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# ENGINEERING AND ECONOMIC EVALUATION
OF
# WET/DRY COOLING TOWERS
FOR
# WATER CONSERVATION

**NOVEMBER 1976**



PREPARED FOR THE

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united engineers
& constructors inc.

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## FOREWORD

This "Engineering and Economic Evaluation of Wet/Dry Cooling Towers for Water Conservation" is one of several studies directed to the development and understanding of the economic impact of cooling systems on power plant operations. The report contains an account of the work sponsored by the Division of Nuclear Research and Applications, United States Energy Research and Development Administration (ERDA), under Contract E(11-1)-2442. The project was completed under the direction of Mr. W. F. Savage, ERDA Project Officer and Mr. J. H. Crowley, Manager of the Advanced Engineering Department of United Engineers & Constructors, Inc. The following personnel at United Engineers & Constructors contributed to the completion of the work:

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## SUMMARY AND CONCLUSIONS

This report presents the results of a design and cost study for wet/dry tower systems used in conjunction with 1000 MWe nuclear power plants to reject waste heat while conserving water. The objective of this study is to provide design and cost information for wet/dry tower systems, and to compare these cooling system alternatives with wet and dry tower systems to determine whether the wet/dry tower concept is an economically viable alternative.

The wet/dry cooling tower concept investigated in this study is one which combines physically separated wet towers and dry towers into an operational unit. In designing the wet/dry tower, a dry cooling tower is sized to carry the plant heat load at low ambient temperatures, and a separate wet tower is added to augment the heat rejection of the dry tower at higher ambient temperatures. These wet/dry towers are designed to operate with a conventional low back pressure turbine commercially available today. The component wet and dry towers are state-of-the-art designs.

The method used in the economic analysis 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 each cooling system must be gauged. Inability to meet this demand will be charged as a penalty cost which is to be added to the capital cost of the cooling system. Other penalty costs include the cost of supplying make-up water and cooling system maintenance cost. The make-up water penalty is of special significance, since availability of water is a primary concern of this study. The sum of the penalty costs and capital cost of a cooling system is called the total evaluated cost (TEC).

The cooling system evaluation involves sizing and pricing a cooling system, determining its thermal performance, water consumption, auxiliary power and energy needs and other requirements during a typical annual cycle. The performance information is used to assess the economic penalties which will accrue over the lifetime of the plant. Finally, from a series of designs which meet certain criteria and specific water consumption requirements, the minimum cost cooling system is selected.

The scope of this study included an engineering design study and an economic sensitivity analysis at a base site (Middletown, U.S.A.), and an evaluation at two alternate sites (Atlanta, Ga. and San Juan, N.M.). The basic economic factors used to develop the system costs are shown below:

| | |
|---|---|
| Year of Pricing | 1985 |
| Average Plant Capacity Factor | 0.75 |
| Annual Fixed Charge Rate | 18% |
| Plant Life | 40 years |
| Capacity Penalty Charge Rate | $600/kW |
| Fuel Cost | 153c/MBtu (145¢/GJ) |
| Operation and Maintenance Cost | 0.724 mills/kWhr |
| Water Cost | 27¢/1000 gal. (7¢/$m^3$) |

The total evaluated cost for wet, dry, and wet/dry cooling systems for a plant designed for operation at Middletown, U.S.A. are shown in Figure S.1. (Middletown is the base site of this study and it is ERDA's standard site for power plant cost analysis.) The total evaluated cost expressed in terms of operating costs (mills/kWhr) is shown in Table S.1.

Water supply costs for power plants at a distance from a water way can be significantly greater than the base water cost used in this study. Water supply costs for specific water make-up requirements at a designated power plant site should be determined, and added directly to the total evaluated costs generated with a base water cost.

CONCLUSIONS

1. Wet/dry cooling systems can be designed to provide a significant economic advantage over dry cooling yet closely matching the dry tower's ability to conserve water. A wet/dry system which saves as much as 99 percent of the make-up water required by a wet tower can maintain that economic advantage. Therefore, for power plant sites where water is in short supply, wet/dry cooling is the economic choice over dry cooling.

2. Where water is available, wet cooling will continue to be the economic choice in most circumstances. Only if resource limitation or environmental criteria make water costs excessive, can wet/dry cooling become economically in par with wet cooling.

3. The economic advantage of wet/dry cooling over dry cooling reduces the need for further development of high back pressure turbines for nuclear power plant applications.

4. The dry surfaces needed for wet/dry options are, in general, less than that required for the dry cooling systems using the high back pressure turbines, but remain large in size. Therefore, the development of improved dry surfaces should be continued for use in wet/dry cooling.

5. In response to changing economics, the minimum total evaluated cost of a cooling system can be estimated from an optimized "base system" without requiring re-optimization for the new economics. The adjustment can be made by simply pro-rating the cost elements comprising the total evaluated cost of the base system.

6. Meteorological and site elevation differences exert significant impact on both the economics and design of wet/dry systems. For the three sites evaluated, the costs vary by 10 to 30 percent.

7. A significant economic advantage is available to wet/dry cooling from the substitution of natural draft dry towers for the mechanical draft dry towers in the wet/dry systems.

TABLE S.1

MAJOR COST SUMMARY FOR OPTIMIZED COOLING TOWER SYSTEMS (mills/kWhr)

SITE: MIDDLETOWN, U.S.A. PRICING YEAR: 1985

| Item | Mech. Dry (H)* | Mech. Dry (L)† | Percentage Make-up Requirements - Mech. Series Wet/Dry | | | | | Mech. Wet |
|---|---|---|---|---|---|---|---|---|
| | | | 1% | 10% | 20% | 30% | 40% | |
| Total Capital Cost (Direct & Indirect Capital Costs) | 2.83 | 5.61 | 3.82 | 3.10 | 2.91 | 2.62 | 2.51 | 1.41 |
| Total Capacity Penalty (Capacity & Auxiliary Power) | 2.82 | 1.73 | 1.35 | 1.06 | 0.88 | 0.86 | 0.84 | 0.59 |
| Total Operating Penalty (Replacement & Auxiliary Energies, Make-up Water & Maintenance) | 2.09 | 1.14 | 0.91 | 0.94 | 0.92 | 0.99 | 0.99 | 0.55 |
| Total Evaluated Cost (Sum of Capital & Penalty Costs) | 7.74 | 8.48 | 6.08 | 5.10 | 4.71 | 4.47 | 4.34 | 2.55 |

* H-High Back Pressure Turbine

† L-Conventional Low Back Pressure Turbine

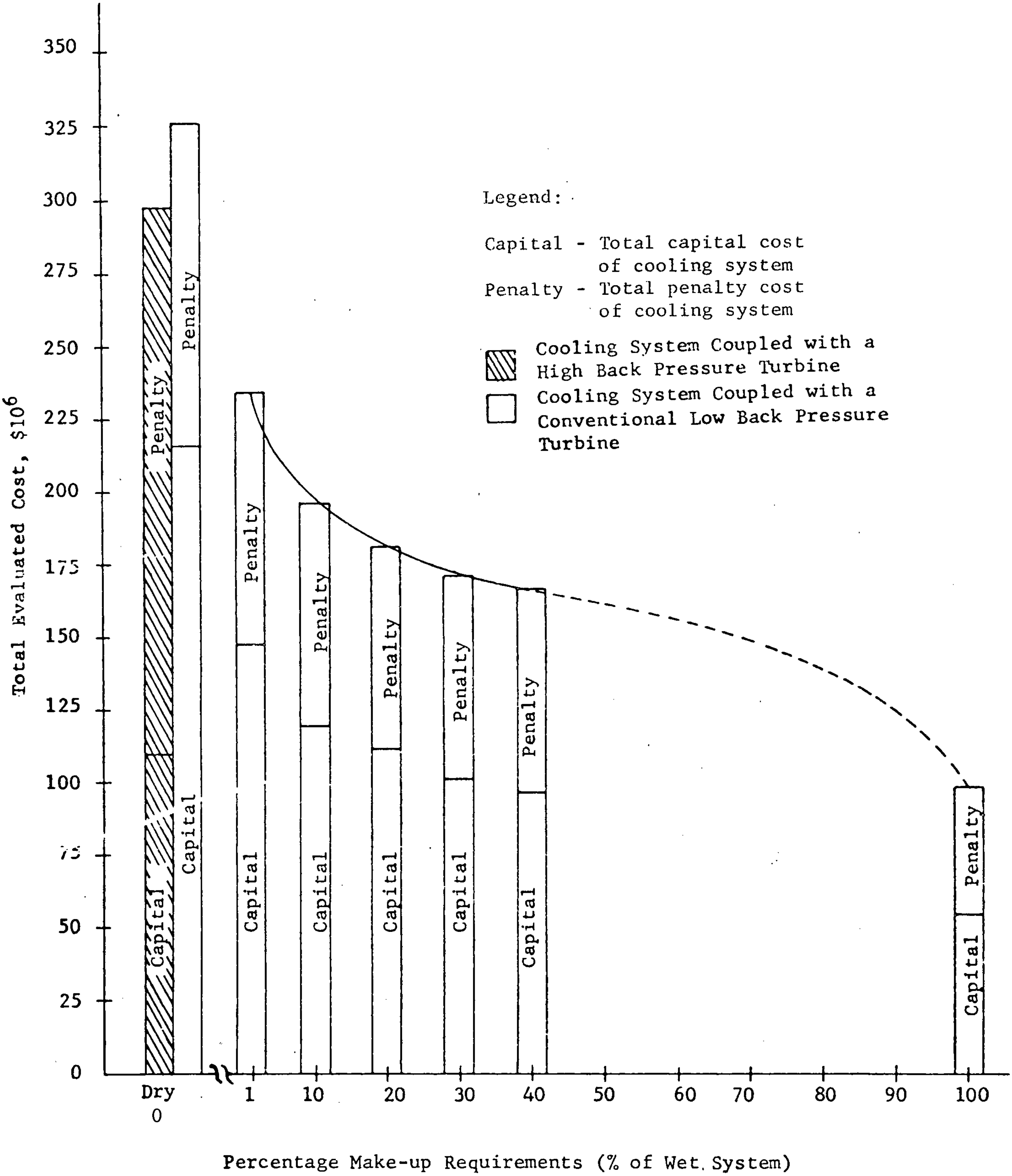



Figure S.1 Total Evaluated Cost and the Penalty and Capital Components for the Optimized Systems (Middletown, Mechanical Series, S1 Mode, 1985)

# CHAPTER 1

## INTRODUCTION

### 1.1 PURPOSE

One of the primary goals at the Energy Research and Development Administration (ERDA) is to obtain an assessment of resource utilization needed for energy generation. In this regard, ERDA is continually assessing the impact of existing technology as well as future developments of existing technology, the impact of current and proposed federal and state regulations, and public policy in the national interest which may affect energy generation and utilization.

The purpose of this report is to document an economic and engineering evaluation of the use of separate wet and dry cooling towers operating in combination to reduce the consumptive water requirement of condenser cooling in electric generating stations. This cooling concept (denoted wet/dry throughout this report) concerns all three of the above listed criteria. This study was prepared for ERDA by United Engineers & Constructors Inc. It is an assessment of the engineering, economic and operational aspects of wet/dry cooling and provides design and cost information needed by ERDA for a better understanding of the degree of resources (energy, water, capital) which must be balanced in the national interest.

This study was initiated in fiscal 1975 as a detailed engineering and economic evaluation of alternate wet/dry cooling concepts for a nominal 1000 MWe light water reactor fueled electric generating station at ERDA's hypothetical Middletown Site. This program was then extended in fiscal 1976 to include two other sites (Southwestern and Southeastern U.S.A.) and to encompass a wide range of economic .ditions. A complementary study was initiated by EPA in fiscal 1976 for nominal 1000 MWe coal fired stations. The EPA study was designed to evaluate site specific conditions at six designated power plant sites, five to forty miles from specific sources of water. Both studies use the same basic analysis and evaluation tools. The data base used for the analysis included vendor quotes for labor, materials and equipment which have been used by UE&C for the evaluation of cooling systems for utility plant applications.

## 1.2 ENVIRONMENTAL CONSTRAINT ON CONSUMPTION OF WATER

Consumptive water use is expected to be a major environmental concern in all parts of the United States late in this century (1). Effective planning and use of the limited water resources in the United States is in process, especially in the water-deficient areas of the western states (2, 3). The states have assessed the quantities and qualities of the water available and other factors that will shape the control and use of their waters. In addition, in some areas, major water basin commissions have been empowered by the states to regulate water use in their collective interest. Currently, however, there is no law which comprehensively and uniformly manages the consumptive use of water in the national interest. As the pressures of industrial, agricultural and municipal growth compete for water use in the future, all consumptive use of water in the United States will be regulated (1).

Consumptive use of water for agricultural and municipal growth has been taking place at a rate proportional to the rate of growth of population, while consumptive use of water for industrial and utility plant growth is taking place on an exponential scale.

us, the competition of all segments of the economy for consumptive use of water is expected to provide a major environmental impact by the end of this century. For this reason, regulators of various state, federal and regional agencies have advocated the use of dry cooling for utility plant applications. In response to requests from these agencies, numerous evaluations* have been performed which have indicated: 1) the use of dry cooling would increase considerably the costs of construction and operation of steam electric power plants; 2) their use would result in a significant loss of capacity during the same high temperature conditions when most utilities experience their peak electrical demand; and, 3) the loss of capacity and peak demand are coincident with the time that the environmental impact of consumptive water use is most severe.

The costs associated with construction and operation of a dry tower system is approximately three times that associated with a wet tower system (see Chapters 5 and 7). Substitution of dry cooling for wet cooling could increase the total cost of generation by 10 to 15 percent. However, a significant fraction of the cost differential is due to the loss of capacity and the associated energy loss expected during high temperature operation.

This loss of capacity and energy for the dry tower system can be significantly reduced by the use of an evaporative cooling tower to assist the dry tower. Although the addition of a wet helper tower increases the capital cost and

*Applications for construction permits for both fossil and nuclear power plants require environmental reports as the basis for the application. These environmental reports include sections in which the economics and environmental impact of alternate condenser cooling systems are compared. Recent examples of these evaluations prepared by United Engineers & Constructors Inc. can be ound in References 4, 5 and 6.

consumes water; these towers also reduce the economic penalty associated with the operation of dry cooling by reducing the capacity and energy losses. Wet/dry cooling costs, therefore, lie between the evaporative and the dry cooling system costs.

The use of wet helper towers for peak temperature operation is not new to the power industry. Many power plants designed to operate with once-through cooling use wet towers for summer operations to meet water quality regulations at peak power demand.

The first wet/dry cooling towers for water conservation have been purchased by Public Service Company of New Mexico for use at their San Juan site (Farmington, New Mexico). These units, each 450 MWe, are expected to be operational in 1979 and 1981, and are designed to save 60 percent of the water consumed by evaporative cooling towers.

The successful application of the wet/dry concept will significantly reduce the environmental pressures of consumptive water use expected from an expanded electrical base capacity by the end of this century.

## 1.3 IMPLICATION OF WET/DRY COOLING TO POWER PLANT SITE SELECTION

One of the basic criterion for site selection is the availability of water for condenser cooling. This criterion usually limits site selection for power plants using evaporative cooling to areas within 20 to 25 miles of a major water source or to the construction of a major impoundment along a smaller waterway. Uncertainty relative to water availability and the absence of a structured approach to consumptive water use by the regulators, has contributed to delays in obtaining permits to construct and operate power plants. The e of wet/dry cooling permits the relaxation of this hydrologic criteria, can potentially open vast areas of land previously considered impractical for power plant sites, and should alleviate many licensing problems.

Engineering analysis provided in this report can be used to estimate the economic penalty which must be charged to the plant using the wet/dry cooling option.

This option may allow siting within transmission corridors, and in specific site selection programs, provide a significant reduction in both the economic cost of the power plant operation and the environmental impact of additional transmission corridors and right-of-way costs.

Of even greater importance may be the intangible impact on the licensing sequence. The ability to site a power station away from the populous areas adjacent to most waterways and into reasonably remote areas should significantly shorten the time necessary to qualify a site for a nuclear power plant.

1.4 ECONOMIC OPTIMUM

The economic analysis provided in this report attempts to identify the optimum or minimum cost cooling system, wherein the capital costs of the cooling system are balanced with the economic penalties associated with operating the cooling system. The sum of the capital and penalty costs is defined as the Total Evaluated Cost (TEC). The economic optimum occurs because of the nature of the capital and penalty cost functions. For most cases, the more capital paid initially for the cooling system the smaller will be the capitalized penalty, and vice versa. These costs and penalties can, therefore, be balanced to provide an economic optimum.

When providing economic analysis of cooling systems for utilities, purchase of the minimum total evaluated cost system is recommended and detailed design and cost information for that system is provided. This procedure was followed in this study.

# CHAPTER 2

## METHOD OF ECONOMIC EVALUATION

### 2.1 INTRODUCTION

The method of economic evaluation of alternate cooling systems is the means by which the costs of different systems are assessed on a common basis. A number of methods have been used in previous studies to perform the economic evaluation (7, 8, 9, 10, 11 & 12). A review of these methods can be found in reference 13.

The method of analysis used in this study for the cooling tower system is consistent with that used in reference 7. The method may be classified as a fixed source-fixed demand approach. It assumes that the reference plant has a fixed heat source and that there is a fixed demand for the plant output. As the plant performance changes due to the change in cooling system performance, the capacity and energy generated are compared to the fixed demand required of the plant. If the cooling system causes the plant to operate below the fixed demand, a penalty equivalent to an increase in capital cost is added to the capital cost of the cooling system. A credit is taken if the plant operates above the demand value. A penalty is also assessed for the cooling system auxiliary power and energy requirements.

In general, as the size of the cooling system becomes larger, its performance improves, the capital cost of the cooling system increases, but the penalty cost decreases. At some point, a minimum exists for the combined cost of capital and penalty which represents the best trade-off between the two costs. Such a cooling system is called an optimum or optimized system. The purpose of the economic evaluation is to determine these optimum systems.

The essential elements of the method of economic evaluation include the following items which are described in this and subsequent chapters.

1. the plant model for the reference power plant;
2. the cooling system model;
3. the treatment of loss of plant performance;
4. the economic penalty evaluation;
5. the economic factors;
6. the procedure for determining the optimum cooling systems; and,
7. the description of the plant site and ambient temperature condition.

## 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 demand is fixed to establish a common basis for comparison. The heat source size is fixed to eliminate the need for considering the capital cost change and fuel charge for the reference plant itself when evaluating various cooling systems. The treatment of the loss of plant performance is illustrated in Figure 2.1.

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

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.

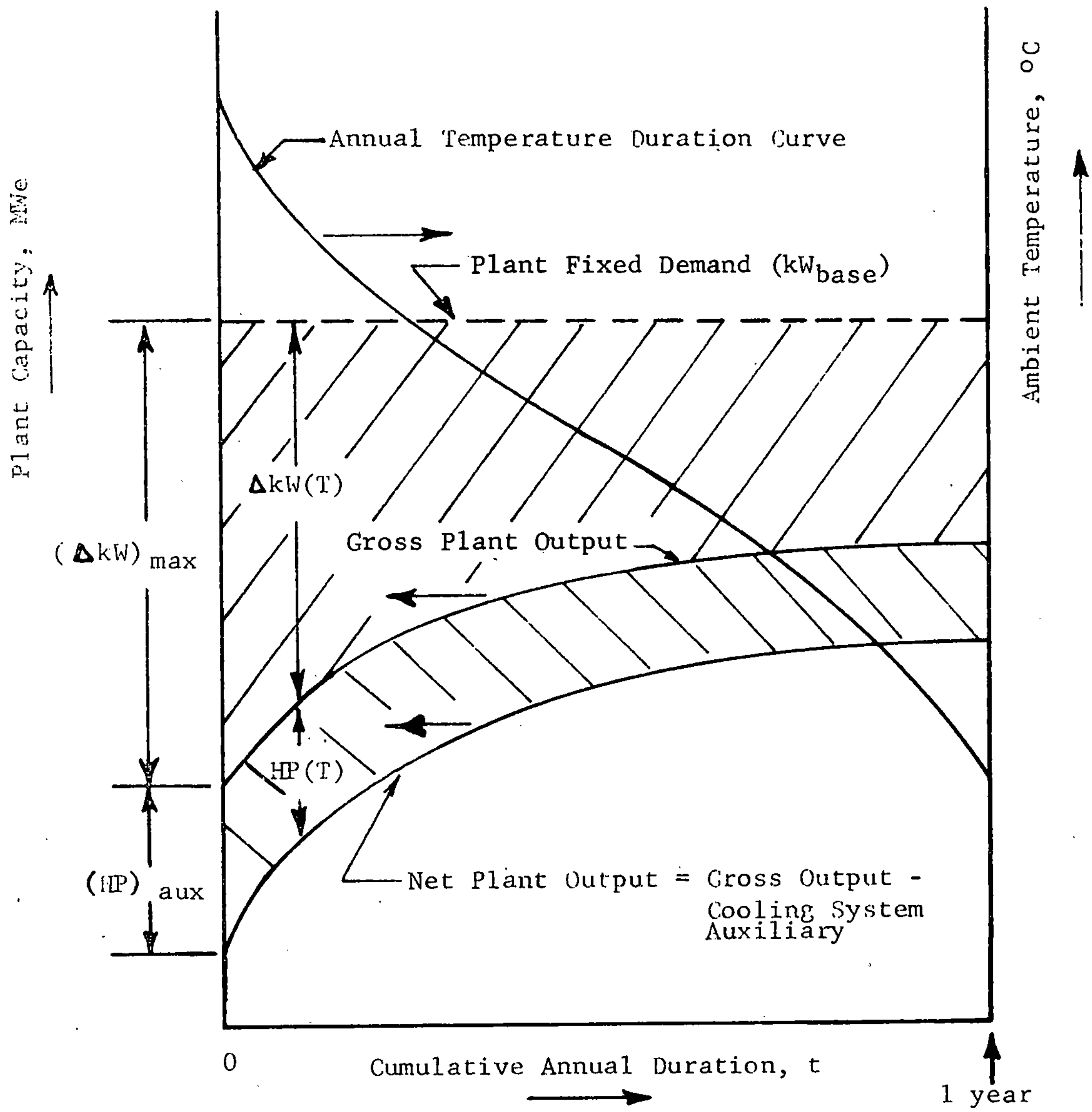



Figure 2.1 Ambient Temperature Duration And Corresponding Plant Performance

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

Capacity Penalty ($P_1$):

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

Replacement Energy Penalty ($P_2$):

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

Cooling System Auxilliary Power ($P_3$):

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

Cooling System Auxiliary Energy ($P_4$):

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

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 (\$/GJ).

$(HP)_{aux}$ = 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 (kJ/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), $^oF$ ($^oC$).

$T_{max}$ = peak ambient temperature, $^oF$ ($^oC$).

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.

## 2.4 ECONOMIC FACTORS

The source of capacity replacement which serves as the basis for the assessment of the associated economic factors K, F and OAM includes the following:

1. high capital cost, low operating cost base load units;
2. low capital cost, high operating cost peaking units;

3. a mixture of generating unit types; and,

4. purchased power from another utility system.

The selection of the capacity replacement is dependent on economics and on the type of duty for which the capacity is to be replaced. For duties which require relatively constant loads or large amounts of energy, the replacement choice, on economic grounds, should be a base load capacity. Such is the case for the auxiliary power and the capacity loss due to ambient change for the wet/dry and dry cooling concepts (see Figures 5.3 and 5.4). Therefore, all the economic factors used in this study were assessed on the basis of base load units similar to the reference plant; the numerical assessments of these factors are given in Appendix A.

## 2.5 COOLING SYSTEM MAKE-UP WATER COST 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 three components:

1. Capital cost for the make-up water system which includes:
    a. pumps and associated structures; and,
    b. pipelines.
2. Pumping cost which includes both the capacity charge for the

power required by the pumps and the energy charge for pumping the water.

3. Water purchase and treatment cost.

For specific power plants, all these component costs can be accurately estimated as shown in Chapter 8 and Appendix I. However, since the sites for this study are 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 ($m^3$/year).

$C_w$ = cost for supplying make-up water, \$/1000 gal (\$/$m^3$) of water.

## 2.6 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.

$$P_6 = \text{cooling system maintenance penalty}$$

$$= aC_c + bC_p + cC_T \qquad (6)$$

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.

## 2.7 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 and serves as the criterion for cooling system optimization and comparison.

## 2.8 OPTIMIZATION PROCEDURE

The basic procedures used in the optimization are as follows:

1. Size and cost the major components comprising the cooling system for a set of design parameters;
2. Evaluate the performance of the cooling system in response to ambient temperature changes during an annual cycle;
3. At these off-design conditions, determine the impact of cooling system operation on the plant performance;
4. Assess the penalties due to loss of performance, make-up supply and cooling system maintenance requirements;
5. Calculate the total evaluated cost of the cooling system which includes the capital cost as well as penalty costs; and,
6. Change the cooling tower and condenser design parameters and repeat steps a through d until the design with the lowest total evaluated cost is found.

# CHAPTER 3

# DESIGN AND PERFORMANCE CHARACTERISTICS OF THE REFERENCE POWER PLANT AND COOLING TOWERS

## 3.1 INTRODUCTION

The reference power plant assumed for the wet/dry cooling tower system evaluation in this study was a nominal 1000 MWe light water reactor (LWR). The tower systems evaluated include wet towers, dry towers and wet/dry towers which combine the separate wet and dry towers into an operational unit. In this chapter, the design and performance characteristics of the reference power plant and the cooling towers are described.

Figures 3.1 and 3.2 show schematic diagrams of pressurized and boiling water reactor power plants interfaced with a wet tower system. The reactor types are both classified as light water reactors. Power plants designed for both reactors have similar design and performance characteristics.

Figure 3.1 also illustrates the major components of a cooling system. The cooling system is shown to the right of Section B-B; and it interacts with the reference plant through the condensing steam at the turbine flange according to the performance characteristics of the plant.

## 3.2 CHARACTERISTICS OF THE REFERENCE POWER PLANT

The fixed heat source of the reference power plant is rated at 3173 MW thermal This heat source may be coupled with either a conventional turbine or a high back pressure turbine. When coupled with the conventional turbine, the generator delivers 1094 MWe at a turbine back pressure of 2 in-HgA (50.8 mm-HgA). This output, which is assumed to be equal to the fixed demand, is referred to as the base output of the reference plant. The selection of these quantities was based on a typical LWR plant design as described in Reference 14.

The general design characteristics of an LWR plant which affect the plant heat rate are:

1. Steam at the turbine inlet is either saturated or slightly superheated.
2. Pressure levels are approximately 1000 psig ($6.89 \times 10^6$ Pa).
3. The plants are usually designed with moisture separators and steam reheaters to increase turbine efficiency and to avoid severe erosion of turbine blades by the moisture entrained in the steam.

For low back pressure operation, the turbine assumed in this study is the conventional type. This turbine type is typically used in power plants with once-through cooling or with wet cooling towers. It is the only turbine type being marketed in the United States for nuclear applications. The operating back pressure limitation ranges from 5 to 6 in-HgA (127 to 152.4 mm-HgA) depending on the turbine manufacturer.

For high back pressure operation with dry cooling towers, the study assumed a high back pressure turbine of the intermediate annulus type. This type of turbine is currently not available for nuclear applications, but it is offered by the General Electric Company for fossil plants. The 330 MWe dry tower fossil unit currently under construction at Wyodak utilizes such a turbine; the maximum rating commercially available, according to General Electric, is 750 MWe.

The effect of cooling system performance on the turbine-generator output is calculated using the heat rate versus back pressure curves shown in Figures 3.3 and 3.4. Figure 3.3 shows the typical heat rate curve for an LWR plant in the 1000 MWe range coupled with a conventional turbine. Figure 3.4 shows a hypothetical heat rate curve projected for the same plant coupled with a high back pressure turbine of the intermediate annulus type.

## 3.3 COOLING SYSTEM TYPE

All the cooling systems evaluated in the study are the indirect type with surface condensers as shown in Figure 3.1. The cooling water loop is completely separated from the feedwater loop of the nuclear power plant. The indirect system is necessary for the wet and wet/dry towers evaluated because these systems require continuous circulating water, and the cooling water is open to the atmosphere. It is also a preferred system for nuclear applications due to safety reasons, since it prevents radioactive contamination in the turbine exhaust steam from being released to the condenser cooling system.

## 3.4 REVIEW OF COOLING TOWER DESIGN

### 3.4.1 Wet and Dry Towers

Three types of wet and dry towers were considered in the design of combination wet/dry towers. These are:

1. Mechanical draft wet tower;
2. Mechanical draft dry tower; and
3. Natural draft dry tower.

All three towers are of conventional state-of-the-art designs. Their design and operational characteristics can be found in Appendix B.

The mechanical draft wet and dry towers can be either of modular design or integral design, such as the currently marketed round mechanical tower. The modular design, selected for investigation in this study, allows more flexibility in the design and evaluation of the wet and wet/dry towers. The natural draft dry tower was assumed to be a concrete tower with fin-tube heat exchangers mounted vertically around the base of the tower.

Specific designs commonly offered by cooling tower manufacturers were used for the mechanical draft wet tower module, the dry tower module and the finned-tube heat exchanger module of the natural draft dry tower. The design specifications of these three modules are given in Appendix C.

In addition to their use as components of the wet/dry towers, the mechanical draft wet and the mechanical draft dry towers were also evaluated independently. These tower systems are referred to as reference tower systems, and they serve as benchmarks for comparison with the wet/dry towers. The design and performance of the towers were based on empirical correlations.

### 3.4.2 Wet/Dry Cooling Towers

A number of possible arrangements exists for combining separate wet and dry towers into wet/dry towers which can conserve make-up water while rejecting the power plant waste heat. Many of these wet/dry towers have been described in the literature (15, 16, 17). Evaluation of all possible arrangements is beyond the scope of this study. After preliminary evaluation and discussions with ERDA, the following wet/dry combinations were selected for evaluation:

1. Mechanical series wet/dry tower: This system combines separate mechanical draft wet and dry towers into an operational unit by means of a cooling water circuit which flows through the dry and wet towers in series.
2. Mechanical parallel wet/dry tower: This system combines separate mechanical draft wet and dry towers into an operational unit by means of a cooling water circuit which flows through the wet and dry tower in parallel.
3. Natural series wet/dry tower: This system combines separate natural draft dry towers and mechanical draft wet towers into an operational unit by means of a series water circuit as in the towers described in (1) above.

Mechanical wet/dry towers with either series or parallel water flow represent the current commercial offering of wet/dry towers for water conservation. Tower 3 is a variation of Tower 1. The advantage of Tower 3 lies in the fact that the use of natural draft dry towers eliminates the fan power requirement of its mechanical counterpart even though its capital cost may be greater.

The separate arrangement of wet and dry towers provides flexibility in tower design and operation. It allows independent sizing and control of the component wet and dry towers, thus making possible different size combinations and operational modes. These design variables affect both the thermal performance and water consumption requirement.

### 3.4.3 Design and Operation of Series Flow Wet/Dry Systems

A schematic diagram for the series water flow towers is shown in Figure 3.5. The two cooling towers are connected so that water flows first to the dry tower and then to the wet cooling tower.

The dry tower is designed to reject the entire heat load at a low ambient temperature while maintaining the turbine back pressure within specified limits. The performance of the dry tower is then evaluated at the peak ambient temperature condition to determine the maximum capability of the dry towers without exceeding the specified limiting back pressure. This result is then used to size the wet helper tower needed to reject the remaining waste heat.

For all three wet/dry cooling systems evaluated, the dry cooling is the basic heat rejection mechanism, and wet cooling is used to provide supplementary heat rejection when necessary. The dry tower is designed to operate continuously during the year although provision is included to shut down dry cells if they are not needed at low ambient temperatures.

#### Modes of Operation for Series Flow Towers

Two different modes of operation were analyzed and are described below -

Mode S1 - The first mode is termed the S1 mode (S for series). The main objective of this mode is to operate the wet helper tower as little as practically possible. During the peak summer ambient temperature, both the wet and dry towers are operating at full capacity. As the ambient temperature falls, the wet cells are turned off in succession to maintain the turbine back pressure essentially constant at the wet tower design value. The back pressure of a typical turbine operating with this system is schematically presented in Figure 3.6. When point 3 is reached, all of the wet cells have been shut down and the dry tower can reject the entire heat load. The back pressure curve between points 2 and 3 is saw-tooth shape because a discrete number of wet cells are taken out of service as the ambient temperature and the turbine back pressure decrease. Although operation of the tower system produces a characteristic saw-tooth operation for the S1 mode, throughout this document, all subsequent figures will show the wet tower operation at the constant back pressure maximum as shown in Figure 3-6.

This operational mode requires continuous feedback controls for the operation of the wet towers. Most new stations are being designed with sufficient computer capacity to provide for this additional measure of station control.

Mode S2 - The second mode of operation analyzed represents a system operating with much less control of the wet tower. In this mode, all the wet cells are operated continuously until the dry tower design temperature is reached. As the ambient temperature decreases, the turbine back pressure is allowed to fall. When the dry tower design temperature is reached, all of the wet cells are shut down and the entire heat load is handled by the dry tower. A schematic of this system operation is presented in Figure 3.7. As the ambient temperature passes through the dry tower design point, an apparent instantaneous jump in back pressure occurs. However in reality, this transition would occur over a long enough time span so as not to create any damaging thermal shock to the turbine and associated equipment. Turbine manufacturers have indicated that changes in back pressures of this magnitude occur daily during the operating life of the turbine.

Wet/dry cooling systems operating in the S1 mode are more water conservative at the expense of greater energy consumption than the same system operating in the S2 mode. Conversely, systems operating in the S2 mode are more energy conservative at the expense of higher water consumption.

### 3.4.4 Design and Operation of Parallel Flow Wet/Dry Systems

Figure 3.8 is a schematic diagram of the parallel water flow wet/dry cooling system. The cooling water leaving the condenser is divided into two streams which flow through the wet and dry towers in parallel. The two streams are rejoined before entering the condenser.

The design procedure is similar to that of the series water flow wet/dry towers. The dry cooling tower is designed to reject the entire heat load at a low ambient temperature while maintaining the turbine back pressure within specified limits. The performance of the dry tower is then evaluated at the peak condition and the wet tower is designed to reject the remaining waste heat. One major difference between parallel and series flow is that during wet/dry operation, the dry tower operates with partial flow. The modes of operation considered are described below.

Mode P1 - This mode (P for parallel) is analogous to the series S1 mode with the following exceptions:

a. During wet/dry operation, the dry tower operates with partial water flow,

b. As the wet cells are sequentially shut down, the water is diverted back through the dry cells.

Mode P2 - The second mode is analagous to the S2 mode with the following exceptions:

a. During wet/dry operation, the dry tower operates with a constant partial water flow.

b. When the ambient temperature reaches the design dry bulb temperature all the wet cells are taken out of service, and the entire wet tower flow is returned to the dry tower.

### 3.4.5 Parallel Flow Wet/Dry Tower System - Closed Water Loop

The wet/dry tower systems evaluated in this study are open water loop systems. The cooling water is open to the atmosphere at the junction where the wet and dry towers are joined together. The parallel flow design is amendable to a closed water circuit for the dry tower and a separate open water circuit for the wet tower. A schematic diagram of this design is shown in Figure 3-9. This design has been advocated by tower manufacturers (15, 17). A detailed evaluation of this concept was outside the scope of the contract.

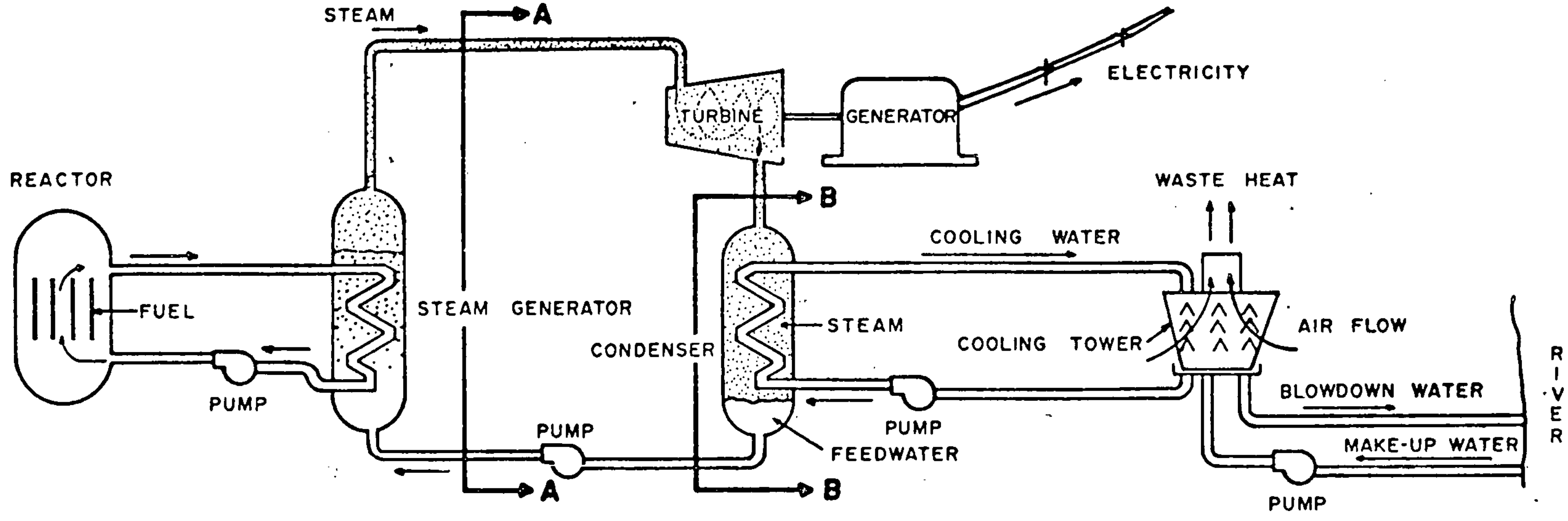



Figure 3.1 Power Generation and Waste Heat Rejection - Pressurized Water Reactor (PWR) With Evaporative Cooling Tower

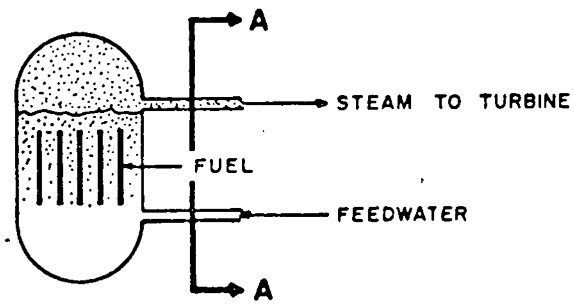



Figure 3.2 Boiling Water Reactor (BWR)

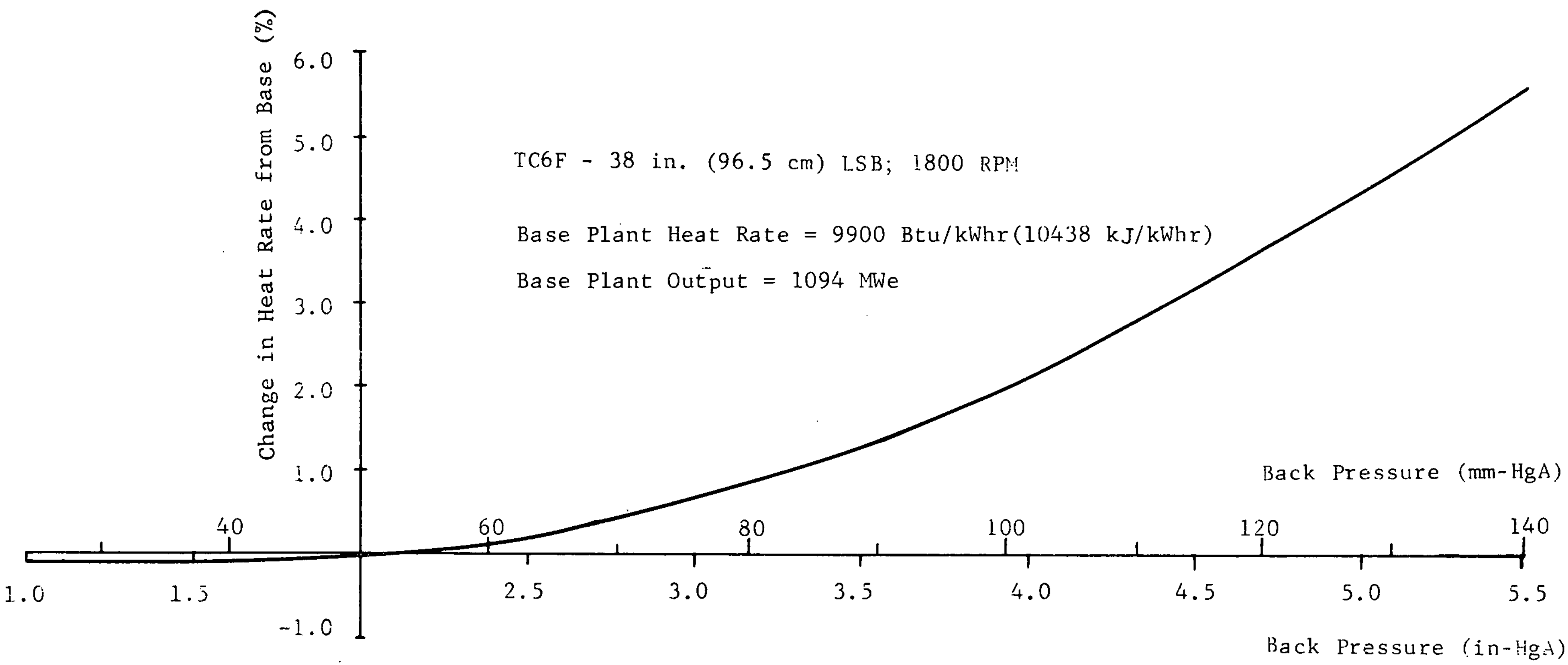



Figure 3.3 Heat Rate Correction Curve for a Plant with a Conventional Turbine

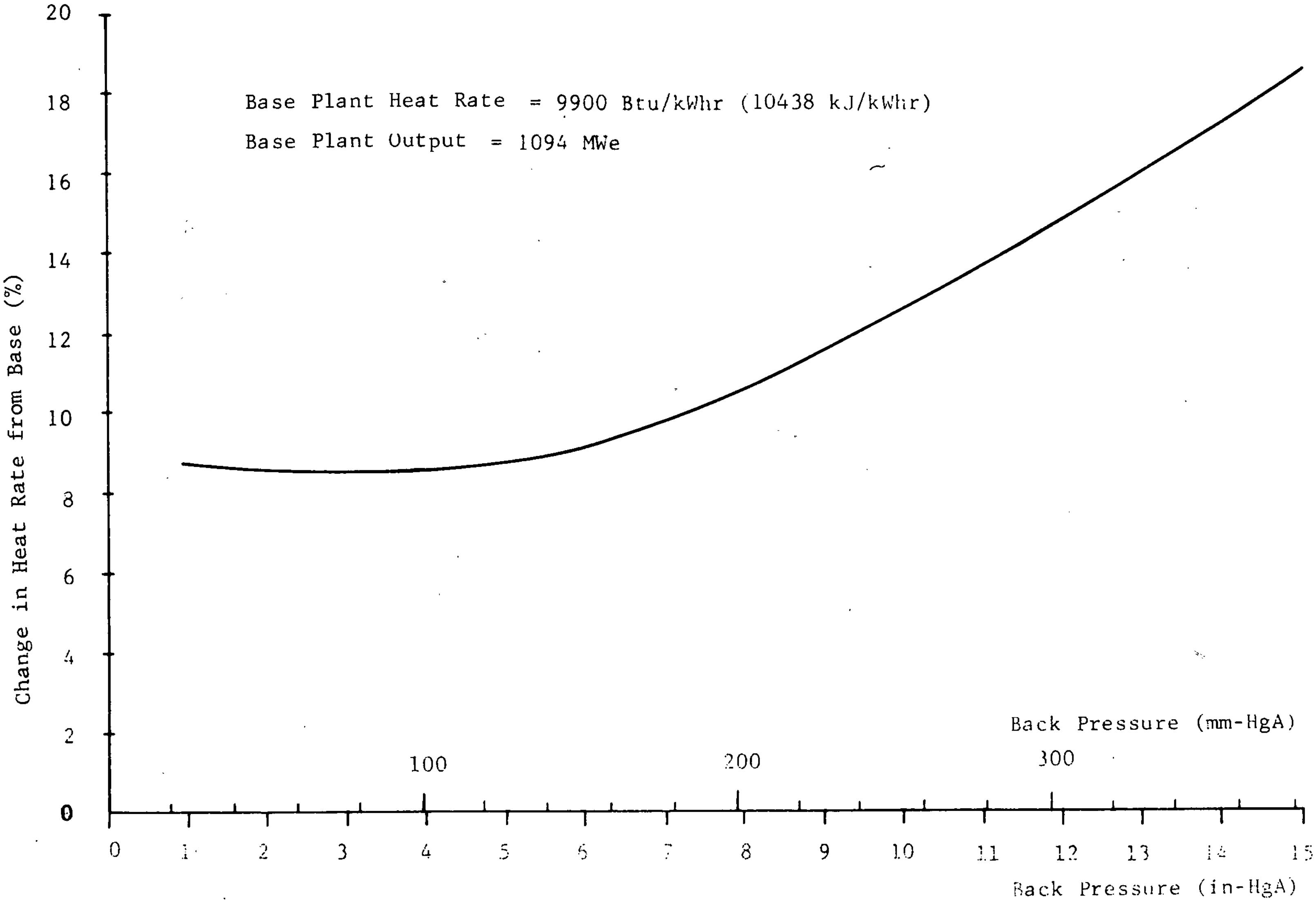



Figure 3.4 Heat Rate Correction Curve for a Plant with a Hypothetical High Back Pressure Turbine

