S1 |
| Design Parameters for Dry Towers: | | | | |
| Dry Bulb/Wet Bulb Temperatures, °F | 64/55 | 55/50 | 44/43 | 32/32 |
| Cold Water Temperature, °F | 93 | 89 | 83 | 88 |
| Cooling Range, °F | 17 | 22 | 26 | 29 |
| Tower ITD, °F | 46 | 56 | 65 | 85 |
| Condenser Heat Load, $10^9$ Btu/hr | 5.37 | 5.37 | 5.36 | 5.41 |
| Design Parameters for Wet Helper Tower: | | | | |
| Dry Bulb/Wet Bulb Temperatures, °F | 105/75 | 105/75 | 105/75 | 105/75 |
| Tower Approach Temperature, °F | 26 | 26 | 19 | 13.5 |
| Design and Maximum Operating Back Pressure $P_{max}$, in-HgA | 5.0 | 4.5 | 4.0 | 3.7 |
| Condenser Heat Load $P_{max}$, $10^9$ Btu/hr | 5.51 | 5.47 | 5.44 | 5.42 |
| Heat Load Distribution at $P_{max}$- Wet Tower/ Dry Tower, % | 49.4/50.6 | 65.1/34.9 | 76.4/23.6 | 85.1/14.9 |
| Annual Make-up Water Usage, $10^6$ gal. | 114 | 326 | 662 | 1,308 |

TABLE 4.8 (cont'd)

| Variable | Annual Make-up Water Usage, % of Wet Tower | | | |
|---|---|---|---|---|
| | 3.6 | 10.1 | 20.7 | 40.9 |
| <u>Condenser</u> | | | | |
| Surface Area, $10^3$ $ft^2$ ($m^2$) | 762 | 676 | 628 | 588 |
| Number of Tubes | 82,100 | 63,500 | 53,600 | 48,500 |
| Tube Length, ft (m) | 35.4 | 40.6 | 44.8 | 46.3 |
| <u>Circulating Water Flow & Pump</u> | | | | |
| Circulating Water Flow Rate, $10^3$ gpm ($m^3$ /min) | 632 | 489 | 413 | 373 |
| Number of Pumps | 4 | 3 | 3 | 3 |
| Pumping Head, ft (m) of Water | 67 | 69 | 68 | 77 |
| Motor Rating, hp (kW) per pump | 3,500 | 3,500 | 3,000 | 3,000 |
| Motor Brake Horsepower, hp (kW) per pump | 3,000 | 3,190 | 2,660 | 2,720 |
| <u>Flow & Booster Pump for Wet Tower</u> | | | | |
| Percentage of Circulating Water to Wet Helper Tower | 45.9 | 91.5 | 100 | 100 |
| Number of Pumps | 2 | 3 | 3 | 3 |
| Pumping Head, ft (m) of Water | 41 | 41 | 41 | 41 |
| Motor Rating, hp (kW) per pump | 2,000 | 2,000 | 2,000 | 2,000 |
| Motor Brake Horsepower, hp (kW) per pump | 1,690 | 1,730 | 1,600 | 1,450 |
| <u>Cooling Tower</u> | | | | |
| Number of Cells: Wet/Dry | 9/151 | 12/126 | 19/109 | 27/79 |

TABLE 4.9

CAPITAL AND PENALTY COST+ SUMMARY FOR VARIOUS COOLING SYSTEMS DESIGNED FOR 855 MWe FOSSIL PLANT AT MODESTO, CALIFORNIA

| Cooling System | Dry Tower** | Wet/Dry Tower | | | | Wet Tower |
|---|---|---|---|---|---|---|
| Annual Water Usage ($10^6$ gal/% of Wet Tower) | 0/0 | 116/5.2 | 217/9.6 | 466/20.7 | 931/41.3 | 2252/100.0 |
| CAPITAL COST ($\$10^3$): | | | | | | |
| Plant Cooling System Direct Cost Excluding Condenser | 34,105 | 51,501 | 49,263 | 40,483 | 36,229 | 18,829 |
| Indirect Cost* | 8,526 | 12,875 | 12,316 | 10,121 | 9,057 | 4,707 |
| Total Capital Cost | 42,631 | 64,376 | 61,579 | 50,604 | 45,286 | 23,536 |
| PENALTY COST ($\$10^3$): | | | | | | |
| Capacity | 62,135 | 16,563 | 12,012 | 12,012 | 9,440 | 5,049 |
| Auxiliary Power | 12,542 | 15,894 | 15,486 | 12,439 | 10,876 | 6,035 |
| Replacement Energy | 79,441 | 12,716 | 13,507 | 23,436 | 21,140 | 2,700 |
| Auxiliary Energy | 27,013 | 32,837 | 30,124 | 25,027 | 23,047 | 13,432 |
| Make-up Water | | 646 | 1,202 | 2,590 | 5,170 | 12,517 |
| Cooling System Maintenance | 1,595 | 2,701 | 2,753 | 2,258 | 2,066 | 1,360 |
| Total Penalty | 182,726 | 81,357 | 75,084 | 77,762 | 71,739 | 41,093 |
| TOTAL EVALUATED COST: | | | | | | |
| Total Cost ($\$10^3$) | 225,357 | 145,733 | 136,663 | 128,366 | 117,025 | 64,629 |
| Unit Cost ($/kW) | 264 | 170 | 160 | 150 | 137 | 76 |

* 25% of Direct Cost
** High Back Pressure Turbine
\+ January, 1980 Price

TABLE 4.10

CAPITAL COST BREAKDOWN FOR VARIOUS COOLING SYSTEMS DESIGNED FOR 855 MWe FOSSIL PLANT AT MODESTO, CALIFORNIA

| Cooling System | | Dry Tower** | Wet/Dry Tower | | | | Wet Tower |
|---|---|---|---|---|---|---|---|
| Annual Water Usage ($10^6$ gal/% of Wet Tower) | | 0/0 | 116/5.2 | 217/9.6 | 466/20.7 | 931/41.3 | 2253/100.0 |
| Account No. | Account Description | Capital Cost+ ($\$10^6$) | | | | | |
| 233.121 | Surface Condenser | 4,945 | 5,916 | 5,450 | 4,920 | 4,575 | 5,108 |
| 261. | Cooling System Structure | 1,071 | 1,569 | 1,553 | 1,489 | 1,471 | 1,983 |
| 262.11 | Water Intake Equipment | | 124 | 147 | 160 | 175 | 200 |
| 262.12 | Circulating Water System | 4,731 | 9,955 | 9,225 | 7,744 | 6,982 | 5,146 |
| 262.13 | Cooling Towers | 25,271 | 33,529 | 32,012 | 25,760 | 22,746 | 8,662 |
| 262.15 | Make-up and Blowdown Equipment | | 1,071 | 1,270 | 1,381 | 1,513 | 1,730 |
| | Sub-Total 262. | 30,002 | 44,679 | 42,654 | 35,045 | 31,416 | 15,738 |
| 26. | Main Condenser Heat Rejection System | 31,073 | 46,248 | 44,207 | 36,534 | 32,887 | 17,721 |
| | Cooling System Electric Equipment* | 3,032 | 5,253 | 5,056 | 3,949 | 3,342 | 1,108 |
| | Total (Account 233.121, Account 26, and Electric Equipment | 39,050 | 57,417 | 54,713 | 45,403 | 40,804 | 23,937 |

* This is the electric equipment cost attributed to the complete cooling system and included in the plant electric equipment cost account (Account 24).

** High Back Pressure Turbine.

\+ January, 1980 Price.

TABLE 4.11

SUMMARY OF DESIGN DATA FOR THE DRY AND WET TOWER COOLING SYSTEMS DESIGNED FOR AN 855 MWe FOSSIL PLANT AT MODESTO, CA.

| Variable | Mechanical Dry Tower (High BP Turbine) | Mechanical Wet Tower (Low BP Turbine) |
|---|---|---|
| General Design Data | | |
| Design Temperatures, °F | | |
| Dry Bulb | 102 | 102 |
| Wet Bulb | 71 | 71 |
| Cold Water | 138 | 87 |
| Cooling Range | 26 | 22 |
| ITD (Dry Tower) or Approach (Wet Tower) | 62 | 16 |
| Design Turbine Back Pressure, in-HgA | 12.04 | 2.92 |
| Maximum Operating Back Pressure, in-HgA | 12.98 | 3.10 |
| Design Heat Load, $10^9$ Btu/hr | 4.07 | 3.77 |
| Plant Capacity at Cooling System Design Point, MWe | 761.6 | 848.8 |
| Annual Make-up Water Usage, $10^6$ gal. | 0 | 2,253 |

TABLE 4.11 (cont'd)

SUMMARY OF DESIGN DATA FOR THE DRY AND WET TOWER COOLING SYSTEMS DESIGNED FOR AN 855 MWe FOSSIL PLANT AT MODESTO, CA.

| Variable | Mechanical Dry Tower (High BP Turbine) | Mechanical Wet Tower (Low BP Turbine) |
|---|---|---|
| Condenser | | |
| Surface Area, $10^3$ $ft^2$ | 462 | 476 |
| Number of Tubes | 40,700 | 44,500 |
| Tube Length, ft | 43.4 | 40.8 |
| Circulating Water Flow & Pump | | |
| Circulating Water Flow Rate, $10^3$ gpm | 313 | 343 |
| Number of Pumps | 2 | 2 |
| Pumping Head, ft of Water | 61 | 84 |
| Motor Rating, hp per pump | 3,000 | 4,500 |
| Motor Brake Horsepower, hp per pump | 2,710 | 4,100 |
| Cooling Tower | | |
| Number of Cells | 90 | 22 |

TABLE 4.12

DESIGN DATA FOR WET/DRY COOLING SYSTEMS DESIGNED FOR 855 MWe FOSSIL PLANT AT MODESTO, CA.