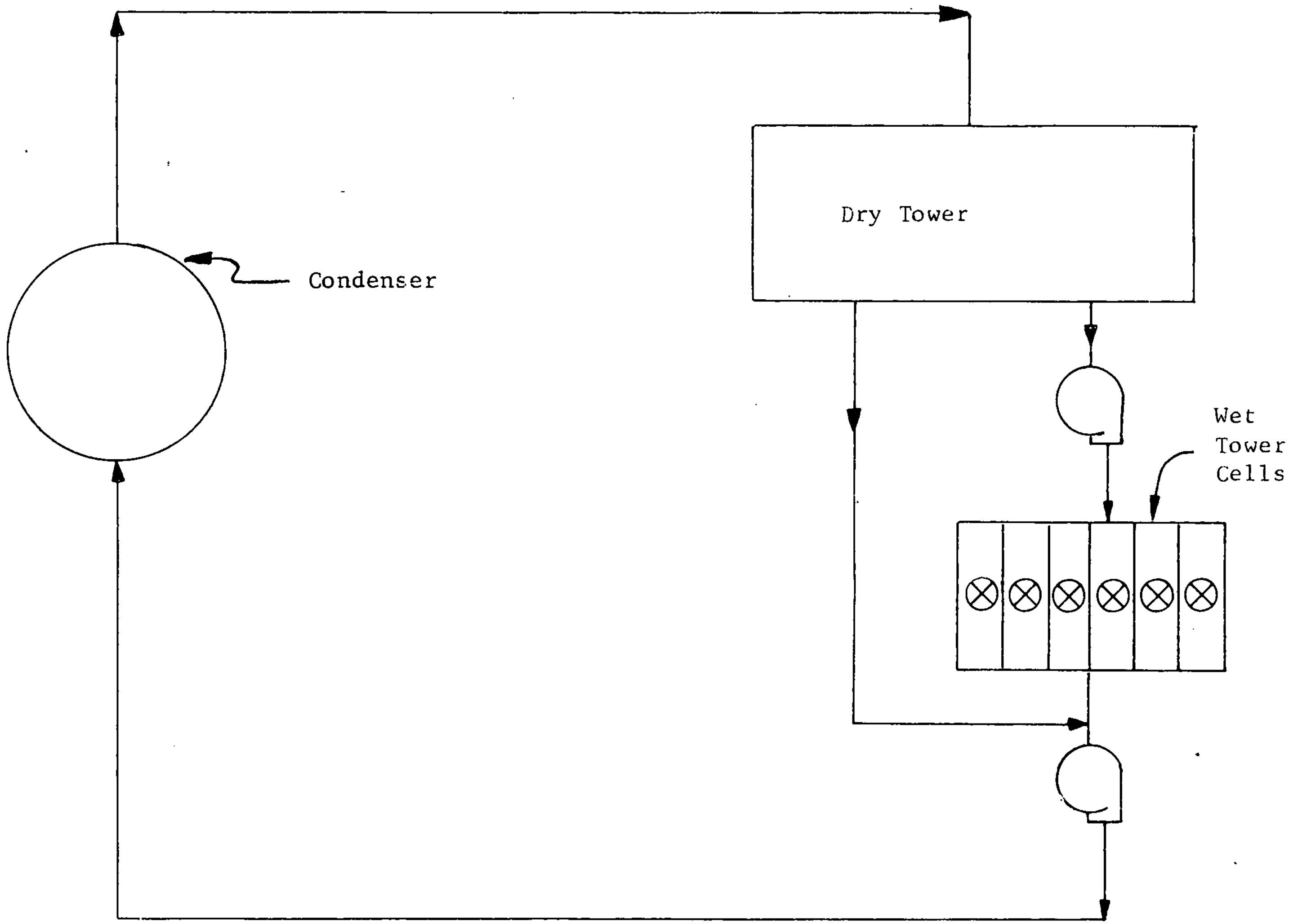



Figure 3.5 Series-Water Flow Wet/Dry Tower

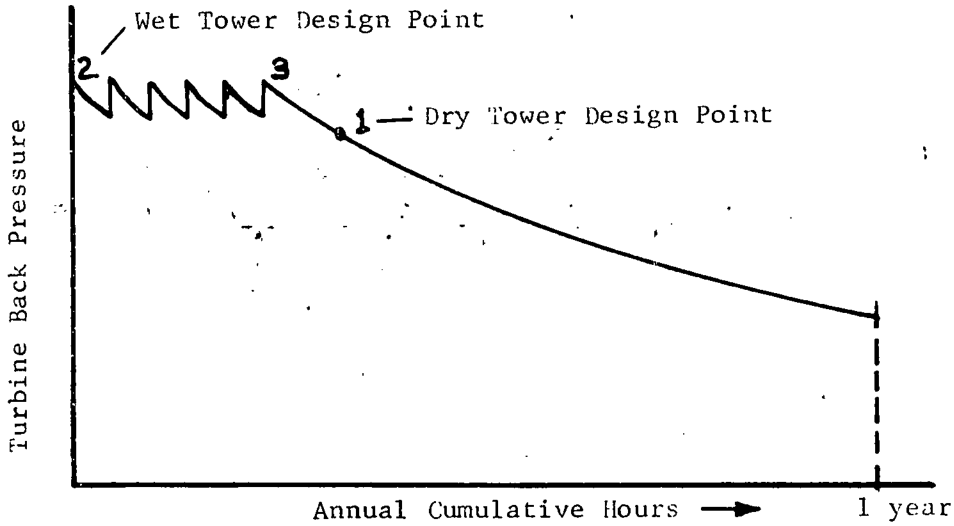



Figure 3.6 Wet/Dry Tower-Mode 1 Operation

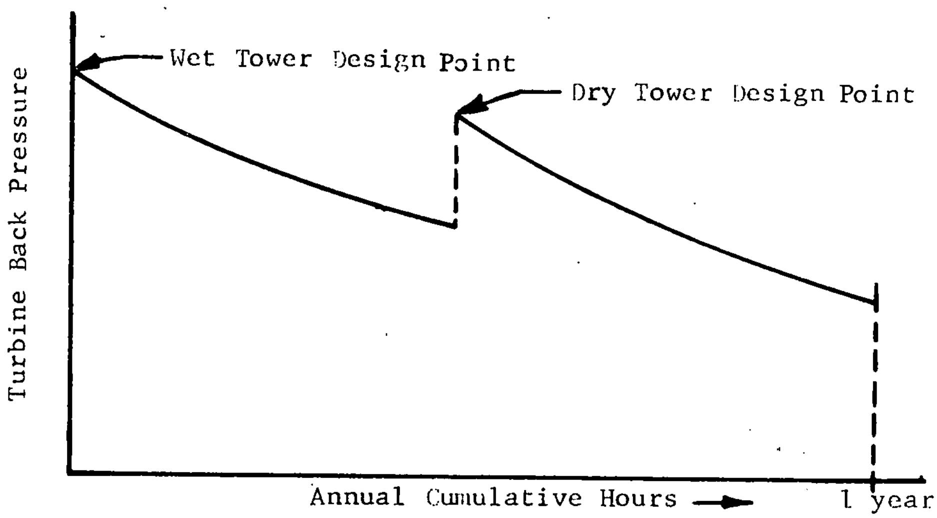



Figure 3.7 Wet/Dry Tower-Mode 2 Operation

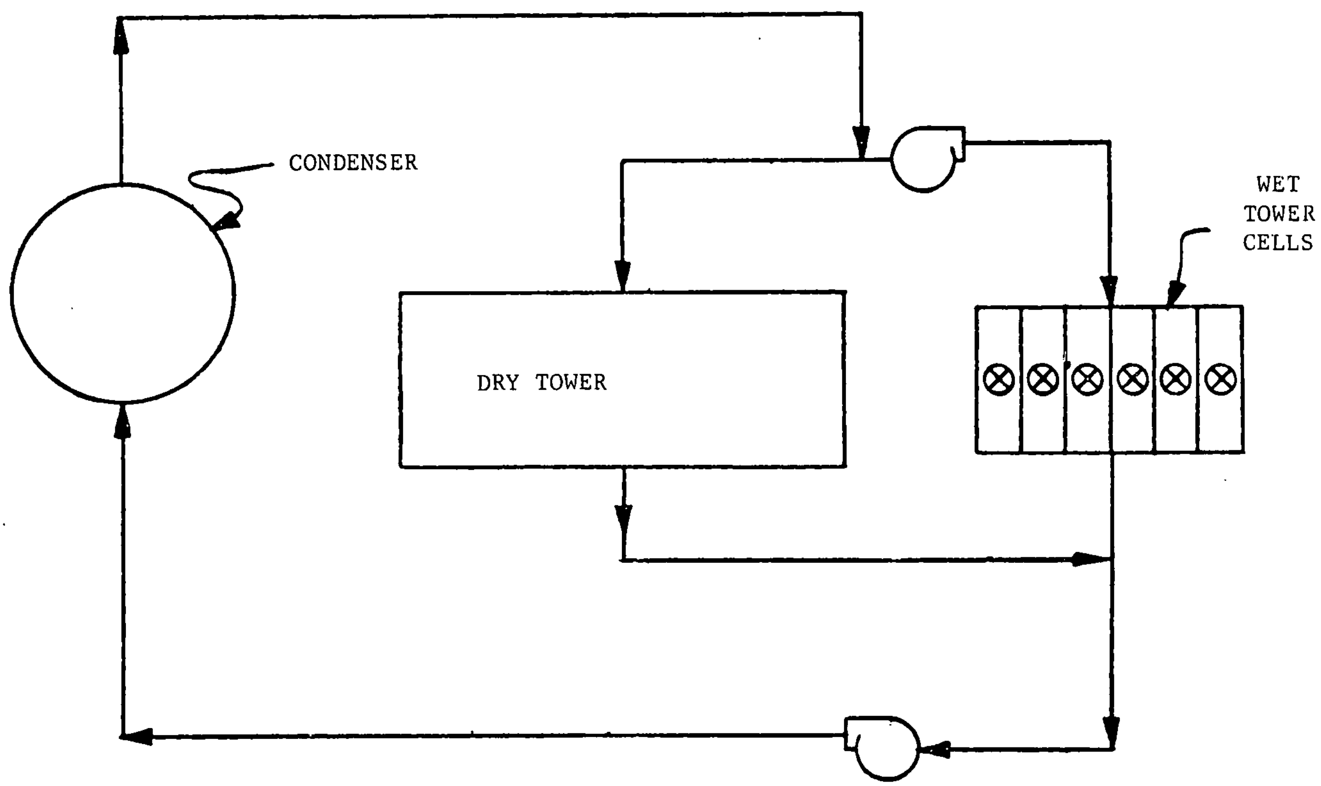



Figure 3.8 Parallel-Water Flow Wet/Dry Tower

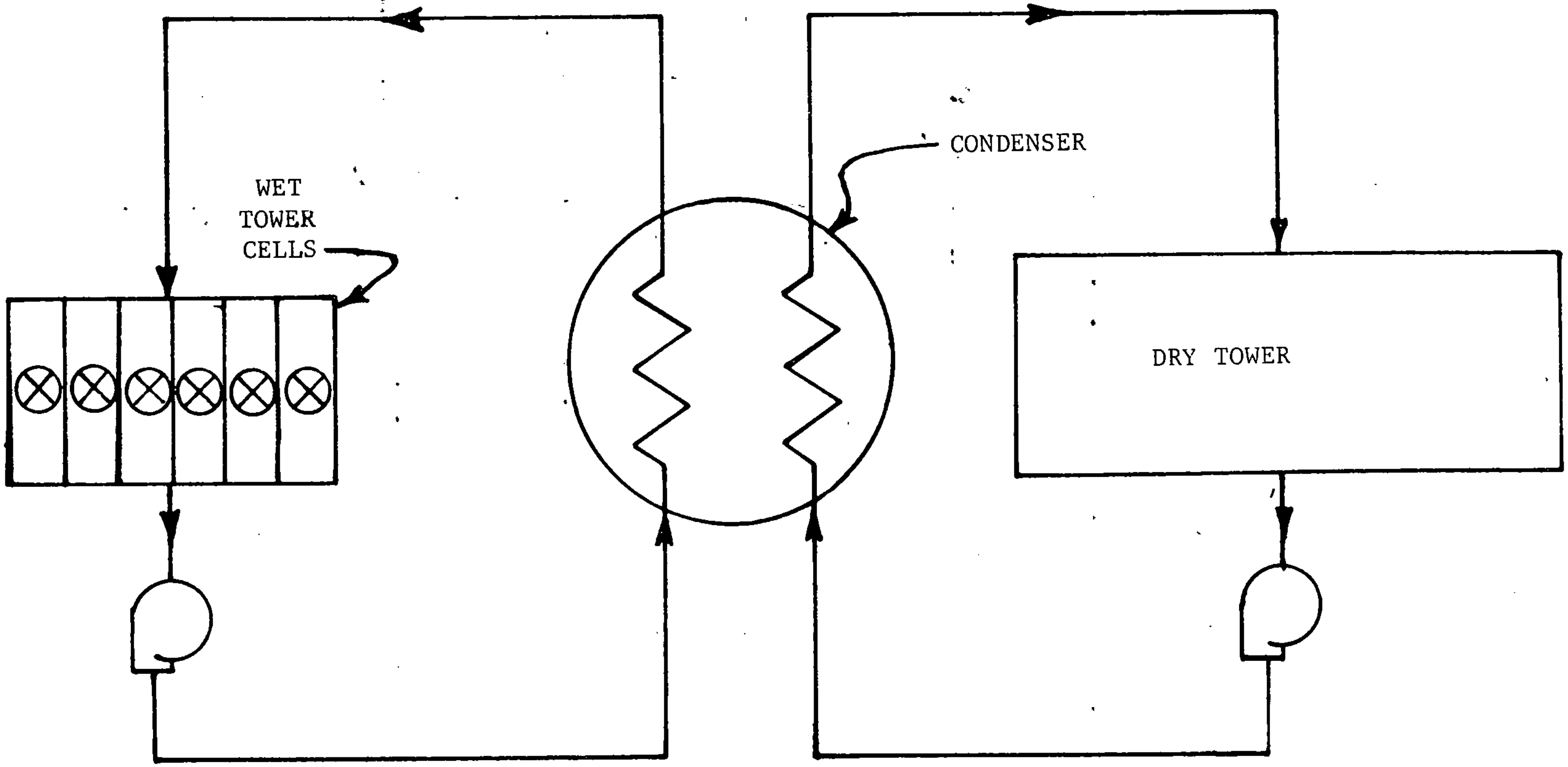



Figure 3.9 Parallel-Water Flow Wet/Dry Cooling Tower Circuit
Closed Water Loop

# CHAPTER 4

# MAJOR ASSUMPTIONS AND ECONOMIC FACTORS

## 4.1 INTRODUCTION

A number of assumptions concerning the method of economic analysis, economic factors, the reference power plant model, the cooling system model and site constraints were described in the previous chapters. These assumptions, constraints and economic factors are summarized in this section. An understanding of these assumptions is essential to the interpretation and utilization of the results obtained in this study.

## 4.2 MAJOR ASSUMPTIONS

Method of Analysis:

The method of analysis uses a fixed source-fixed demand approach. The reference plant which interfaces with the cooling systems is assumed to have a fixed heat source and there is a fixed demand for the plant output. It is against this constant output that the cooling system is gauged. The fixed source is a 3173 MW thermal LWR coupled to a turbine which delivers 1094 MWe gross at a turbine back pressure of 2 in-HgA (50.8 mm-HgA).

Treatment of Loss of Plant Capacity and Energy:

Capacity loss and auxiliary power are replaced by the base load capacity of the utility system. These base load units are assumed to be of similar size and characteristics as the reference plant. Replacement energy and auxiliary energy required for pumps and fans are provided by energy generated by the base load units.

Treatment of Make-up Water Cost Penalty:

There are three components included in the cost of supplying the make-up water; i.e., treatment and purchase cost, capital cost of the make-up water systems and pumping cost. These costs were developed and lumped as dollars per unit quantity of make-up water. A specific example of the component cost breakdown is given in Appendix I.

Optimization Criteria:

The reference wet or dry towers were optimized on the basis of minimal total evaluated cost.

For the wet/dry towers, two criteria were used in the optimization:

1. Fixed make-up water requirement expressed as a percentage make-up of the optimized wet system.
2. Minimum total evaluated cost.

Reference Power Plant:

1. Plant Type and Nominal Size:

   This study is limited to nominal 1000 MWe light water reactor power plants.

2. Base Output (Gross):

   1094 MWe

3. Load Profile:

   The reference plant is assumed to either operate at full capacity or be off line and to have an average capacity factor of 75 percent.

4. Turbine Type and Availability:

Two types of turbines are assumed:

a. A conventional steam turbine with a maximum operating back pressure of 5 to 6 in-HgA (127 to 152.4 mm-HgA).

b. A hypothetical high back pressure turbine with a maximum operating back pressure of 15 in-HgA (381 mm-HgA).

Plant Performance:

The heat rate as a function of turbine back pressure for a plant operating with a conventional turbine is shown in Figure 3.3.

The heat rate as a function of turbine back pressure for a plant operating with a high back pressure turbine is shown in Figure 3.4. The heat rate curve is hypothetical and is for study purposes only.

Cooling System Type:

Indirect tower system with a separate water loop for the cooling system as shown in Figure 3.1.

Major Components of Cooling System:

The major components included in the evaluation are:

1. Condensers;

2. Cooling towers, including basin and foundation for the towers;

3. Circulating water system which includes pumps, pipelines and structures; and

4. Electric equipment for pumps and fan motors.

Condenser Design:

The condensers are surface condensers with single pressure design.

Cooling Tower Design:

The wet/dry towers are composed of separate wet and dry towers. The mechanical draft wet or dry towers are of fixed module design, as are the heat exchanger modules of the natural draft dry tower. Concrete structures are used for the wet tower modules and for the dry natural draft shell. The mechanical draft dry modules are made of carbon steel.

Design Criteria of Wet/Dry Towers:

The criteria used in the design of wet/dry towers for water conservation are:

1. Conventional steam turbines will be used and the maximum operation back pressure will not exceed 5 in-HgA (127 mm-HgA).

2. The dry tower is designed to reject the entire plant heat load at low ambient temperatures.

3. The wet helper tower is designed to supplement the dry cooling tower such that the turbine back pressure will be equal to a specified value at the maximum ambient temperature.

Cycle of Concentration for Circulating Water:

Total dissolved solids in the circulating water system were allowed to reach ten (10) cycles of concentration with respect to the total dissolved solids in its make-up water. The relationship between the cycle of concentration, the make-up rate and the evaporation rate is as follows:

$$\text{Make-up Flow Rate} = \frac{\left[\text{Evaporation Rate}\right] \times \left[\text{Cycle of Concentration}\right]}{\left[\text{Cycle of Concentration}\right] - 1}$$

Design and Data Base of Cooling System Components:

Module design and cost data were supplied by Vendors. The design specifications of major components are given in Appendix C.

## 4.3 BASIC ECONOMIC FACTORS

The basic economic factors which apply to all cooling systems are given in Table 4.1. The factors for escalation are given in Table 4.2. The assessment of annual fixed charge rate, material and labor cost escalations, capacity charge rate, and fuel cost for replacement energy is discussed in Appendix A.

TABLE 4.1

BASIC ECONOMIC FACTORS

| | |
|---|---|
| Plant Start-up Date | 1985 |
| Average Plant Capacity Factor | 0.75 |
| Annual Fixed Charge Rate | 18% |
| Plant Life | 40 years |
| Capacity Penalty Charge Rate (Incremental Base Load Plant Cost) | $600/kW |
| Fuel Cost (For Base Load Plant) | 153¢/MBtu (145¢/GJ) |
| Operation and Maintenance Cost (For Incremental Base Load Plant) | 0.724 mills/kWhr |
| Water Cost | 27¢/1000 gal (7.13¢/$m^3$) |

TABLE 4.2

FACTORS FOR ESCALATION

| | |
|---|---|
| Construction Period for LWR | 6 years |
| Construction Period for Cooling System | 2 years |
| Escalation on Overall Plant Costs | 7% per year |
| Escalation on Cooling System Equipment and Material | 6% per year |
| Escalation on Cooling System Labor | 8% per year |
| Escalation for Fuel Cost Levelization | 4% per year |
| Interest Rate | 10% per year |
| Base Year Cost Data | 1974 |

# CHAPTER 5

## RESULTS OF OPTIMIZATION FOR WET/DRY TOWERS AT THE HYPOTHETICAL SITE MIDDLETOWN, U.S.A.

### 5.1 INTRODUCTION

The scope of the wet/dry study includes an extensive evaluation at a base site (Middletown, U.S.A.), and two additional sites. The Middletown site is the ERDA hypothetical site defined in Reference 19 as a typical power plant site in the U.S. The pertinent site data used in the analysis are the ambient temperatures (Figure 5.3) and the site elevation (sea level). The meteorological conditions for Middletown are modeled after those of Boston, Mass. (20).

The evaluation at the Middletown Site includes:

1. <u>Engineering and Economic Evaluation of Wet/Dry Cooling Systems</u>

   It is a detailed engineering study of the effect that variations in the basic design and operating parameters of wet/dry cooling have on their economics. The study includes the three basic systems described in Chapter 3.

2. <u>Economic Sensitivity Analysis</u>

   It is a detailed economic study of the effect that variations in capital cost escalation, fuel charges, replacement capacity charges, and fixed charge rate will have on the optimum design selection and economics of wet/dry cooling.

The Engineering and Economic Evaluation is described in Chapter 6. The economic sensitivity results are described in Chapter 8.

The engineering study indicates that in general the economics of the three systems evaluated are comparable, although there is a small economic advantage of the series system over the parallel. In addition, there appears to be a systematic advantage of natural draft systems over the mechanical systems. After discussions with vendors and utilities, and after consideration of the lack of design and operational experience of natural draft dry towers in the United States, the mechanical series wet/dry tower was selected for more detailed evaluation.

The major results of the mechanical series wet/dry cooling systems designed for Middletown are summarized in this chapter. The costs obtained are based on the economic factors given in Table 4.1. The purpose of the presentation of this information is to provide typical results of wet/dry systems designed for water conservation. The results include a direct comparison of the wet/dry option with wet and dry cooling tower systems.

## 5.2 OPTIMIZED WET/DRY TOWERS FOR MIDDLETOWN SITE

The results for the optimized wet/dry tower systems for various water make-up requirements and reference tower systems are shown in Tables 5.1 through 5.3. The make-up requirement is expressed as a percentage of the make-up required by an optimized wet tower system.

Table 5.1 shows a summary of the major design data for the optimized cooling systems. Included in this table are the tower size and operating mode, the maximum operating back pressure, the gross generator output, the plant heat load at the maximum back pressure, the heat load distribution between the wet and dry towers at the maximum back pressure, and the annual water make-up for the tower systems. All of the wet/dry systems had the minimum cost when designed to operate in Mode 1.

Table 5.1 indicates that dry cooling tower systems of manageable size can be designed for utility applications by shaving the heat load with evaporative helper towers. The dry surface needed for the wet/dry options are comparable to or less than that required for the dry cooling system using a hypothetical high back pressure turbine. The surface for the dry system using a conventional turbine, however, is over twice the size of that required by the dry system using a high back pressure turbine. The data in Table 5.1 also show that the capacity deficit (147.3 MWe) incurred on the dry system using the high back pressure turbine can be reduced more than 100 MWe even with the wet/dry system requiring one percent make-up. Recall that all wet/dry systems are designed for conventional turbines.

Table 5.2 summarizes the capital costs and the penalty costs for the tower systems described in Table 5.1. As previously discussed, the operating penalties are capitalized over the 40 year lifetime of the plant. The total capital cost and the total capacity penalty are both capital dollars which must be expended by the utility owner at the beginning of the plant lifetime. As expected, the sum of the total capital cost and capacity penalty cost is highest for the dry tower system using a low back pressure turbine and the lowest for the wet system using the same turbine.

For the wet/dry systems, the costs range between the dry and the wet systems; the costs of the wet/dry systems decrease monotonically as the make-up water requirement is allowed to increase (see Figure 5.1). The total evaluated costs for all of the wet/dry systems are significantly lower than that for the dry systems, but significantly higher than the wet systems. As shown in Figure 5.1 and in Table 5.2, the total evaluated cost for the 1 percent wet/dry system is over 21 percent lower than the cost of the two dry systems; the total evaluated cost for the 40 percent wet/dry system is 70 percent higher than the cost of the wet system. Further comparisons of the wet and wet/dry systems which include the impact of make-up water supply cost will be described in Section 5.5.

The major capital and penalty cost elements are itemized in Table 5.3. Further design and cost details are included in Appendix E. The data indicate that the tower cost of each of the wet/dry systems constitutes approximately 50 percent of the capital cost of the cooling system and approximately 30 percent of the total evaluated cost.

## 5.3 PLANT PERFORMANCE

An example of the plant performance for a wet/dry system is shown in Figure 5.2 for a 10 percent make-up wet/dry tower system operating in the S1 mode. The performance shown includes the gross and net generator output, turbine back pressure, and make-up flow rate over an annual cycle.

When the wet and dry towers are operating together, the turbine back pressure is maintained near its design value of 4.5 in-HgA (114.3 mm-HgA), and the gross plant output (MWe) is at its lowest value. The wet tower modules are gradually taken out of service as the ambient temperature decreases. The dry tower takes over completely when it is able to carry the plant heat load while maintaining the turbine back pressure below the design value. At this point, all the wet towers are out of service and no water is required as shown by the make-up curve. When the dry tower operates alone, in response to the falling dry bulb temperature, the efficiency of the dry tower system increases, resulting in lower back pressure and greater gross and net generator outputs. The gross plant output reflects the back pressure variation as described above.

A comparison of the gross generator output for different percentage make-up wet/dry and reference systems is shown in Figure 5.3. The corresponding ambient temperatures at which the cooling system and plant performance were determined are shown superimposed on the figure.

The constant gross generator output for the wet/dry systems reflects back pressure differences of 0.5 in (12.7 mm) of HgA and approximately 11 MWe difference in generator output. Although the lower fraction make-up systems suffer larger capacity reductions, operations of their larger dry systems result in shorter durations of combined wet and dry tower operation where the maximum capacity deficit occurs.

Integration of the capacity deficit over the annual cycle determines the amount of replacement energy required for the wet/dry and the reference systems. The amount of replacement energy is represented in Figure 5.3 by the area bound between the constant base output line and the gross output curve for each cooling system. The figure clearly shows the relative magnitude of the replacement energy needed by the wet/dry, wet and dry systems. It also shows that the higher percentage make-up wet/dry systems require more replacement energies than the lower percentage make-up systems. This is obvious between the 1 and 10 percent systems and also between the 30 and 40 percent systems. This situation occurs because the lower percentage make-up systems require a large number of dry cells to control water consumption. Operation of these large number of dry cells at low ambient temperatures allow these systems to attain lower back pressure than the controlled constant operating back pressure. Consequently, the plant operates at higher gross output during a part of the year, resulting in lower replacement energy requirement. The amounts of replacement energy required by different cooling systems are also reflected in the replacement energy penalty costs tabulated in Table 5.3.

A comparison of the net generator output for those systems represented in Figure 5.3 is shown in Figure 5.4. Examination of these curves shows that the total energy which must be replaced with reference to the fixed demand is essentially constant over the annual cycle and independent of the water consumption for all of the wet/dry systems designed. This information can be verified in Table 5.3 where the sum of the replacement energy and the auxiliary energy cost are approximately constant. It follows that the net available energy (MW-hrs), independent of the make-up requirement, is approximately constant for all of the mechanical series wet/dry systems operating in S1 mode. Thus, the cost for conserving water for the wet/dry systems is derived directly from the sum of the capital cost of the cooling system and the capital cost of the make-up capacity including the auxiliary power requirement.

## 5.4 WATER USAGE

One of the criteria used in the design of an optimum wet/dry tower is the annual make-up requirement. The annual make-up is determined as the summation of the water usage during each interval of an ambient temperature cycle.

Since most streams generally have a low stream flow in summer when the cooling tower make-up requirements are the highest, it is important to determine the water usage requirements on a monthly or a daily basis during the annual cycle.

Figure 5.5 shows the total amount of make-up required for each month during a typical annual cycle. Figure 5.6 shows the maximum make-up flow rate during each month. Although the annual percentage make-up is small, the maximum flow rate can be large. For example, even for the one percent make-up system, the maximum make-up flow rate is almost one third of that required by the wet system because the system requires about a third of the wet cells needed for the wet tower. Total monthly requirement, however, is less than ten percent of the wet system requirement. The information given in Figures 5.5 and 5.6 can be used to determine whether stream flow conditions match the make-up requirements, or to size the reservoir or impoundment necessary for station operation. An example of the use of these data is shown in Appendix I.

## 5.5 WATER COSTS

In this study, wet/dry tower systems were optimized for specific make-up water requirements. This method of approach was designed to allow the optimization to be independent of water supply cost. Since all of the systems designed for a specific make-up requirement require the same amount of water and have the same make-up supply penalty cost, any change in water supply cost will not affect the optimization of a wet/dry system requiring the specified make-up. The advantage of this method is that site specific water supply costs in excess of the base water costs can be determined for each make-up requirement, and can then be added directly to the total evaluated costs for the wet and wet/dry cooling systems for the purpose of economic comparison.

There are many factors which influence the water supply cost for specific sites; among them distance, terrain, elevation changes and legal requirements. The water supply costs should be developed during a preliminary engineering or site selection phase of an engineering program and added to total evaluated cost to compare the systems.

The impact of water supply cost on the economic comparison is demonstrated in Figure 5.7. Two different types of water cost analysis were prepared for Middletown. To address the general impact of water supply cost, uniform water costs were incrementally added to the base cost. The basic analysis was performed for water costs of \$0.27/1000 gal (\$0.07/$m^3$). This base cost was estimated on the basis of current utility practice for a plant sited adjacent to a river with fresh water make-up. For a general site where water must be purchased and extensively treated to prevent scaling or corrosion in cooling towers, this base cost can be regarded as representing the water purchase and treatment costs. The cost was increased to \$2/1000 gal (\$0.53/$m^3$) and then in \$2 (\$0.53) increments to \$8/1000 gal (\$2.12/$m^3$).

For study purposes, the general water cost results provide an indication of the approximate break-even water cost for wet/dry versus wet cooling (shown in Figure 5.7) as approximately \$4.50/1000 gal (\$1.19/$m^3$). This cost amounts to a water supply requirement \$100 million in excess of the total evaluated cost for the optimized evaporative cooling system using the base water cost.

For comparison with this general type analysis, a specific analysis for a hypothetical condition at the Middletown site was also prepared. The river which provides the make-up supply is assumed to be 29 miles(46.7 km) from the plant. In addition, the river has legal restrictions on water consumption which requires a major impoundment for the wet tower. The results of this analysis are shown superimposed on Figure 5.7. This figure shows that the lowest cost wet/dry system is the 40 percent make-up system, and it is 36 million dollars more expensive than the wet system. This cost difference is considerably smaller than the 69 million dollar difference obtained with the base water cost, but the wet system remains the economic choice over the wet/dry system. The summary and details of the analysis are included in Chapter 8 and Appendix I respectively.

These data indicate that a high water supply cost is required to make wet/dry cooling economically comparable to that of wet cooling. Water availability coupled with legal requirements or other environmental constraints will dictate whether wet/dry cooling should be used for nuclear power plants.

TABLE 5.1

MAJOR DESIGN DATA FOR THE OPTIMIZED COOLING TOWER SYSTEMS

SITE: MIDDLETOWN, U.S.A. BASE OUTPUT: 1094 MWe WET/DRY TYPE: MECHANICAL SERIES (S1)

| Item | Mech. Dry (H)* | Mech. Dry (L)† | Percentage Make-up Requirement Mechanical Series Wet/Dry | | | | | Mech. Wet |
|---|---|---|---|---|---|---|---|---|
| | | | 1% | 10% | 20% | 30% | 40% | |
| Number of Tower Cells, Wet Tower/Dry Tower | 0/156 | 0/338 | 13/192 | 19/136 | 26/114 | 27/90 | 30/79 | 33/0 |
| Mode of Wet/Dry Tower Operation | - | - | S1 | S1 | S1 | S1 | S1 | - |
| Maximum Operating Back Pressure $P_{max}$, in-HgA (mm-HgA) | 12.51 (317.8) | 5.06 (128.5) | 5.0 (127.0) | 4.5 (114.3) | 4.0 (101.6) | 4.0 (101.6) | 4.0 (101.6) | 3.90 (99.1) |
| Gross Plant Output at $P_{max}$, MWe | 946.7 | 1046.8 | 1048.4 | 1059.5 | 1069.9 | 1069.9 | 1069.9 | 1071.9 |
| Heat Load at $P_{max}$, $10^9$ Btu/hr ($10^{12}$ J/hr) | 7.60 (8.02) | 7.26 (7.66) | 7.25 (7.65) | 7.22 (7.61) | 7.18 (7.57) | 7.18 (7.57) | 7.18 (7.57) | 7.17 (7.57) |
| Heat Load Distribution at $P_{max}$, (Wet Tower/Dry Tower), % | 0.0/ 100.0 | 0.0/ 100.0 | 42.7/ 57.3 | 63.7/ 36.3 | 73.8/ 26.2 | 78.2/ 21.8 | 80.5/ 19.5 | 100.0/ 0.0 |
| Annual Make-up Water for Wet Towers, $10^8$ gal ($10^6$ $m^3$) | 0.0 (0.0) | 0.0 (0.0) | 0.435 (0.165) | 4.40 (1.66) | 8.45 (3.20) | 13.29 (5.03) | 16.35 (6.19) | 42.34 (16.06) |

* H-High Back Pressure Turbine
L-Conventional Low Back Pressure Turbine

TABLE 5.2

MAJOR COST SUMMARY FOR OPTIMIZED COOLING TOWER SYSTEMS ($\$10^6$)

SITE: MIDDLETOWN, U.S.A. PRICING YEAR: 1985 WET/DRY TYPE: MECHANICAL SERIES (S1)

| Item | Mech. Dry (H)* | Mech. Dry (L)† | Percentage Make-up Requirement Mechanical Series Wet/Dry | | | | | Mech. Wet |
|---|---|---|---|---|---|---|---|---|
| | | | 1% | 10% | 20% | 30% | 40% | |
| Total Capital Cost (Direct & Indirect Capital Costs) | 108.82 | 215.54 | 146.83 | 118.96 | 111.82 | 100.76 | 96.44 | 54.44 |
| Total Capacity Penalty (Capacity & Auxiliary Power) | 108.32 | 66.35 | 51.85 | 40.95 | 33.90 | 32.95 | 32.17 | 22.65 |
| Total Operating Penalty (Replacement & Auxiliary Energies, Make-up Water & Maintenance) | 80.16 | 43.89 | 35.15 | 35.99 | 35.45 | 37.99 | 38.23 | 21.01 |
| Total Evaluated Cost (Sum of Capital & Penalty Costs) | 297.30 | 325.78 | 233.83 | 195.90 | 181.17 | 171.70 | 166.84 | 98.10 |

* H-High Back Pressure Turbine

† L-Conventional Low Back Pressure Turbine

TABLE 5.3

MAJOR CAPITAL AND PENALTY COST COMPONENTS FOR OPTIMIZED COOLING TOWER SYSTEMS ($$10^6$)

SITE: MIDDLETOWN U.S.A. PRICING YEAR: 1985 WET/DRY TYPE: MECHANICAL SERIES (S1)

| | Mech. Dry (H)* | Mech. Dry (L)† | Percentage Make-up Requirement Mechanical Series Wet/Dry | | | | | Mech. Wet |
|---|---|---|---|---|---|---|---|---|
| | | | 1% | 10% | 20% | 30% | 40% | |
| Capital Cost: | | | | | | | | |
| Cooling Tower | 54.42 | 116.90 | 74.56 | 58.59 | 55.07 | 47.27 | 45.22 | 19.48 |
| Condenser | 15.20 | 20.88 | 15.98 | 14.11 | 13.64 | 13.62 | 13.25 | 13.61 |
| Circulating Water System | 10.02 | 17.92 | 14.74 | 13.01 | 12.23 | 12.35 | 11.77 | 8.22 |
| Electrical Equipment | 7.32 | 15.72 | 12.18 | 9.46 | 8.52 | 7.37 | 6.91 | 2.25 |
| Indirect Cost | 21.86 | 44.12 | 29.37 | 23.79 | 22.36 | 20.15 | 19.29 | 10.88 |
| Total Capital Cost | 108.82 | 215.54 | 146.83 | 118.96 | 111.82 | 100.76 | 96.44 | 54.44 |
| Penalty Cost: | | | | | | | | |
| Capacity | 88.97 | 28.33 | 27.36 | 20.72 | 14.46 | 14.46 | 14.44 | 13.27 |
| Auxiliary Power | 19.35 | 38.02 | 24.49 | 20.23 | 19.44 | 18.49 | 17.73 | 9.38 |
| Replacement Energy | 55.56 | 0.29 | 5.48 | 11.39 | 11.34 | 13.74 | 14.25 | 3.07 |
| Auxiliary Energy | 19.23 | 33.03 | 22.33 | 17.71 | 17.02 | 16.89 | 16.34 | 9.02 |
| Make-up Water | 0 | 0 | 0.06 | 0.65 | 1.25 | 1.97 | 2.42 | 6.28 |
| Cooling System Maintenance | 5.37 | 10.57 | 7.28 | 6.24 | 5.84 | 5.39 | 5.22 | 2.64 |
| Total Penalty | 188.48 | 110.24 | 87.01 | 76.94 | 69.35 | 70.94 | 70.40 | 43.66 |

H-High Back Pressure Turbine
L-Conventional Low Back Pressure Turbine

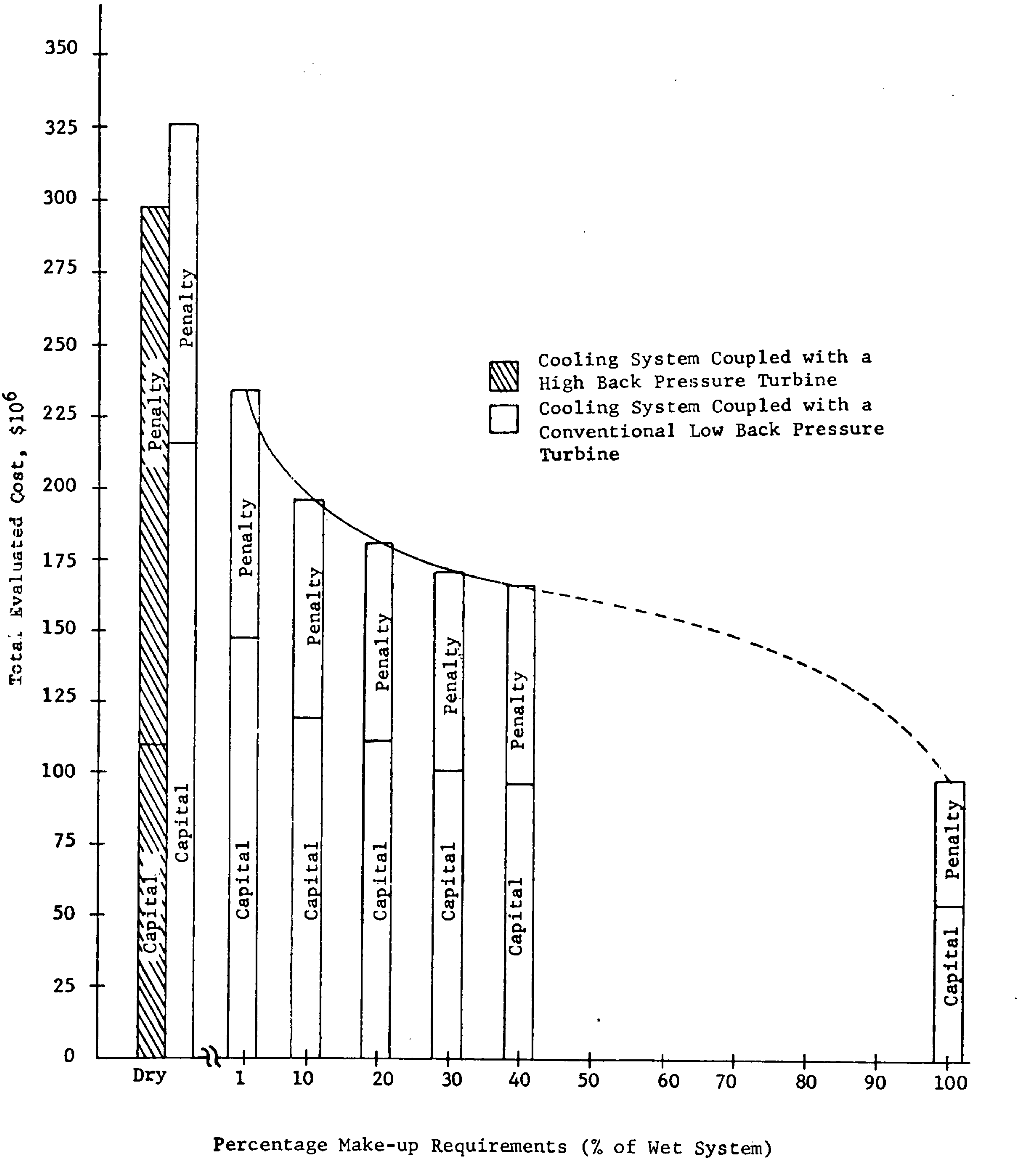



Figure 5.1 Total Evaluated Cost and the Penalty and Capital Components for the Optimized Systems (Middletown, Mechanical Series, S1 Mode, 1985)