| Variable | Annual Make-up Water Usage, % of Wet Tower | | | |
|---|---|---|---|---|
| | 5.2 | 9.6 | 20.7 | 41.3 |
| **General Design Data** | | | | |
| Mode of Wet/Dry Tower Operation | S1 | S1 | S1 | S1 |
| Design Parameters for Dry Towers: | | | | |
| Dry Bulb/Wet Bulb Temperatures, °F | 64/55 | 64/55 | 44/43 | 32/32 |
| Cold Water Temperature, °F | 93 | 95 | 85 | 89 |
| Cooling Range, °F | 16 | 19 | 24 | 28 |
| Tower ITD, °F | 45 | 50 | 65 | 85 |
| Condenser Heat Load, $10^9$ Btu/hr | 3.77 | 3.78 | 3.77 | 3.80 |
| Design Parameters for Wet Helper Tower: | | | | |
| Dry Bulb/Wet Bulb Temperatures, °F | 105/75 | 105/75 | 105/75 | 105/75 |
| Tower Approach Temperature, °F | 26 | 26 | 21.1 | 14.5 |
| Design and Maximum Operating Back Pressure $P_{max}$, in-HgA | 4.5 | 4.0 | 4.0 | 3.7 |
| Condenser Heat Load $P_{max}$, $10^9$ Btu/hr | 3.84 | 3.81 | 3.81 | 3.80 |
| Heat Load Distribution at $P_{max}$- Wet Tower/ Dry Tower, % | 56.5/43.5 | 69.1/30.9 | 76.4/23.6 | 85.1/14.9 |
| Annual Make-up Water Usage, $10^6$ gal. | 116 | 216 | 466 | 931 |

TABLE 4.12 (cont'd)

| Variable | Annual Make-up Water Usage, % of Wet Tower | | | |
|---|---|---|---|---|
| | 5.2 | 9.6 | 20.7 | 41.3 |
| <u>Condenser</u> | | | | |
| Surface Area, $10^3$ $ft^2$ ($m^2$) | 550 | 507 | 458 | 420 |
| Number of Tubes | 61,200 | 51,800 | 40,800 | 35,200 |
| Tube Length, ft (m) | 34.3 | 37.4 | 42.8 | 45.5 |
| <u>Circulating Water Flow & Pump</u> | | | | |
| Circulating Water Flow Rate, $10^3$ gpm ($m^3$ /min) | 471 | 398 | 314 | 271 |
| Number of Pumps | 3 | 3 | 2 | 2 |
| Pumping Head, ft (m) of Water | 65 | 65 | 73 | 81 |
| Motor Rating, hp (kW) per pump | 3,500 | 3,000 | 3,500 | 3,500 |
| Motor Brake Horsepower, hp (kW) per pump | 2,920 | 2,450 | 3,250 | 3,130 |
| <u>Flow & Booster Pump for Wet Tower</u> | | | | |
| Percentage of Circulating Water to Wet Helper Tower | 55.5 | 98.1 | 100 | 100 |
| Number of Pumps | 2 | 3 | 2 | 2 |
| Pumping Head, ft (m) of Water | 41 | 41 | 41 | 41 |
| Motor Rating, hp (kW) per pump | 2,000 | 2,000 | 2,500 | 2,000 |
| Motor Brake Horsepower, hp (kW) per pump | 1,520 | 1,520 | 1,830 | 1,580 |
| <u>Cooling Tower</u> | | | | |
| Number of Cells: Wet/Dry | 8/107 | 10/99 | 12/74 | 18/55 |

TABLE 4.13

PERFORMANCE OF 808 MWe HTGR-GT PLANT (RATED GROSS OUTPUT)

| Cooling System | Water Usage $10^6$ gal/yr | Annual Percentage of Time Plant Output at or Above Rated Output, % | Average Plant Output/Output Deficit, MWe/MWe | Output/Output Deficit at Maximum Ambient Temperature, MWe |
|---|---|---|---|---|
| All-Dry | 0 | 57 | 808.5/ 2.5 | 726.5/81.5 |
| 5% Wet/Dry | 112 | 40 | 798.1/ 9.9 | 772.0/36.0 |
| 15% Wet/Dry | 358 | 0 | 798.2/ 9.8 | 774.5/33.5 |
| 47% Wet/Dry | 1,182 | 0 | 798.0/10.0 | 774.5/33.5 |
| All-Wet | 2,465 | 3 | 797.2/10.8 | 777.5/30.5 |

TABLE 4.14

PERFORMANCE OF 838 MWe PWR PLANT (RATED GROSS OUTPUT)

| Cooling System | Water Usage $10^6$ gal/yr | Annual Percentage of Time Plant Output at or Above Rated Output, % | Average Plant Output/Output Deficit, MWe/MWe | Output/Output Deficit at Maximum Ambient Temperature, MWe |
|---|---|---|---|---|
| All-Dry | 0 | 0 | 765.7/72.3 | 706.7/131.3 |
| 3.5% Wet/Dry | 114 | 23 | 819.6/18.4 | 783.9/ 54.1 |
| 10% Wet/Dry | 326 | 3 | 811.5/26.5 | 793.9/ 44.1 |
| 20% Wet/Dry | 663 | 0 | 808.3/29.7 | 804.2/ 33.8 |
| 40% Wet/Dry | 1,308 | 0 | 810.3/27.7 | 810.2/ 27.7 |
| All-Wet | 3,200 | 3 | 834.2/ 3.8 | 822.5/ 15.5 |

TABLE 4.15

PERFORMANCE OF 855 MWe FOSSIL PLANT (RATED GROSS OUTPUT)

| Cooling System | Water Usage $10^6$ gal/yr | Annual Percentage of Time Plant Output at or Above Rated Output, % | Average Plant Output/Output Deficit, MWe/MWe | Output/Output Deficit at Maximum Ambient Temperature, MWe |
|---|---|---|---|---|
| All-Dry | 0 | 0 | 797.8/57.2 | 754.9/100.1 |
| 5% Wet/Dry | 116 | 23 | 845.9/ 9.1 | 828.3/ 26.7 |
| 10% Wet/Dry | 217 | 10 | 845.3/ 9.7 | 835.7/ 19.3 |
| 20% Wet/Dry | 466 | 0 | 838.1/16.9 | 835.7/ 19.3 |
| 40% Wet/Dry | 931 | 0 | 839.8/15.2 | 839.8/ 15.2 |
| All-Wet | 2,253 | 3 | 853.1/ 1.9 | 846.9/ 8.1 |

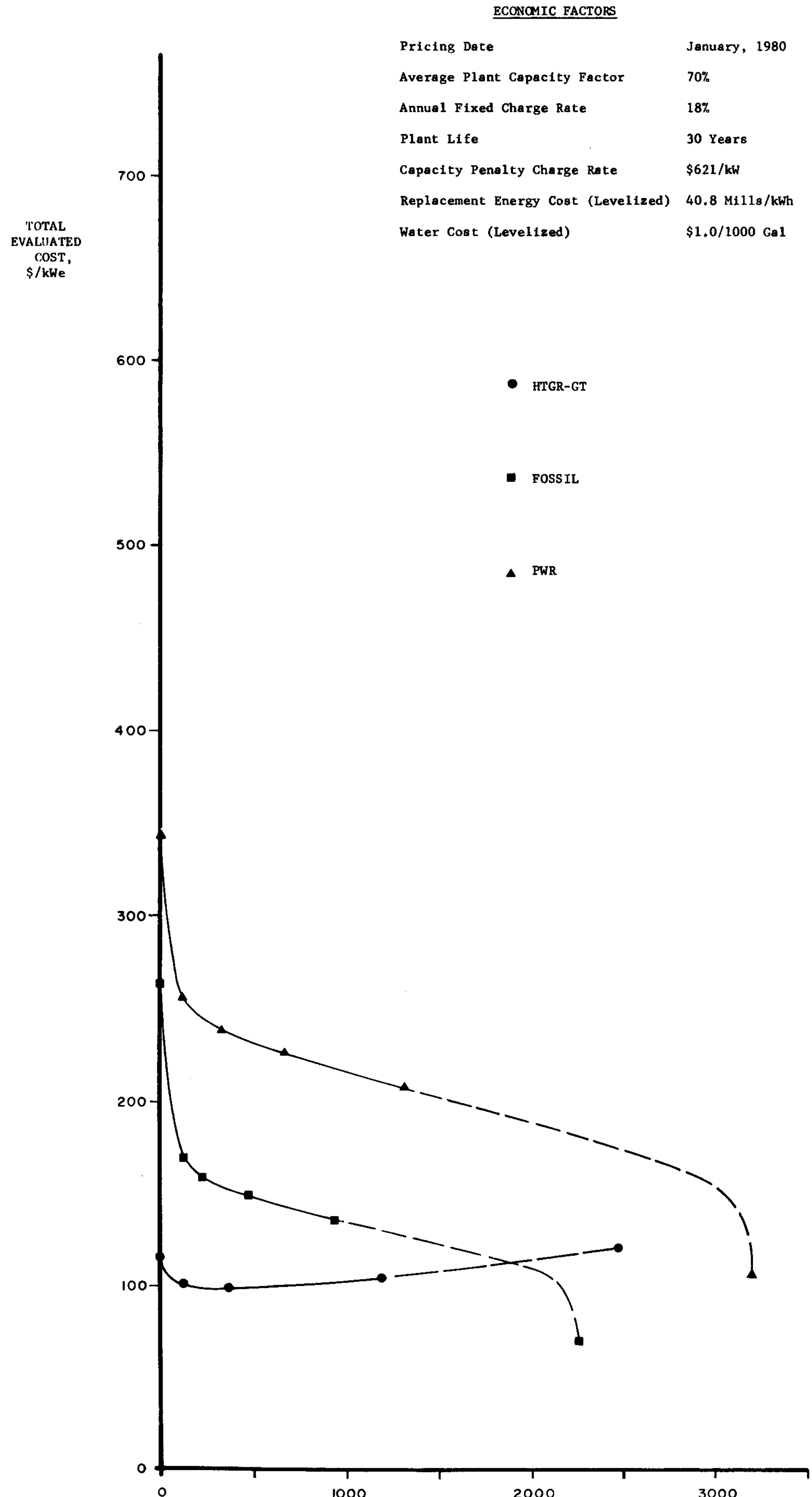


Figure 4.1

COMPARISON OF TOTAL EVALUATED COST CHARACTERISTICS OF 800 MWe (NOMINAL) POWER PLANTS AT MODESTO, CALIFORNIA

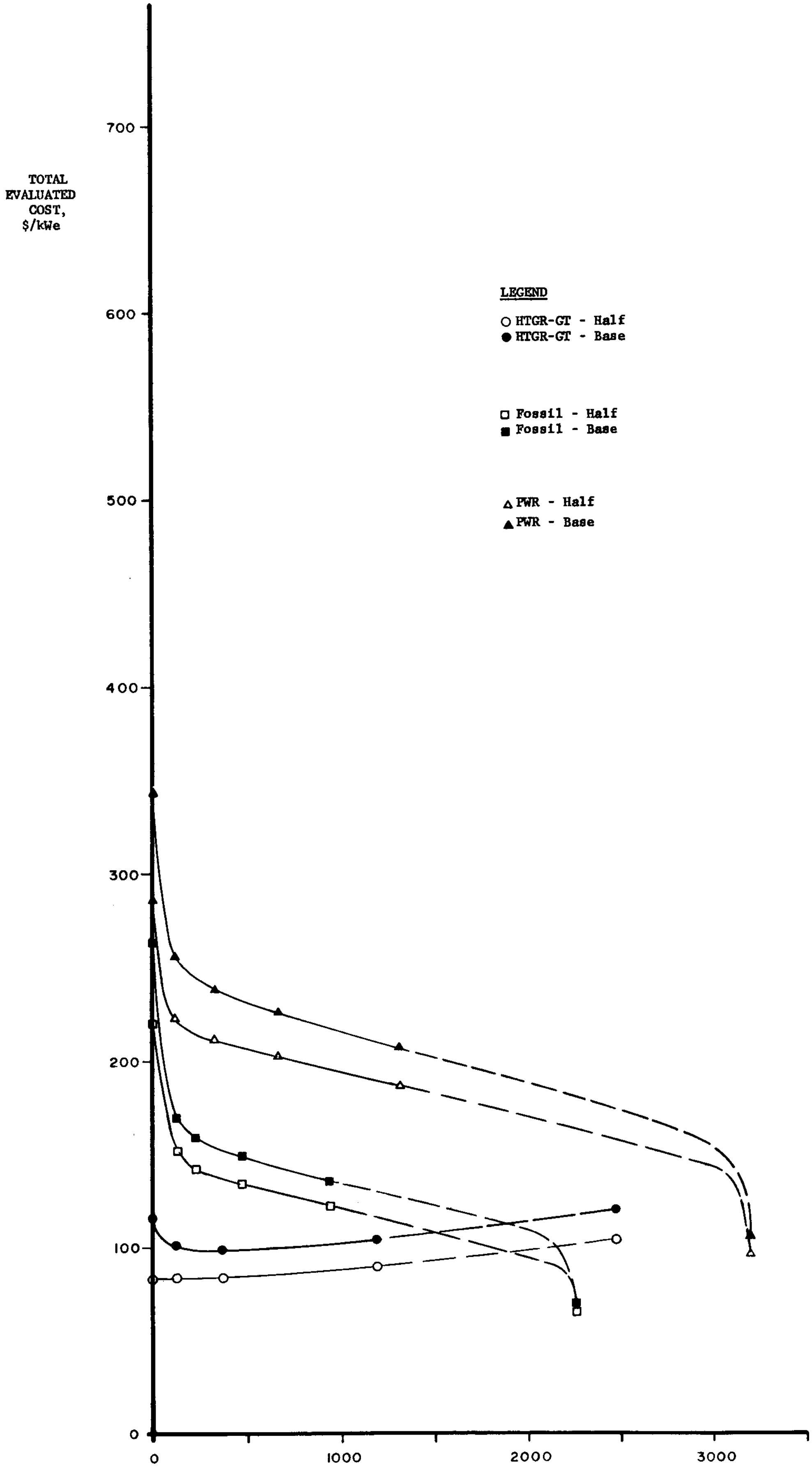


Figure 4.2

EFFECTS OF DECREASING THE CAPACITY CHARGE RATE TO HALF OF THE BASE VALUE ON THE TOTAL EVALUATED COSTS OF ALTERNATE COOLING SYSTEMS

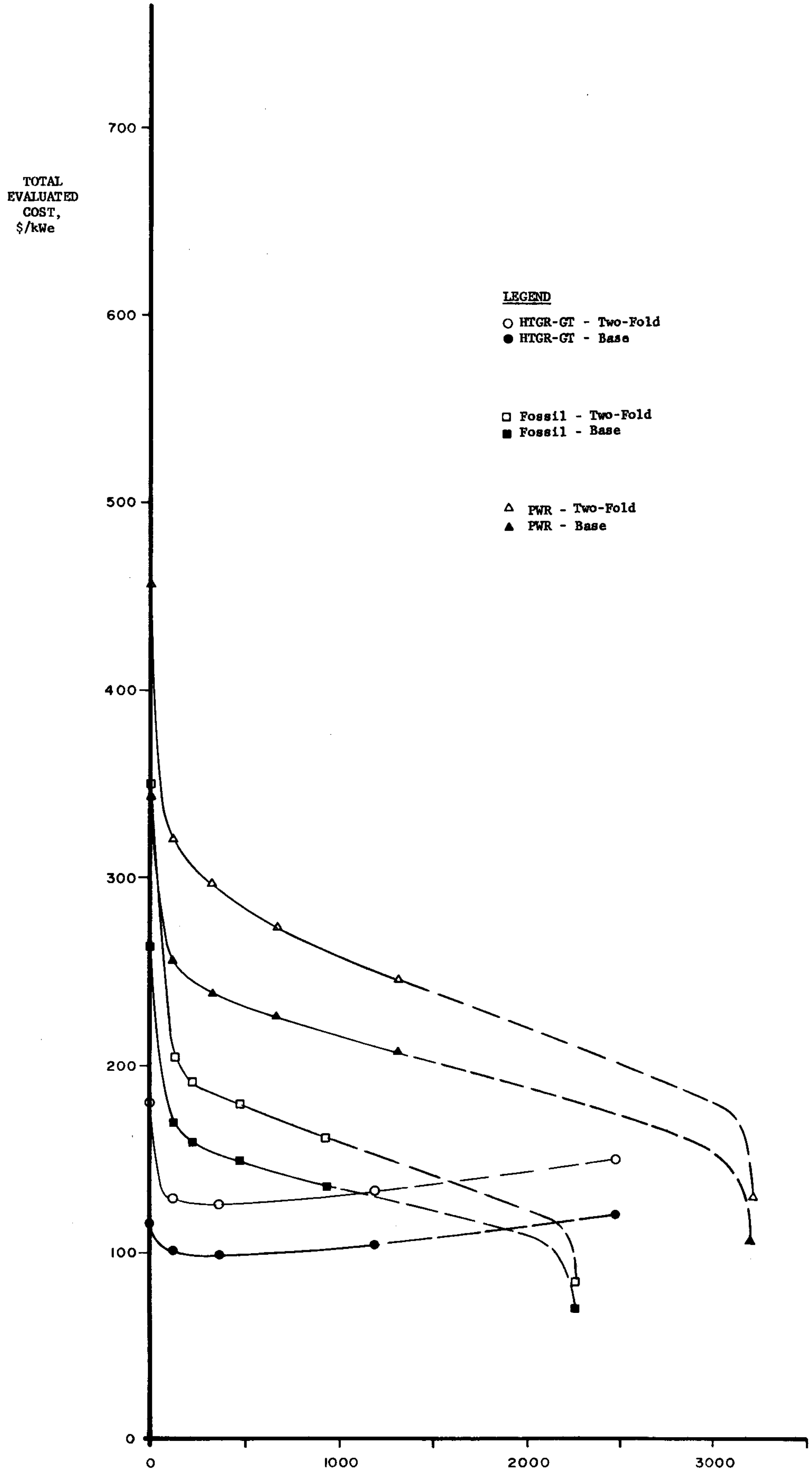


FIGURE 4.3

EFFECTS OF INCREASING THE CAPACITY CHARGE RATE TO TWO-FOLD OF THE BASE VALUE ON THE TOTAL EVALUATED COSTS OF ALTERNATE COOLING SYSTEMS