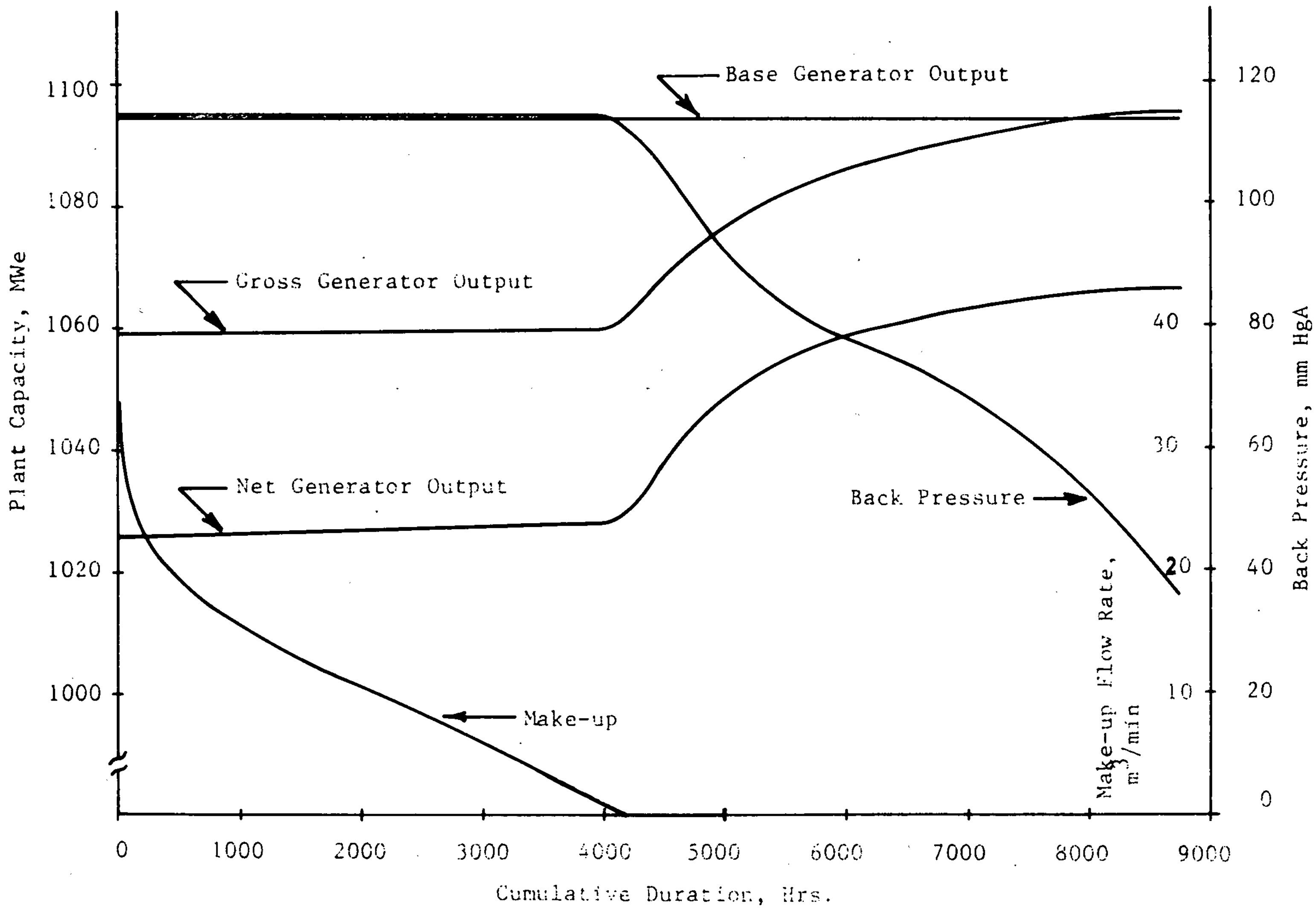



Figure 5.2 Performance Curves For a 10% Wet/Dry Cooling System
Middletown

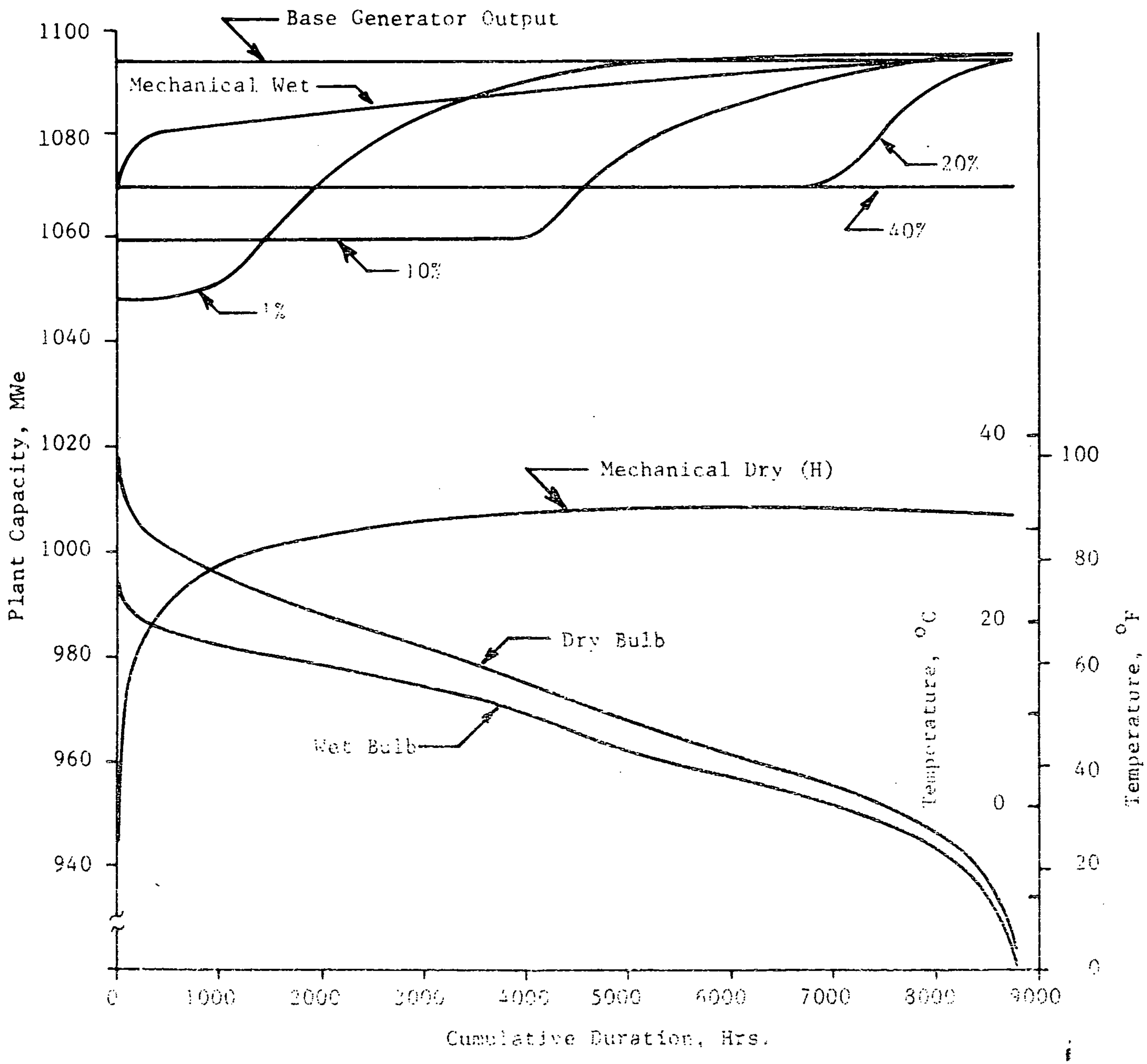



Figure 5.3 Gross Generator Output - Middletown

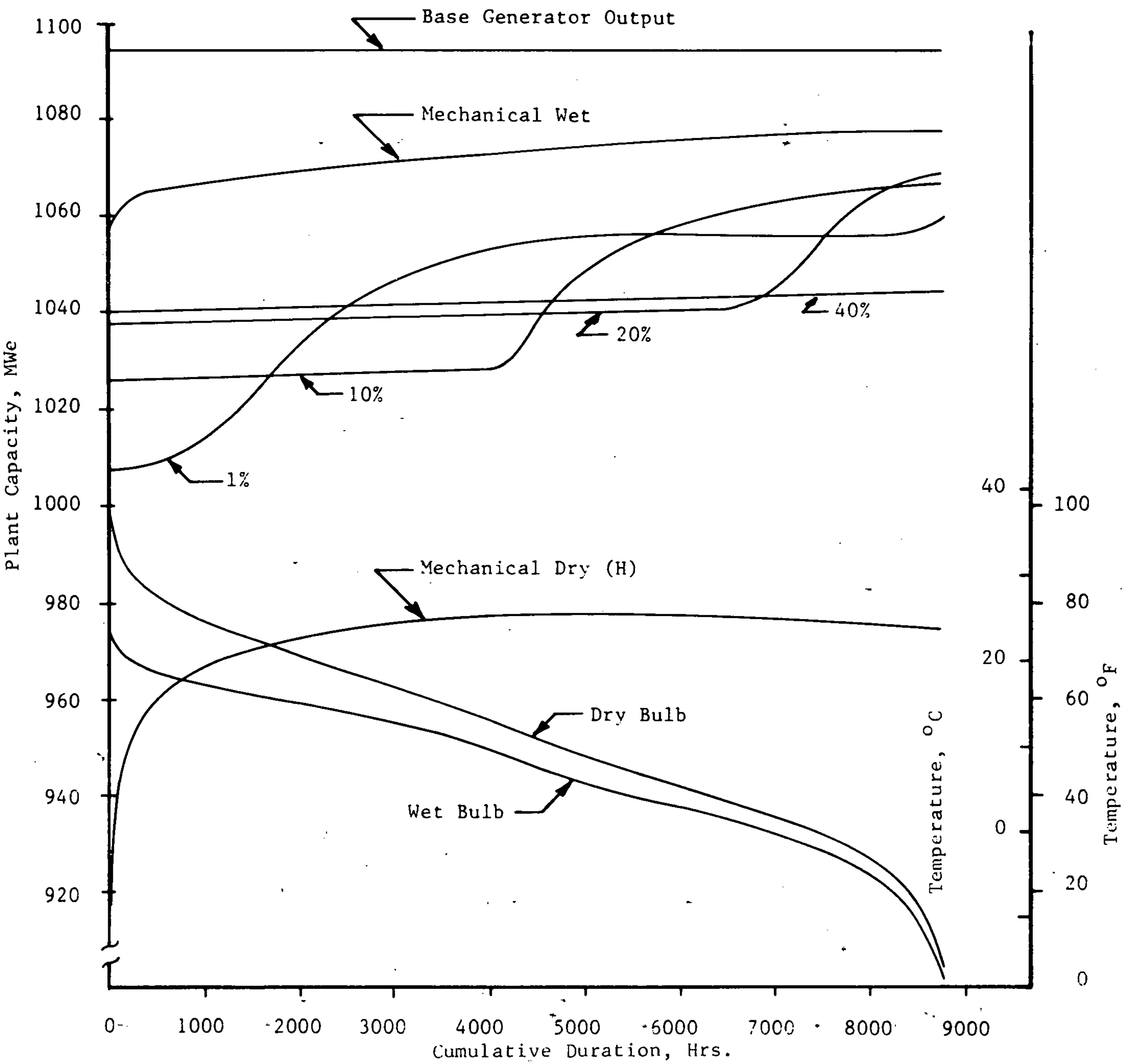



Figure 5.4 Net Generator Output - Middletown

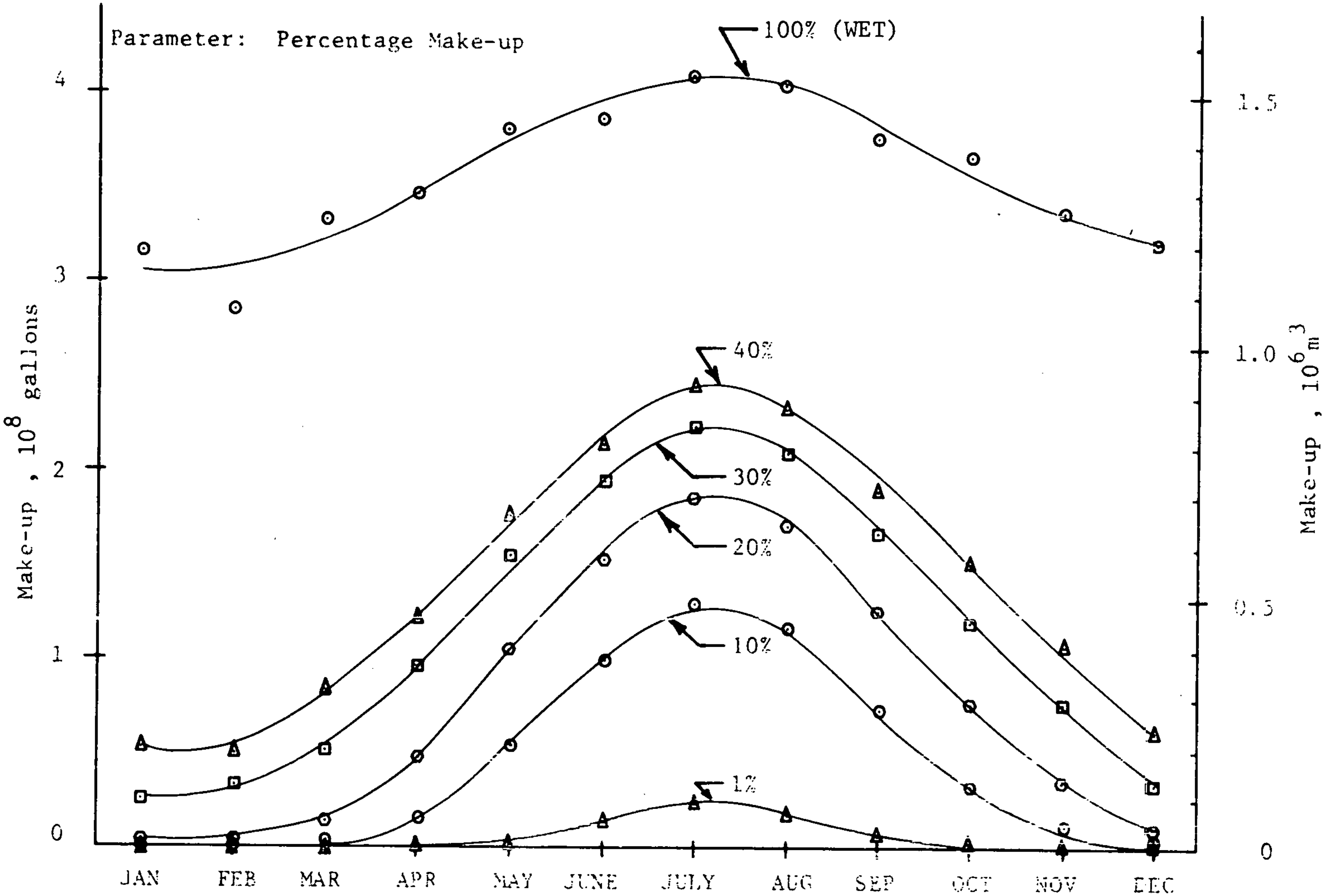



Figure 5.5 Total Make-up Requirement for Each Monthly Period
Middletown

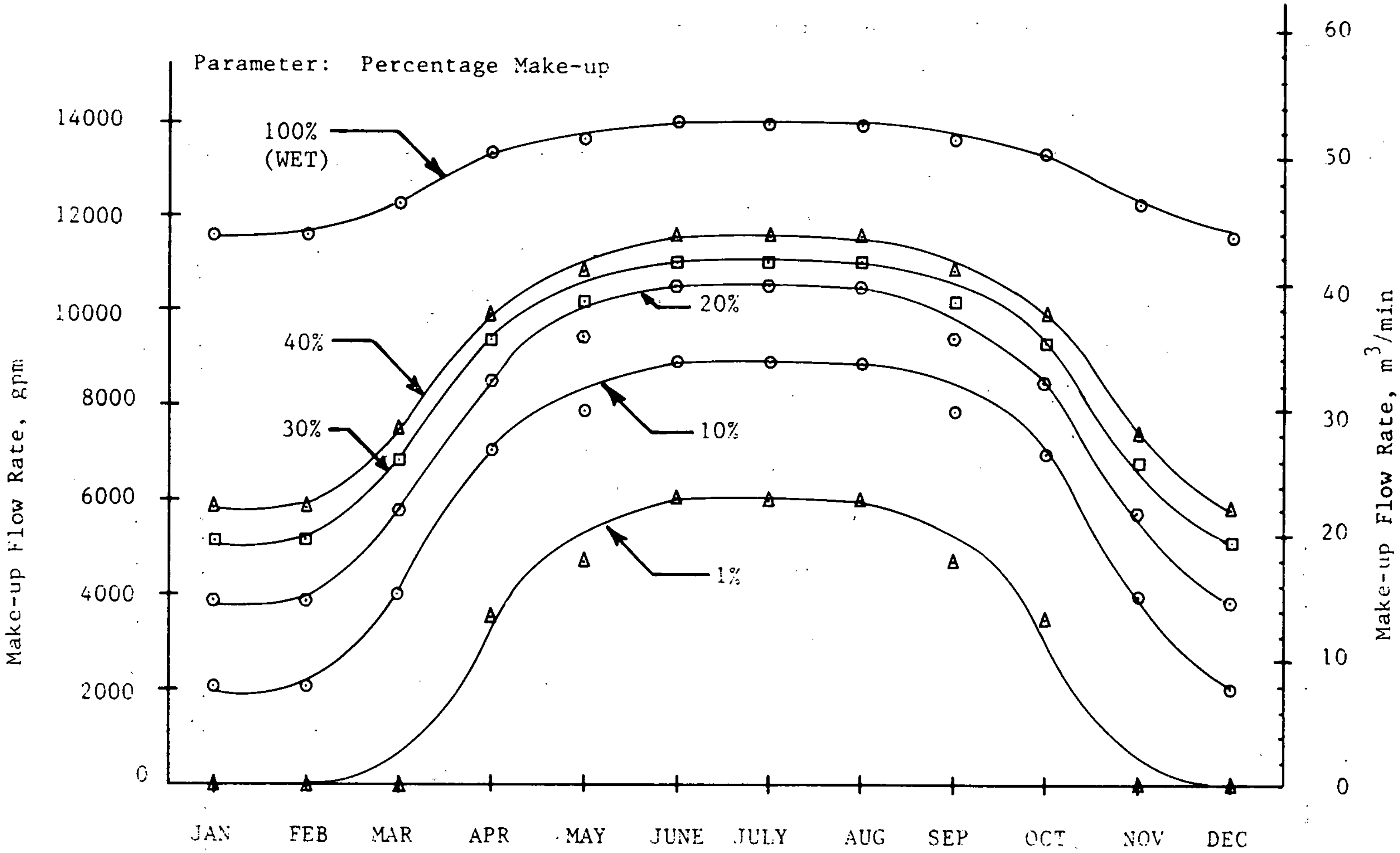



Figure 5.6 Maximum Make-up Flow Rate for Each Monthly Period Middletown

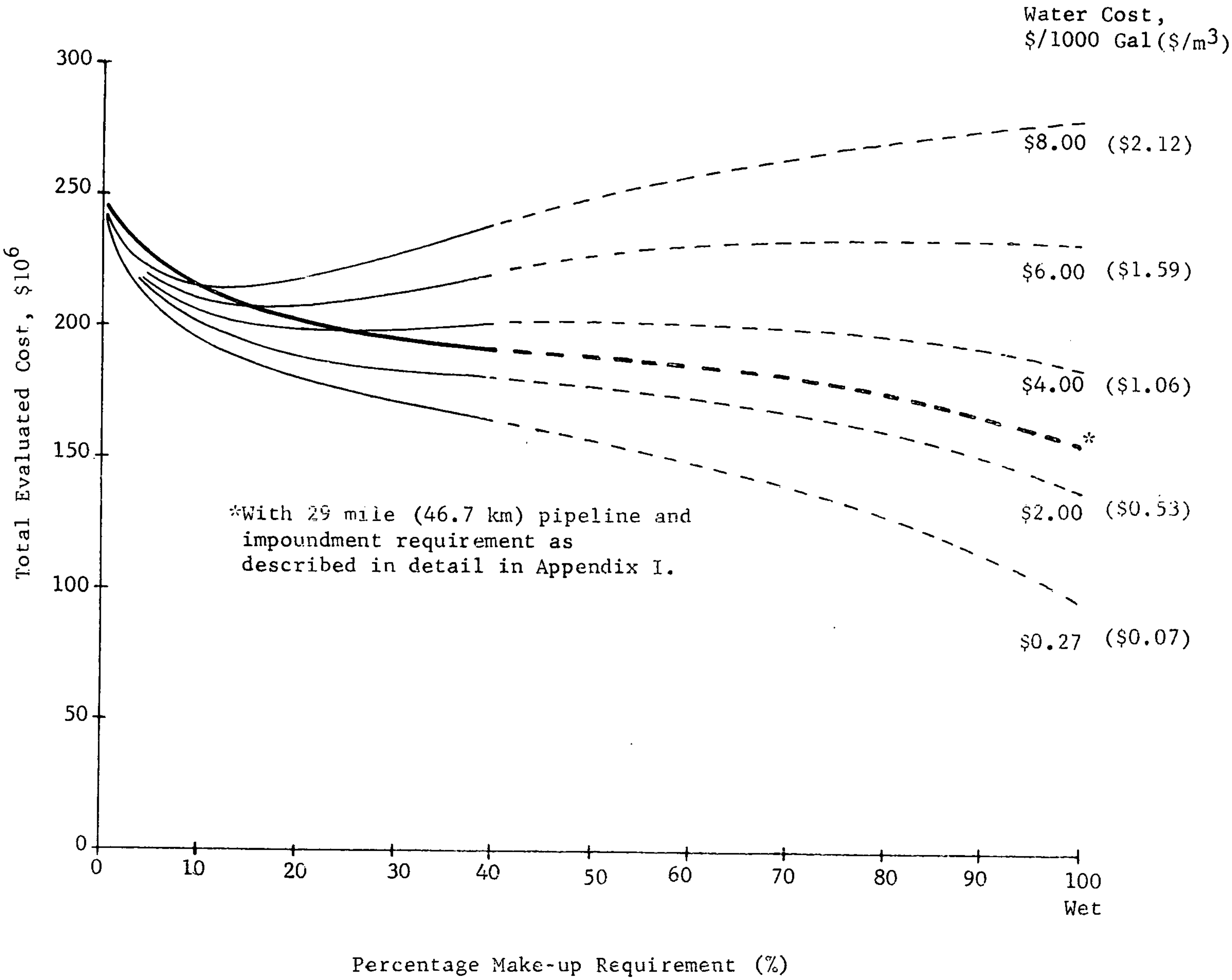



Figure 5.7 Impact of Water Cost on the Total Evaluated Cost of the Optimized Wet and Wet/Dry Systems (Middletown, Mechanical Series, S1 Mode, 1985)

# CHAPTER 6

# ENGINEERING AND ECONOMIC EVALUATION OF WET/DRY COOLING SYSTEMS FOR WATER CONSERVATION

## 6.1 INTRODUCTION

This chapter describes the engineering and economic evaluation of wet/dry cooling towers for water conservation. The major objectives of this evaluation are to determine the effect of the wet/dry tower system design parameters on the economics of wet/dry cooling and to compare the economics of the three types of wet/dry tower systems. In order to accomplish these objectives, a systematic study of each of the three systems was performed. The evaluation used Middletown site conditions and the base economics (Chapter 4).

Three wet/dry tower systems were evaluated: mechanical draft series wet/dry towers; mechanical draft parallel wet/dry towers; and natural draft series wet/dry towers. All three wet/dry towers are composed of physically separate wet and dry cooling towers. In addition, mechanical draft wet and dry tower systems were evaluated to serve as benchmarks. Natural draft dry cooling towers were included in the wet/dry combinations for comparative purposes to assess the impact of the elimination of the energy and power requirements of fans.

Two operational modes which govern the system operation were considered:

Mode 1: Wet cells are turned off sequentially to maintain a nominally constant back pressure until the weather conditions permit the dry tower to carry the entire heat load.

Mode 2: All of the wet cells operate until weather conditions permit the dry tower to carry the entire heat load.

## 6.2 DESIGN OF WET/DRY TOWER SYSTEMS

### 6.2.1 Design Criteria

The wet/dry tower systems were designed to meet the following criteria:

1) Conventional low back pressure turbines are to be used. Thus, the wet/dry towers are to be designed and operated at a turbine back pressure not to exceed the back pressure limit of conventional turbines. This back pressure limit ranges from 5 to 6 in-HgA (127 to 152.4 mm-HgA). The lower limit of 5 in-HgA (127 mm-HgA) was used in this study.

2) The dry tower is designed to carry the entire plant load at low ambient temperatures.

3) The wet tower is sized to supplement the dry cooling such that the turbine back pressure is equal to a specified design value at the maximum ambient temperature.

### 6.2.2 Design Parameters

In designing the separate wet and dry towers, the design parameters which are varied to obtain the optimum systems include the following:

1) Specified design turbine back pressure for sizing the wet helper tower.

2) Design ambient temperatures for sizing the dry tower.

3) Design condenser cooling range.

4) Design approach temperature or initial temperature difference for the dry tower.

5) Wet tower design approach temperature.

6) Mode of operation of the wet/dry tower.

The definitions of temperatures in condensers and cooling towers are illustrated in Figure 6.1.

### 6.2.3 Design Procedure

The procedure for sizing the tower system and calculating its performance at various ambient conditions during an annual cycle is as follows: the dry tower is sized at a sufficiently low ambient design temperature to handle the plant heat load. The other equipment sized at this design point are the condenser, and the circulating water pumps and pipelines. The performance of the cooling system is then evaluated at the highest ambient temperatures and the specified maximum turbine back pressure to determine the heat rejection capability of the dry tower at these conditions. The result is then used to determine the size of the wet helper tower, needed to supplement the dry tower.

The thermal performance of the wet/dry cooling tower system is then evaluated over the annual meteorological cycle. The annual cycle is divided into a series of time intervals; each has a constant ambient dry bulb temperature and a coincident ambient wet bulb temperature. For each interval, the gross turbine output, the pump and fan capacity and energy requirements, and the water consumption are evaluated. The performance information is used to calculate the penalties at each time interval. These penalties are then summed over the annual cycle and capitalized over the lifetime of the plant. The capitalized penalties are added to the capital cost of the cooling system to obtain the total evaluated cost.

By systematically varying the design parameters listed in 6.2.2, a series of wet/dry tower systems with various water consumption requirements are obtained. From all the wet/dry tower systems with a given water consumption requirement, the system with the minimum total evaluated cost is selected as the optimum system for the given water consumption.

## 6.3 METHOD OF OPTIMIZATION

The optimum design of a cooling system is obtained through a trade-off between capital cost and operating penalties. The procedure by which this optimum design is selected is described in this section.

### 6.3.1 Optimization of Reference Systems

Several series of wet and dry cooling systems were designed by varying the range and approach temperatures. For each system, the capital cost of the design was determined. Than, by evaluating the performance of this design throughout the year, and capitalizing these penalties over the lifetime of the plant, the operating penalties were assessed. The sum of the capital cost and the capitalized operating penalties is the total evaluated cost of the system. The system with the lowest total evaluated cost is selected as the optimum cooling system. The detailed procedure is explained below using the reference wet system as an example.

The trade-off between the capital cost and penalty cost for the reference wet tower system is shown in Figure 6.2. This figure shows that, for a constant approach, as the range increases, the capital cost decreases and the penalty cost increases. The decrease in capital cost results from the decrease in the size of the cooling system; the increase in penalty cost results from the decreased plant efficiency due to the reduced cooling system size. The economic trade-off is obtained by adding the capital and penalty costs to identify the cooling system with the minimum total evaluated cost for the specified approach temperature.

This procedure is performed for a series of approach temperatures as shown in Figure 6.3. The optimum economic trade-off is obtained by identifying the cooling system with the minimum total evaluated cost.

6.3.2 Optimization of Wet/Dry Tower Systems

It is unrealistic to optimize wet/dry towers solely on the basis of total evaluated cost as is the case for the wet or dry cooling systems. Therefore, the optimization has been performed for a series of wet/dry systems with specific make-up requirements.

By varying the design parameters listed in Section 6.2.2, wet/dry systems with specified make-up are sized; and, from these systems, the lowest total evaluated cost system is then selected as the optimized system for the given water consumption.

The optimization of wet/dry systems is illustrated by using a 10 percent make-up system as an example. Figure 6.4 shows the total evaluated cost of the wet/dry systems as a function of range for a series of specified turbine back pressures, all of the wet/dry systems are 10 percent make-up systems. From these data, the minimum total evaluated cost system for each specified back pressure is obtained. The results are plotted in Figure 6.5, from which the optimum selection of the 10 percent system is determined. The figure also shows the trade-offs of the capital cost and penalty cost of the wet/dry system.

### 6.3.3 Effect of Back Pressure on Optimization

Figure 6.4 and Figures 6.6 through 6.8 illustrate the effect of the specified design turbine back pressure on the selection of the optimum wet/dry tower system for various percentage make-up requirements. These figures indicate that the optimization is strongly affected by the design turbine back pressure especially for the low make-up fractions. The final optimum selection for each percentage make-up wet/dry system is illustrated in Figure 6.9. In this figure, the minimum total evaluated cost for each specified back pressure is plotted as a function of the back pressure. This figure indicates that the wet/dry cooling systems designed for different make-up requirements optimize at different design turbine back pressures. The lower percentage make-up system optimizes at high back pressure, and vice versa.

Turbine manufacturers currently warrant conventional steam turbines for operation at 5 to 6 in-HgA (127 to 152.4 mm-HgA). For this reason, the maximum design back pressure used for the wet/dry systems was conservatively assumed to be 5 in-HgA (127 mm-HgA).

To investigate whether this lower limit constrains the optimum selection of wet/dry tower systems, data were generated for 5.4 in-HgA (137.2 mm-HgA) for the wet/dry systems of 1 percent and 5 percent make-up requirements. The results are presented in Figures 6.6, 6.7 and 6.9 which were discussed above. Figure 6.9 shows that the 5 percent system optimizes at the 5 in-HgA (127 mm-HgA) limit. Since the trend is that the optimum back pressure decreases as the percentage make-up increases, it follows that the 10 percent and higher make-up systems reported are not affected by the back pressure constraint. Figure 6.9 also shows that the 1 percent make-up system, instead of optimizing at 5 in-HgA (127 mm-HgA) as reported, actually optimizes at about 5.4 in-HgA (137.2 mm-HgA). The difference in total evaluated cost, however, between the true optimum and the optimum obtained under the 5 in-HgA (127 mm-HgA) back pressure constraint is minimal. Therefore, the maximum back pressure limit of 5 in-HgA (127 mm-HgA) used in this study is justified.

## 6.4 RESULTS OF THE OPTIMIZATION ANALYSIS

### 6.4.1 Optimization of Mechanical Series Wet/Dry Tower Systems

An optimization was performed for the mechanical series wet/dry tower systems operating in both the S1 and S2 modes. For each of the operational modes, the optimized systems have been obtained for a series of specific make-up water requirements in increments of 5 percent. Comparison was made between the two modes to select final optimized systems.

Figure 6.10 shows the total evaluated cost versus percentage make-up for wet/dry systems operating in the S1 mode optimized at constant specified back pressures. Each constant back pressure curve is obtained by plotting the minimum total evaluated cost of different percentage make-up systems optimized at that back pressure. Figure 6.11 shows similar information for systems operating in Mode S2. Comparison of these two figures shows a fundamental difference. Operating in Mode S1, the optimum design back pressure changes as the percentage make-up requirement changes. For systems operating in Mode S2, however, the minimum cost system always occurs at the maximum specified design back pressure (5 in-HgA (127 mm-HgA)).

The summary results of the design, cost and penalty of the optimized system for the S1 mode are given in Chapter 5. The summary results of design, cost and penalty of the optimized systems for the S2 mode are given in Tables 6.1, 6.2 and 6.3. Detailed results are given in Appendix E.

Comparisons between the tabulated results for the S2 mode and the corresponding results for the S1 mode (Chapter 5) indicate for the same make-up percentage: (1) the system optimized for the S1 mode requires more dry cells and less wet cells than that for the S2 mode. However, the capital costs are essentially the same for the two modes. (2) The optimum systems designed for the S1 mode have consistently lower capacity penalty cost, but higher energy cost.

A graphical comparison of the total evaluated costs of the optimized systems for the S1 and S2 modes are given in Figure 6.12. The figure shows that the costs of the wet/dry systems designed to operate in the S1 mode are consistently less expensive than those designed to operate in the S2 mode. Therefore, the optimized systems presented in Chapter 5 for the mechanical series are all designed to operate in the S1 mode.

### 6.4.2 Mechanical Parallel Wet/Dry Cooling Systems

The system operational modes are analogous to the operational modes of the series-connected wet/dry system. Initial calculations indicated that the results of the model operation were also analogous, with the P2 mode providing more expensive systems than P1 at the same make-up percentages. Consequently, detailed calculations were limited to P1 operation.

A summary of the data for the optimized systems is given in Tables 6.4 through 6.6. A direct comparison of the capital and penalty costs for the series and parallel systems is given in Figure 6.13.

The comparison shows that the parallel systems are consistently more expensive than the corresponding series systems. For systems with percentage make-up less than 20 percent the capital costs of the two types of systems are approximately equal with the penalty costs accounting for most of the difference in the total. For systems greater than 20 percent the cost disadvantage of the parallel system is primarily in the capital cost.

6.4.3 Natural Series Wet/Dry Cooling Systems

In comparison with mechanical draft towers, the capital cost of the natural draft cooling towers designed for the same heat rejection capability can be more expensive than the mechanical draft because of the costs associated with the massive concrete shell. The natural draft system can be less expensive in terms of total evaluated cost because of the elimination of both capacity and energy penalties for the cooling tower fans and a reduction in electrical equipment costs. To determine if there is an economic advantage available with the use of natural draft dry towers, an evaluation of the natural series wet/dry cooling system was performed.

A summary of the data for the optimized systems is given in Tables 6.7 through 6.9. A direct comparison of capital penalty and total evaluated costs for the mechanical series and natural series systems is given in Figure 6.14. The comparison of total evaluated costs demonstrates a systematic economic advantage of natural over mechanical series systems. This advantage increases as the make-up requirement increases.

This comparison clearly shows the trade-off of capital and auxiliary penalty costs between the two types of systems. For the one percent make-up system, the auxiliary penalty advantage of the natural draft system is practically offset by the capital cost of the tower, and the overall advantage of the natural draft system is small. For the 10 to 40 percent systems, the capital cost disadvantage of the natural draft tower system becomes much smaller, and the economic advantage of the small auxiliary power requirement of the natural draft system provides a significant overall advantage. At forty percent almost the entire economic advantage is derived from the auxiliary penalty cost.

### 6.4.4 Comparison of the Three Types of Wet/Dry Cooling Systems

The overall comparison of the total evaluated cost of the three types of wet/dry tower systems is shown in Figure 6.15. This comparison is included to better portray the relative economic advantages of the three systems. The natural draft series is shown to be economically superior.

In discussions with the cooling tower manufacturers, it was determined that none of the manufacturers are trying to sell natural draft dry cooling towers in the United States, although they would quote them if a utility requested, and build them if authorized. Limited economic and performance data are available from the manufacturers for natural draft dry towers. For this reason, there is some uncertainty associated with the economics and performance values developed.

The major advantage of the mechanical draft system is its engineering and operational flexibility. The modules are small, easily isolated for maintenance and repair. The operation can be reasonably well predicted since

:he airflow is controlled.

For the above reasons, the mechanical series system was selected for the site studies and for the economic sensitivity analysis.

## 6.5 ALTERNATE DRY COOLING TOWER MODULE DESIGN

Alternate dry tower module designs can influence both the capital cost and the total operating penalties of dry and wet/dry cooling systems. All analyses reported in this study used a pre-designed module described in Appendix C. The modules are characterized by number of rows and passes, diameter and length of tube, number of fins per inch and fin height. Any or all of these parameters can be changed to provide a broad spectrum of different modules. Most changes require new quotations on cost from manufacturers.

A brief evaluation of the impact of module design change on the distribution of costs as well as the total evaluated cost was prepared for a mechanical draft dry cooling tower. The results of this evaluation are shown in Table 6.10. All evaluations used the same ITD, and a constant range and cold water temperature.

This evaluation indicates that although some trade-off between penalties and capital cost occurs; except for several "poor" designs, the total evaluated costs are within a few percent of each other. The module used for this analysis is indicated by the arrow in the table.

For variation in ITD, range or cold water temperature, it is possible that other small variation in total evaluated cost may take place. However, for this engineering assessment, these results are deemed adequate to justify the selection of the module design used for this study.

TABLE 6.1

MAJOR DESIGN DATA FOR THE OPTIMIZED COOLING TOWER SYSTEMS

SITE: MIDDLETOWN, U.S.A. BASE OUTPUT: 1094 MWe WET/DRY TYPE: MECHANICAL SERIES (S2)

| Item | Mech. Dry (H)* | Mech. Dry (L)† | Percentage Make-up Requirement Mechanical Series Wet/Dry | | | Mech. Wet |
|---|---|---|---|---|---|---|
| | | | 20% | 30% | 40% | |
| Number of Tower Cells, Wet Tower/Dry Tower | ** | ** | 18/125 | 19/104 | 20/95 | ** |
| Mode of Wet/Dry Tower Operation | | | S2 | S2 | S2 | |
| Maximum Operating Back Pressure $P_{max}$, in-HgA (mm-HgA) | | | 5.00 (127.0) | 5.00 (127.0) | 5.00 (127.0) | |
| Gross Plant Output at $P_{max}$, MWe | | | 1048.4 | 1049.0 | 1049.0 | |
| Heat Load at $P_{max}$, $10^9$ Btu/hr ($10^{12}$ J/hr) | | | 7.25 (7.65) | 7.25 (7.65) | 7.25 (7.65) | |
| Heat Load Distribution at $P_{max}$, (Wet Tower/Dry Tower), % | | | 61.2/ 38.8 | 67.3/ 32.7 | 69.8/ 30.2 | |
| Annual Make-up Water for Wet Towers, $10^8$ gal ($10^6$ $m^3$) | | | 8.41 (3.18) | 12.9 (4.88) | 16.7 (6.32) | |

* H-High Back Pressure Turbine

† L-Conventional Low Back Pressure Turbine

** Given in Table 5.1

TABLE 6.2

MAJOR COST SUMMARY FOR OPTIMIZED COOLING TOWER SYSTEMS ($\$10^6$)

SITE: MIDDLETOWN, U.S.A. PRICING YEAR: 1985 WET/DRY TYPE: MECHANICAL SERIES (S2)

| Item | Mech. Dry (H)* | Mech. Dry (L)† | Percentage Make-up Requirement Mechanical Series Wet/Dry | | | Mech. Wet |
|---|---|---|---|---|---|---|
| | | | 20% | 30% | 40% | |
| Total Capital Cost (Direct & Indirect Capital Costs) | ** | ** | 111.38 | 99.42 | 95.25 | ** |
| Total Capacity Penalty (Capacity & Auxiliary Power) | | | 46.69 | 45.11 | 44.43 | |
| Total Operating Penalty (Replacement & Auxiliary Energies, Make-up Water & Maintenance) | | | 30.57 | 30.92 | 28.60 | |
| Total Evaluated Cost (Sum of Capital & Penalty Costs) | | | 188.64 | 175.45 | 168.28 | |

* H-High Back Pressure Turbine

† L-Conventional Low Back Pressure Turbine

** Given in Table 5.2

TABLE 6.3

MAJOR CAPITAL AND PENALTY COST COMPONENTS FOR OPTIMIZED COOLING TOWER SYSTEMS ($$10^6$)

SITE: MIDDLETOWN, U.S.A. PRICING YEAR: 1985 WET/DRY TYPE: MECHANICAL SERIES (S2)

| | Mech. Dry (H)* | Mech. Dry (L)† | Percentage Make-up Requirement Mechanical Series Wet/Dry | | | Mech. Wet |
|---|---|---|---|---|---|---|
| | | | 20% | 30% | 40% | |
| Capital Cost: | ** | ** | | | | ** |
| Cooling Tower | | | 55.21 | 47.45 | 44.89 | |
| Condenser | | | 13.40 | 13.18 | 12.84 | |
| Circulating Water System | | | 11.72 | 11.29 | 11.38 | |
| Electrical Equipment | | | 8.77 | 7.62 | 7.09 | |
| Indirect Cost | | | 22.28 | 19.88 | 19.05 | |
| Total Capital Cost | | | 111.38 | 99.42 | 95.25 | |
| Penalty Cost: | | | | | | |
| Capacity | | | 27.38 | 26.99 | 27.03 | |
| Auxiliary Power | | | 19.31 | 18.12 | 17.40 | |
| Replacement Energy | | | 6.90 | 7.57 | 4.77 | |
| Auxiliary Energy | | | 16.73 | 16.18 | 16.23 | |
| Make-up Water | | | 1.23 | 1.91 | 2.48 | |
| Cooling System Maintenance | | | 5.71 | 5.26 | 5.12 | |
| Total Penalty | | | 77.26 | 76.03 | 73.03 | |

* H-High Back Pressure Turbine

† L-Conventional Low Back Pressur Turbine

** Given in Table 5.3

TABLE 6.4

MAJOR DESIGN DATA FOR THE OPTIMIZED COOLING TOWER SYSTEMS

SITE: MIDDLETOWN, U.S.A. BASE OUTPUT: 1094 MWe WET/DRY TYPE: MECHANICAL PARALLEL

| Item | Mech. Dry (H)* | Mech. Dry (L)† | Percentage Make-up Requirement Mechanical Parallel Wet/Dry | | | | | Mech. Wet |
|---|---|---|---|---|---|---|---|---|
| | | | 1% | 10% | 20% | 30% | 40% | |
| Number of Tower Cells, Wet Tower/Dry Tower | ** | ** | 12/197 | 18/136 | 21/110 | 28/97 | 36/81 | ** |
| Mode of Wet/Dry Tower Operation | | | P1 | P1 | P1 | P1 | P1 | |
| Maximum Operating Back Pressure $P_{max}$, in-HgA (mm-HgA) | | | 5.0 (127.0) | 5.0 (127.0) | 4.5 (114.3) | 4.0 (101.6) | 4.0 (101.6) | |
| Gross Plant Output at $P_{max}$, MWe | | | 1048.4 | 1048.4 | 1059.5 | 1069.9 | 1069.9 | |
| Heat Load at $P_{max}$, $10^9$ Btu/hr ($10^{12}$ J/hr) | | | 7.25 (7.65) | 7.25 (7.65) | 7.21 (7.61) | 7.18 (7.57) | 7.18 (7.57) | |
| Heat Load Distribution at $P_{max}$, (Wet Tower/Dry Tower), % | | | 47.7/ 52.3 | 71.6/ 28.4 | 80.1/ 19.9 | 87.9/ 12.1 | 89.8/ 10.2 | |
| Annual Make-up Water for Wet Towers, $10^8$ gal ($10^6$ $m^3$) | | | 0.374 (0.141) | 4.08 (1.55) | 8.34 (3.16) | 12.8 (4.85) | 17.4 (6.60) | |

** Given in Table 5.1

* H-High Back Pressure Turbine

† L-Conventional Low Back Pressure Turbine

TABLE 6.5

MAJOR COST SUMMARY FOR OPTIMIZED COOLING TOWER SYSTEMS ($\$10^6$)

SITE: MIDDLETOWN, U.S.A. PRICING YEAR: 1985 WET/DRY TYPE: MECHANICAL PARALLEL

| Item | Mech. Dry (H)* | Mech. Dry (L)† | Percentage Make-up Requirement Mechanical Parallel Wet/Dry | | | | | Mech. Wet |
|---|---|---|---|---|---|---|---|---|
| | | | 1% | 10% | 20% | 30% | 40% | |
| Total Capital Cost (Direct & Indirect Capital Costs) | ** | ** | 148.57 | 117.20 | 108.99 | 109.56 | 106.70 | ** |
| Total Capacity Penalty (Capacity & Auxiliary Power) | | | 51.74 | 46.31 | 39.52 | 33.72 | 32.40 | |
| Total Operating Penalty (Replacement & Auxiliary Energies, Make-up Water & Maintenance) | | | 35.36 | 38.09 | 39.02 | 37.24 | 38.09 | |
| Total Evaluated Cost (Sum of Capital & Penalty Costs) | | | 235.67 | 201.60 | 187.53 | 180.52 | 177.19 | |

** Given in Table 5.2

* H-High Back Pressure Turbine

† L-Conventional Low Back Pressure Turbine

TABLE 6.6

MAJOR CAPITAL AND PENALTY COST COMPONENTS FOR OPTIMIZED COOLING TOWER SYSTEMS ($$10^6$)