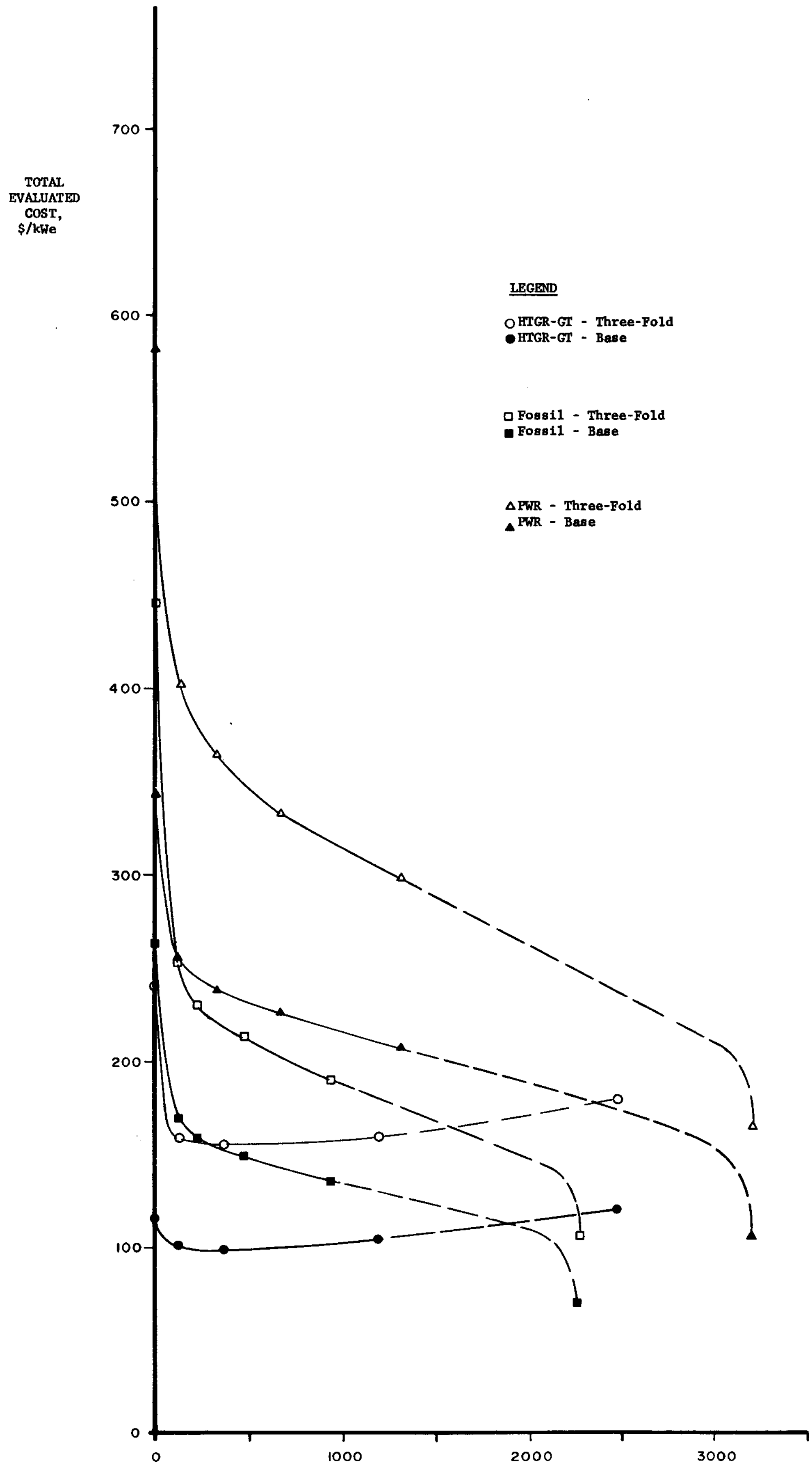


Figure 4.4

EFFECTS OF INCREASING THE CAPACITY CHARGE RATE TO THREE-FOLD OF THE BASE VALUE ON THE TOTAL EVALUATED COSTS OF ALTERNATE COOLING SYSTEMS

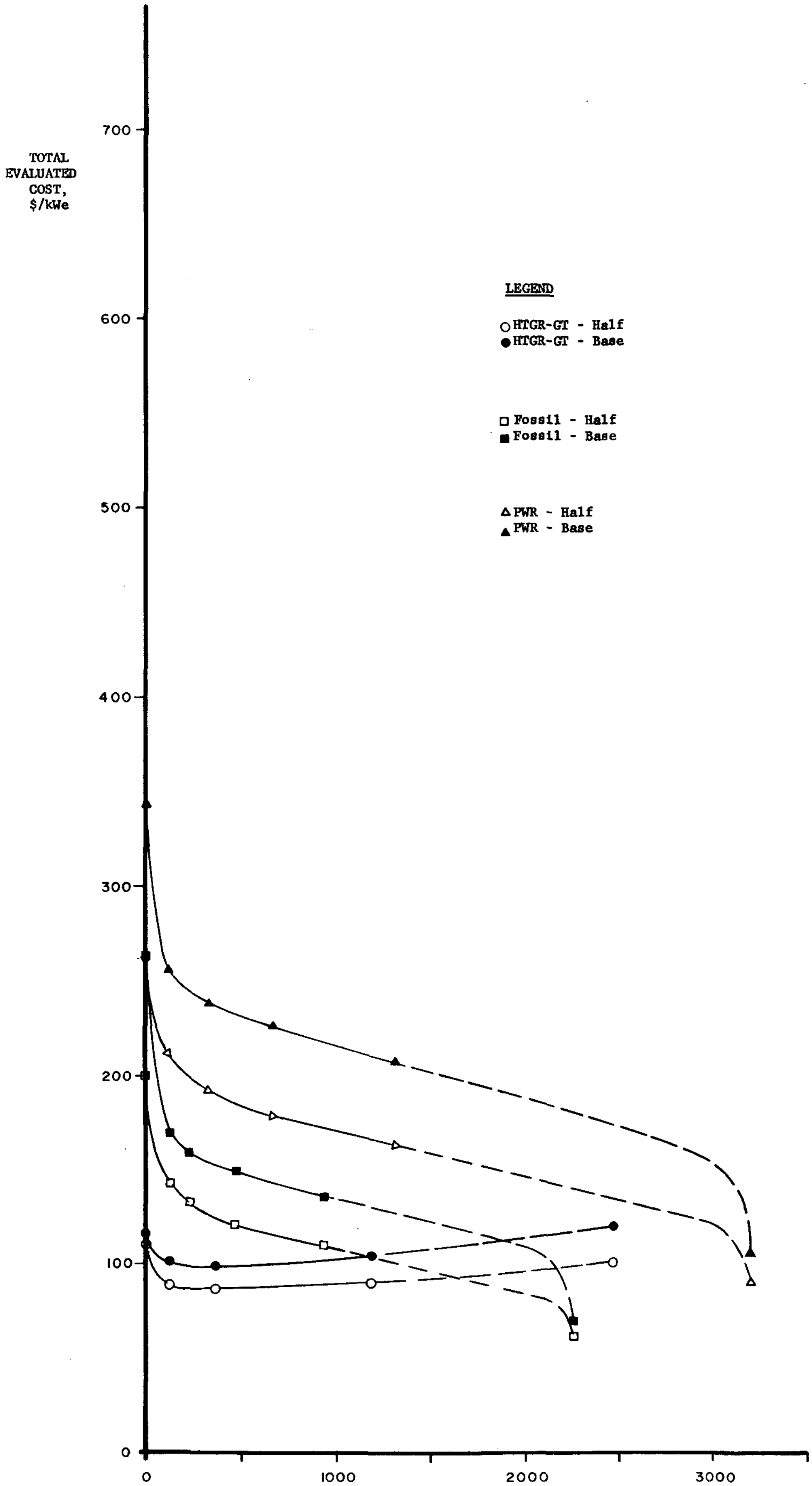


Figure 4.5

EFFECTS OF INCREASING THE REPLACEMENT ENERGY CHARGE RATE TO HALF OF THE BASE VALUE ON THE TOTAL EVALUATED COSTS OF ALTERNATE COOLING SYSTEMS

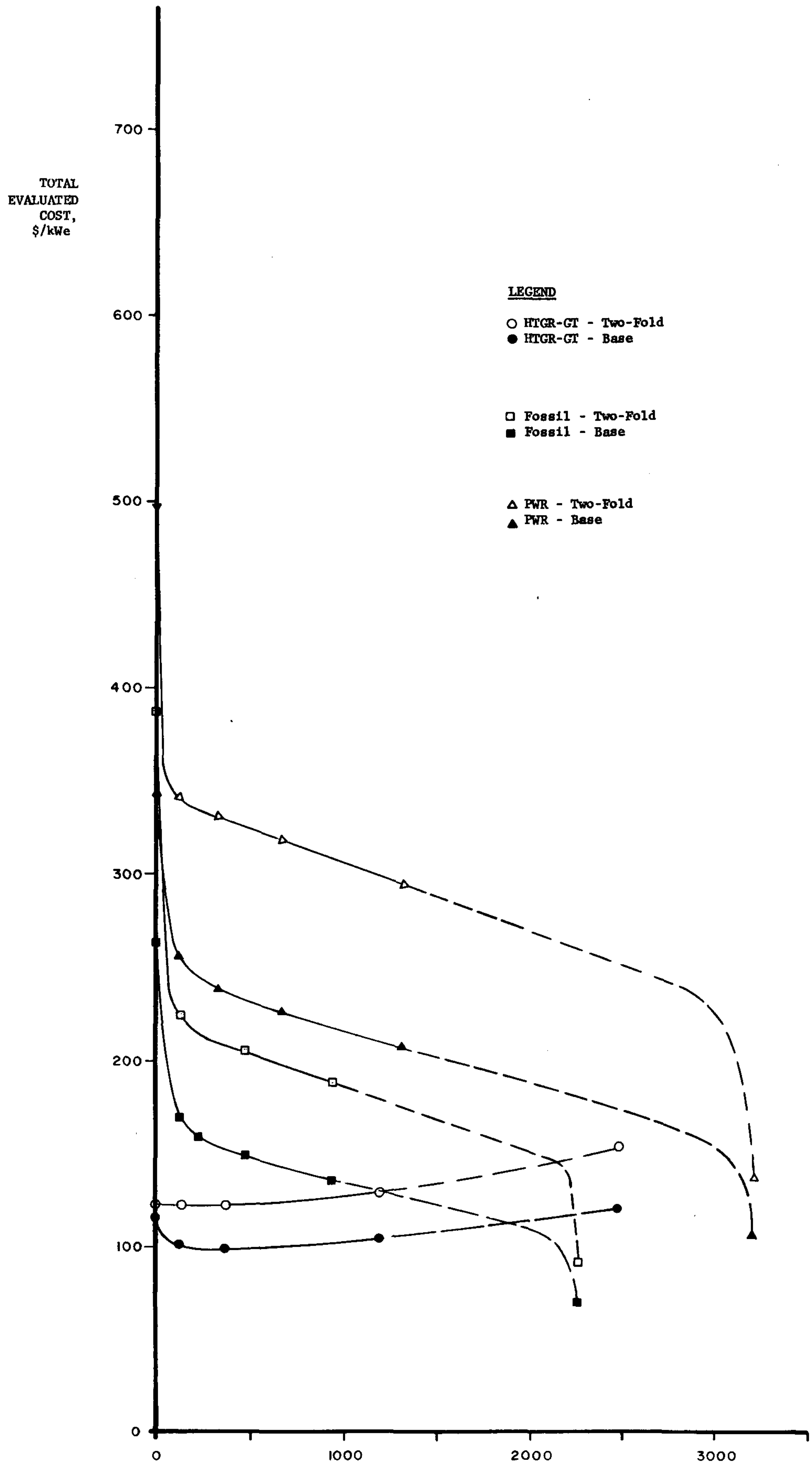


Figure 4.6

EFFECTS OF INCREASING THE REPLACEMENT ENERGY CHARGE RATE TO TWO-FOLD OF THE BASE VALUE ON THE TOTAL EVALUATED COSTS OF ALTERNATE COOLING SYSTEMS