SITE: MIDDLETOWN, U.S.A. PRICING YEAR: 1985 WET/DRY TYPE: MECHANICAL PARALLEL

| | Mech. Dry (H)* | Mech. Dry (L)† | Percentage Make-up Requirement Mechanical Parallel Wet/Dry | | | | | Mech. Wet |
|---|---|---|---|---|---|---|---|---|
| | | | 1% | 10% | 20% | 30% | 40% | |
| Capital Cost: | ** | ** | | | | | | ** |
| Cooling Tower | | | 75.76 | 58.03 | 50.69 | 50.33 | 49.49 | |
| Condenser | | | 15.98 | 13.61 | 14.10 | 14.20 | 13.34 | |
| Circulating Water System | | | 14.59 | 12.65 | 13.92 | 14.85 | 14.73 | |
| Electrical Equipment | | | 12.53 | 9.47 | 9.48 | 8.27 | 7.80 | |
| Indirect Cost | | | 29.71 | 23.44 | 21.80 | 21.91 | 21.34 | |
| Total Capital Cost | | | 148.57 | 117.20 | 108.99 | 109.56 | 106.70 | |
| Penalty Cost: | | | | | | | | |
| Capacity | | | 27.36 | 27.36 | 20.72 | 14.44 | 14.44 | |
| Auxiliary Power | | | 24.38 | 18.95 | 18.80 | 19.28 | 17.96 | |
| Replacement Energy | | | 5.08 | 14.74 | 15.77 | 13.08 | 14.27 | |
| Auxiliary Energy | | | 22.62 | 16.35 | 15.70 | 15.64 | 14.44 | |
| Make-up Water | | | .06 | .60 | 1.24 | 1.90 | 2.59 | |
| Cooling System Maintenance | | | 7.60 | 6.40 | 6.31 | 6.62 | 6.79 | |
| Total Penalty | | | 87.10 | 84.40 | 78.54 | 70.96 | 70.49 | |

* H-High Back Pressure Turbine

† L-Conventional Low Back Pressure Turbine

** Given in Table 5.3

TABLE 6.7

MAJOR DESIGN DATA FOR THE OPTIMIZED COOLING TOWER SYSTEMS

SITE: MIDDLETOWN, U.S.A. BASE OUTPUT: 1094 MWe WET/DRY TYPE: NATURAL SERIES

| Item | Mech. Dry (H)* | Mech. Dry (L)† | Percentage Make-up Requirement Natural Series Wet/Dry | | | | | Mech. Wet |
|---|---|---|---|---|---|---|---|---|
| | | | 1% | 10% | 20% | 30% | 40% | |
| Number of Wet Tower Cells | ** | ** | 14 | 19 | 25 | 26 | 26 | ** |
| Number of Dry Towers | | | 3 | 2 | 2 | 1 | 1 | |
| Number of Heat Exchangers per Tower | | | 258 | 232 | 216 | 304 | 264 | |
| Diameter/Height, ft (m) | | | 424/460 (129/140) | 381/405 (116/123) | 355/378 (108/115) | 499/479 (152/146) | 434/396 (132/120) | |
| Maximum Operating Back Pressure $P_{max}$, in-HgA (mm-HgA) | | | 5.0 (127.0) | 5.0 (127.0) | 4.0 (101.6) | 4.0 (101.6) | 4.0 (101.6) | |
| Gross Plant Output at $P_{max}$, MWe | | | 1048.4 | 1048.4 | 1069.9 | 1069.9 | 1069.9 | |
| Heat Load at $P_{max}$, $10^9$ Btu/hr ($10^{12}$ J/hr) | | | 7.25 (7.65) | 7.25 (7.65) | 7.18 (7.57) | 7.18 (7.57) | 7.18 (7.57) | |
| Heat Load Distribution at $P_{max}$, (Wet Tower/Dry Tower), % | | | 49.1/ 50.9 | 69.7/ 30.3 | 82.1/ 17.9 | 85.4/ 14.6 | 88.1/ 11.9 | |
| Annual Make-up Water for Wet Towers, $10^8$ gal ($10^6$ $m^3$) | | | 0.413 (0.156) | 4.49 (1.70) | 8.67 (3.28) | 12.9 (4.88) | 17.1 (6.47) | |

** Given in Table 5.1

* H-High Back Pressure Turbine

† L-Conventional Low Back Pressure Turbine

TABLE 6.8

MAJOR COST SUMMARY FOR OPTIMIZED COOLING TOWER SYSTEMS ($\$10^6$)

SITE: MIDDLETOWN, U.S.A. PRICING YEAR: 1985 WET/DRY TYPE: NATURAL SERIES

| Item | Mech. Dry (H)* | Mech. Dry (L)† | Percentage Make-up Requirement Natural Series Wet/Dry | | | | | Mech. Wet |
|---|---|---|---|---|---|---|---|---|
| | | | 1% | 10% | 20% | 30% | 40% | |
| Total Capital Cost (Direct & Indirect Capital Costs) | ** | ** | 177.15 | 122.86 | 120.87 | 106.13 | 96.86 | ** |
| Total Capacity Penalty (Capacity & Auxiliary Power) | | | 35.79 | 35.29 | 23.71 | 23.75 | 23.78 | |
| Total Operating Penalty (Replacement & Auxiliary Energies, Make-up Water & Maintenance) | | | 15.62 | 24.81 | 22.19 | 26.36 | 28.54 | |
| Total Evaluated Cost (Sum of Capital & Penalty Costs) | | | 228.56 | 182.96 | 166.77 | 156.24 | 149.18 | |

* H-High Back Pressure Turbine

† L-Conventional Low Back Pressure Turbine

** Given in Table 5.2

TABLE 6.9

MAJOR CAPITAL AND PENALTY COST COMPONENTS FOR OPTIMIZED COOLING TOWER SYSTEMS ($\$10^6$)

SITE: MIDDLETOWN, U.S.A. PRICING YEAR: 1985 WET/DRY TYPE: NATURAL SERIES

| | Mech. Dry (H)* | Mech. Dry (L)† | Percentage Make-up Requirement Natural Series Wet/Dry | | | | | Mech. Wet |
|---|---|---|---|---|---|---|---|---|
| | | | 1% | 10% | 20% | 30% | 40% | |
| Capital Cost: | ** | ** | | | | | | ** |
| Cooling Tower | | | 105.20 | 67.73 | 66.38 | 54.57 | 47.21 | |
| Condenser | | | 17.32 | 14.65 | 14.23 | 14.20 | 14.15 | |
| Circulating Water System | | | 17.37 | 13.94 | 13.73 | 13.73 | 13.73 | |
| Electrical Equipment | | | 1.83 | 1.97 | 2.36 | 2.40 | 2.40 | |
| Indirect Cost | | | 35.43 | 24.57 | 24.17 | 21.23 | 19.37 | |
| Total Capital Cost | | | 177.15 | 122.86 | 120.87 | 106.13 | 96.86 | |
| Penalty Cost: | | | | | | | | |
| Capacity | | | 27.36 | 27.36 | 14.46 | 14.46 | 14.46 | |
| Auxiliary Power | | | 8.43 | 7.92 | 9.25 | 9.30 | 9.33 | |
| Replacement Energy | | | 4.49 | 14.62 | 10.11 | 12.78 | 13.91 | |
| Auxiliary Energy | | | 5.53 | 5.02 | 6.11 | 7.22 | 7.83 | |
| Make-up Water | | | .06 | .67 | 1.28 | 1.92 | 2.53 | |
| Cooling System Maintenance | | | 5.54 | 4.51 | 4.69 | 4.43 | 4.26 | |
| Total Penalty | | | 51.41 | 60.10 | 45.90 | 50.11 | 52.32 | |

** Given in Table 5.3

* H-High Back Pressure Turbine

† L-Conventional Low Back Pressure Turbine

TABLE 6.10

COMPARISON OF DRY TOWER COOLING SYSTEM COST FOR VARIOUS HEAT EXCHANGER DESIGNS

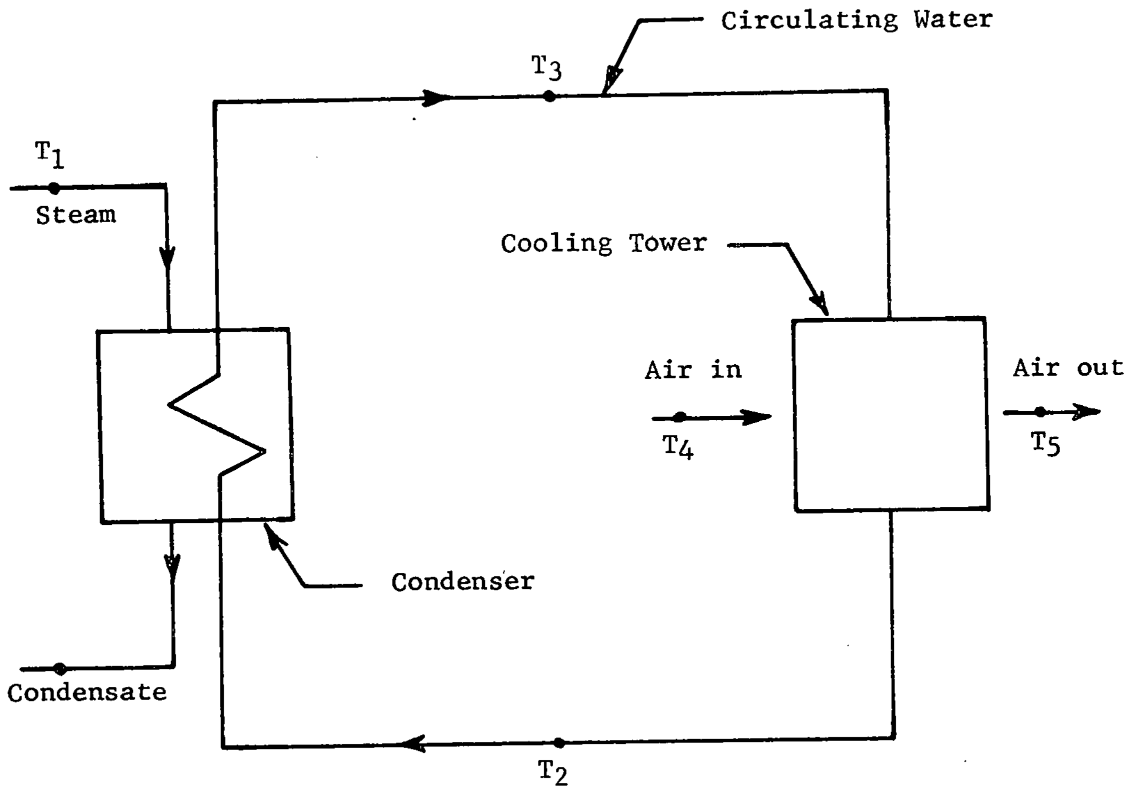
SITE: MIDDLETOWN, U.S.A. PLANT: 1000 MWe LWR PRICING YEAR: 1985

Heat Exchanger Design Data*

| Tubes/Row | Tube Dia., Inch (mm) | No. of Rows | No. of Passes | No. of Cells | Penalty, $\$10^6$ | Total Capital Cost, $\$10^6$ | Total Evaluated Cost, $\$10^6$ |
|---|---|---|---|---|---|---|---|
| 194 | 1 (25.4) | 3 | 2 | 175 | 195.8 | 114.0 | 309.7 |
| → 194 | 1 (25.4) | 4 | 2 | 156 | 188.5 | 108.8 | 297.3 ← |
| 194 | 1 (25.4) | 5 | 2 | 170 | 176.1 | 127.7 | 303.9 |
| 194 | 1 (25.4) | 6 | 2 | 140 | 182.1 | 116.9 | 299.0 |
| 194 | 1 (25.4) | 7 | 4 | 159 | 182.0 | 135.9 | 317.8 |
| 194 | 1 (25.4) | 8 | 2 | 154 | 176.6 | 137.2 | 313.8 |
| 194 | 1 (25.4) | 8 | 4 | 179 | 179.2 | 179.1 | 358.2 |
| 170 | 1 (25.4) | 3 | 2 | 204 | 197.2 | 127.1 | 324.3 |
| 170 | 1¼ (31.8) | 4 | 2 | 166 | 182.2 | 128.9 | 311.1 |

*Design Parameters: Dry Bulb = 93°F (33.9°C)
Wet Bulb = 74°F (23.3°C)
Tower ITD = 66°F (36.7°C)
Cooling Range = 24°F (13.3°C)

Air Cooled Heat Exchanger & Tube Sizes:
Width of Heat Exchanger = 42 ft (12.77 m)
Tube Length = 52 ft (15.81 m)
Tube Material = Admiralty
Fin Height = 5/8 in. (1.59 cm)
No. of Fin per Inch = 10 (3.94 fins/cm)




| | Wet Tower | Dry Tower |
|---|---|---|
| Cooling Range | $T_3 - T_2$ | $T_3 - T_2$ |
| Tower Approach | $T_2 - T_4$ (Wet Bulb) | $T_2 - T_4$ (Dry Bulb) |
| Initial Temperature Difference | $T_3 - T_4$ (Wet Bulb) | $T_3 - T_4$ (Dry Bulb) |
| Terminal Temperature Difference | $T_1 - T_3$ | $T_1 - T_3$ |

Figure 6.1 Definitions of Temperatures in the Cooling Systems

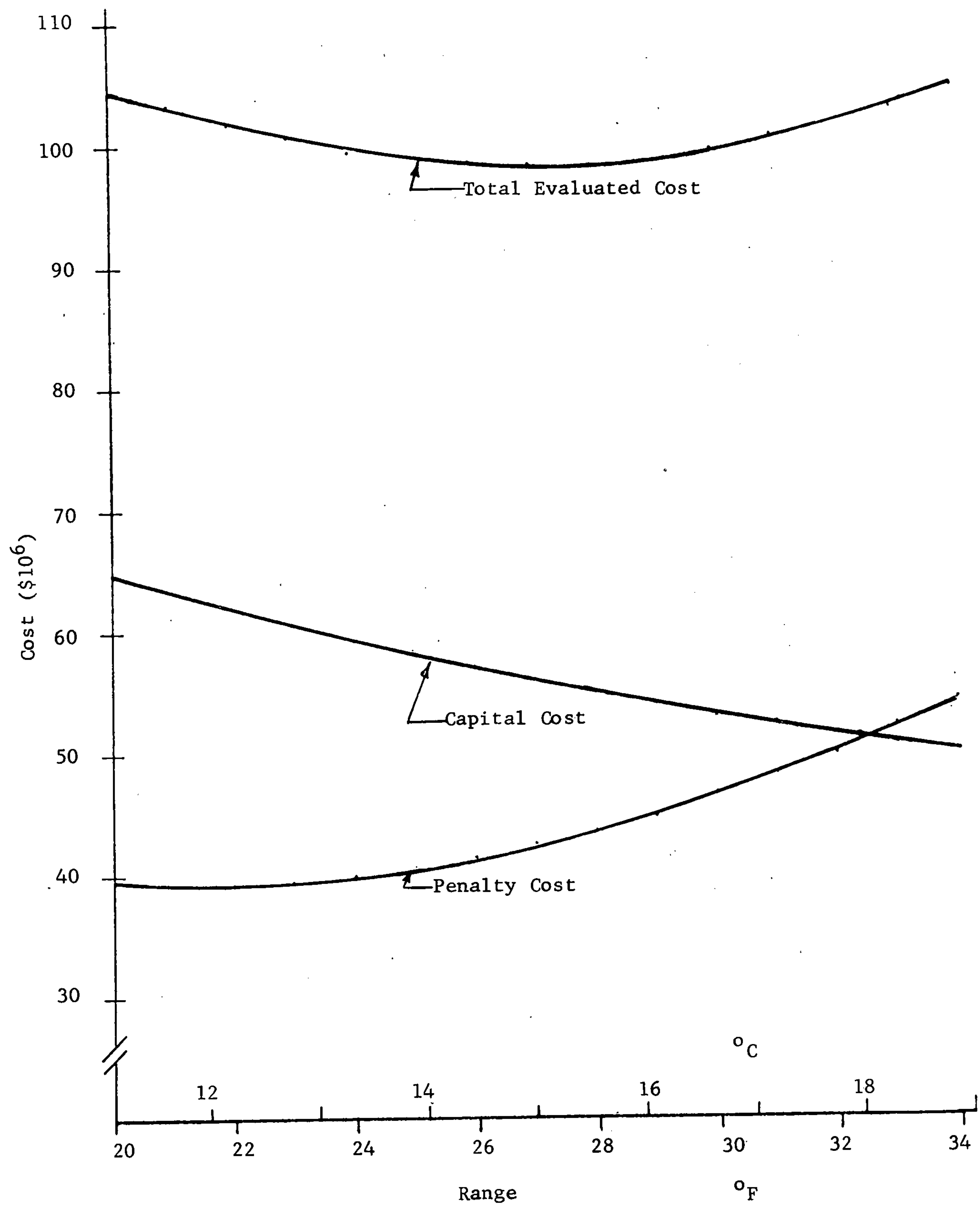



Figure 6.2 Typical Capital and Penalty Trade-off for Mechanical Wet Tower Systems (Middletown, Constant Approach = 17°F (9.4°C))

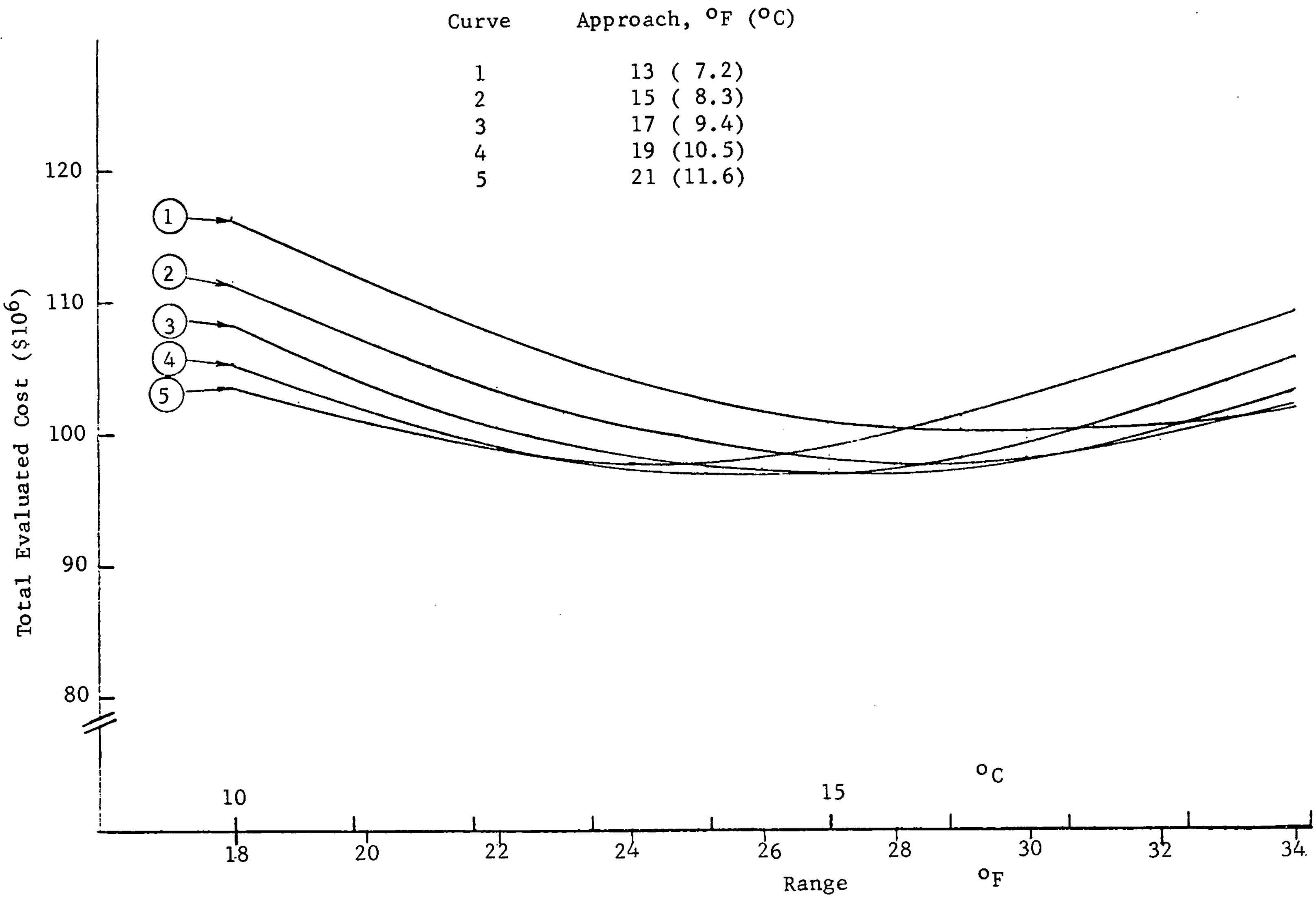



Figure 6.3 Effect of Approach Temperature on the Optimum Selection of the Wet Tower System (Middletown, Mechanical Wet Tower, 1985)

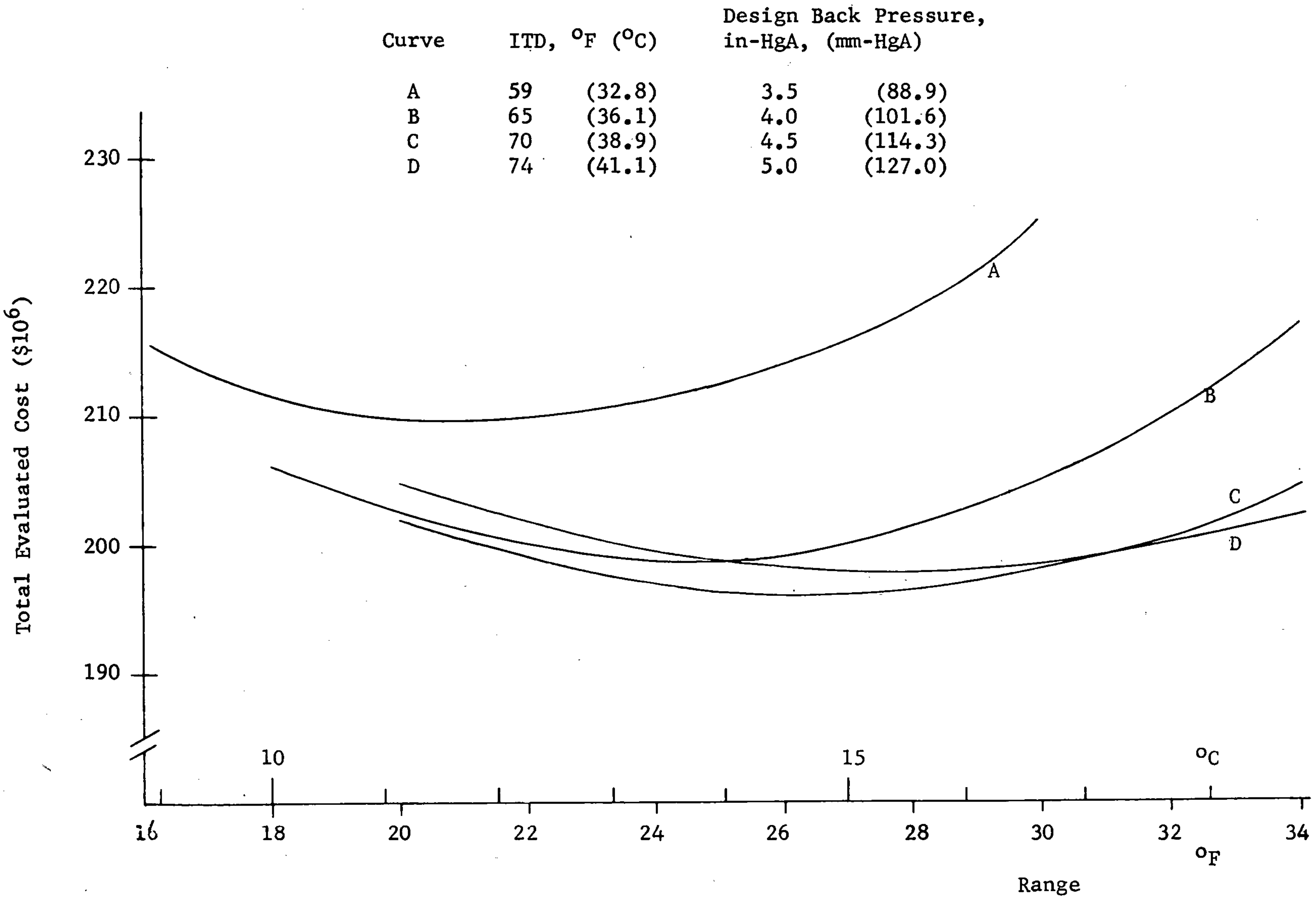



Figure 6.4 Optimization of a 10 Percent Wet/Dry System for a Series of Specified Design Back Pressures (Middletown, Mechanical Series, S1 Mode)

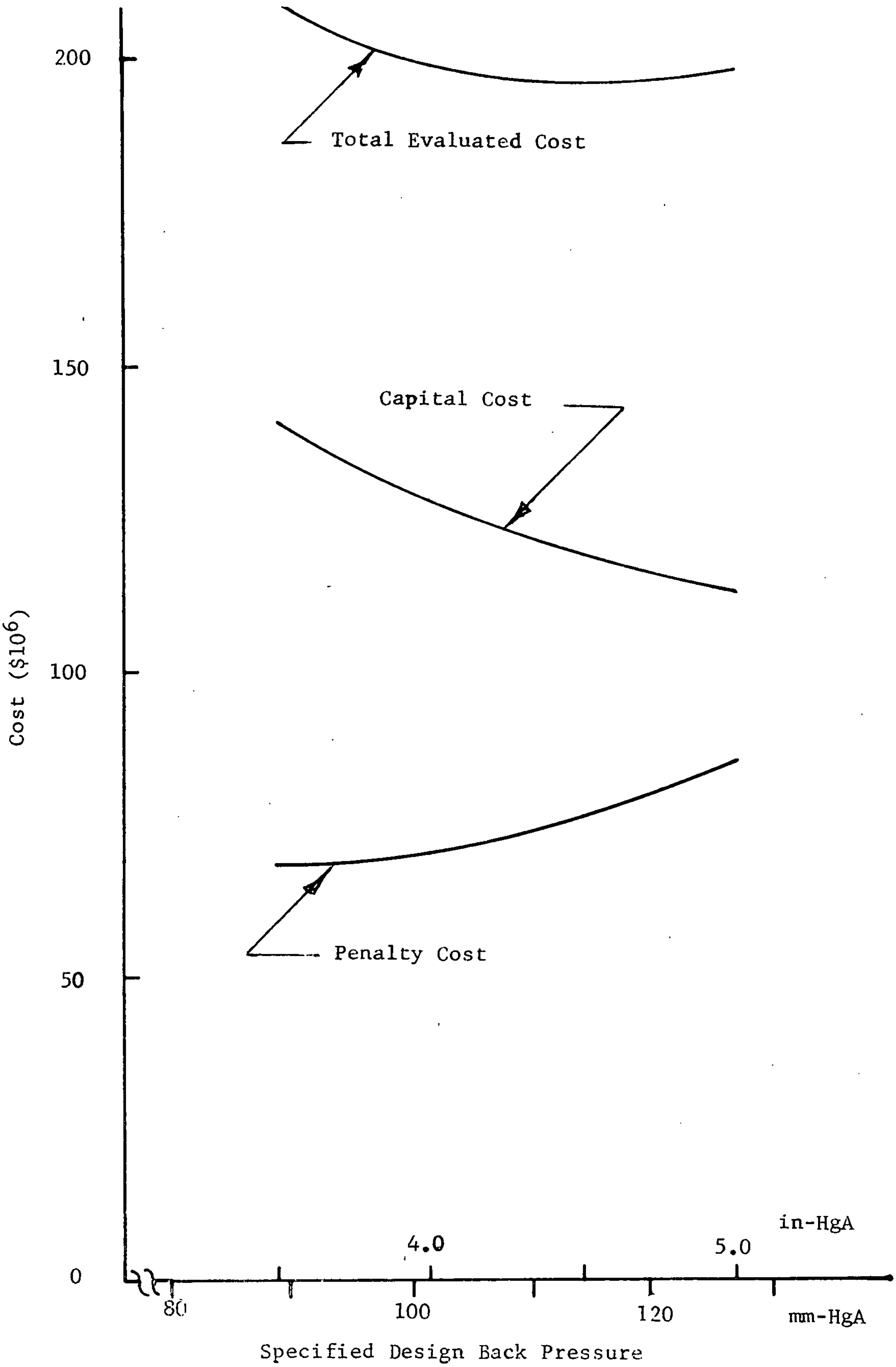



Figure 6.5 Optimum Selection and Economic Trade-offs of a 10 Percent Wet/Dry System (Middletown, Mechanical Series, S1 Mode)

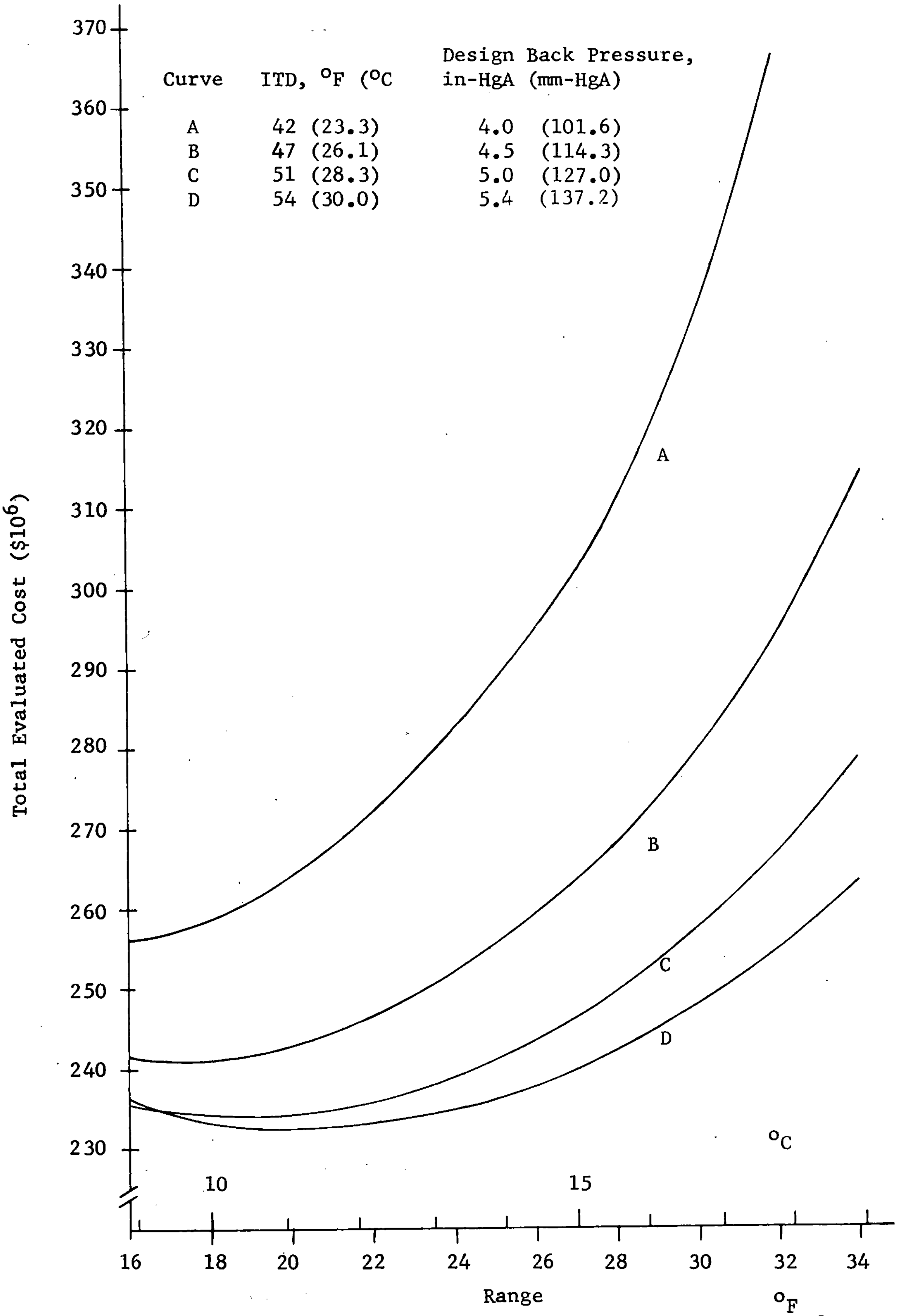



**Figure 6.6** Optimization of a 1 Percent Wet/Dry System for a Series of Specified Design Back Pressures (Middletown, Mechanical Series, S1 Mode

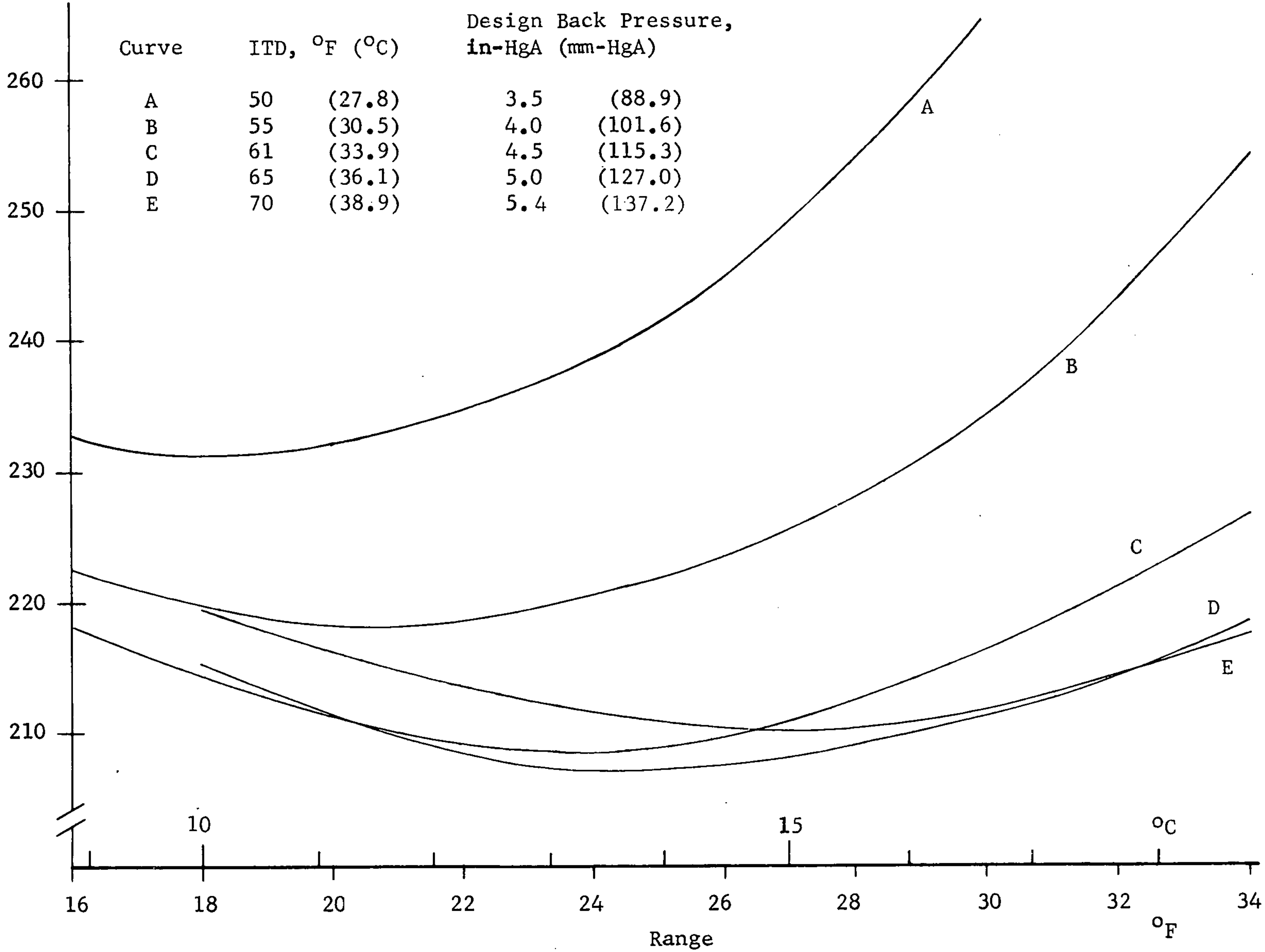



Figure 6.7 Optimization of a 5 Percent Wet/Dry System for a Series of Specified Design Back Pressures (Middletown, Mechanical Series, S1 Mode)

| Curve | ITD, °F (°C) | | Design Back Pressure, in-HgA (mm-HgA) | |
|---|---|---|---|---|
| A | 75 | (41.6) | 3.5 | (88.9) |
| B | 81 | (45.0) | 4.0 | (101.6) |
| C | 86 | (47.8) | 4.5 | (114.3) |
| D | 91 | (50.5) | 5.0 | (127.0) |

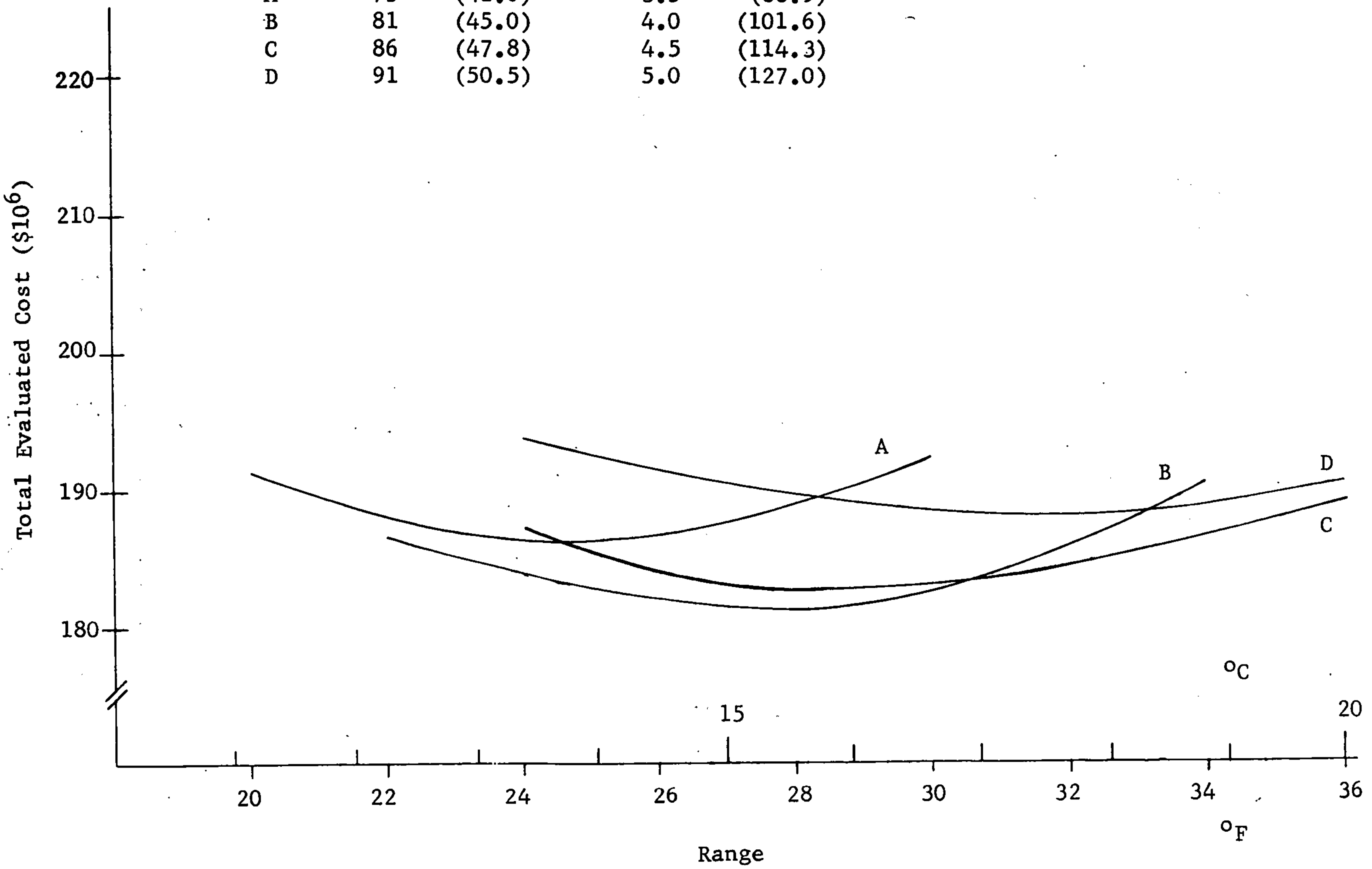



Figure 6.8 Optimization of a 20 Percent Wet/Dry System for a Series of Specified Design Back Pressures (Middletown, Mechanical Series, S1 Mode)

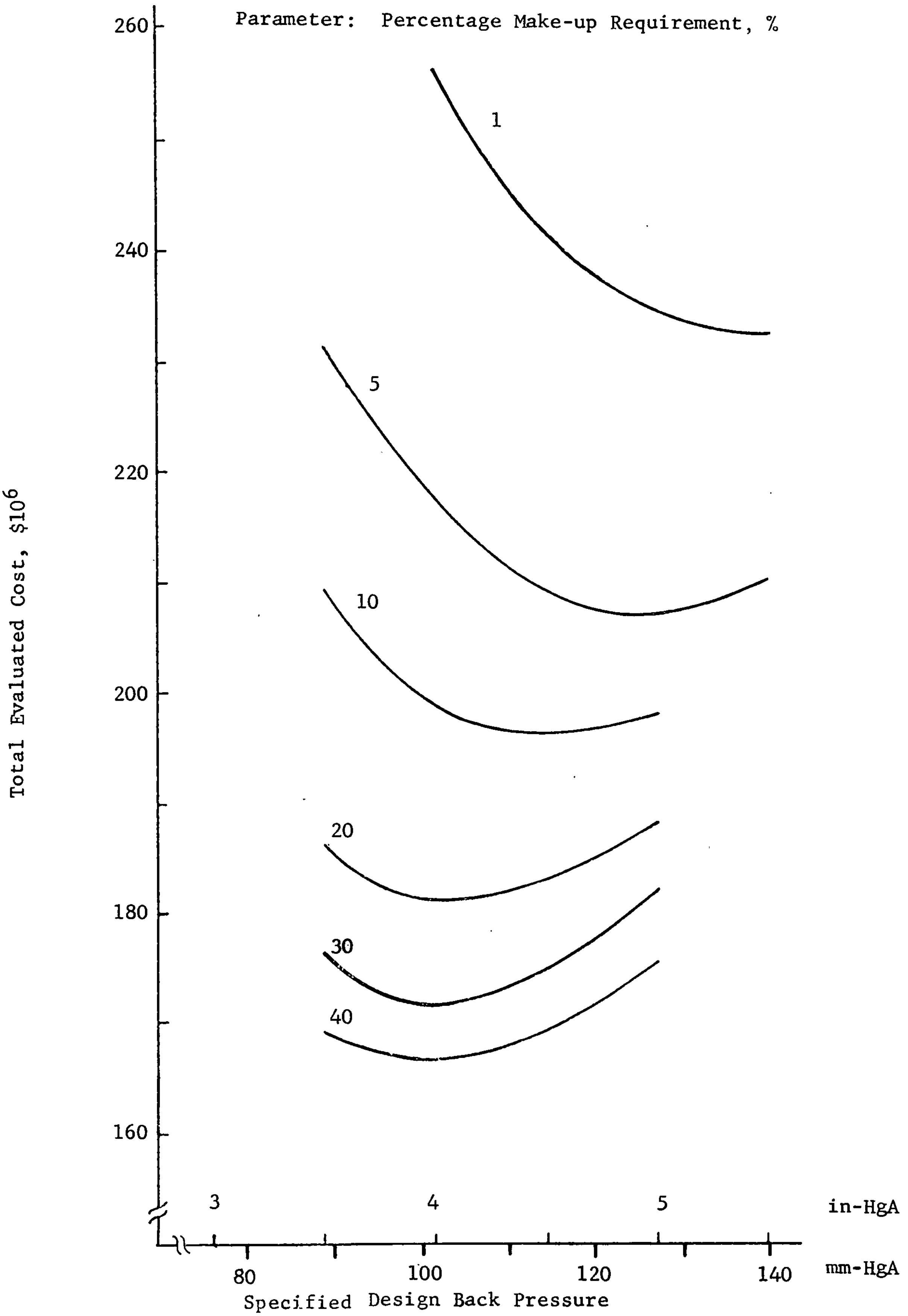



Figure 6.9 Optimum Selection of Wet/Dry Systems Requiring 1 to 40 Percent Make-up

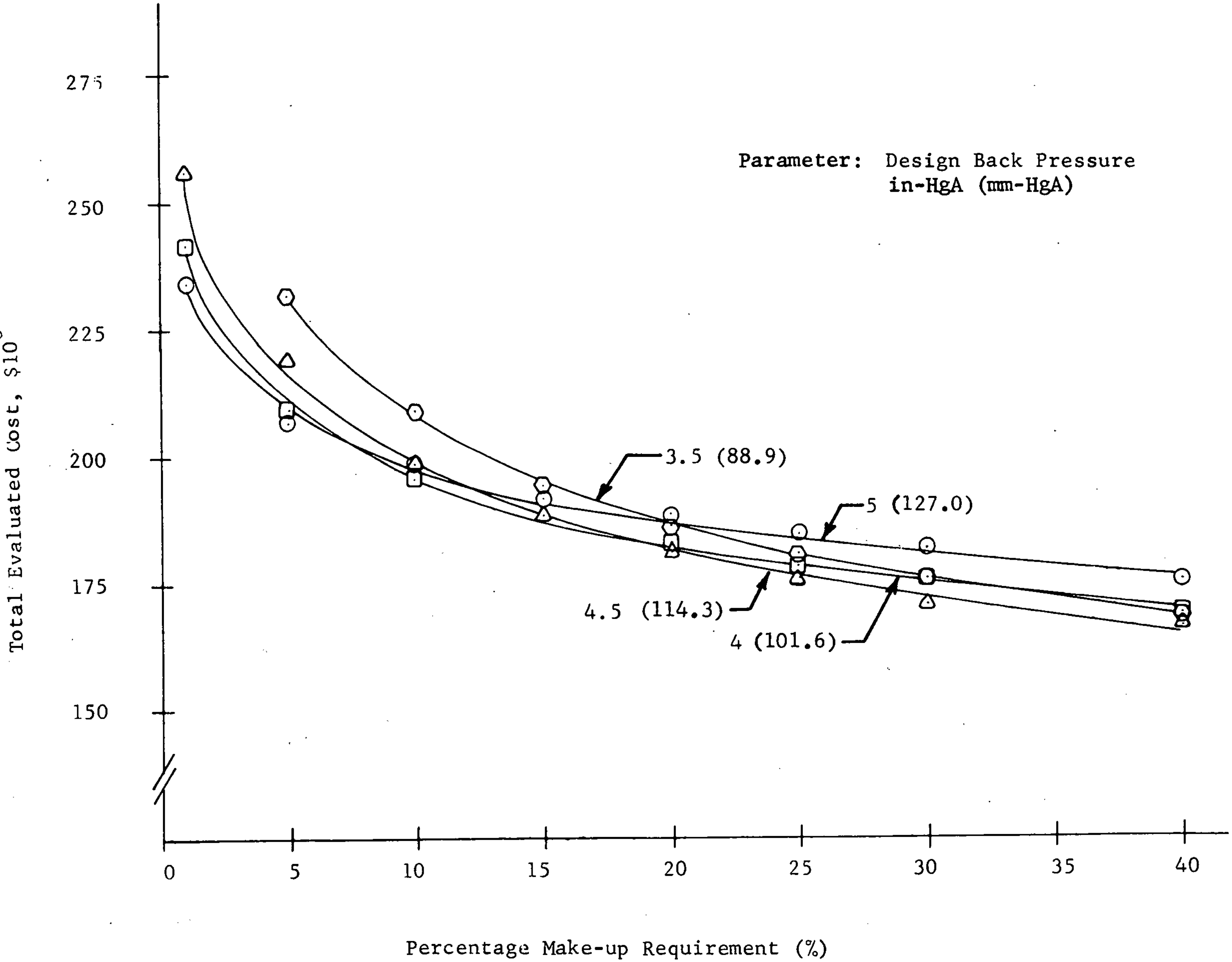



Figure 6.10 Total Evaluated Costs of Optimized Wet/Dry Systems Operating in S1 Mode for Various Specified Design Back Pressures (Middletown, Mechanical Series, 1985)

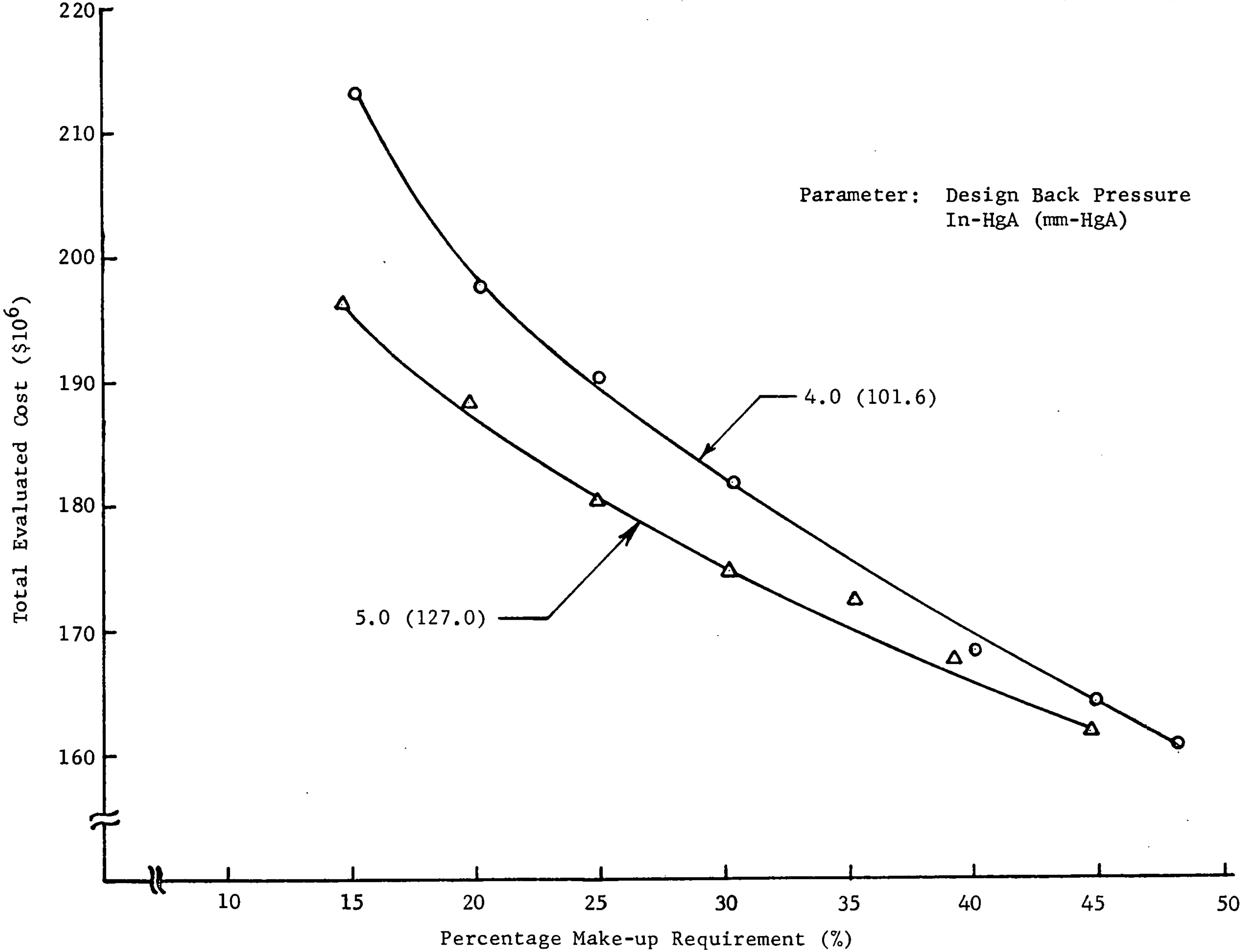



Figure 6.11 Total Evaluated Costs of Optimized Wet/Dry Systems Operating in S2 Mode for Various Specified Design Back Pressures (Middletown, Mechanical Series, 1985)

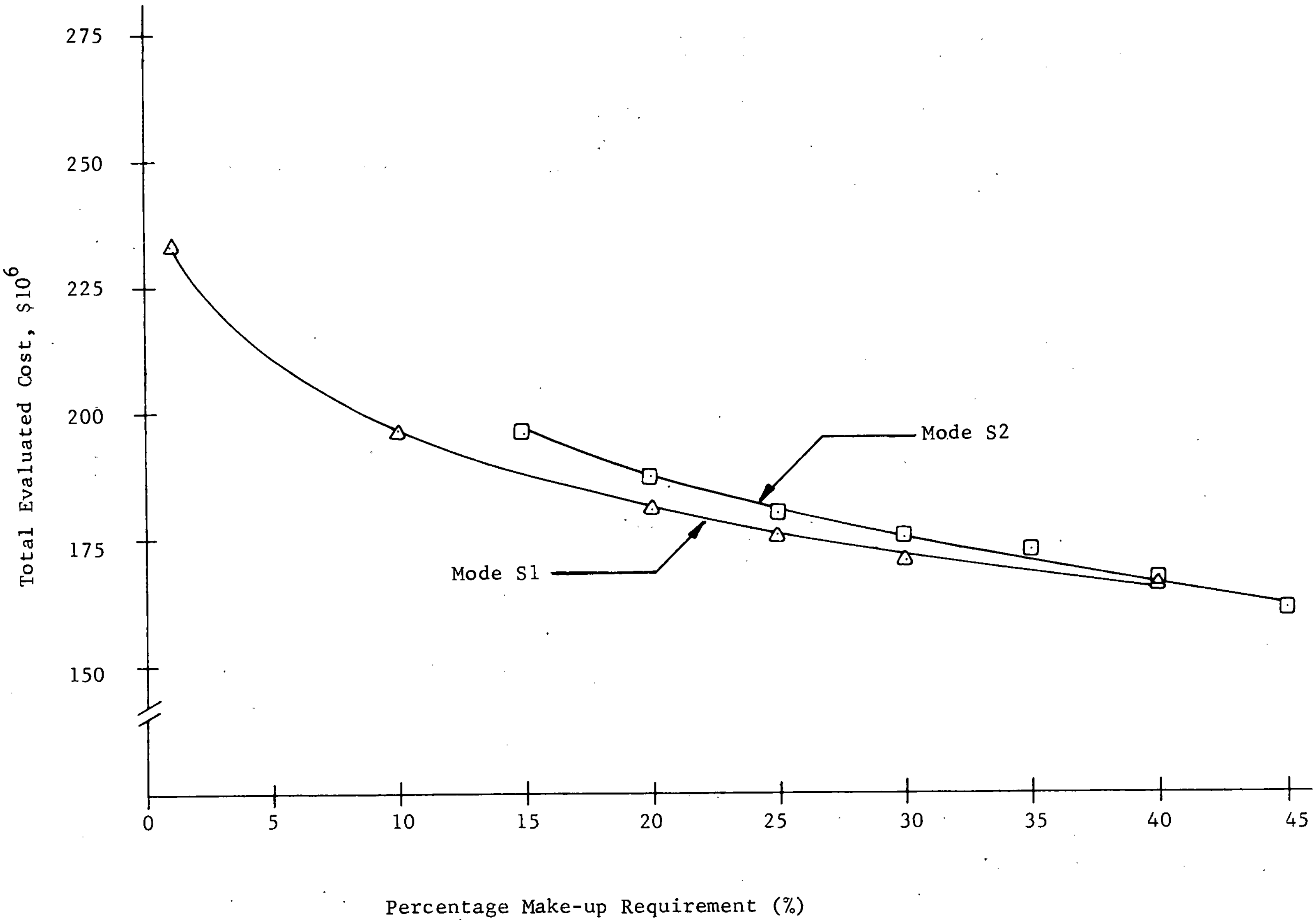
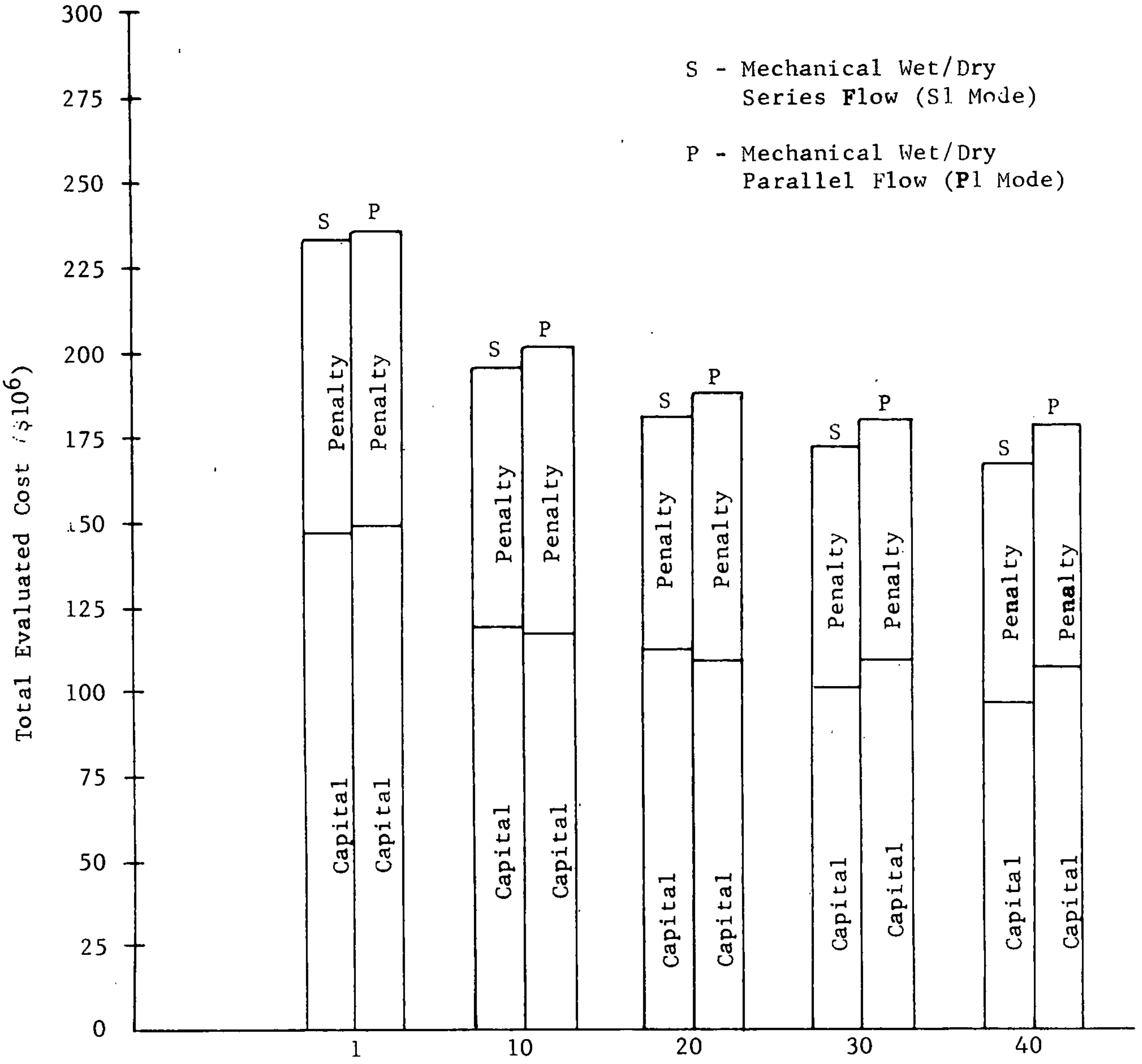



Figure 6.12 Comparison of the Optimized Systems Operating in the S1 and S2 Modes (Middletown, Mechanical Series, 1985)




Percentage Make-up Requirement (%)

Figure 6.13 Comparison of Series (S1) and Parallel (P1) Mechanical Wet/Dry Cooling Tower Systems (Middletown)

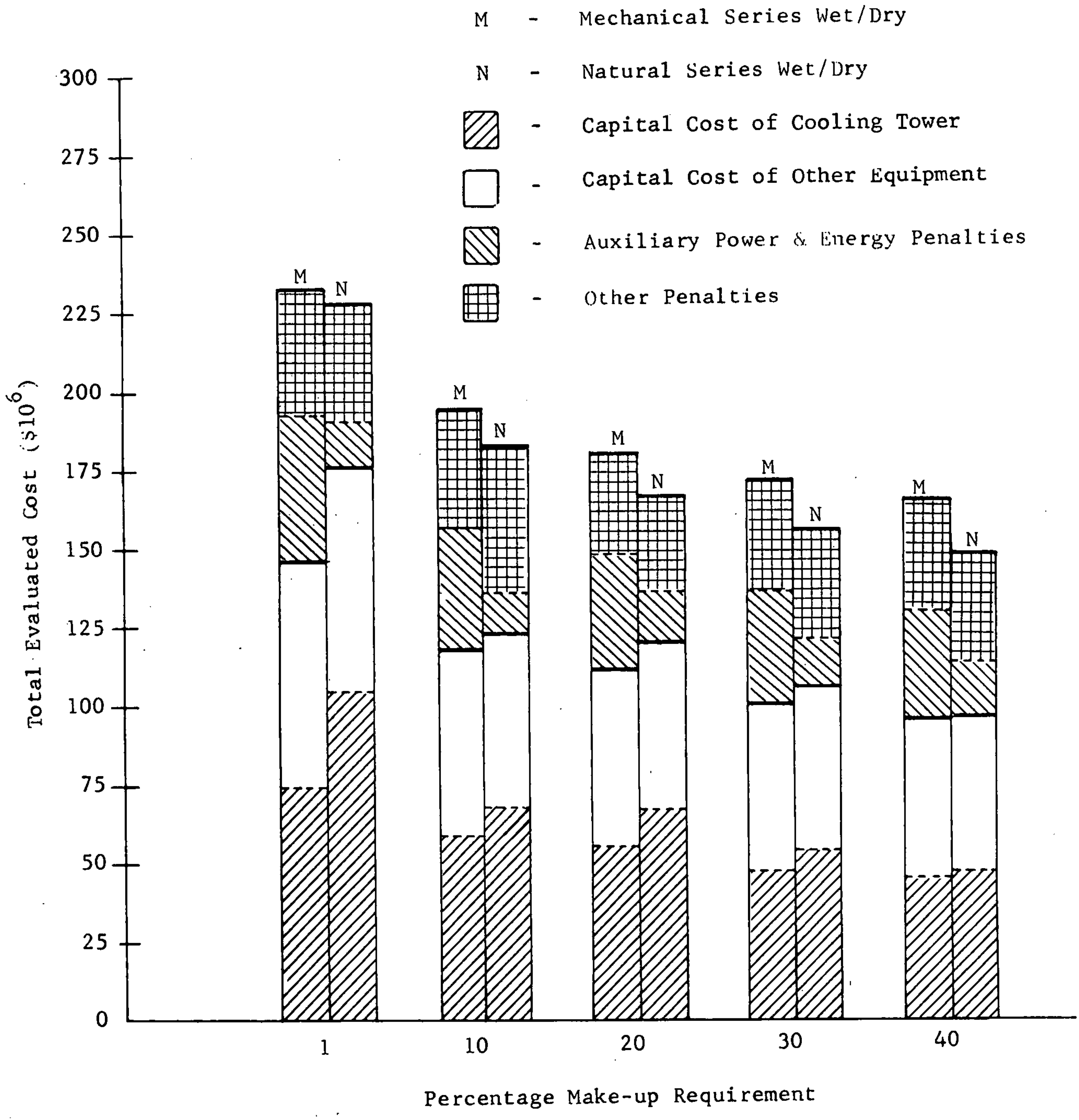



Figure 6.14 Comparison of Natural Series and Mechanical Series Wet/Dry Cooling Tower Systems (Middletown, S1 Mode)

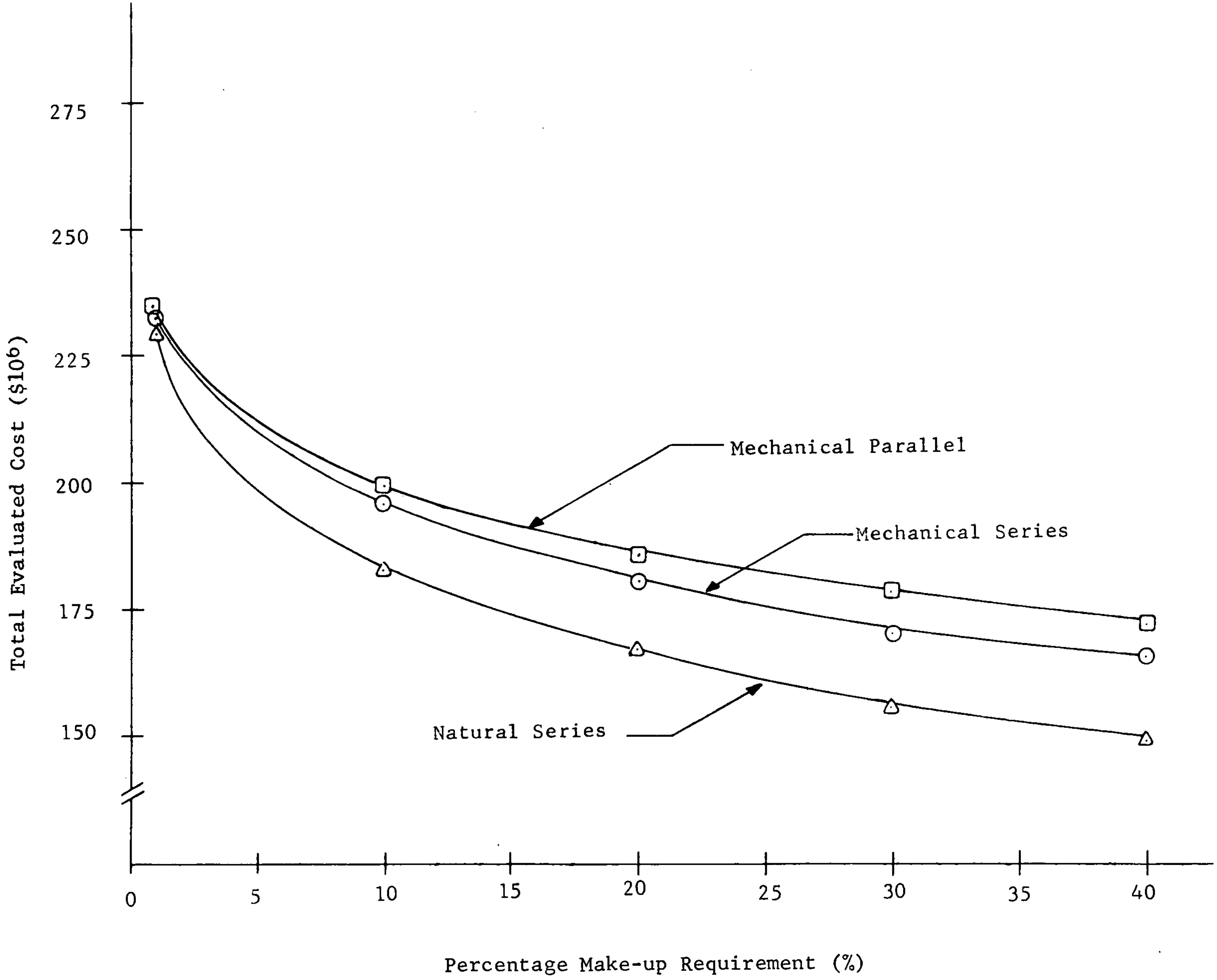



Figure 6.15 Comparison of Three Types of Wet/Dry Systems (Middletown, 1985)

# CHAPTER 7

## SITE STUDIES

### 7.1 INTRODUCTION

The objective of the site studies was to determine the impact that different meteorology and site elevations have on the design and economics of wet/dry cooling systems.

The cooling systems are designed to provide the best trade-off between the capital and penalty costs for a power plant at a site with specific ambient conditions. The results presented in Chapters 5 and 6 of this report are concerned with power plants sited at Middletown, U.S.A.; therefore, those designs are applicable only to sites which have ambient temperature conditions and site elevation similar to that of the Middletown location.

In order to extend the usefulness of the results, two additional sites with meteorology significantly different from that of Middletown were selected for analysis similar to that reported in Chapter 5 for the mechanical series wet/dry tower system. The meteorological data for these sites were taken from Reference 20.

### 7.2 SITE IDENTIFICATION

The two additional sites chosen are in the southeast and southwest Regions of the United States. These alternate sites were chosen on the basis of potential water shortages in the areas as well as their distinctive site meteorological conditions and elevations with respect to each other and to the base site.

The southeast site was chosen to correspond to the meteorological condition and elevation of Atlanta, Georgia. Atlanta is an inland site with an elevation of about 1,000 feet (305 metre) above sea level. Middletown and Atlanta have approximately the same maximum dry bulb and wet bulb temperatures; however, throughout most of the year both the wet bulb and dry bulb temperatures at Atlanta are significantly higher than those of Middletown (see Figures 7.1 and 7.2).

The third site was chosen to represent the southwest, and the site condition was modeled after San Juan, New Mexico. San Juan is located in the Four Corners region of the Southwest United States at an elevation of approximately 5,500 feet (1676 metre) above sea level. The Public Service Company of New Mexico will operate the first wet/dry cooling system purchased in the United States at their San Juan station near Farmington. The maximum and average dry bulb temperatures at San Juan are higher than the maximum and average dry bulb temperatures at Middletown, while the maximum and average wet bulb temperatures at Atlanta are lower than those of Middletown (see Figures 7.1 and 7.3).

## 7.3 ALTERNATE SITE EVALUATION

The design parameters and economic results for the minimum cost cooling systems designed for operation at Atlanta and San Juan are reported in this section. The cooling systems evaluated include the mechanical draft wet tower, mechanical draft dry tower and mechanical draft series wet/dry cooling systems operating in both the S1 and S2 modes. The minimum cost wet/dry systems for both sites occur in the S1 mode. This confirms the engineering assessment made in Chapter 6 for Middletown that there is a systematic economic advantage for systems designed to operate in the S1 mode over those designed o operate in the S2 mode. The design and economic data for the wet/dry cooling systems operating in the S1 mode are presented in this Chapter; the data generated for the S2 mode are given in Appendices F and G. The evaluations were performed using the same economic factors as those used for Middletown. The results presented are analogous to those presented in Chapter 5 for Middletown. (A direct comparison of the Middletown, Atlanta and San Juan results is given in Section 7.4.)

7.3.1 Site: Atlanta, Georgia

Tables 7.1 to 7.3 and Figure 7.4 contain a summary of the major design and cost data for the Atlanta site. A comparison of the design data for Middletown and Atlanta shows that at Atlanta, more dry cells and fewer wet cells are required for the same percentage make-up wet/dry systems; the lower make-up systems (10 percent and 20 percent) optimized at half an inch (12.7 mm) higher back pressure and 11 MWe lower gross power output. Both the capital and penalty costs are higher because of the larger systems needed, since the ambient temperatures at Atlanta are significantly higher than those of Middletown during most of the year.

7.3.2 Site: San Juan, New Mexico

Tables 7.4 to 7.6 and Figure 7.5 contain a summary of the major design and cost data for the San Juan site. A comparison of the design data for Middletown and San Juan shows that for wet/dry cooling at San Juan more dry cells and fewer wet cells are required; as at Atlanta the lower make-up systems (10 and 20 percent) optimized at half an inch (12.7 mm) higher back pressure and 11 MWe lower gross output; and, both the capital and penalty costs are higher because of the larger systems needed. The 1 percent system is significantly larger than that at Middletown because of the very high maximum dry bulb temperature, the 30 percent and 40 percent systems are comparable in size to those at Middletown.

7.3.3 <u>Site: Middletown, U.S.A.</u>

To aid in the comparison of the sites, information reported in Chapter 5 is reproduced in this section as shown in Figure 7.6 and Tables 7.7 through 7.9.

## 7.4 COMPARISON OF COOLING SYSTEMS AT ALTERNATE SITES

A direct comparison of the total evaluated cost of the wet/dry and the reference wet cooling system designed for operation at the three sites is shown in Figure 7.7. The cost comparisons are limited to the effect of ambient temperature and elevation differences.

The maximum and average ambient conditions, the elevation and the total evaluated costs at each site are listed in Table 7.10.

The results presented in this comparison indicate that although the general trend of the wet/dry system costs are similar at each of the three sites, the differences in meteorology and elevation do affect the design and the total evaluated cost of the systems.

The total evaluated cost for optimized wet/dry cooling systems designed for use at different sites can be significantly different. This is especially evident for the low make-up systems where the costs can differ by 25 percent to 30 percent ($65 million for the 1 percent make-up system). At the higher make-up fractions the differences are much smaller (8 percent to 12 percent).

The results portrayed are probably typical for systems designed for operation n the three regions, and can be used for estimating the costs of wet/dry cooling for New England, Southeast and Southwest United States, or for sites with similar elevations and meteorology.

TABLE 7.1

MAJOR DESIGN DATA FOR THE OPTIMIZED COOLING TOWER SYSTEMS

SITE: ATLANTA, GEORGIA WET/DRY TYPE: MECHANICAL SERIES S1 BASE OUTPUT: 1094 MWe

| Item | Mech. Dry (H)* | Mech. Dry (L)† | Percentage Make-up Requirement Mechanical Series Wet/Dry | | | | | Mech. Wet |
|---|---|---|---|---|---|---|---|---|
| | | | 1% | 10% | 20% | 30% | 40% | |
| Number of Tower Cells, Wet Tower/Dry Tower | 0/170 | 0/346 | 9/244 | 15/162 | 19/145 | 24/130 | 25/107 | 33/0 |
| Mode of Wet/Dry Tower Operation | - | - | S1 | S1 | S1 | S1 | S1 | - |
| Maximum Operating Back Pressure $P_{max}$, in-HgA (mm-HgA) | 11.6 (294.6) | 5.07 (128.8) | 5.0 (127.0) | 5.0 (127.0) | 4.5 (114.3) | 4.0 (101.6) | 4.0 (101.6) | 3.7 (93.7) |
| Gross Plant Output at $P_{max}$, MWe | 955.1 | 1046.7 | 1048.2 | 1048.2 | 1059.5 | 1069.9 | 1069.9 | 1075.8 |
| Heat Load at $P_{max}$, $10^9$ Btu/hr ($10^{12}$ J/hr) | 7.57 (7.98) | 7.26 (7.66) | 7.25 (7.66) | 7.25 (7.66) | 7.21 (7.61) | 7.18 (7.57) | 7.18 (7.57) | 7.16 (7.55) |
| Heat Load Distribution at $P_{max}$, (Wet Tower/Dry Tower), % | 0.0/ 100 | 0.0/ 100 | 29.1/ 70.9 | 51.6/ 48.4 | 62.6/ 37.4 | 71.7/ 28.3 | 75.5/ 24.5 | 100./ 0.0 |
| Annual Make-up Water for Wet Towers, $10^8$ gal ($10^6$ $m^3$) | 0.0 | 0.0 | 0.442 (0.167) | 5.05 (1.91) | 9.42 (3.57) | 14.1 (5.34) | 18.3 (6.93) | 46.3 (17.5) |

H-High Back Pressure Turbine

L-Conventional Low Back Pressure Turbine

TABLE 7.2

MAJOR COST SUMMARY FOR OPTIMIZED COOLING TOWER SYSTEMS ($\$10^6$)

SITE: ATLANTA, GEORGIA PRICING YEAR: 1985 WET/DRY TYPE: MECHANICAL SERIES (S1)

| Item | Mech. Dry (H)* | Mech. Dry (L)† | Percentage Make-up Requirement Mechanical Series Wet/Dry | | | | | Mech. Wet |
|---|---|---|---|---|---|---|---|---|
| | | | 1% | 10% | 20% | 30% | 40% | |
| Total Capital Cost (Direct & Indirect Capital Costs) | 115.64 | 219.44 | 175.58 | 132.20 | 123.29 | 118.31 | 107.55 | 56.31 |
| Total Capacity Penalty (Capacity & Auxiliary Power) | 102.86 | 65.82 | 55.42 | 48.84 | 40.94 | 34.34 | 33.20 | 20.60 |
| Total Operating Penalty (Replacement & Auxiliary Energies, Make-up Water & Maintenance) | 83.24 | 47.60 | 42.13 | 44.92 | 42.89 | 39.69 | 40.09 | 23.89 |
| Total Evaluated Cost (Sum of Capital & Penalty Costs) | 301.74 | 332.86 | 273.13 | 225.96 | 207.12 | 192.34 | 180.84 | 100.80 |

* H-High Back Pressure Turbine

† L-Conventional Low Back Pressure Turbine

TABLE 7.3

MAJOR CAPITAL AND PENALTY COST COMPONENTS FOR OPTIMIZED COOLING TOWER SYSTEMS ($$10^6$)

SITE: ATLANTA, GEORGIA PRICING YEAR: 1985 WET/DRY TYPE: MECHANICAL SERIES (S1)

| | Mech. Dry (H)* | Mech. Dry (L)† | Percentage Make-up Requirement Mechanical Series Wet/Dry | | | | | Mech. Wet |
|---|---|---|---|---|---|---|---|---|
| | | | 1% | 10% | 20% | 30% | 40% | |
| Capital Cost: | | | | | | | | |
| Cooling Tower | 59.30 | 120.70 | 90.35 | 65.30 | 61.75 | 59.48 | 52.07 | 19.48 |
| Condenser | 15.18 | 30.88 | 17.84 | 15.26 | 14.14 | 13.65 | 13.63 | 14.09 |
| Circulating Water System | 10.02 | 17.92 | 17.41 | 14.60 | 12.89 | 12.23 | 12.23 | 9.04 |
| Electrical Equipment | 8.01 | 16.05 | 14.86 | 10.60 | 9.85 | 9.29 | 8.11 | 2.44 |
| Indirect Cost | 23.13 | 43.89 | 35.12 | 26.44 | 24.66 | 23.66 | 21.51 | 11.26 |
| Total Capital Cost | 115.64 | 219.44 | 175.58 | 132.20 | 123.29 | 118.31 | 107.55 | 56.31 |
| Penalty Cost: | | | | | | | | |
| Capacity | 83.36 | 28.40 | 27.48 | 27.40 | 20.72 | 14.46 | 14.46 | 10.91 |
| Auxiliary Power | 19.50 | 37.42 | 27.94 | 21.44 | 20.22 | 19.88 | 18.74 | 9.69 |
| Replacement Energy | 58.20 | 2.14 | 7.30 | 17.83 | 16.67 | 13.18 | 14.08 | 4.84 |
| Auxiliary Energy | 19.37 | 34.71 | 26.28 | 19.71 | 18.43 | 18.29 | 17.63 | 9.34 |
| Make-up Water | 0.0 | 0.0 | 0.07 | 0.75 | 1.40 | 2.09 | 2.72 | 6.86 |
| Cooling System Maintenance | 5.67 | 10.75 | 8.48 | 6.23 | 6.39 | 6.13 | 5.66 | 2.85 |
| Total Penalty | 186.10 | 113.42 | 97.55 | 93.76 | 83.83 | 74.03 | 73.29 | 44.49 |

* H-High Back Pressure Turbine

† L-Conventional Low Back Pressure Turbine

TABLE 7.4

MAJOR DESIGN DATA FOR THE OPTIMIZED COOLING TOWER SYSTEMS

SITE: SAN JUAN, NEW MEXICO BASE OUTPUT: 1094 MWe WET/DRY TYPE: MECHANICAL SERIES (S1)

| Item | Mech. Dry (H)* | Mech. Dry (L)† | Percentage Make-up Requirement Mechanical Series Wet/Dry | | | | | Mech. Wet |
|---|---|---|---|---|---|---|---|---|
| | | | 1% | 10% | 20% | 30% | 40% | |
| Number of Tower Cells, Wet Tower/Dry Tower | 0/175 | 0/431 | 9/263 | 15/170 | 18/138 | 21/119 | 25/102 | 32/0 |
| Mode of Wet/Dry Tower Operation | - | - | S1 | S1 | S1 | S1 | S1 | - |
| Maximum Operating Back Pressure $P_{max}$, in-HgA (mm-HgA) | 13.09 (332.5) | 5.03 (127.8) | 5.00 (127.0) | 5.00 (127.0) | 4.50 (114.3) | 4.00 (101.6) | 4.00 (101.6) | 3.30 (83.8) |
| Gross Plant Output at $P_{max}$, MWe | 939.8 | 1047.5 | 1048.2 | 1048.4 | 1059.5 | 1069.9 | 1069.9 | 1082.2 |
| Heat Load at $P_{max}$, $10^9$ Btu/hr ($10^{12}$ J/hr) | 7.62 (8.04) | 7.26 (7.65) | 7.25 (7.65) | 7.25 (7.65) | 7.22 (7.61) | 7.18 (7.57) | 7.18 (7.57) | 7.14 (7.53) |
| Heat Load Distribution at $P_{max}$, (Wet Tower/Dry Tower) , % | 0.0/ 100.0 | 0.0/ 100.0 | 33.4/ 66.6 | 57.8/ 42.2 | 69.6/ 30.4 | 78.2/ 21.8 | 81.7/ 18.3 | 100.0/ 0.0 |
| Annual Make-up Water for Wet Towers, $10^8$ gal ($10^6$ $m^3$) | 0.0 (0.0) | 0.0 (0.0) | 0.494 (.187) | 4.57 (1.73) | 9.11 (3.45) | 14.19 (5.37) | 18.78 (7.11) | 47.02 (17.80) |

* H-High Back Pressure Turbine

† L-Conventional Low Back Pressure Turbine

TABLE 7.5

MAJOR COST SUMMARY FOR OPTIMIZED COOLING TOWER SYSTEMS ($\$10^6$)

SITE: SAN JUAN, NEW MEXICO PRICING YEAR: 1985 WET/DRY TYPE: MECHANICAL SERIES (S1)

| Item | Mech. Dry (H)* | Mech. Dry (L)† | Percentage Make-up Requirement Mechanical Series Wet/Dry | | | | | Mech. Wet |
|---|---|---|---|---|---|---|---|---|
| | | | 1% | 10% | 20% | 30% | 40% | |
| Total Capital Cost (Direct & Indirect Capital Costs) | 119.31 | 263.42 | 194.14 | 136.42 | 121.81 | 112.88 | 103.55 | 53.39 |
| Total Capacity Penalty (Capacity & Auxiliary Power) | 113.28 | 73.06 | 59.66 | 49.19 | 40.89 | 33.77 | 31.81 | 16.28 |
| Total Operating Penalty (Replacement & Auxiliary Energies, Make-up Water & Maintenance) | 84.38 | 53.38 | 44.33 | 41.82 | 41.13 | 38.72 | 38.80 | 21.17 |
| Total Evaluated Cost (Sum of Capital & Penalty Costs) | 316.97 | 389.86 | 298.13 | 227.43 | 203.83 | 185.37 | 174.16 | 90.84 |

* H-High Back Pressure Turbine

† L-Conventional Low Back Pressure Turbine

TABLE 7.6

MAJOR CAPITAL AND PENALTY COST COMPONENTS FOR OPTIMIZED COOLING TOWER SYSTEMS ($\$10^6$)

SITE: SAN JUAN, NEW MEXICO PRICING YEAR: 1985 WET/DRY TYPE: MECHANICAL SERIES (S1)

| | Mech. Dry (H)* | Mech. Dry (L)† | Percentage Make-up Requirement Mechanical Series Wet/Dry | | | | | Mech. Wet |
|---|---|---|---|---|---|---|---|---|
| | | | 1% | 10% | 20% | 30% | 40% | |
| Capital Cost: | | | | | | | | |
| Cooling Tower | 61.05 | 150.35 | 96.93 | 68.05 | 58.71 | 53.90 | 50.32 | 18.88 |
| Condenser | 15.22 | 20.96 | 19.08 | 14.63 | 14.25 | 13.69 | 12.29 | 13.69 |
| Circulating Water System | 10.96 | 19.80 | 23.18 | 15.49 | 14.94 | 14.21 | 12.56 | 7.93 |
| Electrical Equipment | 8.22 | 19.63 | 16.12 | 10.97 | 9.55 | 8.50 | 7.67 | 2.21 |
| Indirect Cost | 23.86 | 52.68 | 38.83 | 27.28 | 24.36 | 22.58 | 20.71 | 10.68 |
| Total Capital Cost | 119.31 | 263.42 | 194.14 | 136.42 | 121.81 | 112.88 | 103.55 | 53.39 |
| Penalty Cost: | | | | | | | | |
| Capacity | 92.54 | 27.90 | 27.49 | 27.38 | 20.72 | 14.46 | 14.44 | 7.05 |
| Auxiliary Power | 20.74 | 45.17 | 32.17 | 21.81 | 20.17 | 19.32 | 17.37 | 9.22 |
| Replacement Energy | 58.06 | 1.28 | 4.86 | 14.17 | 15.06 | 12.94 | 14.19 | 2.70 |
| Auxiliary Energy | 20.54 | 39.50 | 30.10 | 20.23 | 18.54 | 17.91 | 16.43 | 8.88 |
| Make-up Water | 0.0 | 0.0 | .07 | .68 | 1.35 | 2.10 | 2.79 | 6.98 |
| Cooling System Maintenance | 5.78 | 12.59 | 9.30 | 6.74 | 6.18 | 5.76 | 5.39 | 2.62 |
| Total Penalty | 197.66 | 126.44 | 103.99 | 91.01 | 82.02 | 72.49 | 70.61 | 37.45 |

* H-High Back Pressure Turbine

† L-Conventional Low Back Pressure Turbine

TABLE 7.7

MAJOR DESIGN DATA FOR THE OPTIMIZED COOLING TOWER SYSTEMS

SITE: MIDDLETOWN, U.S.A. BASE OUTPUT: 1094 MWe WET/DRY TYPE: MECHANICAL SERIES (S1)

| Item | Mech. Dry (H)* | Mech. Dry (L)† | Percentage Make-up Requirement Mechanical Series Wet/Dry | | | | | Mech. Wet |
|---|---|---|---|---|---|---|---|---|
| | | | 1% | 10% | 20% | 30% | 40% | |
| Number of Tower Cells, Wet Tower/Dry Tower | 0/156 | 0/338 | 13/192 | 19/136 | 26/114 | 27/90 | 30/79 | 33/0 |
| Mode of Wet/Dry Tower Operation | - | - | S1 | S1 | S1 | S1 | S1 | - |
| Maximum Operating Back Pressure $P_{max}$, in-HgA (mm-HgA) | 12.51 (317.8) | 5.06 (128.5) | 5.0 (127.0) | 4.5 (114.3) | 4.0 (101.6) | 4.0 (101.6) | 4.0 (101.6) | 3.90 (99.1) |
| Gross Plant Output at $P_{max}$, MWe | 946.7 | 1046.8 | 1048.4 | 1059.5 | 1069.9 | 1069.9 | 1069.9 | 1071.9 |
| Heat Load at $P_{max}$, $10^9$ Btu/hr ($10^{12}$ J/hr) | 7.60 (8.02) | 7.26 (7.66) | 7.25 (7.65) | 7.22 (7.61) | 7.18 (7.57) | 7.18 (7.57) | 7.18 (7.57) | 7.17 (7.57) |
| Heat Load Distribution at $P_{max}$, (Wet Tower/Dry Tower) , % | 0.0/ 100.0 | 0.0/ 100.0 | 42.7/ 57.3 | 63.7/ 36.3 | 73.8/ 26.2 | 78.2/ 21.8 | 80.5/ 19.5 | 100.0/ 0.0 |
| Annual Make-up Water for Wet Towers, $10^8$ gal ($10^6$ $m^3$) | 0.0 (0.0) | 0.0 (0.0) | 0.435 (0.165) | 4.40 (1.66) | 8.45 (3.20) | 13.29 (5.03) | 16.35 (6.19) | 42.34 (16.06) |

*-High Back Pressure Turbine

†- Conventional Low Back Pressure Turbine

TABLE 7.8

MAJOR COST SUMMARY FOR OPTIMIZED COOLING TOWER SYSTEMS ($$10^6$)

SITE: MIDDLETOWN, U.S.A. PRICING YEAR: 1985 WET/DRY TYPE: MECHANICAL SERIES (S1)

| Item | Mech. Dry (H)* | Mech. Dry (L)† | Percentage Make-up Requirement Mechanical Series Wet/Dry | | | | | Mech. Wet |
|---|---|---|---|---|---|---|---|---|
| | | | 1% | 10% | 20% | 30% | 40% | |
| Total Capital Cost (Direct & Indirect Capital Costs) | 108.82 | 215.54 | 146.83 | 118.96 | 111.82 | 100.76 | 96.44 | 54.44 |
| Total Capacity Penalty (Capacity & Auxiliary Power) | 108.32 | 66.35 | 51.85 | 40.95 | 33.90 | 32.95 | 32.17 | 22.65 |
| Total Operating Penalty (Replacement & Auxiliary Energies, Make-up Water & Maintenance) | 80.16 | 43.89 | 35.15 | 35.99 | 35.45 | 37.99 | 38.23 | 21.01 |
| Total Evaluated Cost (Sum of Capital & Penalty Costs) | 297.30 | 325.78 | 233.83 | 195.90 | 181.17 | 171.70 | 166.84 | 98.10 |