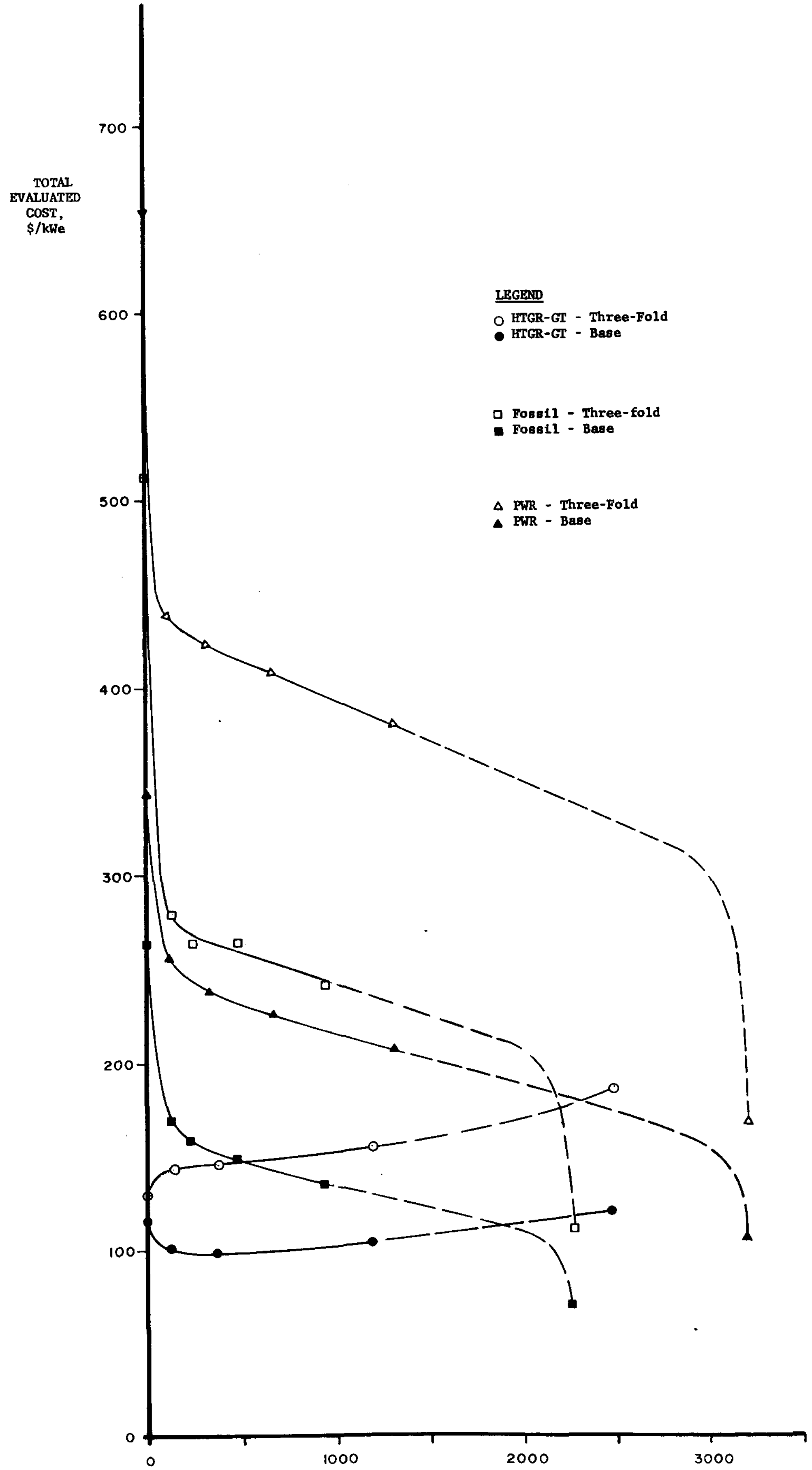


Figure 4.7

EFFECTS OF INCREASING THE REPLACEMENT ENERGY CHARGE RATE TO THREE-FOLD OF THE BASE VALUE ON THE TOTAL EVALUATED COSTS OF ALTERNATE COOLING SYSTEMS

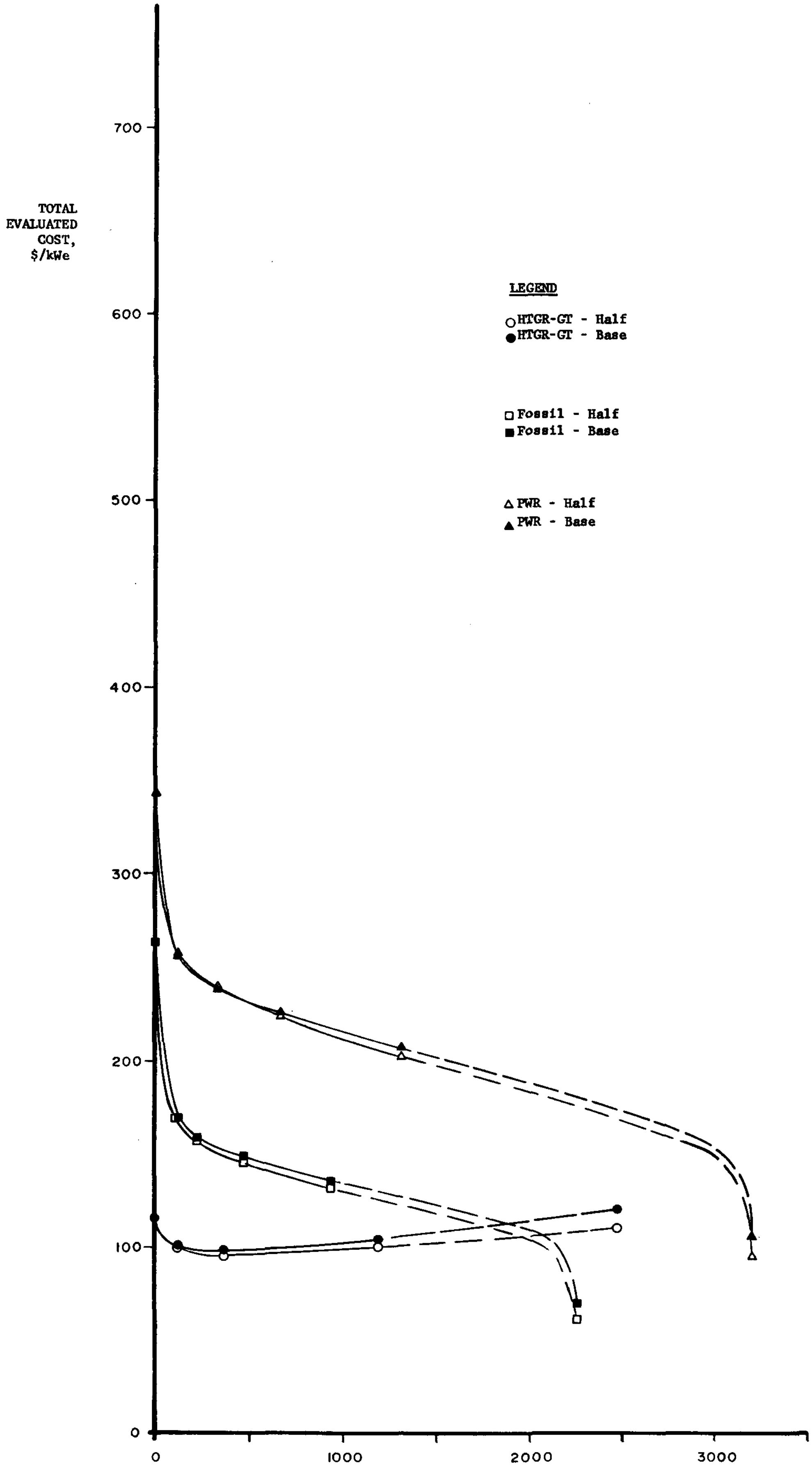


Figure 4.8

EFFECTS OF DECREASING THE CAPACITY CHARGE RATE TO HALF OF THE BASE VALUE ON THE TOTAL EVALUATED COSTS OF ALTERNATE COOLING SYSTEMS