* H-High Back Pressure Turbine

† L-Conventional Low Back Pressure Turbine

TABLE 7.9

MAJOR CAPITAL AND PENALTY COST COMPONENTS FOR OPTIMIZED COOLING TOWER SYSTEMS ($\$10^6$)

SITE: MIDDLETOWN, U.S.A. PRICING YEAR: 1985 WET/DRY TYPE: MECHANICAL SERIES (S1)

| | Mech. Dry (H)* | Mech. Dry (L)† | Percentage Make-up Requirement Mechanical Series Wet/Dry | | | | | Mech. Wet |
|---|---|---|---|---|---|---|---|---|
| | | | 1% | 10% | 20% | 30% | 40% | |
| Capital Cost: | | | | | | | | |
| Cooling Tower | 54.42 | 116.90 | 74.56 | 58.59 | 55.07 | 47.27 | 45.22 | 19.48 |
| Condenser | 15.20 | 20.88 | 15.98 | 14.11 | 13.64 | 13.62 | 13.25 | 13.61 |
| Circulating Water System | 10.02 | 17.92 | 14.74 | 13.01 | 12.23 | 12.35 | 11.77 | 8.22 |
| Electrical Equipment | 7.32 | 15.72 | 12.18 | 9.46 | 8.52 | 7.37 | 6.91 | 2.25 |
| Indirect Cost | 21.86 | 44.12 | 29.37 | 23.79 | 22.36 | 20.15 | 19.29 | 10.88 |
| Total Capital Cost | 108.82 | 215.54 | 146.83 | 118.96 | 111.82 | 100.76 | 96.44 | 54.44 |
| Penalty Cost: | | | | | | | | |
| Capacity | 88.97 | 28.33 | 27.36 | 20.72 | 14.46 | 14.46 | 14.44 | 13.27 |
| Auxiliary Power | 19.35 | 38.02 | 24.49 | 20.23 | 19.44 | 18.49 | 17.73 | 9.38 |
| Replacement Energy | 55.56 | 0.29 | 5.48 | 11.39 | 11.34 | 13.74 | 14.25 | 3.07 |
| Auxiliary Energy | 19.23 | 33.03 | 22.33 | 17.71 | 17.02 | 16.89 | 16.34 | 9.02 |
| Make-up Water | 0 | 0 | 0.06 | 0.65 | 1.25 | 1.97 | 2.42 | 6.28 |
| Cooling System Maintenance | 5.37 | 10.57 | 7.28 | 6.24 | 5.84 | 5.39 | 5.22 | 2.64 |
| Total Penalty | 188.48 | 110.24 | 87.01 | 76.94 | 69.35 | 70.94 | 70.40 | 43.66 |

* H-High Back Pressure Turbine

-Conventional Low Back Pressure Turbine

TABLE 7.10

COMPARISON OF SITE DATA AND TOTAL EVALUATED COST FOR OPTIMIZED COOLING TOWER SYSTEMS

a. SITE DATA

| Site | Maximum DB/WB, °F (°C) | Annual Average DB/WB, °F (°C) | Site Elevation, feet (metre) above sea level |
|---|---|---|---|
| Middletown, U.S.A. | 99/75 (37.2/23.9) | 50/43 (10.0/6.1) | 0 (0) |
| Atlanta, Georgia | 99/74 (37.2/23.3) | 62/54 (16.7/12.2) | 1000 (305) |
| San Juan, New Mexico | 102/63 (38.9/17.2) | 55/41 (12.8/5.0) | 5500 (1676) |



b. TOTAL EVALUATED COST - 1985 DOLLARS ($\$10^6$)

| Site | Mech. Dry (H)* | Mech. Dry (L)+ | Percentage Make-up Requirement-Mech. Series Wet/Dry 1% | 10% | 20% | 30% | 40% | Mech. Wet |
|---|---|---|---|---|---|---|---|---|
| Middletown, U.S.A. | 297.32 | 325.78 | 223.83 | 195.90 | 181.17 | 171.69 | 166.83 | 98.10 |
| Atlanta, Georgia | 301.74 | 332.86 | 273.13 | 225.96 | 207.12 | 192.34 | 180.84 | 100.80 |
| San Juan, New Mexico | 316.97 | 389.86 | 298.13 | 227.43 | 203.83 | 185.37 | 174.16 | 90.84 |

*H - High Back Pressure Turbine
+L - Conventional Low Back Pressure Turbine

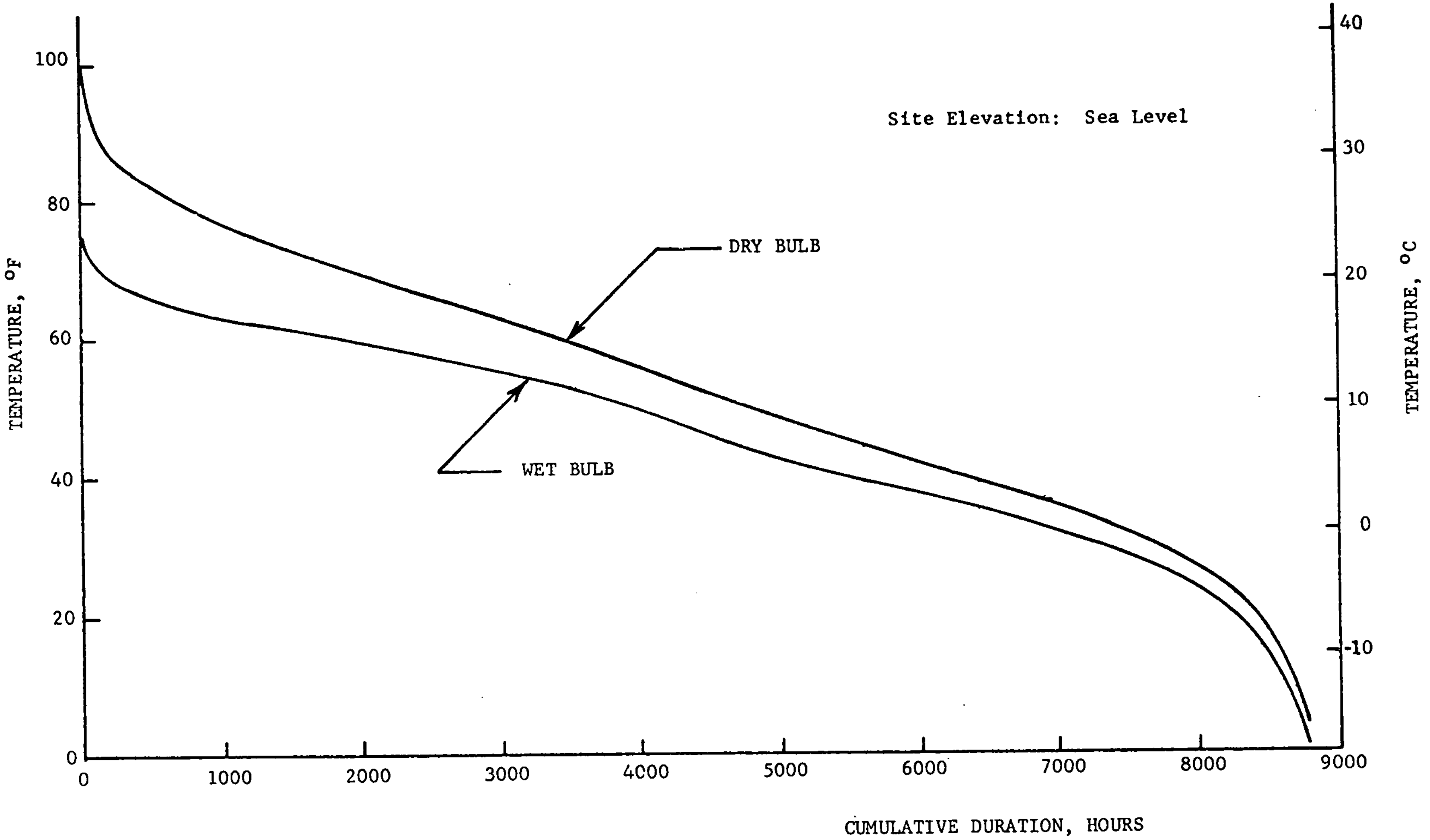



Figure 7.1 Temperature Duration Curve: Middletown, U.S.A.

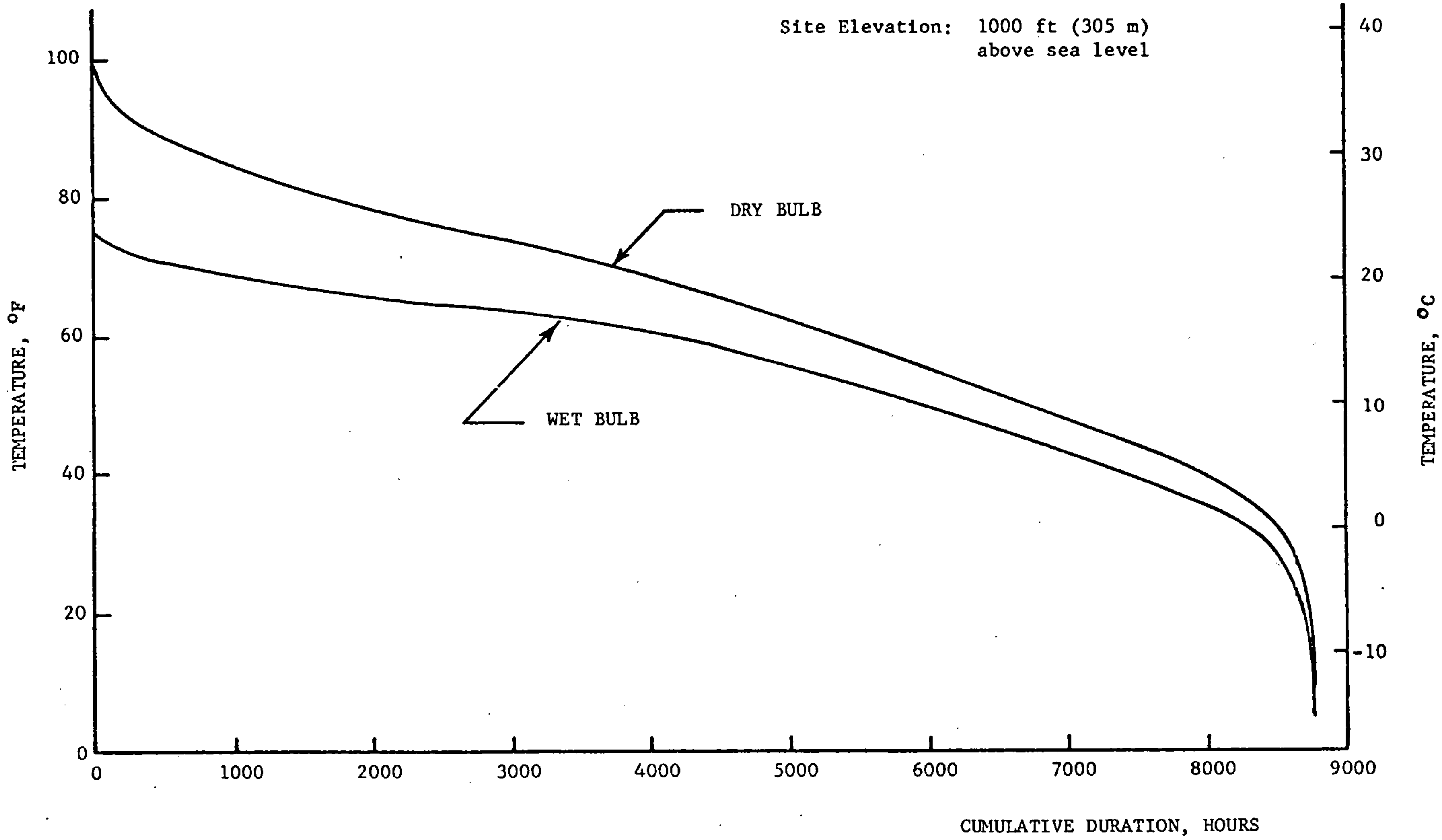



Figure 7.2 Temperature Duration Curve: Atlanta, Georgia

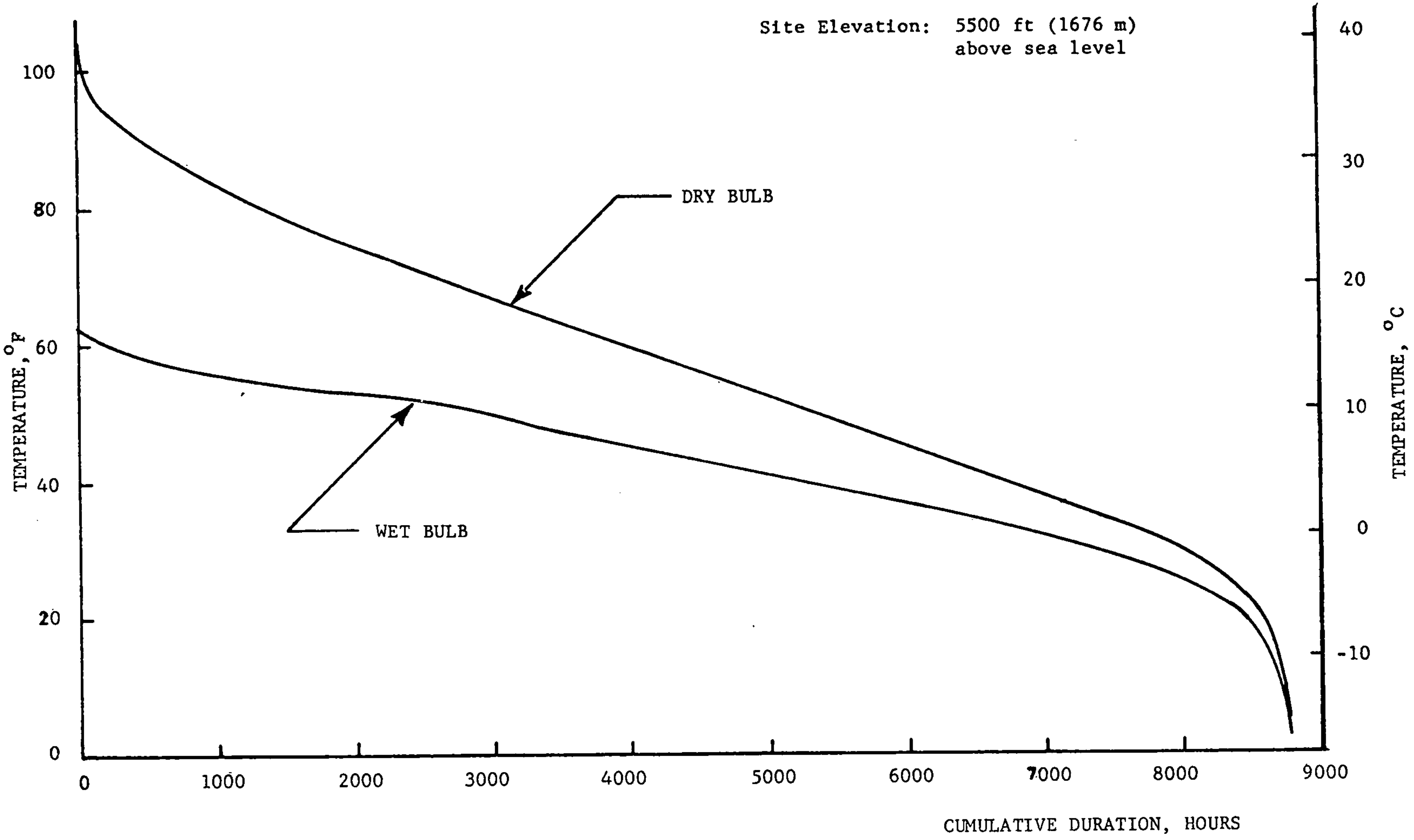



Figure 7.3 Temperature Duration Curve: San Juan, New Mexico

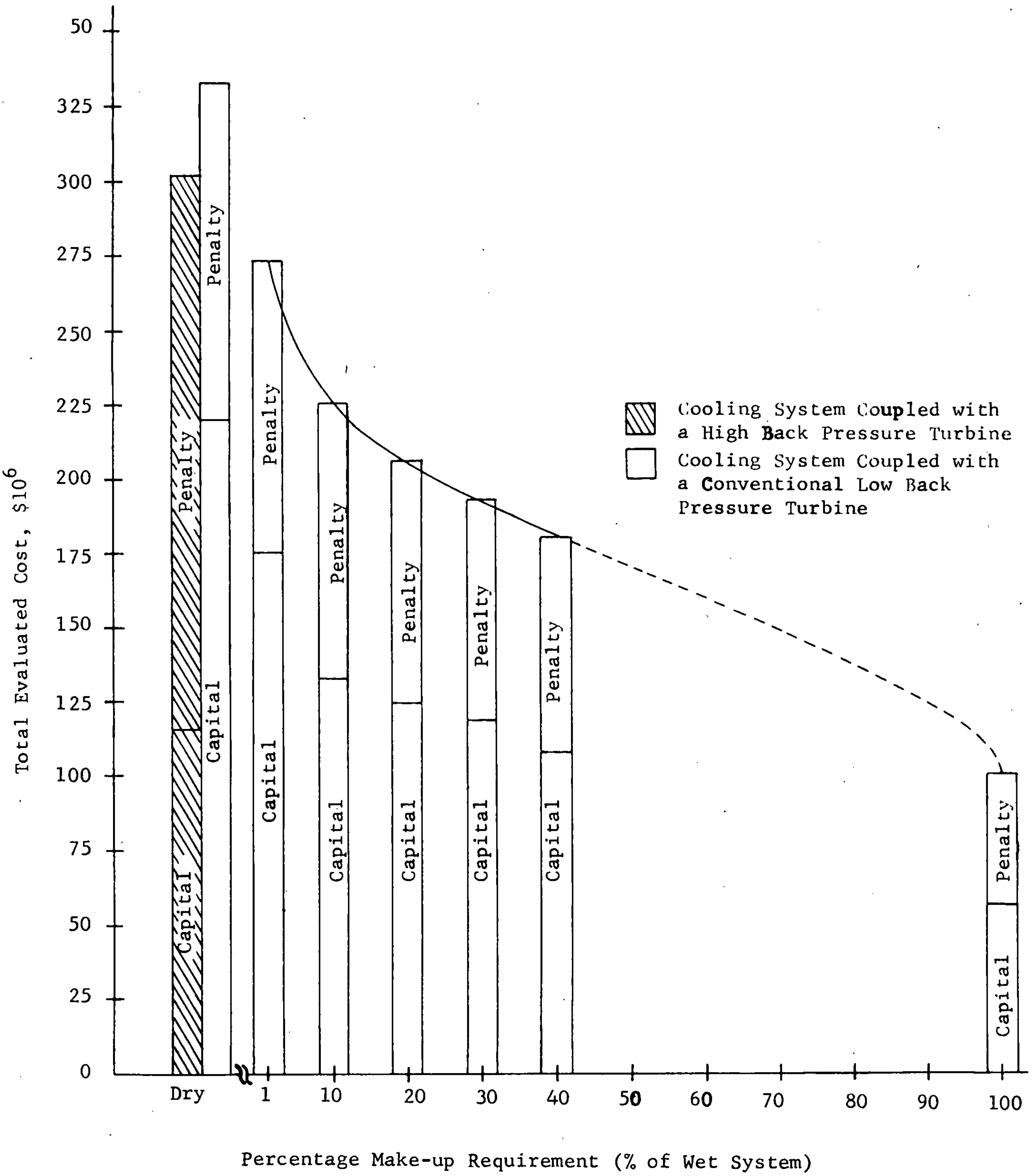



Figure 7.4 Total Evaluated Cost and the Penalty and Capital Components for the Optimized Systems (Atlanta, Mechanical Series, S1 Mode, 1985)

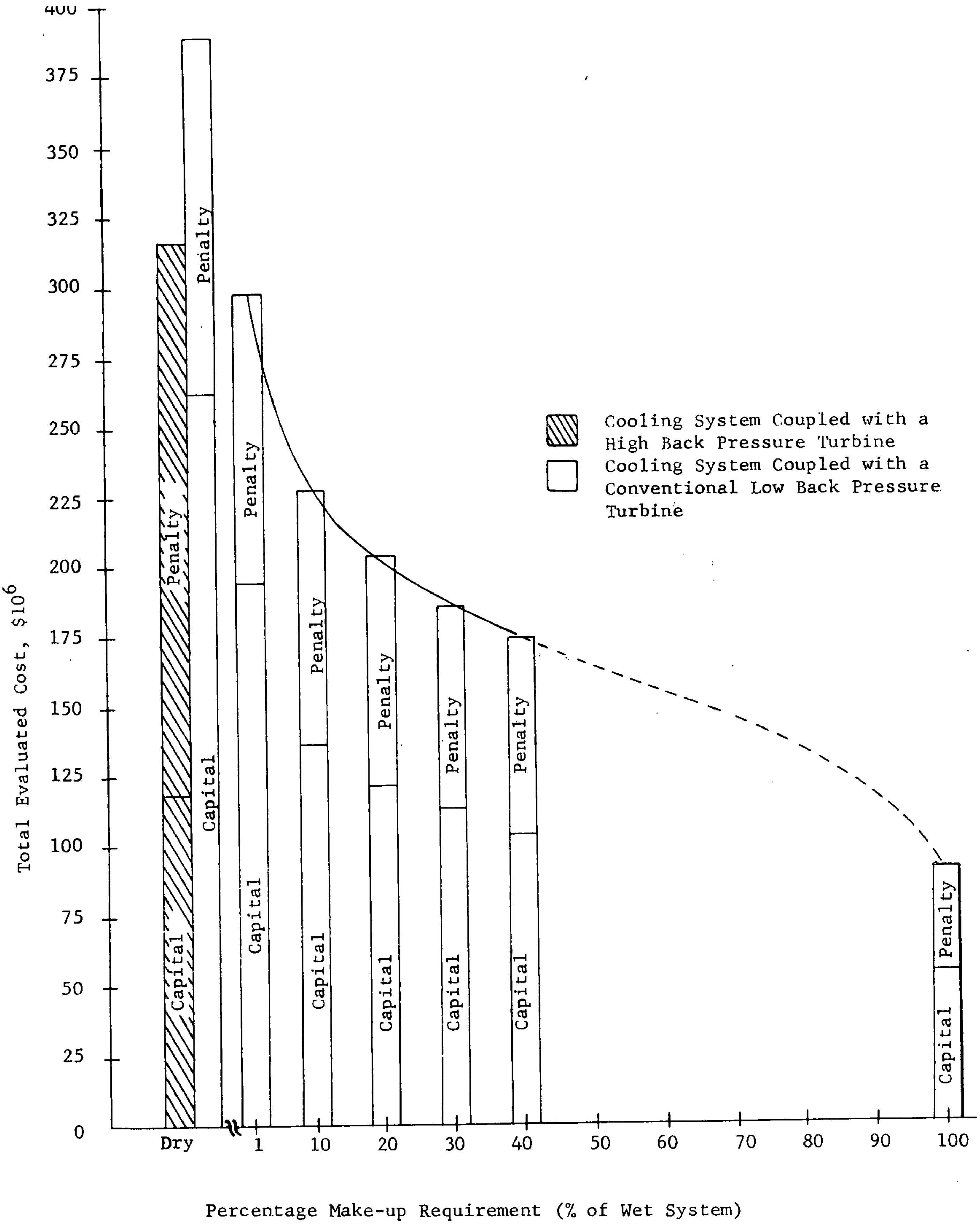



Figure 7.5 Total Evaluated Cost and the Penalty and Capital Components for the Optimized Systems (San Juan, Mechanical Series, SI Mode, 1985)

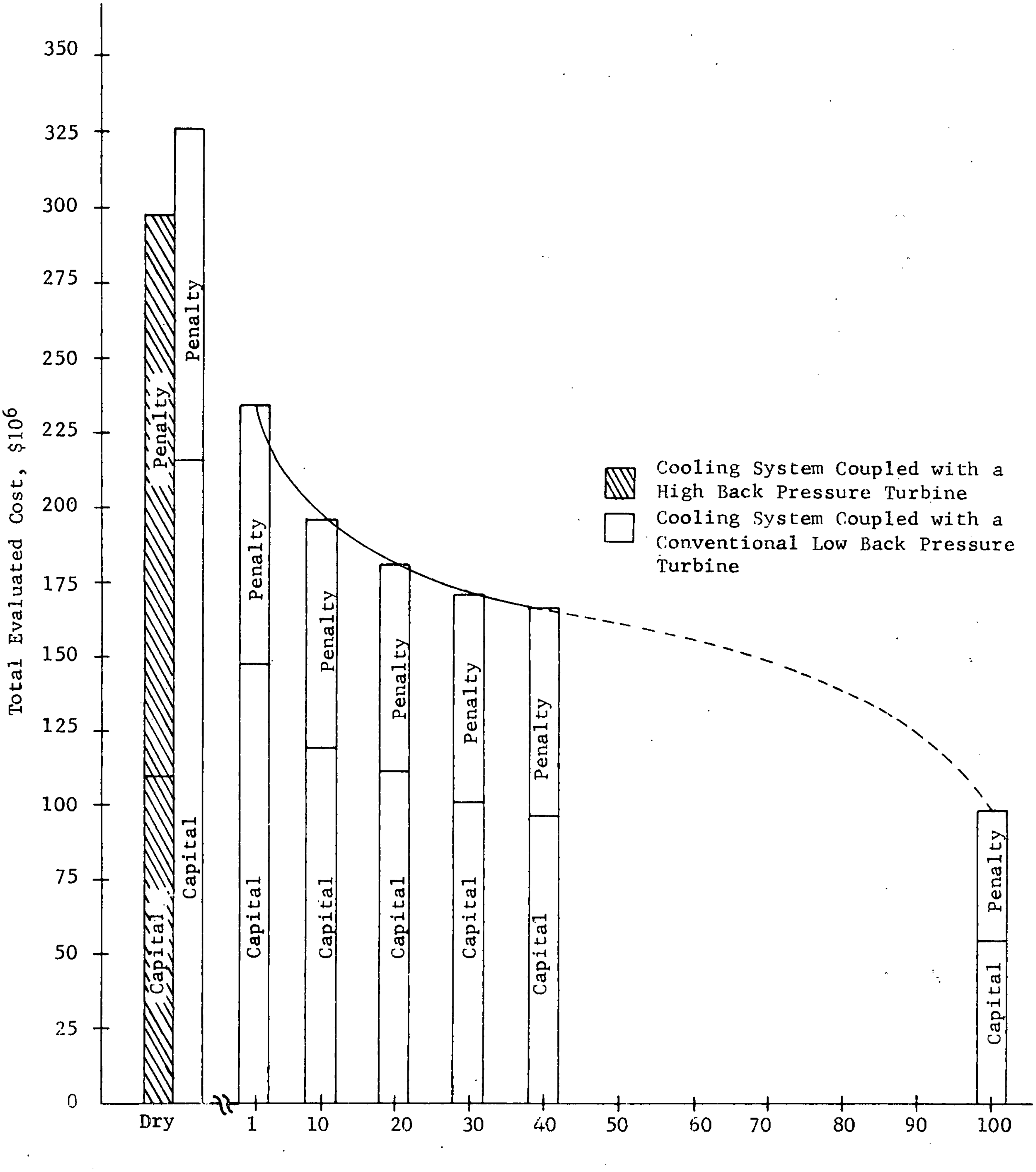



Figure 7.6 Total Evaluated Cost and the Penalty and Capital Components for the Optimized Systems (Middletown, Mechanical Series, SI Mode, 1985)

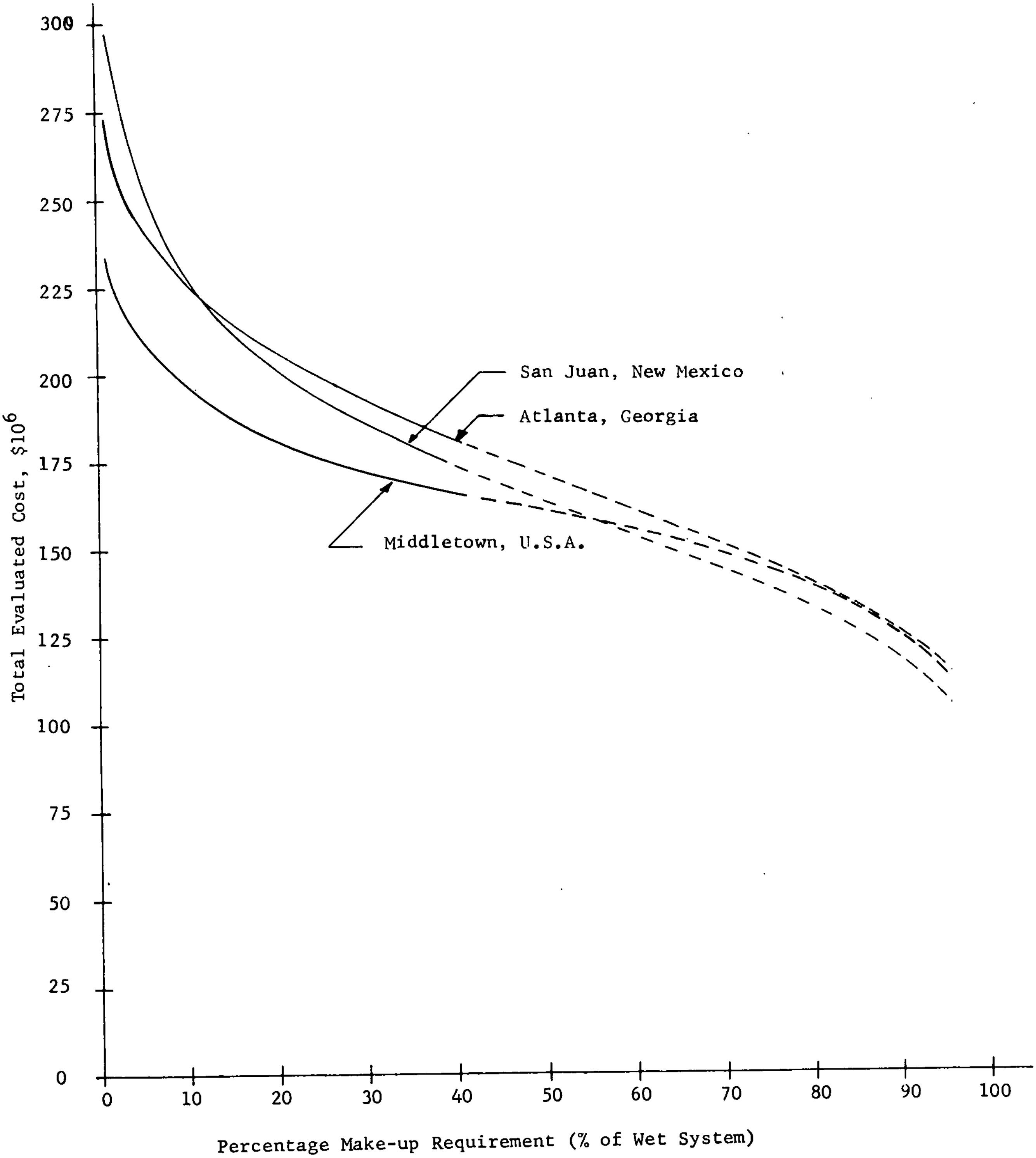



Figure 7.7 Comparison of Alternate Sites

# CHAPTER 8

## ECONOMIC SENSITIVITY ANALYSIS

### 8.1 INTRODUCTION

The results of the analysis reported in Chapters 5 and 6 are valid for power plants designed to be operational in 1985, if the economic factors used in the projection remain in force during the next decade. If the economy of the United States changes during the next decade, an adjustment of the costs must be made. If the economic factors change significantly, the optimum design may also change.

For these reasons, a comprehensive economic sensitivity analysis of all the cooling systems at each site was completed to determine the effects that changes in the economic parameters will have on system size, capital cost and the total evaluated cost. The principal economic factors which influence the cooling system design selection and system costs are: replacement capacity charge ($/kWe), fuel cost ($/MBtu or $/Joule), annual fixed charge rate (percent) and escalation rates of material, equipment and labor (percent). These factors were varied systematically to determine their effect on system costs.

An important aspect of wet/dry cooling system evaluation is an assessment of the impact of water supply costs on the economic comparison of wet and wet/dry cooling. Sensitivity analysis of water supply cost was performed and is described in this chapter.

### 8.2 METHODS OF ECONOMIC SENSITIVITY ANALYSIS

All of the systems described in Chapters 5, 6 and 7 were optimized using a base set of economic data representative of a 1985 start-up date. These systems are referred to as the "base systems".

The economic sensitivity analysis is divided into two parts. In the first part, each cooling system was reoptimized using the economic factors shown in Table 8.1. This part of the sensitivity analysis is called "optimization analysis". For this optimization, each of the four factors was varied sequentially while keeping the other three factors constant. In this way, optimized systems for each new set of economic factors were obtained.

A second part of the sensitivity analysis is called "transfer analysis". In this analysis, the "base system" design is kept unchanged, and the individual elements of the capital and penalty costs are adjusted by prorating the cost elements affected by the new economic factors. Finally, a comparison is made between the results of the "transfer" and "optimization" analyses.

The objectives of the sensitivity analysis were: 1) to determine how much change would occur in the total evaluated cost of each of the optimized cooling systems in response to the changes in economic factors; 2) to determine how sensitive is the selection of the optimum design to changes in the economic factors; 3) to determine whether the "transfer" type analysis can be used to estimate the minimum total evaluated cost of cooling systems without introducing significant errors; and 4) to determine the impact of water supply cost on the economic comparison of wet and wet/dry cooling.

## 8.3 RESULTS OF ECONOMIC SENSITIVITY ANALYSIS

### 8.3.1 Optimization Analysis

The economic sensitivity analyses were performed for the three sites: Middletown; Atlanta, Georgia; and San Juan, New Mexico. The results obtained for all the sites are similar; therefore, typical results for iddletown are reported in this section. Sensitivity analysis results for San Juan and Atlanta and a part of the sensitivity results for the Middletown site are included in Appendix I.

Figures 8.1 through 8.4 illustrate the changes in total evaluated cost of the optimized wet/dry systems, as each of the economic factors are varied from the base value. The sensitivity of the total evaluated cost corresponding to the change in economics is shown in Table 8.2. In this table, the data are given in terms of percentage change in the total evaluated costs relative to the base values.

The results presented can be used to estimate the total evaluated costs of the tower systems for economic factors other than those used in the base analysis. For example, if $1,000/kWe is to be used for the capacity charge, the impact of this value on total evaluated cost can be determined by interpolation the data given in Figure 8.2 or Table 8.2.

8.3.2 <u>Transfer Analysis</u>

Transfer analysis is performed by taking the "base system" design and adjusting the total evaluated cost for the new economics. For example, if the escalation rate was 12 percent per year, rather than 6 percent, all of the capital cost elements would be increased proportionately to provide a new total evaluated cost value. Comparisons of the results of the "transferred analysis" and the optimization analysis are shown in Figures 8.5 through 8.8. The format for each of the figures is described below:

1. a single bar representing the optimum base 1985 cooling system (fixed charge rate of 18 percent, fuel cost of $1.53/MBtu ($1.45/GJ), replacement capacity of $600/KWe, material escalation multiplier

of 1.91 and labor escalation multiplier of 2.29);

2. two sets of bars which represent the impact of the fixed charge rate (12.5% and 25%);
3. three sets of bars which represent the impact of material/labor cost escalations (0%/0%, 12.2%/16.6%, 19%/21%);
4. three sets of bars which represent the three fuel costs ($0.76, $3 and $6/MBtu ($0.72, $2.84 and $5.68/GJ)); and,
5. three sets of bars which represent the three replacement capacity charges ($300, $900 and $1,200/kWe).

By referring to the results shown in Figures 8.5 through 8.8, the following observations can be made:

1. In most cases, variations of economic factors result in different optimum cooling system designs. This is reflected in the bar graphs by the difference in capital costs between the optimized systems and the "transferred" systems. Among the four factors studied, the trend is as follows:
   a) Capital cost escalations (material and labor) have the strongest effect on the selection of the optimized systems. In almost all cases involving the effect of capital cost escalation, the reoptimized systems result in significantly different designs compared to the "transferred" systems.
   b) Variation of annual fixed charge rate has no effect on the selection of optimum systems, resulting in the same design and cost between the optimized and the "transferred" systems.

2. Even for the large variations used in this study, e.g., material and labor cost escalations which are three times the base value, fuel charges six times the base value and capacity charges two times the base value, the difference in total evaluated cost between the optimized and transferred systems is less than four percent.

### 8.3.3 Conclusion of Economic Sensitivity Analysis

An important conclusion can be drawn from the sensitivity analysis which is useful for cost estimating purposes. In response to changing economics, the minimum total evaluated cost of a cooling system can be estimated from an optimized "base system" without requiring reoptimization using the new set of economic factors. The adjustment can be made by simply prorating the cost elements comprising the total evaluated cost of the base system.

## 8.4 WATER SUPPLY COST ANALYSIS

### 8.4.1 Economic Sensitivity

In performing the design and evaluation of a wet/dry cooling system for a specific percentage make-up requirement, the optimization analysis is independent of water supply cost. All systems designed for a specific percentage make-up require the same amount of water and the same water supply cost. Thus, in making a comparison among the wet and wet/dry systems designed for different percentage make-up requirements, the specific water supply cost for each system should be determined and added to the total evaluated cost of each system.

The impact of the water supply cost on an economic comparison of the wet/dry systems was shown in Figure 5.7. The basic analysis reported in Chapters 5, 6 and 7 was performed using a water supply cost of \$0.27/1000 gal (\$0.07/$m^3$). This cost was uniformly increased, first to \$2/1000 gal (\$0.53/$m^3$) and then in \$2 (\$0.53) increments to \$8/1000 gal (\$2.12/$m^3$).

For study purposes, this type of analysis is useful to understand the water supply costs needed to obtain economic par for wet/dry systems compared to wet systems.

8.4.2 Site Specific Analysis

For comparison with the uniform water supply cost analysis, an evaluation was performed for cooling systems designed for Middletown. The river which provides the make-up was assumed to be from 1 to 29 miles (1.6 to 46.7 km) away from the plant. It was further assumed that legal restrictions limit consumptive use of water to a fixed percentage of the average daily river flow. Although there is sufficient water available for the wet tower make-up over most of the annual cycle, low river water flow during September to December requires the use of a storage impoundment to augment the maximum allowable river withdrawal. Details of the available water and cooling system flow requirements are described in Appendix I.

The wet/dry systems also require some on-site impoundments to satisfy system requirements in the event of a make-up pump or pipeline failure. The impoundments for the wet/dry systems are large enough to provide make-up water for two days at the maximum consumption rate.

he results of this analysis are given in Tables 8.3 and 8.4. Table 8.3 summarizes the total costs of the make-up supply systems which include the capital and pumping costs of these systems. Table 8.4 lists the capital cost elements included in the make-up systems and provides data for the 29 mile (46.7 km) pipeline case. The costs given in Table 8.3 for the 1 to 29 mile (1.6 to 46.7 km) pipeline cases are added directly to the base total evaluated costs of various cooling systems. The final results are shown in Figure 8.9. The figure illustrates the impact of additional water supply cost on the economic comparison of wet and wet/dry systems. These sample cases show that while the total evaluated cost difference between the wet and wet/dry systems can be narrowed significantly for higher water cost, the wet system remains the economic choice where water is available.

Water supply conditions vary for different plant sites and different locations in the United States, and as shown in this analysis, these conditions impact significantly the costs of the heat rejection systems. Thus, the site specific water supply costs should be developed during a preliminary engineering or site selection phase of an engineering program. and added to the total evaluated cost of the cooling system to compare the costs of the wet and wet/dry options.

TABLE 8.1

FACTORS USED FOR ECONOMIC SENSITIVITY ANALYSIS

| Variable | | BASE 1985 | 1 | 2 | 3 |
|---|---|---|---|---|---|
| Replacement Capacity, $/kWe | | 600 | 300 | 900 | 1,200 |
| Fuel Cost, Cents/MBtu (¢/GJ) | | 153 (145) | 76 (72) | 300 (284) | 600 (568) |
| Annual Fixed Charge Rate, $ | | 18 | 12.5 | 25 | --- |
| ESCALATION MULTIPLIER (ANNUAL RATE) | MATERIAL AND EQUIPMENT | 1.91 (6.0%) | 1.10 (0.0%) | 3.30 (12.2%) | 5.75 (19.0%) |
| | LABOR | 2.29 (8.0%) | 1.10 (0.0%) | 4.75 (16.6%) | 6.75 (21.0%) |

# TABLE 8.2

## IMPACT OF CHANGING ECONOMICS ON TOTAL EVALUATED COST (MIDDLETOWN, MECHANICAL SERIES, S1 MODE)

| Sensitivity Parameters | | Percentage Change from Base Optimum, % | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Mech. Dry* | Make-up Water Requirements - Mech. Series Wet/Dry | | | | | Mech. Wet |
| | | | 1% | 10% | 20% | 30% | 40% | |
| Annual Fixed Charge Rate, % | = 12.5 | + 11.9 | + 6.6 | + 8.0 | + 8.5 | + 9.6 | + 9.9 | + 8.8 |
| [18] ** | = 25.0 | - 9.2 | - 4.2 | - 5.1 | - 5.4 | - 6.1 | - 6.3 | - 5.6 |
| Fuel Cost, $/MBtu ($/GJ) | = .76 (.72) | - 12.1 | - 5.7 | - 7.1 | - 8.1 | - 8.6 | - 8.8 | - 6.1 |
| [1.53 (1.45)] ** | = 3.00 (2.84) | + 23.2 | + 10.9 | + 13.6 | + 14.4 | + 16.2 | + 15.8 | + 11.4 |
| | = 6.00 (5.68) | + 70.3 | + 33.2 | + 39.1 | + 41.3 | + 44.6 | + 45.1 | + 33.4 |
| Replacement Capacity Cost, $/kW | = 300 | - 19.1 | - 11.1 | - 10.8 | - 9.9 | - 9.6 | - 9.6 | - 12.1 |
| [600] ** | = 900 | + 17.4 | + 11.1 | + 11.0 | + 10.9 | + 11.0 | + 11.0 | + 11.2 |
| | = 1,200 | + 34.1 | + 22.2 | + 20.0 | + 18.7 | + 19.1 | + 18.4 | + 21.8 |
| Escalation Multiplier (Material/Labor) | = 1.1/1.1 | - 17.8 | - 29.6 | - 29.6 | - 29.5 | - 29.0 | - 29.3 | - 28.5 |
| [1.91/2.29] ** | = 3.30/4.75 | + 29.3 | + 53.3 | + 50.3 | + 50.2 | + 50.7 | + 48.4 | + 48.7 |
| | = 5.75/6.75 | + 71.8 | +131. | +122. | +118. | +117. | +111. | +109. |

* High back pressure turbine
** Base economic value

| | Mech. Dry* | Make-up Water Requirements - Mech. Series Wet/Dry | | | | | Mech. Wet |
|---|---|---|---|---|---|---|---|
| | | 1% | 10% | 20% | 30% | 40% | |
| Base Total Evaluated Cost, $$10^6$ | 297.30 | 233.84 | 195.91 | 181.17 | 171.70 | 166.84 | 98.10 |

TABLE 8.3

SUM OF CAPITAL AND PUMPING COSTS ($$10^6$) OF MAKE-UP SUPPLY FOR SPECIAL CONDITIONS AT MIDDLETOWN

| Cooling Tower System | Impoundment Size, acre-foot ($10^4$ $m^3$) | Pipeline Length, mile (km) | | | |
|---|---|---|---|---|---|
| | | 1 (1.6) | 10 (16.1) | 20 (32.2) | 29 (46.7) |
| Wet | 2295 (283.1) | 34.61 | 40.84 | 48.74 | 57.57 |
| 40% Wet/Dry | 135 ( 16.6) | 5.53 | 10.72 | 17.34 | 24.45 |
| 10% Wet/Dry | 60 ( 7.4) | 3.96 | 8.24 | 14.04 | 19.98 |
| 1% Wet/Dry | 30 ( 3.7) | 2.61 | 5.58 | 9.39 | 13.41 |

TABLE 8.4

CAPITAL COST ($$10^6$) FOR A MAKE-UP SUPPLY SYSTEM WITH A 29 MILE (46.7 KM) PIPELINE AND IMPOUNDMENT

| Equipment Item | 1% Wet/Dry | 10% Wet/Dry | 40% Wet/Dry | Wet |
|---|---|---|---|---|
| Pipeline (Installed) | 7.825 | 11.690 | 13.460 | 15.959 |
| Intake Structure at River | 0.933 | 1.302 | 1.533 | 1.743 |
| Intake Pumps and Motors | 0.763 | 1.005 | 1.194 | 1.296 |
| Electrical Equipment | 0.327 | 0.413 | 0.451 | 0.530 |
| Impoundment Pond | 0.317 | 0.633 | 1.425 | 24.228 |
| Intake Structure, Pumps and Motors at Impoundment | 0.533 | 0.747 | 0.878 | 0.994 |
| Direct Capital Cost of Water Supply System | 10.698 | 15.790 | 18.941 | 44.750 |
| Indirect Cost | 2.675 | 3.948 | 4.735 | 11.188 |
| Total Capital Cost of Water Supply System | 13.373 | 19.738 | 23.676 | 55.938 |

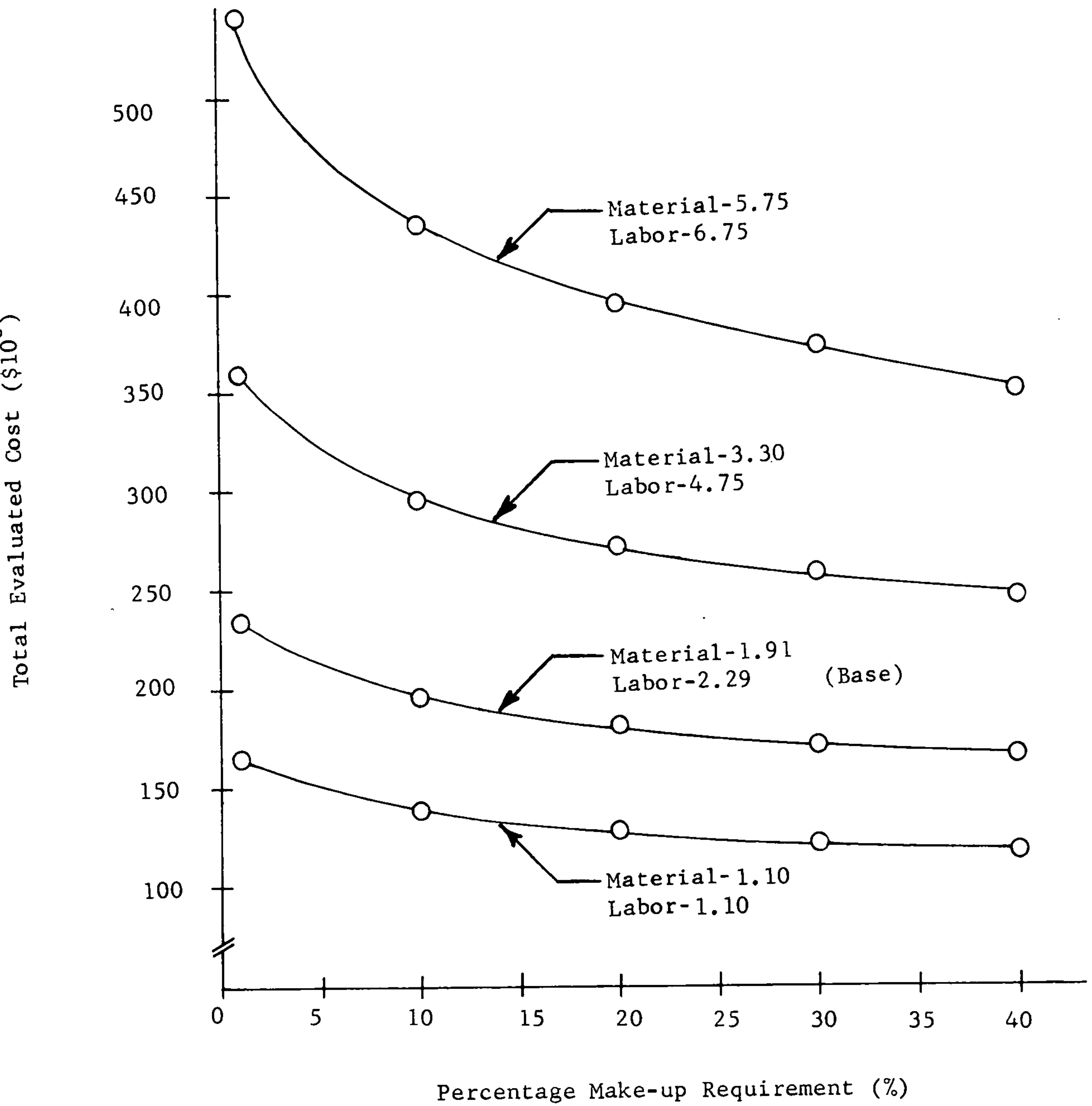



Figure 8.1 Effect of Material and Labor Escalation Rates on Total Evaluated Cost for the Wet/Dry Systems (Middletown, Mechanical Series)

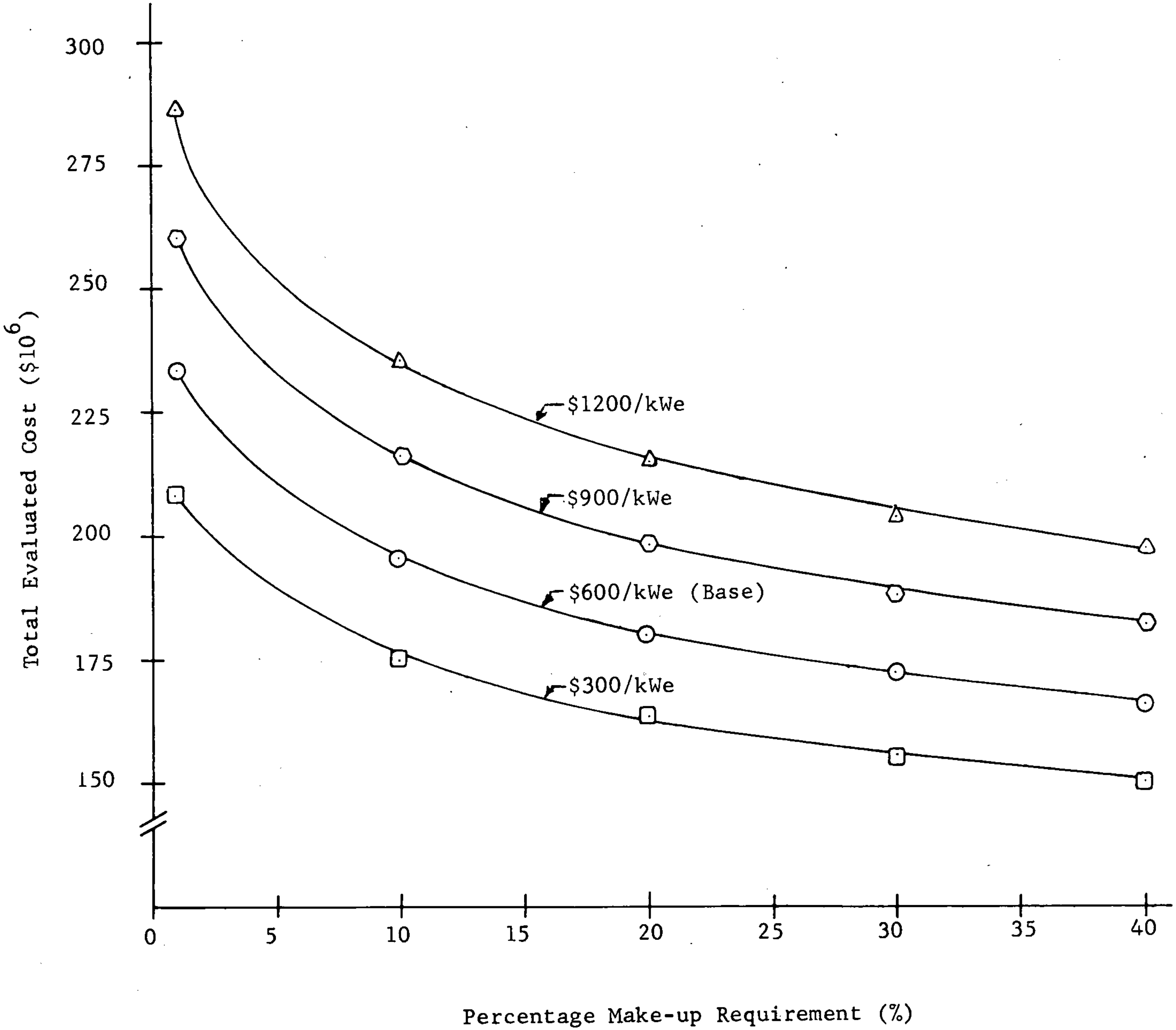



Figure 8.2 Effect of Replacement Capacity on Total Evaluated Cost for the Wet/Dry Systems (Middletown, Mechanical Series)

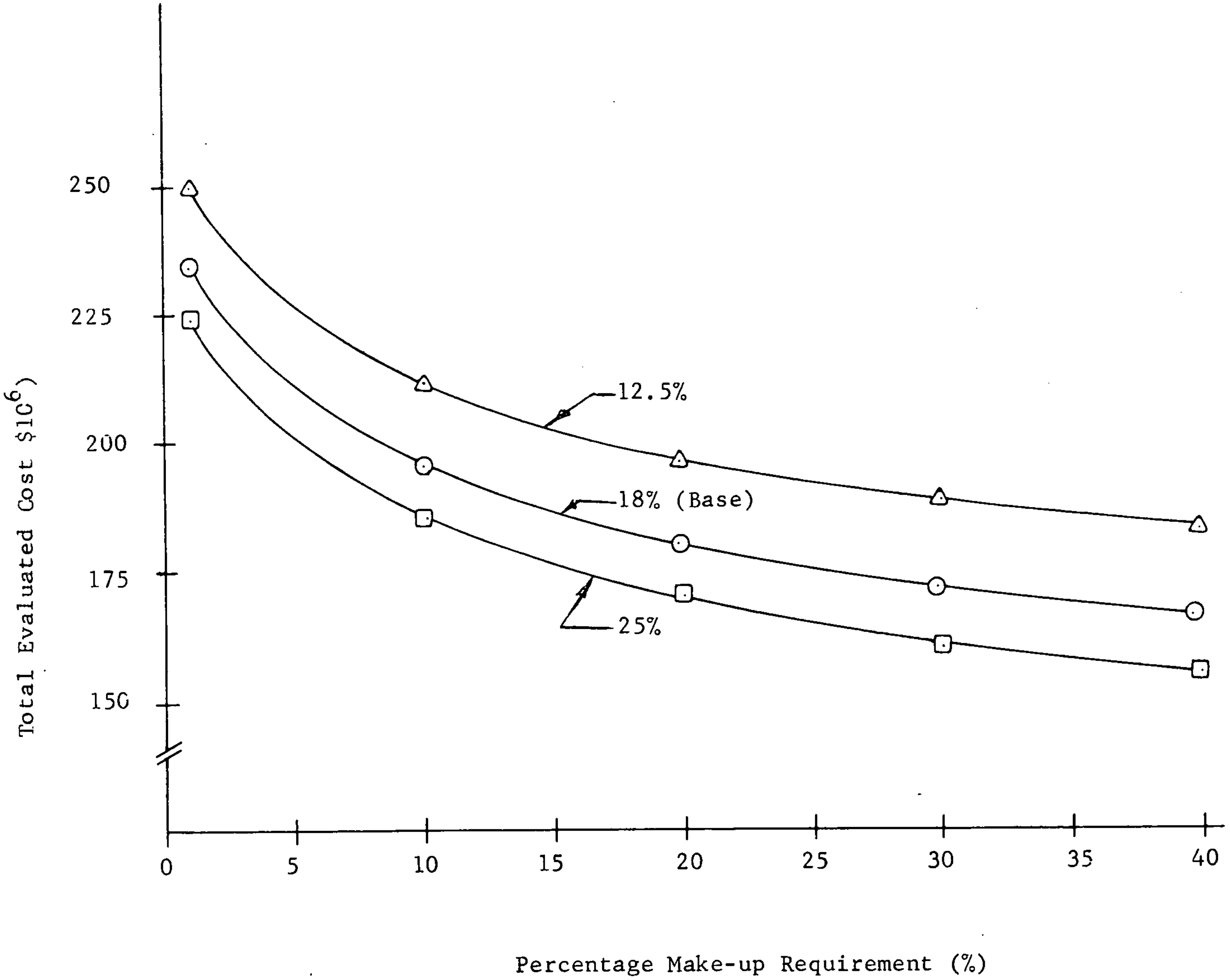



Figure 8.3 Effect of Annual Fixed Charge Rate on Total Evaluated Cost For the Wet/Dry Systems (Middletown, Mechanical Series)

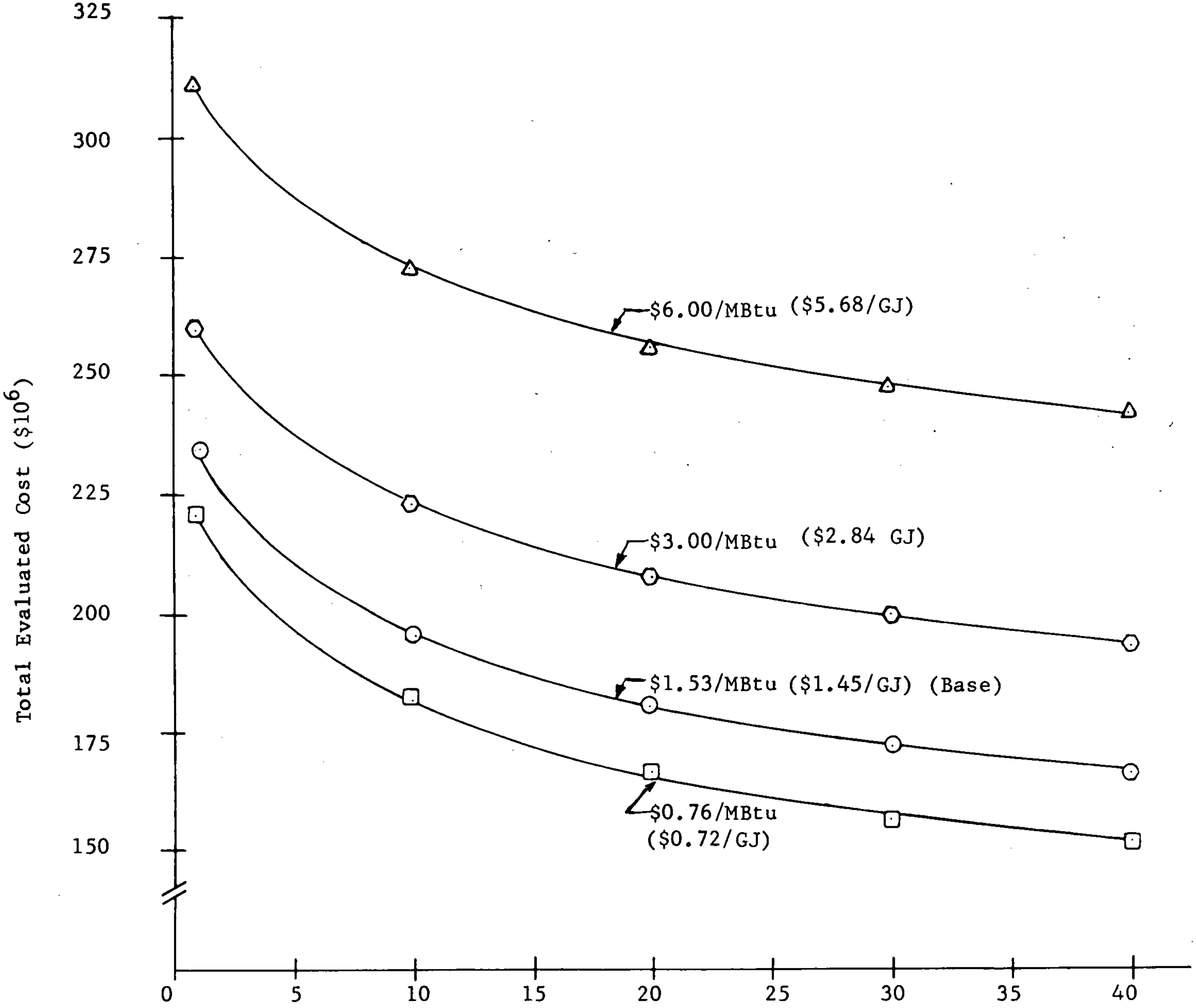



Figure 8.4 Effect of Fuel Cost on Total Evaluated Cost for the Wet/Dry Systems (Middletown, Mechanical Series)

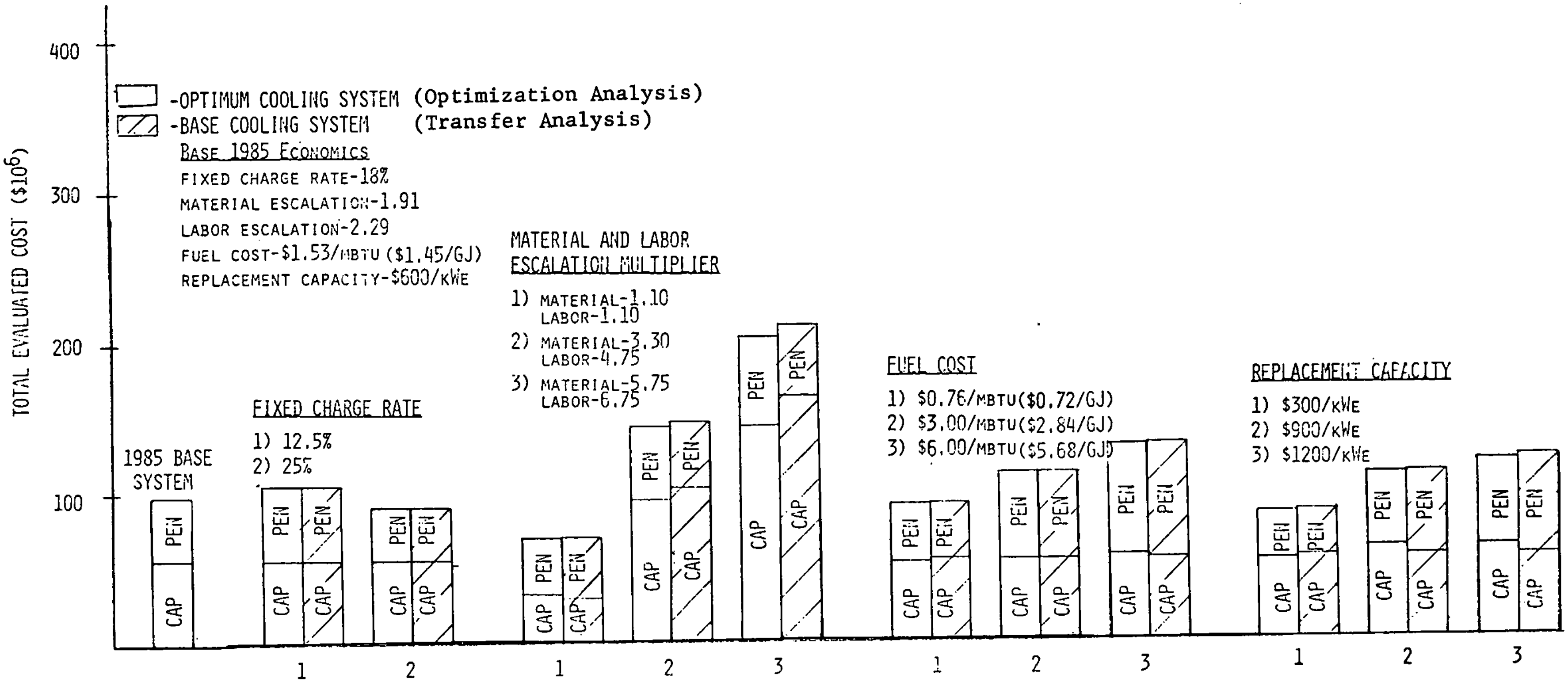



Figure 8.5 Effect of Economic Factors on Costs Obtained by Optimization and Transfer Analyses (Middletown, Mechanical Wet)

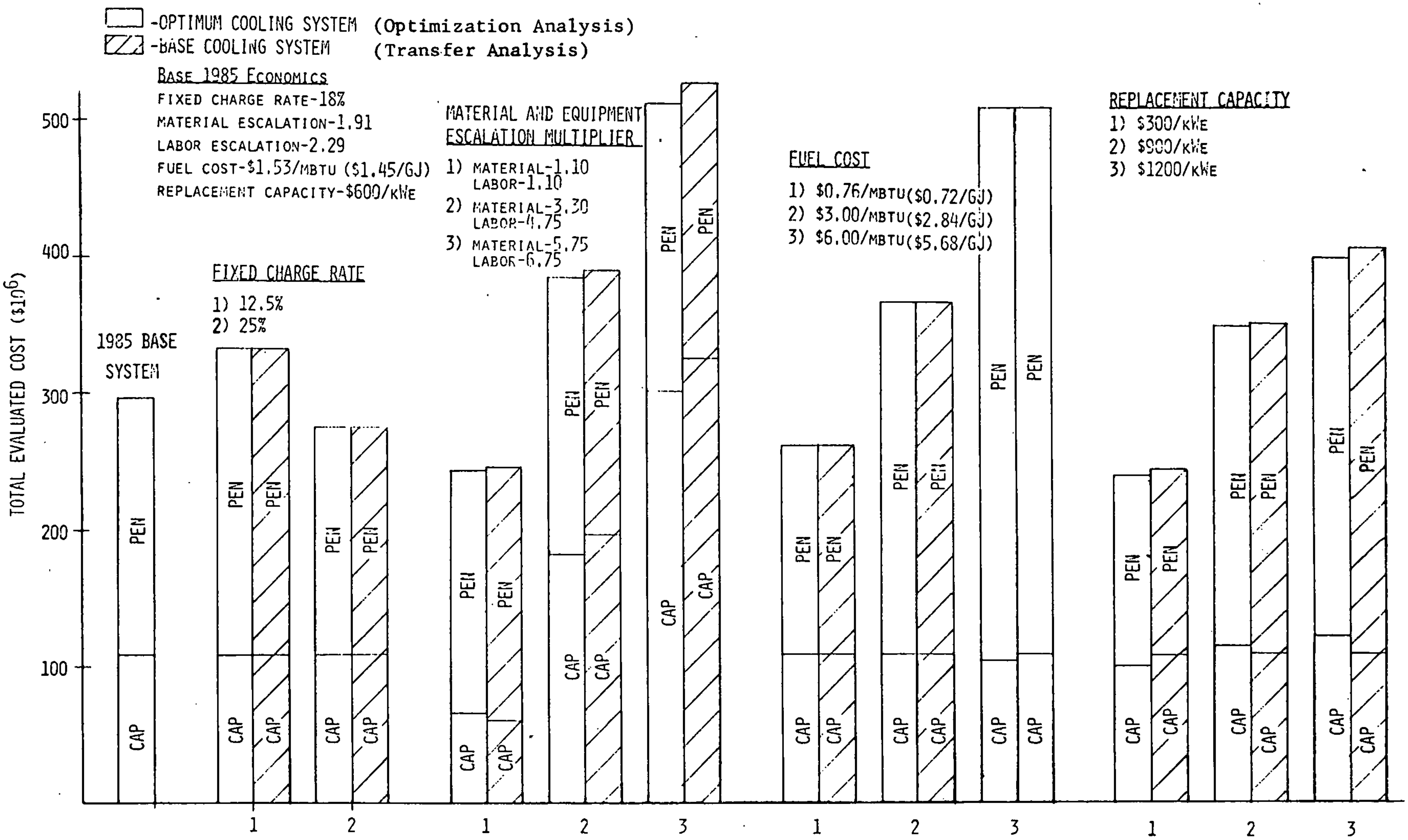



Figure 8.6 Effect of Economic Factors on Costs Obtained by Optimization and Transfer Analyses (Middletown, Mechanical Dry)

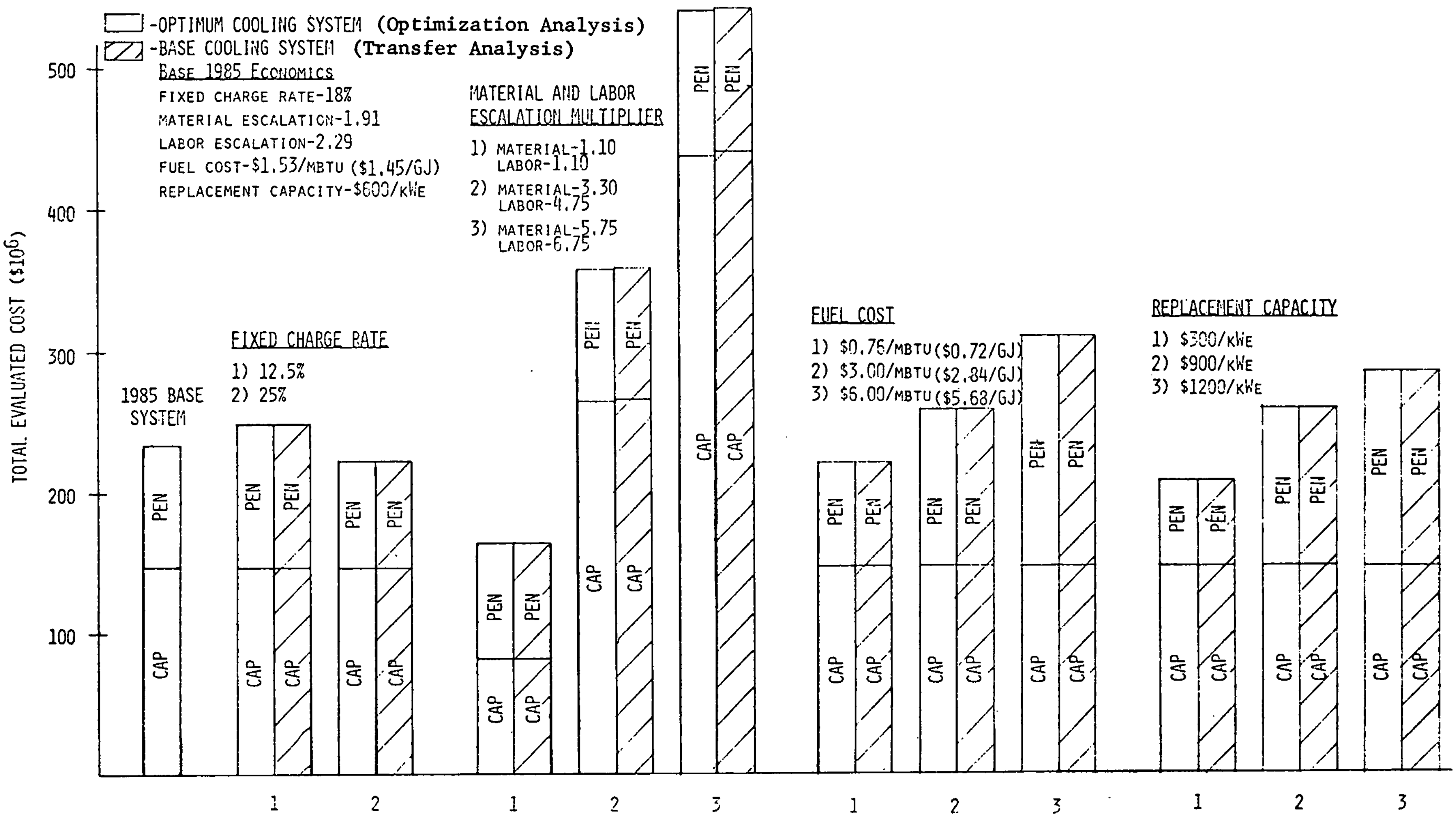



Figure 8.7 Effect of Economic Factors on Costs Obtained by Optimization and Transfer Analyses (Middletown, 1% Wet/Dry)

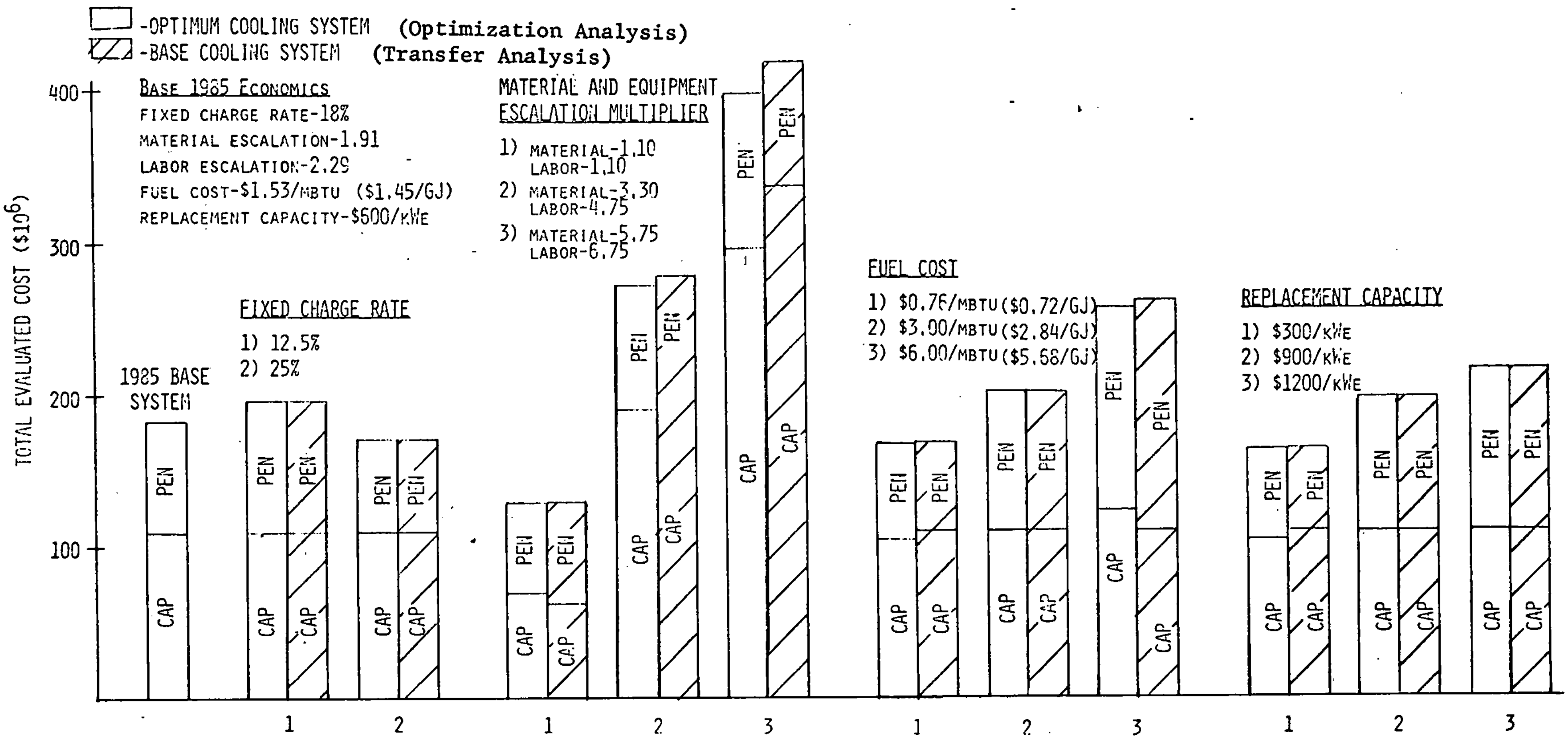



Figure 8.8 Effect of Economic Factors on Costs Obtained by Optimization and Transfer Analyses (Middletown, 20% Wet/Dry)

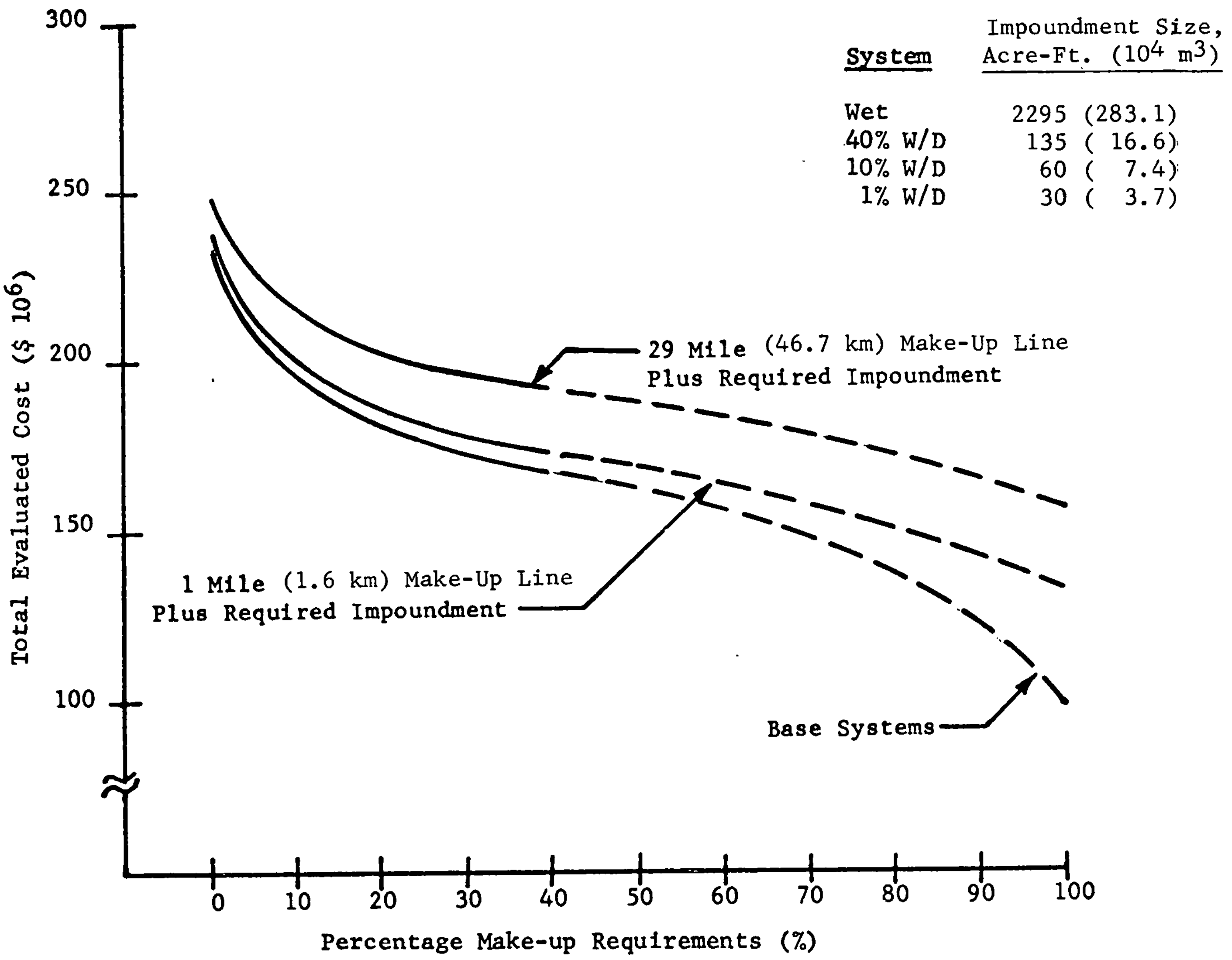



Figure 8.9 **Cooling System Costs Incorporating Extended Water Supply Lines and Impoundments**

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# APPENDIX A

## ASSESSMENT OF ECONOMIC FACTORS

A brief economic analysis was made to obtain a number of the economic factors used in this report. The economic climate, utility make-up, financial standing and performance, capital floatation costs and the general complexity of these factors are beyond the scope of this document.

The values described here represent approximations obtained by means of simplified economic equations to establish the major components of the economic factors used in this study.

### Interest Rate

The interest rate used in power plant analysis represents an average cost of capital to the utility. This cost of capital for most utilities includes a cost associated with common equity, preferred stock and debt. The table shown below indicates how the cost of capital was obtained. A general rate of inflation of 6 percent was assumed. The fraction of capitalization was assumed based on typical utility operation.

| COMPONENT | FRACTION OF CAPITALIZATION | COMPONENT COST (%) | WEIGHTED COST (%) |
|---|---|---|---|
| COMMON EQUITY | 0.35 | 12 | 4.2 |
| PREFERRED STOCK | 0.10 | 10 | 1.0 |
| DEBT | 0.55 | 9 | 4.9 |
| TOTAL | | | 10.1 |

Fixed Charge Rate

There are certain fixed charges, dependent only upon the initial investment, which a utility will incur every year for the life of the plant. The higher the initial investment, the more these fixed charges will be. The annual fixed charges are given by:

$$F = P + D + S + T$$

where:

P = annual charges for property taxes and insurance

D = annual depreciation of the plant

S = annual return on investment

T = annual income taxes

S is equal, in our analysis, to the cost of capital which is 10 percent. The other factors represent an additional 8 percent, thus, the resulting fixed charge rate is 18 percent.

Capital Cost Escalation

All capital costs are presented in a manner that reflects a January, 1985 start up. Costs were escalated from a capital cost data base representing July, 1974 costs. The base escalation multipliers are 1.91 and 2.29 for material and labor respectively; these were calculated using annual escalation rates of 6 percent for material and 8 percent for labor and an interest rate of 10 percent. The construction period for the cooling system is assumed to be two years.

Base costs were escalated to the midpoint of construction, and interest during construction was computed from the midpoint of construction to the date of operation. The particular cash flow curve for the cooling system was not considered; however, experience at UE&C has shown that this method is an excellent approximation when the construction period is short.

The base escalation multipliers were determined as follows:

Material: $(1.06)^{9.5 \text{ years}} (1.10)^{1.0 \text{ year}} = 1.91$

Labor: $(1.08)^{9.5 \text{ years}} (1.10)^{1.0 \text{ year}} = 2.29$

Capacity Penalty Charge Rate

For all the base analysis presented in this report, an incremental base load plant cost of $600/kW was used for the replacement capacity penalty charge. The value represents the capital cost assigned to the incremental capacity of the same type but next larger size unit than the reference plant. This capacity penalty was calculated using the cost data given in Reference 18.

Fuel Cost

For the base analysis reported in Chapters 5, 6, and 7, a nuclear fuel cost of 153¢/MBtu (145¢/GJ) was used. This value represents a fuel cost of 90¢/MBtu in 1985, which is then levelized over the 40 year lifetime of the plant with an escalation rate of 4 percent per year.

# APPENDIX B

## DESIGN AND OPERATIONAL CHARACTERISTICS

This appendix presents a brief description of the design and operation of mechanical draft wet, mechanical draft dry, and natural draft dry cooling systems.

## APPENDIX B

## DESIGN AND OPERATIONAL CHARACTERISTICS

The wet/dry cooling system alternatives studied are designed with separate wet and dry towers. Each of these towers represents equipment which is currently available with the possible exception of the natural draft dry tower.

### Mechanical Draft Wet Cooling Tower

In the evaporative or wet cooling tower systems, most of the waste heat is dissipated to the atmosphere by evaporation of a small portion of the cooling water. Circulating water from the plant condensers is pumped to the top of the tower fill or packing material; the water then flows or splashes down through the fill to the water collecting basin while air sweeps either up or across the fill area. As the water and air come in contact, a small portion of the water becomes vaporized, thus carrying with it the latent heat of evaporation. In the process, air is humidified and the remaining unvaporized water is cooled.

The mechanical draft wet cooling tower is designed to cause a large water surface to come in contact with moving air which is forced through the tower by fans.

The basic components of the tower system are: (1) tower framework, (2) water distribution system, (3) fill or packing material, (4) drift eliminators, (5) inlet louvers, (6) water collecting basin, and (7) fans.

Dry Cooling Towers

The dry cooling tower utilizes a heat transfer surface to reject heat to the atmosphere by convective heat transfer rather than by direct heat and mass transfer between water and air. Circulating water from the condensers passes through heat transfer coils in the dry tower and returns to the condenser after being cooled in the tower in a completely closed loop.

Mechanical draft dry towers have been used for many years in the process industry. Dry towers, because of their relatively high cost as compared to wet (evaporative) towers, have not found wide acceptance among the utilities in this country.

Mechanical Draft Dry Cooling Tower

In the mechanical draft dry cooling tower, ambient air is forced by fans to pass over the heat transfer coils. The coils are made of finned tubes and are arranged in modules or cells. Each cell is complete with a fan, much as the mechanical draft wet cooling tower.

Natural Draft Dry Cooling Tower

The natural draft dry cooling tower differs from the mechanical draft dry cooling tower in that it relies on the density difference between the colder ambient air and the warmer air inside the tower stack to produce the necessary buoyant force to induce air flow.

The tower structure is similar to that of the natural draft wet cooling tower, i.e. hyperbolic shape of concrete construction. The heat exchanger elements in the form of modules are located at the bottom of the tower. These modules are lined up either vertically along the circumference behind the inlet louvers or horizontally inside the tower above the inlet louvers.

# APPENDIX C

## MAJOR EQUIPMENT LIST

This appendix describes the design specifications of the major equipment components of the cooling systems evaluated. The cooling tower descriptions refer both to the reference systems and to the components used in the wet/dry cooling systems.

TABLE C-1. MAJOR EQUIPMENT LIST

| Item | Description |
|---|---|
| Condensers | Each cooling system has three field-tubed main surface condensers with fabricated steel water boxes and steel shell. Each condenser has 1-inch (2.54 cm) O.D., 20 BWG gauge, 304 stainless steel tubes and a design water velocity of 7.0 ft/sec (2.1 m/sec). Each condenser has two tube passes. |
| Circulating Water Pumps and Motors | The circulating water pumps are each of the vertical, wet pit, motor driven type with 4160 volts, 3 phase, 60 cycle motors. The pumps have carbon steel casings with chrome steel shaft and bronze impeller. |
| Cooling Towers | The following are descriptions of the cooling towers. |
| A) Mechanical Draft Wet Cooling Tower | The mechanical draft wet tower cells or modules are the induced draft, cross-flow type of concrete construction with 41 feet (12.5 m) fill height. Each cell has a separate fan; the fan has a diameter of 28 feet (8.6 m) and is driven by a 200 horsepower (149 KW) motor. The cell dimensions are 71 feet (21.6 m) wide, 36 feet (11.0 m) long, and 54 feet (16.5 m) high. |
| E) Mechanical Draft Dry Tower | The mechanical draft dry tower cells are the induced flow type. The cells are arranged back-to-back to form towers. Each cell has 776 tubes arranged in two passes and equipped with a 150 horsepower (111.9 KW) motor and 28-foot (8.6 m) diameter fan. The cell dimensions are 41 feet (12.5 m) wide, 61 feet (18.6 m) long and 65 feet (19.8 m) high. The finned tube heat exchangers have 1-inch (2.54 cm) o.d. admiralty tubes with 10 aluminum fins/inch (3.94 fins/cm) and a fin height of 0.625 inches (1.59 cm). |
| F) Natural Draft Dry Tower | The natural draft tower has a hyperbolic concrete shell with a maximum base diameter of 500 feet (152.4 m) and a minimum thickness of six inches (15.24 cm). The finned tube heat exchanger modules are arranged vertically around the tower base. Each module has 264 tubes in two passes. The tubes are of 1-inch (2.54 cm) O.D. admiralty and have 10 aluminum fins/inch (3.94 fins/cm) with a fin height of 0.625 inches (1.59 cm). |

# APPENDIX D

## DESCRIPTION OF CODES OF ACCOUNTS FOR CAPITAL COST ELEMENTS

This appendix contains the definitions of ERDA's capital cost account numbers used to identify detailed capital cost data for nuclear power plants that are given in Appendices E, F and G.