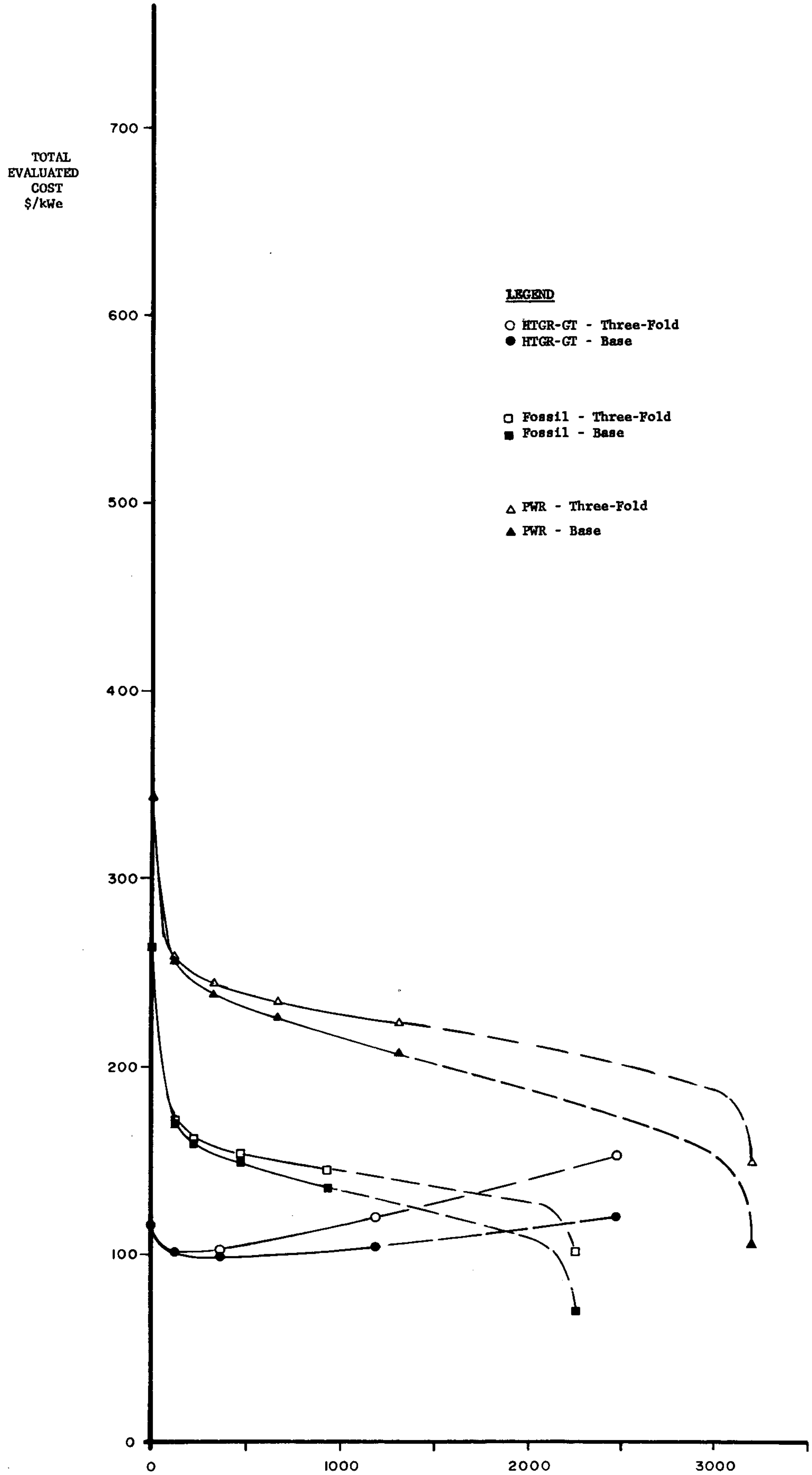


Figure 4.9

EFFECTS OF INCREASING THE CAPACITY CHARGE RATE TO THREE-FOLD OF THE BASE VALUE ON THE TOTAL EVALUATED COSTS OF ALTERNATE COOLING SYSTEMS

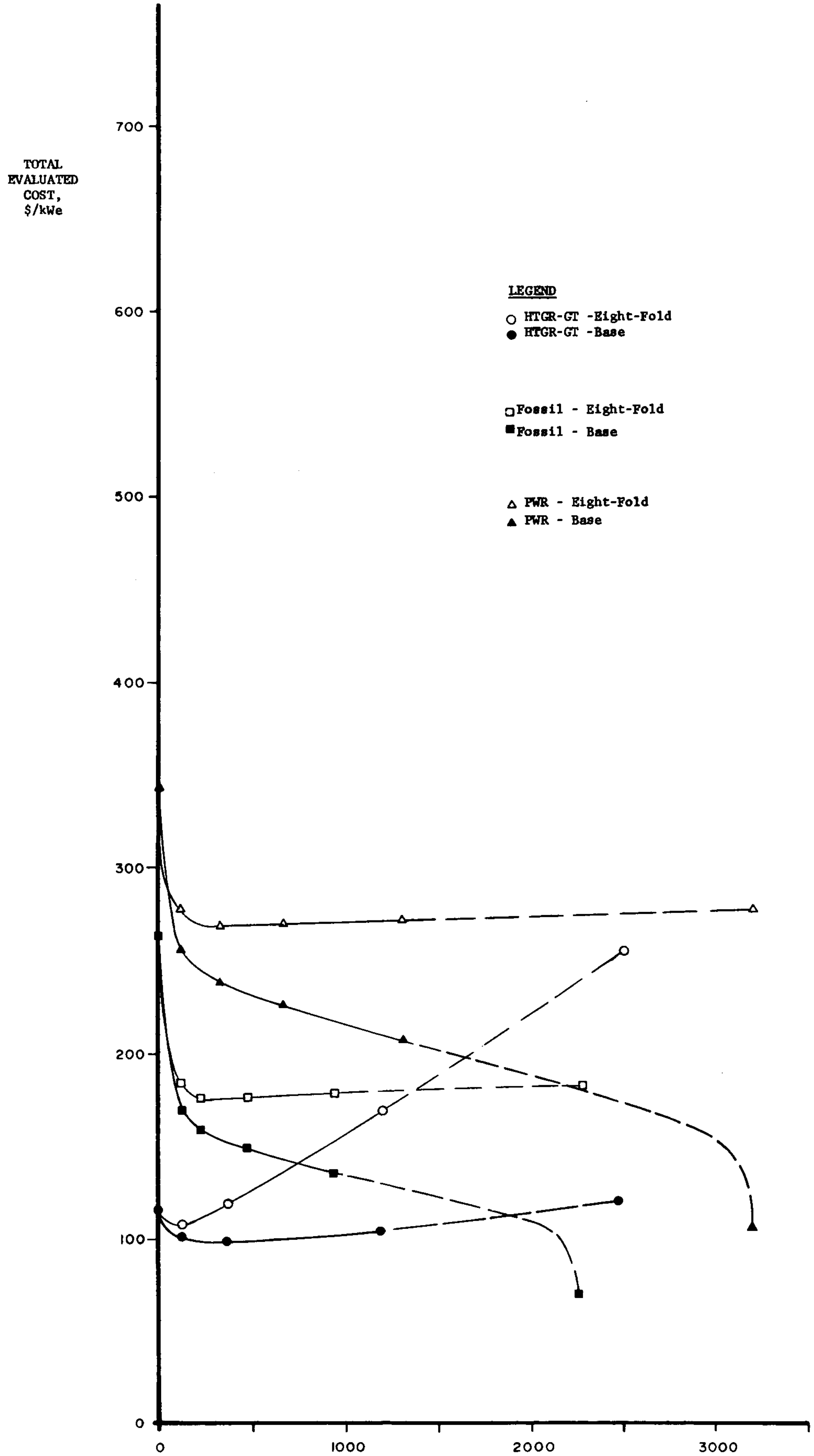


Figure 4.10

EFFECTS OF INCREASING THE UNIT WATER COST TO EIGHT-FOLD
OF THE BASE VALUE ON THE TOTAL EVALUATED COSTS OF ALTERNATE COOLING SYSTEMS

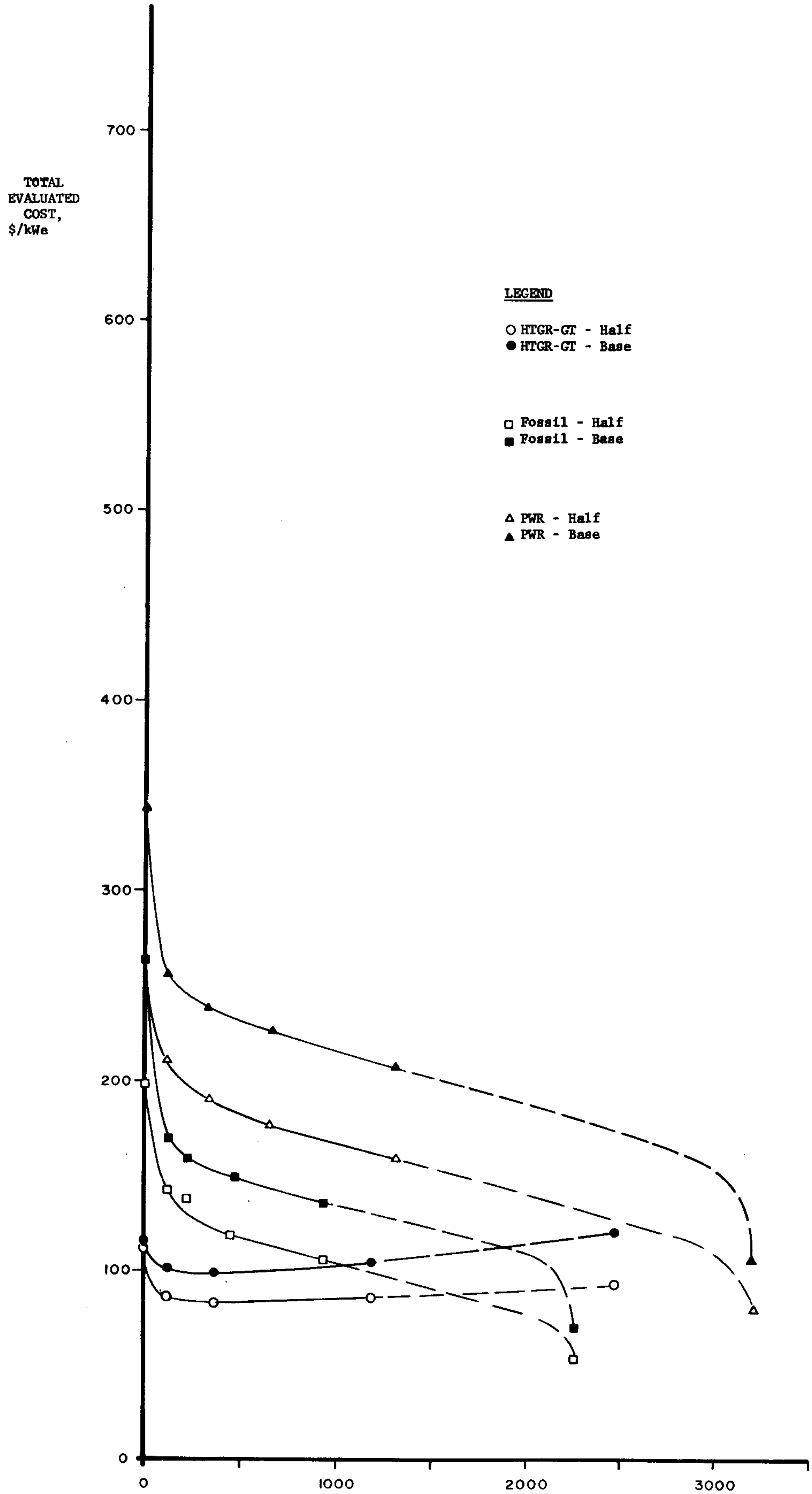


Figure 4.11

COMBINED EFFECTS OF DECREASING THE REPLACEMENT ENERGY CHARGE RATE AND UNIT WATER COST TO HALF OF THEIR BASE VALUES ON TOTAL EVALUATED COSTS OF ALTERNATE COOLING SYSTEMS

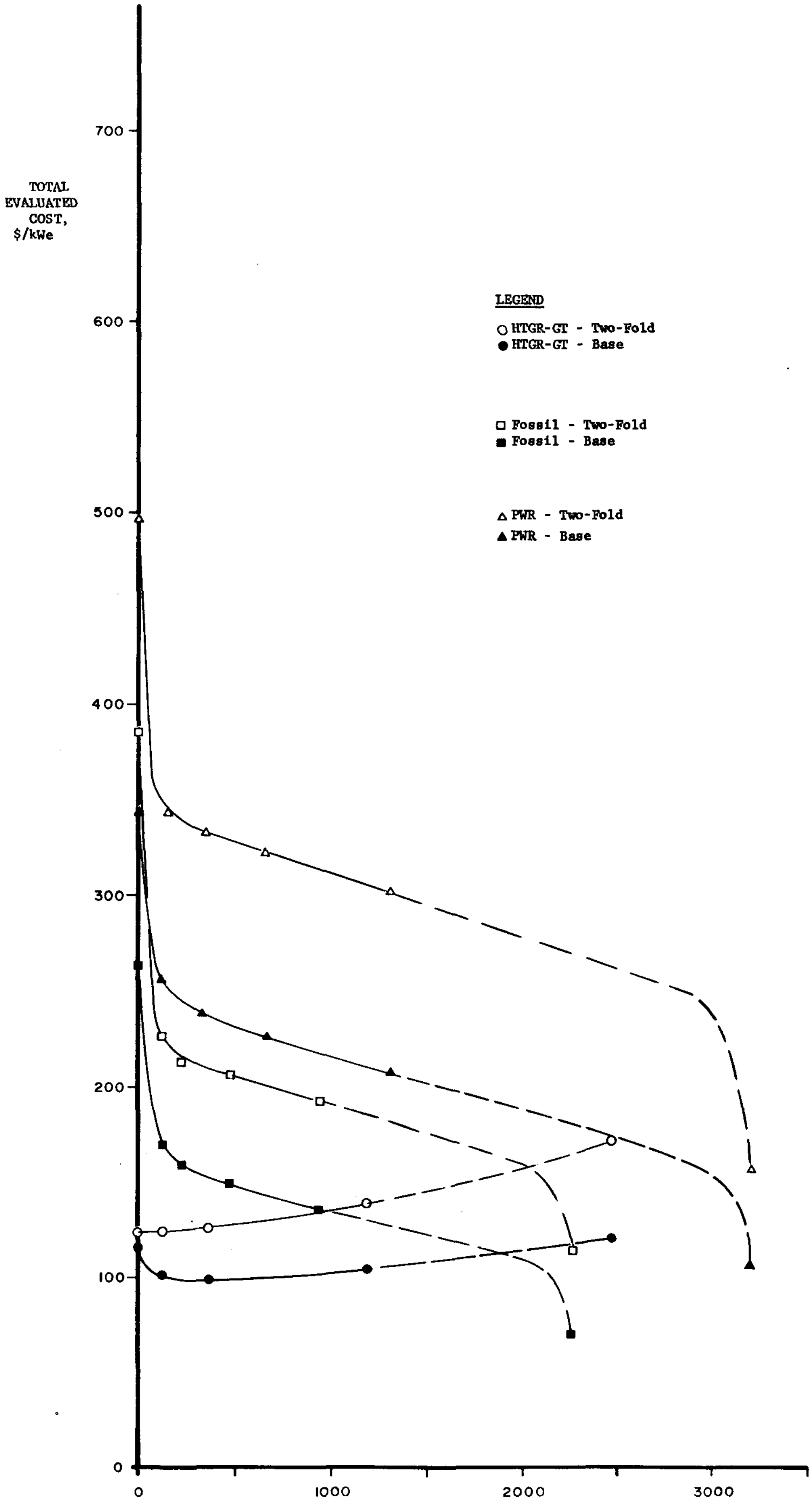


Figure 4.12

COMBINED EFFECTS OF INCREASING THE REPLACEMENT ENERGY CHARGE RATE AND UNIT WATER COST TO TWO-FOLD OF THEIR BASE VALUES ON TOTAL EVALUATED COSTS OF ALTERNATE COOLING SYSTEMS

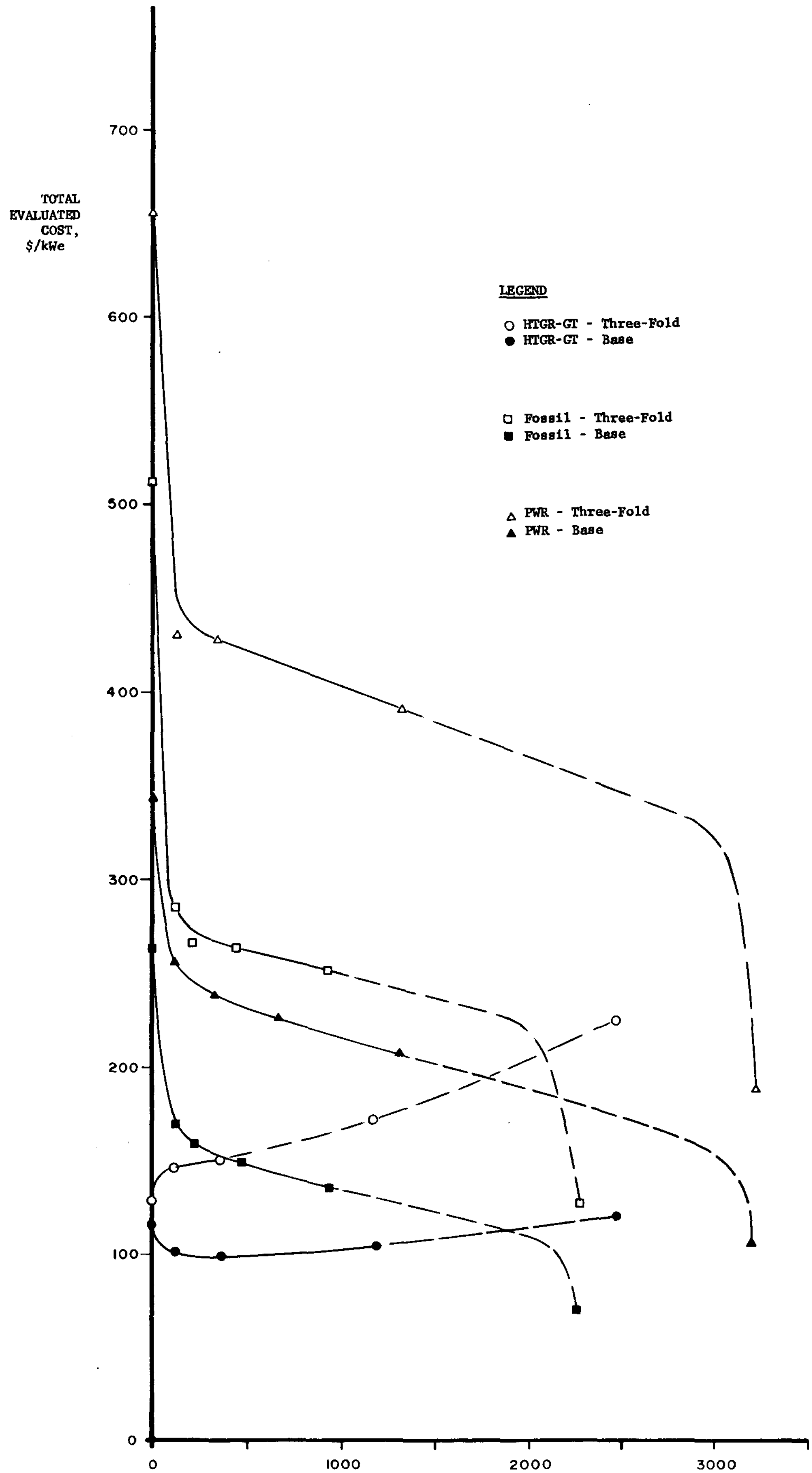


Figure 4.13

COMBINED EFFECTS OF INCREASING THE REPLACEMENT ENERGY CHARGE RATE AND UNIT WATER COST TO THREE-FOLD OF THEIR BASE VALUES ON TOTAL EVALUATED COSTS OF ALTERNATE COOLING SYSTEMS

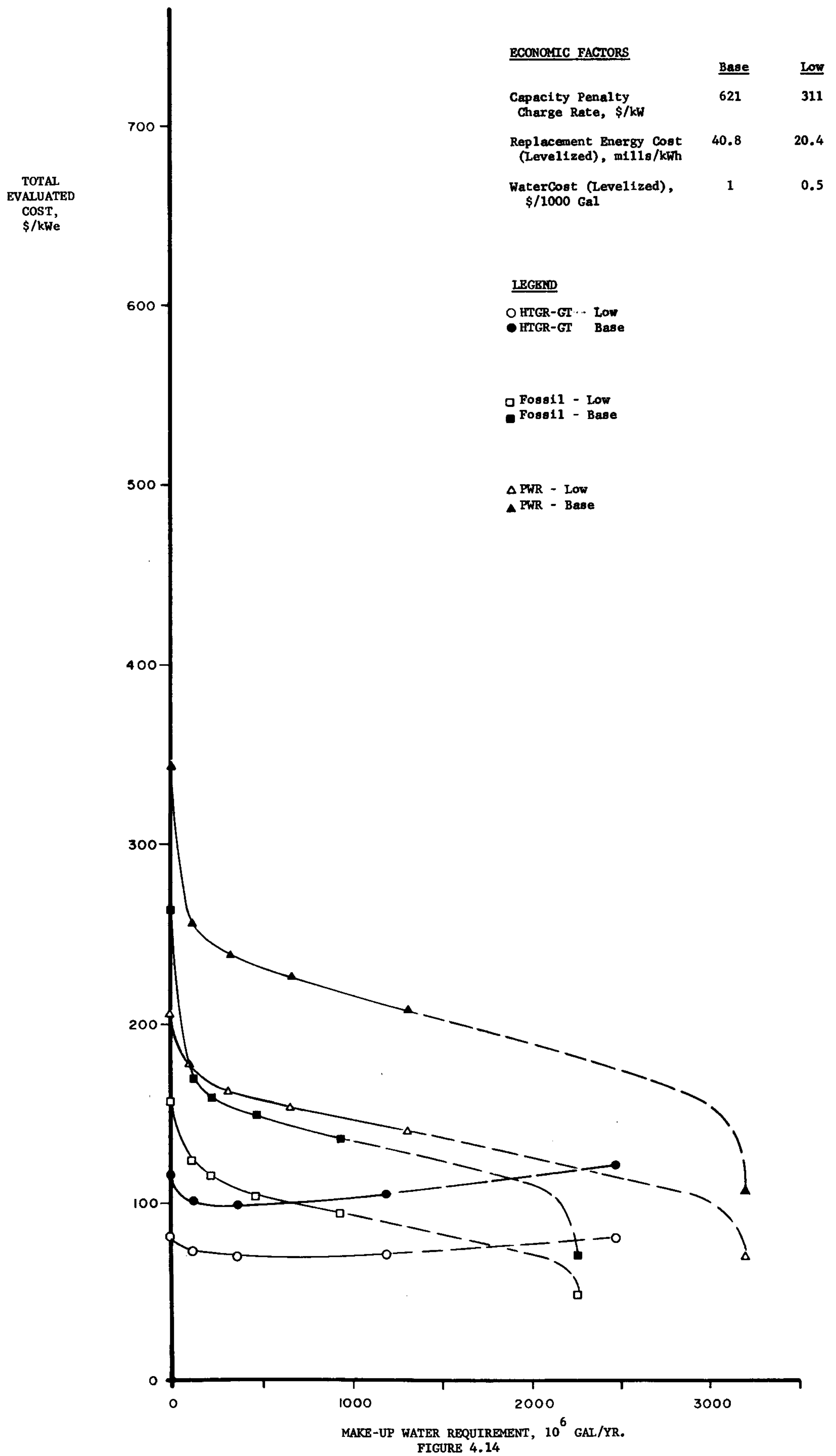


FIGURE 4.14

EFFECTS OF COMPOSITE DECREASES IN THE VALUES OF THE ECONONOMIC FACTORS ON THE TOTAL EVALUATED COSTS OF ALTERNATE COOLING SYSTEMS

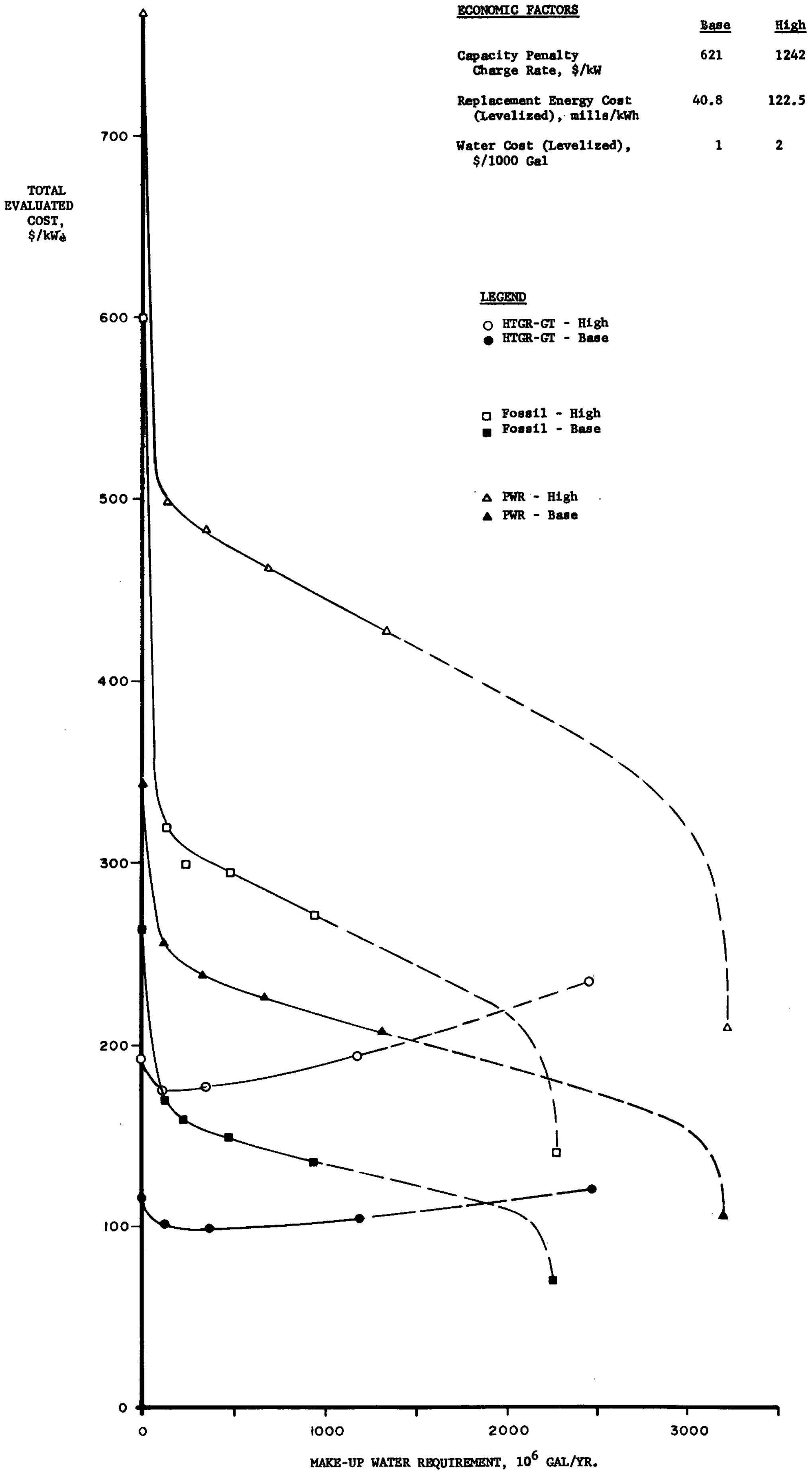


FIGURE 4.15

EFFECTS OF COMPOSITE INCREASES IN THE VALUES OF THE ECONOMIC FACTORS ON THE TOTAL EVALUATED COSTS OF ALTERNATE COOLING SYSTEMS

## SECTION 5.0

## REFERENCES


1. Hu, M.C., G. F. Pavlenco, and G.A. Englesson. Water Consumption and Costs for Various Steam Electric Power Plants Cooling Systems. Prepared for U.S. Environmental Protection Agency by United Engineers & Constructors Inc., Philadelphia, Pennsylvania, EPA-600/7-78-157, 1978. (Available from National Technical Information Service.)

2. Hu, M.C. Engineering and Economic Evaluation of Wet/Dry Cooling Towers for Water Conservation. Prepared for U.S. Research and Development Administration by United Engineers & Constructors Inc., Philadelphia, Pennsylvania, COO-2442-1, 1976. (Available from National Technical Information Service.)

3. Hu, M. C. and G. A. Englesson. Wet/Dry Cooling Systems for Fossil-Fueled Power Plants: Water Conservation and Plume Abatement. Prepared for U.S. Environmental Protection Agency by United Engineers & Constructors Inc. Philadelphia, Pennsylvania, EPA-600/7-77-137, 1977. (Available from National Technical Service.)

4. United Engineers & Constructors, Inc. Preliminary Evaluation of Wet/Dry Cooling Systems for HTGR-GT Power Plants. Unpublished report. Prepared for U.S. Department of Energy Under Contract No. DE-AC02-78ET-34222, 1980.

5. United Engineers & Constructors Inc. Heat Sink Design and Cost Study for Fossil and Nuclear Power Plants. Prepared for U.S. Atomic Energy Commission, Wash-1360, 1974. (Available from National Technical Information Service.)