In the capital cost list, the total indirect charges were assumed to be a constant 25 percent of the total direct capital cost. The direct capital cost items are identified by letters as described below:

| Letter | Cost Item |
|---|---|
| L | Labor |
| E | Equipment (pump, cooling tower, etc.) |
| M | Material (pipe, cable, etc.) |
| T | Total (L + E + M) |

TABLE D-1

DESCRIPTION OF CODES OF ACCOUNTS FOR CAPITAL COST ELEMENTS

| Account Number | Description |
|---|---|
| 218L | Circulating Water Pump Structures<br><br>Circulating water pump house; including concrete work, excavation and backfill, temporary sheeting, stop logs, rip-rap, permanent sheet piling, miscellaneous iron, trash racks, screens, and screen wash pumps. |
| 232.2 | Circulating Water System<br><br>This includes:<br><br>1) Circulating water pumps and drives.<br><br>2) Circulating water intake, discharge and connecting pipe-lines. Excavation, backfill, supports, etc. |
| 232.3 | Cooling Towers<br><br>This includes:<br><br>1) Cooling tower basins and foundations, excavation and backfill, forms, reinforcing steel, concrete, concrete finish and miscellaneous iron.<br><br>2) Cooling Towers (mechanical draft dry, mechanical draft wet, natural draft dry) |
| 233.1 | Condensers |
| 24 | Electrical Equipment<br><br>This includes:<br><br>1) Station Service - switchgear and controls for traveling screens, trash rake, circulating water pumps, screen wash pumps, and cooling tower fans.<br><br>2) Station Service and Startup Transformers - the incremental transformer capacities involved.<br><br>3) Cable Trays and Supports.<br><br>4) Conduit<br><br>5) Station Service Power Wiring |

# APPENDIX E

## DETAILED DATA FOR MIDDLETOWN, U.S.A. SITE

This appendix contains data for cooling systems interfaced with LWR power plants sited at Middletown, U.S.A. Detailed design data, capital cost breakdowns and penalty breakdowns are presented for the reference cooling systems and three types of wet/dry cooling systems.

Tables E-1 through E-3 present data for the reference cooling systems.

Tables E-4 through E-6 present data for the mechanical series wet/dry cooling systems operating in the S1 mode.

Tables E-7 through E-9 present data for the mechanical series wet/dry cooling systems operating in the S2 mode.

Tables E-10 through E-12 present data for the mechanical parallel wet/dry cooling systems operating in the P1 mode.

Tables E-13 through E-15 present data for the natural series wet/dry cooling systems operating in the S1 mode.

The account numbers and abbreviations used in Tables E-2, E-5, E-8, E-11 and E-14 are explained in Appendix D.

Figures E-1 through E-7 provide the performance information for the reference cooling systems and the mechanical series wet/dry cooling systems operating in the S1 mode.

TABLE E-1 (sheet 2 of 3)

DESIGN DATA FOR THE OPTIMIZED REFERENCE COOLING SYSTEMS

SITE: MIDDLETOWN, U.S.A.

| Variable | Mechanical Dry (High BP Turbine) | Mechanical Dry (Low BP Turbine) | Mechanical Wet (Low BP Turbine) |
|---|---|---|---|
| Condenser | | | |
| Surface Area, $10^3$ $ft^2$ ($10^3$ $m^2$) | 1140 (105.9) | 1522 (141.4) | 1006 (93.5) |
| Number of Tubes | 84,500 | 162,100 | 68,900 |
| Tube Length, ft (m) | 51.5 (15.7) | 35.9 (10.9) | 55.8 (17.0) |
| Circulating Water Flow & Pump | | | |
| Circulating Water Flow Rate, $10^3$ gpm ($m^3$/min) | 628 (2377) | 1204 (4558) | 512 (1938) |
| Number of Pumps | 4 | 7 | 3 |
| Pumping Head, ft (m) of Water | 60.7 (18.5) | 52.1 (15.9) | 87.7 (26.7) |
| Motor Rating, hp (kW) per pump | 3000 (2237) | 3000 (2237) | 4500 (3356) |
| Motor Brake Horsepower, hp (kW) per pump | 2705 (2017) | 2540 (1894) | 4250 (3169) |

TABLE E-1 (sheet 1 of 3)

DESIGN DATA FOR THE OPTIMIZED REFERENCE COOLING SYSTEMS

SITE: MIDDLETOWN, U.S.A.

| Variable | Mechanical Dry (High BP Turbine) | Mechanical Dry (Low BP Turbine) | Mechanical Wet (Low BP Turbine) |
|---|---|---|---|
| General Design Data | | | |
| Design Temperatures, °F (°C): | | | |
| Dry Bulb | 93.0 (33.9) | 96.0 (35.6) | 93.0 (33.9) |
| Wet Bulb | 74.0 (23.3) | 75.0 (23.9) | 74.0 (23.3) |
| Cold Water | 135.0 (57.2) | 114.0 (45.6) | 91.0 (32.8) |
| Cooling Range | 24.0 (13.3) | 12.0 (6.7) | 28.0 (15.6) |
| ITD (Dry Tower) or Approach (Wet Tower) | 66.0 (36.6) | 30.0 (16.7) | 17.0 (9.4) |
| Design Turbine Back Pressure, in-HgA (mm-HgA) | 10.61 (269.5) | 4.65 (118.1) | 3.85 (97.8) |
| Maximum Operating Back Pressure, in-HgA (mm-HgA) | 12.51 (317.8) | 5.06 (128.5) | 3.90 (99.1) |
| Design Heat Load, $10^9$ Btu/hr ($10^{12}$ J/hr) | 7.54 (7.95) | 7.23 (7.62) | 7.17 (7.56) |
| Plant Capacity at Cooling System Design Point, MWe | 965 | 1056 | 1073 |
| Annual Make-up Water Requirement, $10^8$ gal. ($10^6$ $m^3$) | 0.0 | 0.0 | 42.34 (16.03) |

TABLE E-1 (sheet 3 of 3)

DESIGN DATA FOR THE OPTIMIZED REFERENCE COOLING SYSTEMS

SITE: MIDDLETOWN, U.S.A.

| Variable | Mechanical Dry (High BP Turbine) | Mechanical Dry (Low BP Turbine) | Mechanical Wet (Low BP Turbine) |
|---|---|---|---|
| Circulating Water Pipelines | | | |
| Condenser Intake: | | | |
| Number of Lines | 1 | 2 | 1 |
| Diameter/Length, in/ft (cm/m) | 144/1720 (366/524) | 144/1720 (366/524) | 132/1390 (335/423) |
| Condenser Discharge: | | | |
| Number of Lines | 1 | 2 | 1 |
| Diameter/Length, in/ft (cm/m) | 144/1080 (366/329) | 144/1080 (366/329) | 132/1010 (335/329) |
| Cooling Tower | | | |
| Size (Number of Cells): | | | |
| Dry Tower | 156 | 338 | - |
| Wet Tower | - | - | 33 |

TABLE E-2

CAPITAL COST BREAKDOWN FOR THE OPTIMIZED REFERENCE COOLING SYSTEMS ($\$10^6$)

SITE: MIDDLETOWN, U.S.A. YEAR: 1985

| Acct. No. | Equipment Item | | Mechanical Dry (High BP Turbine) | Mechanical Dry (Low BP Turbine) | Mechanical Wet (Low BP Turbine) |
|---|---|---|---|---|---|
| 218L | Circulating Water Pump Structures | (M | 1.003 | 1.276 | 0.930 |
| | | (L | 0.802 | 1.019 | 0.742 |
| | | (T | 1.805 | 2.295 | 1.672 |
| 232.211 | Circulating Water Pumps and Motors | (E | 2.995 | 5.242 | 2.604 |
| | | (M | 0.030 | 0.053 | 0.026 |
| | | (L | 0.211 | 0.369 | 0.158 |
| | | (T | 3.236 | 5.664 | 2.788 |
| 232.25 | Concrete Pipelines | (M | 2.903 | 5.806 | 2.185 |
| | | (L | 2.077 | 4.154 | 1.571 |
| | | (T | 4.980 | 9.960 | 3.756 |
| 232.3211 | Cooling Tower Basin and Foundation | (M | 0.476 | 1.031 | 2.141 |
| | | (L | 0.856 | 1.857 | 3.852 |
| | | (T | 1.332 | 2.888 | 5.993 |
| 232.3212 | Cooling Towers, Installed | (E | 47.121 | 102.096 | 8.110 |
| | | (M | 0.476 | 1.031 | 0.082 |
| | | (L | 5.487 | 11.889 | 5.290 |
| | | (T | 53.084 | 115.016 | 13.482 |
| 233.1 | Condensers, Installed | (E | 10.101 | 14.219 | 8.942 |
| | | (M | 0.051 | 0.071 | 0.045 |
| | | (L | 5.043 | 6.595 | 4.624 |
| | | (T | 15.195 | 20.885 | 13.611 |
| 24 | Electrical Equipment | (E | 2.094 | 4.373 | 0.924 |
| | | (M | 1.573 | 3.286 | 0.694 |
| | | (L | 3.756 | 8.061 | 0.634 |
| | | (T | 7.423 | 15.720 | 2.252 |
| | Direct Capital Cost of Cooling System | (E | 62.311 | 125.930 | 20.580 |
| | | (M | 6.512 | 12.554 | 6.103 |
| | | (L | 18.232 | 33.944 | 16.871 |
| | | (T | 87.055 | 172.428 | 43.554 |
| | Indirect Cost | | 21.764 | 43.107 | 10.888 |
| | Total Capital Cost | | 108.819 | 215.535 | 54.442 |

TABLE E-3

PENALTY BREAKDOWN AND COST SUMMARY FOR THE OPTIMIZED REFERENCE COOLING SYSTEMS ($\$10^6$)

SITE: MIDDLETOWN, U.S.A. YEAR: 1985

| Item | Mechanical Dry (High BP Turbine) | Mechanical Dry (Low BP Turbine) | Mechanical Wet (Low BP Turbine) |
|---|---|---|---|
| Penalty Breakdown: | | | |
| Capacity Penalty | 88.968 | 28.327 | 13.273 |
| Replacement Energy Penalty | 55.560 | 0.291 | 3.074 |
| Circulating Water Pumping Power Penalty | 5.380 | 8.845 | 6.336 |
| Circulating Water Pumping Energy Penalty | 5.630 | 8.543 | 6.146 |
| Cooling Tower Fan Power Penalty | 13.968 | 29.175 | 3.039 |
| Cooling Tower Fan Energy Penalty | 13.608 | 24.487 | 2.873 |
| Make-up Water Purchase and Treatment Penalty | 0.000 | 0.000 | 6.280 |
| Cooling System Maintenance Penalty | 5.370 | 10.572 | 2.640 |
| Cost Summary: | | | |
| Total Penalty Cost | 188.484 | 110.240 | 43.661 |
| Total Capital Cost | 108.819 | 215.535 | 54.442 |
| Total Evaluated Cost | 297.303 | 325.775 | 98.103 |

TABLE E-4 (sheet 1 of 3)

DESIGN DATA FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS

SITE: MIDDLETOWN, U.S.A. TOWER: MECHANICAL SERIES

| Variable | Percentage Make-up Requirement | | | | |
|---|---|---|---|---|---|
| | 1% | 10% | 20% | 30% | [illegible] |
| General Design Data | | | | | |
| Mode of Wet/Dry Tower Operation | S1 | S1 | S1 | S1 | S1 |
| Design Parameters for Dry Towers: | | | | | |
| Dry Bulb/Wet Bulb Temperatures, °F (°C) | 65/57 (18.3/13.9) | 45/40 (7.2/4.4) | 35/30 (1.7/-1.1) | 20/15 (-6.7/-9.6) | 5/0 (-15.0/-17.[illegible]) |
| Cold Water Temperature, °F (°C) | 96.0 (35.6) | 89.0 (31.7) | 88.0 (31.1) | 89.0 (31.7) | 85.0 (29.4) |
| Cooling Range, °F (°C) | 20.0 (11.1) | 26.0 (14.4) | 28.0 (15.6) | 28.0 (15.6) | 30.0 (16.7) |
| Tower ITD, °F (°C) | 51.0 (28.3) | 70.0 (38.9) | 81.0 (45.0) | 97.0 (53.9) | 110.0 (61.1) |
| Condenser Heat Load, $10^9$ Btu/hr ($10^{12}$ J/hr) | 7.15 (7.54) | 7.14 (7.54) | 7.15(7.54) | 7.16 (7.55) | 7.14 (7.54) |
| Design Parameters for Wet Helper Tower: | | | | | |
| Dry Bulb/Wet Bulb Temperatures, °F (°C) | 99/75 (37.2/23.9) | 99/75 (37.2/23.9) | 99/75 (37.2/23.9) | 99/75 (37.2/23.9) | 99/75 (37.2/23.9) |
| Tower Approach Temperature, °F (°C) | 20.0 (11.1) | 20.0 (11.1) | 17.3 (9.6) | 17.3 (9.6) | 15.3 (8.5) |
| Design and Maximum Operating Back Pressure $P_{max}$, in-HgA (mmHgA) | 5.0 (127.0) | 4.50 (114.3) | 4.0 (101.6) | 4.0 (101.6) | 4.0 (101.6) |
| Condenser Heat Load at $P_{max}$, $10^9$ Btu/hr ($10^{12}$ J/hr) | 7.25 (7.65) | 7.22 (7.61) | 7.18 (7.57) | 7.18 (7.57) | 7.18 (7.57) |
| Heat Load Distribution at $P_{max}$- Wet Tower/ Dry Tower, % | 42.7/57.3 | 63.7/36.3 | 73.8/26.2 | 78.2/21.8 | 80.5/19.5 |
| Annual Make-up Water Requirement, $10^8$ gal ($10^6$ $m^3$) | 0.435 (0.165) | 4.40 (1.66) | 8.45 (3.20) | 13.29 (5.03) | 16.35 (6.19) |

TABLE E-4 (sheet 2 of 3)

DESIGN DATA FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS

SITE: MIDDLETOWN, U.S.A. TOWER: MECHANICAL SERIES - S1 MODE

| Variable | Percentage Make-up Requirement | | | | |
| --- | --- | --- | --- | --- | --- |
| | 1% | 10% | 20% | 30% | 40% |
| **Condenser** | | | | | |
| Surface Area, $10^3$ $ft^2$ ($10^3$ $m^2$) | 1191 (111) | 1049 (97.4) | 1010 (93.9) | 1009 (93.7) | 980 (91.0) |
| Number of Tubes | 96,200 | 74,000 | 68,700 | 68,800 | 64,100 |
| Tube Length, ft (m) | 47.3 (14.4) | 54.2 (16.5) | 56.1 (17.1) | 56.0 (17.1) | 58.4 (17.8) |
| **Circulating Water Flow & Pump** | | | | | |
| Circulating Water Flow Rate, $10^3$ gpm ($m^3$ /min) | 715 (2707) | 550 (2080) | 511 (1933) | 511 (1935) | 476 (1803) |
| Number of Pumps | 4 | 4 | 3 | 3 | 3 |
| Pumping Head, ft (m) of Water | 66.7 (20.3) | 67.6 (20.6) | 73.1 (22.3) | 84.7 (25.8) | 91.1 (27.8) |
| Motor Rating, hp (kW) per pump | 4000 (2984) | 3000 (2238) | 4000 (2984) | 4500 (3357) | 4500 (3357) |
| Motor Brake Horsepower, hp (kW) per pump | 3353 (2500) | 2636 (1967) | 3533 (2636) | 4093 (3054) | 4105 (3063) |
| **Flow & Booster Pump for Wet Tower** | | | | | |
| Percentage of Circulating Water to Wet Helper Tower | 39 | 83 | 100 | 100 | 100 |
| Number of Pumps | 2 | 3 | 3 | 3 | 3 |
| Pumping Head, ft (m) of Water | 41.0 (12.5) | 41.0 (12.5) | 41.0 (12.5) | 41.0 (12.5) | 41.0 (12.5) |
| Motor Rating, hp (kW) per pump | 2000 (1492) | 2500 (1865) | 2500 (1865) | 2500 (1865) | 2500 (1865) |
| Motor Brake Horsepower, hp (kW) per pump | 1631 (1217) | 1761 (1314) | 1980 (1477) | 1986 (1479) | 1847 (1378) |

TABLE E-4 (sheet 3 of 3)

DESIGN DATA FOR THE OPTIMIZED WET/DRY COOLING SYSTEM

SITE: MIDDLETOWN, U.S.A. TOWER: MECHANICAL SERIES - S1 MODE

| Variable | Percentage Make-up Requirement | | | | |
|---|---|---|---|---|---|
| | 1% | 10% | 20% | 30% | 40% |
| Circulating Water Pipelines | | | | | |
| Condenser Intake: | | | | | |
| Number of Lines | 2 | 1 | 1 | 1 | 1 |
| Diameter/Length, in/ft (cm/m) | 108/1310 (274/399) | 138/1310 (351/399) | 132/1310 (335/399) | 132/1310 (335/399) | 126/1310 (320/399) |
| Condenser Discharge: | | | | | |
| Number of Lines | 2 | 1 | 1 | 1 | 1 |
| Diameter/Length, in/ft (cm/m) | 108/1010 (274/308) | 138/1010 (351/308) | 132/1010 (335/308) | 132/1010 (335/308) | 126/1010 (320/308) |
| Connecting Pipelines: | | | | | |
| Number of Lines | 2 | 1 | 1 | 1 | 1 |
| Diameter/Length, in/ft (cm/m) | 108/1350 (274/412) | 138/1350 (350/412) | 132/1350 (335/412) | 132/1350 (335/412) | 126/1350 (320/412) |
| Cooling Tower | | | | | |
| Size (Number of Cells): | | | | | |
| Dry Tower | 192 | 136 | 114 | 90 | 79 |
| Wet Tower | 13 | 19 | 26 | 27 | 30 |

TABLE E-5

CAPITAL COST BREAKDOWN FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS ($$10^6$)

SITE: MIDDLETOWN, U.S.A. TOWER: MECHANICAL SERIES - S1 MODE YEAR: 1985

| Acct. No. | Equipment Item | | Percentage Make-up Requirement | | | | |
|---|---|---|---|---|---|---|---|
| | | | 1% | 10% | 20% | 30% | 40% |
| 218L | Circulating Water Pump Structures | (M | 1.052 | 0.955 | 0.928 | 0.930 | 0.905 |
| | | (L | 0.840 | 0.763 | 0.742 | 0.742 | 0.724 |
| | | (T | 1.892 | 1.718 | 1.670 | 1.672 | 1.629 |
| 232.211 | Circulating Water Pumps and Motors | (E | 4.652 | 4.797 | 4.612 | 4.731 | 4.731 |
| | | (M | 0.047 | 0.048 | 0.047 | 0.048 | 0.048 |
| | | (L | 0.316 | 0.369 | 0.316 | 0.316 | 0.316 |
| | | (T | 5.015 | 5.214 | 4.975 | 5.095 | 5.095 |
| 232.25 | Concrete Pipelines | (M | 4.208 | 3.520 | 3.180 | 3.180 | 2.802 |
| | | (L | 3.630 | 2.560 | 2.402 | 2.402 | 2.249 |
| | | (T | 7.838 | 6.080 | 5.582 | 5.582 | 5.051 |
| 232.3211 | Cooling Tower Basin and Foundation | (M | 1.431 | 1.650 | 2.038 | 2.028 | 2.191 |
| | | (L | 2.574 | 2.968 | 3.666 | 3.650 | 3.941 |
| | | (T | 4.005 | 4.618 | 5.704 | 5.678 | 6.132 |
| 232.3212 | Cooling Towers, Installed | (E | 61.113 | 45.684 | 40.790 | 33.759 | 31.206 |
| | | (M | 0.617 | 0.461 | 0.412 | 0.341 | 0.315 |
| | | (L | 8.829 | 7.828 | 8.162 | 7.489 | 7.571 |
| | | (T | 70.559 | 53.973 | 49.364 | 41.589 | 39.092 |
| 233.1 | Condensers, Installed | (E | 10.662 | 9.308 | 8.964 | 8.955 | 8.685 |
| | | (M | 0.054 | 0.047 | 0.045 | 0.045 | 0.044 |
| | | (L | 5.262 | 4.756 | 4.628 | 4.626 | 4.520 |
| | | (T | 15.978 | 14.111 | 13.637 | 13.626 | 13.249 |
| 24 | Electrical Equipment | (E | 2.938 | 2.398 | 2.261 | 2.062 | 1.987 |
| | | (M | 2.207 | 1.802 | 1.699 | 1.549 | 1.493 |
| | | (L | 7.033 | 5.256 | 4.564 | 3.758 | 3.428 |
| | | (T | 12.178 | 9.456 | 8.524 | 7.369 | 6.908 |
| | Direct Capital Cost of Cooling System | (E | 79.365 | 62.187 | 56.627 | 49.507 | 46.609 |
| | | (M | 9.616 | 8.483 | 8.349 | 8.121 | 7.798 |
| | | (L | 28.484 | 24.500 | 24.480 | 22.983 | 22.749 |
| | | (T | 117.465 | 95.170 | 89.456 | 80.611 | 77.156 |
| | Indirect Cost | | 29.366 | 23.793 | 22.364 | 20.153 | 19.289 |
| | Total Capital Cost | | 146.831 | 118.963 | 111.820 | 100.764 | 96.445 |

TABLE E-6

PENALTY BREAKDOWN AND COST SUMMARY FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS ($\$10^6$)

SITE: MIDDLETOWN, U.S.A. TOWER: MECHANICAL SERIES - S1 MODE YEAR: 1985

| Item | Percentage Make-up Requirement | | | | |
|---|---|---|---|---|---|
| | 1% | 10% | 20% | 30% | 40% |
| **Penalty Breakdown:** | | | | | |
| Capacity Penalty | 27.363 | 20.723 | 14.457 | 14.457 | 14.444 |
| Replacement Energy Penalty | 5.483 | 11.388 | 11.339 | 13.742 | 14.245 |
| Circulating Water Pumping Power Penalty | 8.348 | 7.868 | 8.222 | 9.061 | 8.877 |
| Circulating Water Pumping Energy Penalty | 6.626 | 6.332 | 7.153 | 8.701 | 8.755 |
| Cooling Tower Fan Power Penalty | 16.140 | 12.358 | 11.220 | 9.429 | 8.849 |
| Cooling Tower Fan Energy Penalty | 15.703 | 11.379 | 9.862 | 8.182 | 7.583 |
| Make-up Water Purchase and Treatment Penalty | 0.065 | 0.652 | 1.254 | 1.972 | 2.425 |
| Cooling System Maintenance Penalty | 7.284 | 6.241 | 5.838 | 5.393 | 5.223 |
| **Cost Summary:** | | | | | |
| Total Penalty Cost | 87.012 | 76.941 | 69.345 | 70.937 | 70.401 |
| Total Capital Cost | 146.831 | 118.963 | 111.820 | 100.764 | 96.445 |
| Total Evaluated Cost | 233.843 | 195.904 | 181.165 | 171.701 | 166.846 |

TABLE E-7 (sheet 1 of 3)

DESIGN DATA FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS

SITE: MIDDLETOWN, U.S.A. TOWER: MECHANICAL SERIES

| Variable | Percentage Make-up Requirement | | |
|---|---|---|---|
| | 20% | 30% | 40% |
| General Design Data | | | |
| Mode of Wet/Dry Tower Operation | S2 | S2 | S2 |
| Design Parameters for Dry Towers: | | | |
| Dry Bulb/Wet Bulb Temperatures, °F (°C) | 50/45 (10/7.2) | 35/30 (1.7/-1.1) | 20/15 (-6.7/-9.6) |
| Cold Water Temperature, °F (°C) | 97.0 (36.1) | 94.0 (34.4) | 84.0 (28.9) |
| Cooling Range, °F (°C) | 29.0 (16.1) | 30.0 (16.6) | 32.0 (17.7) |
| Tower ITD, °F (°C) | 76.0 (42.2) | 89.0 (49.4) | 96.0 (53.3) |
| Condenser Heat Load, $10^9$ (Btu/hr ($10^{12}$ J/hr) | 7.23 (7.63) | 7.21 (7.61) | 7.15 (7.54) |
| Design Parameters for Wet Helper Tower: | | | |
| Dry Bulb/Wet Bulb Temperatures, °F (°C) | 99/75 (37.2/23.9) | 99/75 (37.2/23.9) | 99/75 (37.2/23.9) |
| Tower Approach Temperature, °F (°C) | 20.0 (11.1) | 20.0 (11.1) | 20.0 (11.1) |
| Design and Maximum Operating Back Pressure $P_{max}$, in-HgA (mmHgA) | 5.00 (127.0) | 5.00 (127.0) | 5.00 (127.0) |
| Condenser Heat Load at $P_{max}$, $10^9$ Btu/hr ($10^{12}$ J/hr) | 7.25 (7.65) | 7.25 (7.65) | 7.25 (7.65) |
| Heat Load Distribution at $P_{max}$- Wet Tower/ Dry Tower, % | 61.2/38.8 | 67.3/32.7 | 69.8/30.2 |
| Annual Make-up Water Requirement, $10^8$ gal ($10^6$ $m^3$) | 8.41 (3.18) | 12.9 (4.88) | 16.7 (6.32) |

TABLE E-7 (sheet 2 of 3)

DESIGN DATA FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS

SITE: MIDDLETOWN, U.S.A. TOWER: MECHANICAL SERIES - S2 MODE

| Variable | Percentage Make-up Requirement | | |
|---|---|---|---|
| | 20% | 30% | 40% |
| Condenser | | | |
| Surface Area, $10^3$ $ft^2$ ($10^3$ $m^2$) | 987. (91.7) | 969. (90.0) | 944. (87.7) |
| Number of Tubes | 67,000 | 64,600 | 60,100 |
| Tube Length, ft (m) | 56.2 (17.1) | 57.2 (17.4) | 59.9 (18.3) |
| Circulating Water Flow & Pump | | | |
| Circulating Water Flow Rate, $10^3$ gpm ($m^3$ /min) | 498 (1885) | 480 (1817) | 446 (1688) |
| Number of Pumps | 3 | 3 | 3 |
| Pumping Head, ft (m) of Water | 71.2 (21.7) | 75.7 (23.1) | 76.3 (23.3) |
| Motor Rating, hp (kW) per pump | 4000 (2983) | 4000 (2983) | 3500 (2610) |
| Motor Brake Horsepower, hp (kW) per pump | 3606 (2689) | 3443 (2567) | 3228 (2407) |
| Flow & Booster Pump for Wet Tower | | | |
| Percentage of Circulating Water to Wet Helper Tower | 79 | 85 | 95 |
| Number of Pumps | 3 | 3 | 3 |
| Pumping Head, ft (m) of Water | 41.0 (12.5) | 41.0 (12.5) | 41.0 (12.5) |
| Motor Rating, hp (kW) per pump | 2000 (1491) | 2000 (1491) | 2000 (1491) |
| Motor Brake Horsepower, hp (kW) per pump | 1483 (1106) | 1586 (1183) | 1645 (1227) |

TABLE E-7 (sheet 3 of 3)

DESIGN DATA FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS

SITE: MIDDLETOWN, U.S.A. TOWER: MECHANICAL SERIES - S2 MODE

| Variable | Percentage Make-up Requirement | | |
|---|---|---|---|
| | 20% | 30% | 40% |
| Circulating Water Pipelines | | | |
| Condenser Intake: | | | |
| Number of Lines | 1 | 1 | 1 |
| Diameter/Length, in/ft (cm/m) | 132/1310 (335/399) | 126/1310 (320/399) | 126/1310 (320/399) |
| Condenser Discharge: | | | |
| Number of Lines | 1 | 1 | 1 |
| Diameter/Length, in/ft (cm/m) | 126/1010 (320/308) | 126/1010 (320/308) | 126/1010 (320/308) |
| Connecting Pipelines: | | | |
| Number of Lines | 1 | 1 | 1 |
| Diameter/Length, in/ft (cm/m) | 126/1350 (320/411) | 126/1350 (320/411) | 126/1350 (320/411) |
| Cooling Tower | | | |
| Size (Number of Cells): | | | |
| Dry Tower | 128 | 104 | 95 |
| Wet Tower | 18 | 19 | 20 |

TABLE E-8

CAPITAL COST BREAKDOWN FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS ($$10^6$)

SITE: MIDDLETOWN, U.S.A. TOWER: MECHANICAL SERIES - S2 MODE YEAR: 1985

| Acct. No. | Equipment Item | | Percentage Make-up Requirement | | |
|---|---|---|---|---|---|
| | | | 20% | 30% | 40% |
| 218L | Circulating Water Pump Structures | (M | 0.921 | 0.909 | 0.884 |
| | | (L | 0.735 | 0.726 | 0.708 |
| | | (T | 1.656 | 1.635 | 1.592 |
| 232.211 | Circulating Water Pumps and Motors | (E | 4.130 | 4.249 | 4.374 |
| | | (M | 0.042 | 0.043 | 0.044 |
| | | (L | 0.316 | 0.316 | 0.316 |
| | | (T | 4.488 | 4.608 | 4.734 |
| 232.25 | Concrete Pipelines | (M | 3.180 | 2.802 | 2.802 |
| | | (L | 2.402 | 2.249 | 2.249 |
| | | (T | 5.582 | 5.051 | 5.051 |
| 232.3211 | Cooling Tower Basin and Foundation | (M | 1.560 | 1.553 | 1.589 |
| | | (L | 2.808 | 2.792 | 2.860 |
| | | (T | 4.368 | 4.345 | 4.449 |
| 232.3212 | Cooling Towers, Installed | (E | 43.031 | 36.044 | 33.570 |
| | | (M | 0.435 | 0.364 | 0.339 |
| | | (L | 7.374 | 6.698 | 6.534 |
| | | (T | 50.840 | 43.106 | 40.443 |
| 233.1 | Condensers, Installed | (E | 8.788 | 8.626 | 8.387 |
| | | (M | 0.044 | 0.043 | 0.042 |
| | | (L | 4.569 | 4.507 | 4.413 |
| | | (T | 13.401 | 13.176 | 12.842 |
| 24 | Electrical Equipment | (E | 2.199 | 2.000 | 1.868 |
| | | (M | 1.652 | 1.503 | 1.404 |
| | | (L | 4.921 | 4.115 | 3.822 |
| | | (T | 8.772 | 7.618 | 7.094 |
| | Direct Capital Cost of Cooling System | (E | 58.147 | 50.919 | 48.199 |
| | | (M | 7.834 | 7.217 | 7.104 |
| | | (L | 23.124 | 21.402 | 20.902 |
| | | (T | 89.105 | 79.538 | 76.205 |
| | Indirect Cost | | 22.276 | 19.885 | 19.051 |
| | Total Capital Cost | | 111.381 | 99.423 | 95.256 |

TABLE E-9

PENALTY BREAKDOWN AND COST SUMMARY FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS ($\$10^6$)

SITE: MIDDLETOWN, U.S.A. TOWER: MECHANICAL SERIES - S2 MODE YEAR: 1985

| Item | Percentage Make-up Requirement | | |
|---|---|---|---|
| | 20% | 30% | 40% |
| Penalty Breakdown: | | | |
| Capacity Penalty | 27.382 | 26.994 | 27.025 |
| Replacement Energy Penalty | 6.904 | 7.570 | 4.766 |
| Circulating Water Pumping Power Penalty | 6.980 | 7.501 | 7.267 |
| Circulating Water Pumping Energy Penalty | 5.588 | 6.579 | 6.877 |
| Cooling Tower Fan Power Penalty | 12.327 | 10.619 | 10.135 |
| Cooling Tower Fan Energy Penalty | 11.141 | 9.600 | 9.356 |
| Make-up Water Purchase and Treatment Penalty | 1.234 | 1.912 | 2.477 |
| Cooling System Maintenance Penalty | 5.707 | 5.255 | 5.125 |
| Cost Summary: | | | |
| Total Penalty Cost | 77.263 | 76.030 | 73.028 |
| Total Capital Cost | 111.381 | 99.423 | 95.256 |
| Total Evaluated Cost | 188.644 | 175.454 | 168.284 |

TABLE E-10 (sheet 1 of 3)

DESIGN DATA FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS

SITE: MIDDLETOWN, U.S.A. TOWER: MECHANICAL PARALLEL

| Variable | Percentage Make-up Requirement | | | | |
|---|---|---|---|---|---|
| | 1% | 10% | 20% | 30% | 40% |
| General Design Data | | | | | |
| Mode of Wet/Dry Tower Operation | P1 | P1 | P1 | P1 | P1 |
| Design Parameters for Dry Towers: | | | | | |
| Dry Bulb/Wet Bulb Temperatures, °F (°C) | 65/57 (18.3/13.9) | 50/45 (10.0/7.2) | 35/30 (1.7/-1.1) | 20/15 (-6.7/-9.4) | 5/0 (-15.0/-17.8) |
| Cold Water Temperature, °F (°C) | 95.0 (35.0) | 94.0 (34.4) | 91.0 (32.8) | 84.0 (28.9) | 81.0 (27.2) |
| Cooling Range, °F (°C) | 20.0 (11.1) | 28.0 (15.6) | 26.0 (14.4) | 26.0 (14.4) | 30.0 (16.7) |
| Tower ITD, °F (°C) | 50.0 (27.8) | 72.0 (40.0) | 82.0 (45.6) | 90.0 (50.0) | 106.0 (58.9) |
| Condenser Heat Load, $10^9$ Btu/hr ($10^6$ J/hr) | 7.14 (7.53) | 7.19 (7.58) | 7.16 (7.55) | 7.12 (7.51) | 7.13 (7.52) |
| Design Parameters for Wet Helper Tower: | | | | | |
| Dry Bulb/Wet Bulb Temperatures, °F (°C) | 99/75 (37.2/23.9) | 99/75 (37.2/23.9) | 99/75 (37.2/23.9) | 99/75 (37.2/23.9) | 99/75 (37.2/23.9) |
| Tower Approach Temperature, °F (°C) | 19.8 | 19.9 (11.1) | 19.8 (11.0) | 16.8 ( 9.3) | 12.0 ( 6.7) |
| Design and Maximum Operating Back Pressure $P_{max}$, in-HgA (mmHgA) | 5.00 (127.0) | 5.00 (127.0) | 4.50 (114.3) | 4.00 (101.6) | 4.00 (101.6) |
| Condenser Heat Load at $P_{max}$, $10^9$ Btu/hr ($10^{12}$ J/hr) | 7.25 (7.66) | 7.25 (7.66) | 7.21 (7.60) | 7.18 (7.57) | 7.18 (7.57) |
| Heat Load Distribution at $P_{max}$- Wet Tower/ Dry Tower, % | 47.7/52.3 | 71.6/28.4 | 80.1/19.9 | 87.9/12.1 | 89.8/10.2 |
| Annual Make-up Water Requirement, $10^8$ gal ($10^6$ $m^3$) | 0.374 (0.141) | 4.08 (1.55) | 8.34 (3.16) | 12.8 (4.85) | 17.4 (6.60) |

TABLE E-10 (sheet 2 of 3)

DESIGN DATA FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS

SITE: MIDDLETOWN, U.S.A. TOWER: MECHANICAL PARALLEL - P1 MODE

| Variable | Percentage Make-up Requirement | | | | |
|---|---|---|---|---|---|
| | 1% | 10% | 20% | 30% | 40% |
| **Condenser** | | | | | |
| Surface Area, 10 $ft^2$ ($10^3$ $m^2$) | 1190 (110.6) | 1004 (93.3) | 1046 (97.2) | 1060 (98.5) | 991 (92.1) |
| Number of Tubes | 96,100 | 69,100 | 74,000 | 73,700 | 63,900 |
| Tube Length, ft (m) | 47.3 (14.4) | 55.5 (16.9) | 53.9 (16.4) | 54.9 (16.7) | 59.2 (18.0) |
| **Circulating Water Flow & Pump** | | | | | |
| Circulating Water Flow Rate, $10^3$ gpm ($m^3$ /min) | 714 (2703) | 513 (1942) | 550 (2082) | 547 (2071) | 475 (1798) |
| Number of Pumps | 4 | 3 | 4 | 4 | 3 |
| Pumping Head, ft (m) of Water | 66.3 (20.2) | 67.6 (20.6) | 77.9 (23.7) | 85.5 (26.1) | 91.5 (27.9) |
| Motor Rating, hp (kW) per pump | 4000 (2983) | 4000 (2093) | 3500 (2610) | 4000 (2983) | 4500 (3356) |
| Motor Brake Horsepower, hp (kW) per pump | 3364 (2509) | 3288 (2452) | 3044 (2270) | 3325 (2479) | 4115 (3069) |
| **Flow & Booster Pump for Wet Tower** | | | | | |
| Percentage of Circulating Water to Wet Helper Tower | 29 | 60 | 70 | 80 | 81 |
| Number of Pumps | 12 | 18 | 21 | 28 | 36 |
| Pumping Head, ft (m) of Water | 41.0 (12.5) | 41.0 (12.5) | 41.0 (12.5) | 41.0 (12.5) | 41.0 (12.5) |
| Motor Rating, hp (kW) per pump | 350 (261) | 350 (261) | 350 (261) | 300 (224) | 300 (224) |
| Motor Brake Horsepower, hp (kW) per pump | 198 (148) | 198 (148) | 213 (159) | 183 (136) | 125 (93.2) |

TABLE E-10 (sheet 3 of 3)

DESIGN DATA FOR THE OPTIMIZED WET/DRY COOLING SYSTEM

SITE: MIDDLETOWN, U.S.A. TOWER: MECHANICAL PARALLEL - P1 MODE

| Variable | Percentage Make-up Requirement | | | | |
|---|---|---|---|---|---|
| | 1% | 10% | 20% | 30% | 40% |
| Circulating Water Pipelines | | | | | |
| Condenser Intake: | | | | | |
| Number of Lines | 2 | 1 | 1 | 1 | 1 |
| Diameter/Length, in/ft (cm/m) | 108/1470 (274/448) | 132/1470 (335/448) | 138/1470 (351/448) | 138/1470 (351/448) | 126/1470 (320/448) |
| Condenser Discharge: | | | | | |
| Number of Lines | 2 | 1 | 1 | 1 | 1 |
| Diameter/Length, in/ft (cm/m) | 108/880 (274/268) | 132/880 (335/268) | 138/880 (351/268) | 138/880 (351/268) | 126/880 (320/268) |
| Connecting Pipelines: | | | | | |
| Number of Lines | 2 | 2 | 2 | 2 | 2 |
| Diameter/Length, in/ft (cm/m) | 108/900 (274/274) | 96/900 (244/274) | 96/900 (244/274) | 96/900 (244/274) | 90/900 (229/274) |
| Cooling Tower | | | | | |
| Size (Number of Cells): | | | | | |
| Dry Tower | 197 | 136 | 110 | 97 | [illegible]1 |
| Wet Tower | 12 | 18 | 21 | 28 | 36 |

TABLE E-11

CAPITAL COST BREAKDOWN FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS ($$10^6$)

SITE: MIDDLETOWN, U.S.A. TOWER: MECHANICAL PARALLEL - P1 YEAR: 1985

| Acct. No. | Equipment Item | | Percentage Make-up Requirement | | | | |
|---|---|---|---|---|---|---|---|
| | | | 1% | 10% | 20% | 30% | 40% |
| 218L | Circulating Water Pump Structures | (M | 1.052 | 0.932 | 0.955 | 0.953 | 0.905 |
| | | (L | 0.840 | 0.744 | 0.763 | 0.763 | 0.724 |
| | | (T | 1.892 | 1.676 | 1.718 | 1.716 | 1.629 |
| 232.211 | Circulating Water Pumps and Motors | (E | 4.824 | 4.750 | 5.472 | 6.111 | 6.620 |
| | | (M | 0.049 | 0.048 | 0.055 | 0.062 | 0.067 |
| | | (L | 0.705 | 0.900 | 1.079 | 1.365 | 1.642 |
| | | (T | 5.578 | 5.698 | 6.606 | 7.538 | 8.329 |
| 232.25 | Concrete Pipelines | (M | 3.906 | 2.978 | 3.203 | 3.203 | 2.642 |
| | | (L | 3.213 | 2.297 | 2.398 | 2.398 | 2.134 |
| | | (T | 7.119 | 5.275 | 5.601 | 5.601 | 4.776 |
| 232.3211 | Cooling Tower Basin and Foundation | (M | 1.381 | 1.585 | 1.700 | 2.116 | 2.586 |
| | | (L | 2.485 | 2.851 | 3.059 | 3.806 | 4.653 |
| | | (T | 3.866 | 4.436 | 4.759 | 5.922 | 7.239 |
| 232.3212 | Cooling Towers, Installed | (E | 62.423 | 45.476 | 38.315 | 36.138 | 33.299 |
| | | (M | 0.631 | 0.459 | 0.387 | 0.365 | 0.336 |
| | | (L | 8.842 | 7.662 | 7.231 | 7.895 | 8.606 |
| | | (T | 71.896 | 53.597 | 45.933 | 44.398 | 42.241 |
| 233.1 | Condensers, Installed | (E | 10.662 | 8.938 | 9.293 | 9.379 | 8.755 |
| | | (M | 0.054 | 0.045 | 0.047 | 0.047 | 0.044 |
| | | (L | 5.262 | 4.624 | 4.754 | 4.777 | 4.541 |
| | | (T | 15.798 | 13.607 | 14.094 | 14.203 | 13.340 |
| 24 | Electrical Equipment | (E | 2.988 | 2.350 | 2.212 | 2.265 | 2.204 |
| | | (M | 2.245 | 1.766 | 1.662 | 1.702 | 1.656 |
| | | (L | 7.294 | 5.354 | 4.605 | 4.305 | 3.943 |
| | | (T | 12.527 | 9.470 | 8.479 | 8.272 | 7.803 |
| | Direct Capital Cost of Cooling System | (E | 80.896 | 61.514 | 55.292 | 53.894 | 50.878 |
| | | (M | 9.317 | 7.813 | 8.009 | 8.448 | 8.236 |
| | | (L | 28.641 | 24.432 | 23.888 | 25.309 | 26.244 |
| | | (T | 118.854 | 93.759 | 87.189 | 87.651 | 85.358 |
| | Indirect Cost | | 29.715 | 23.439 | 21.797 | 21.912 | 21.340 |
| | Total Capital Cost | | 148.569 | 117.198 | 108.986 | 109.563 | 106.698 |

TABLE E-12

PENALTY BREAKDOWN AND COST SUMMARY FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS ($$10^6$)

SITE: MIDDLETOWN, U.S.A. TOWER: MECHANICAL PARALLEL - P1 MODE YEAR: 1985

| Item | Percentage Make-up Requirement | | | | |
|---|---|---|---|---|---|
| | 1% | 10% | 20% | 30% | 40% |
| Penalty Breakdown: | | | | | |
| Capacity Penalty | 27.363 | 27.363 | 20.723 | 14.444 | 14.444 |
| Replacement Energy Penalty | 5.082 | 14.744 | 15.769 | 13.082 | 14.274 |
| Circulating Water Pumping Power Penalty | 7.871 | 6.679 | 8.280 | 9.162 | 8.368 |
| Circulating Water Pumping Energy Penalty | 6.525 | 5.022 | 6.396 | 7.155 | 6.796 |
| Cooling Tower Fan Power Penalty | 16.506 | 12.266 | 10.516 | 10.108 | 9.595 |
| Cooling Tower Fan Energy Penalty | 16.092 | 11.324 | 9.309 | 8.487 | 7.644 |
| Make-up Water Purchase and Treatment Penalty | 0.055 | 0.605 | 1.237 | 1.902 | 2.586 |
| Cooling System Maintenance Penalty | 7.602 | 6.395 | 6.310 | 6.616 | 6.785 |
| Cost Summary: | | | | | |
| Total Penalty Cost | 87.096 | 84.398 | 78.540 | 70.956 | 70.492 |
| Total Capital Cost | 148.569 | 117.198 | 108.986 | 109.563 | 106.698 |
| T[illegible] Evaluated Cost | 235.665 | 201.596 | 187.526 | 180.519 | 177.[illegible] |

TABLE E-13 (sheet 1 of 3)

DESIGN DATA FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS

SITE: MIDDLETOWN, U.S.A. TOWER: NATURAL SERIES

| Variable | Percentage Make-up Requirement | | | | |
|---|---|---|---|---|---|
| | 1% | 10% | 20% | 30% | 40% |
| **General Design Data** | | | | | |
| Mode of Wet/Dry Tower Operation | S1 | S1 | S1 | S1 | S1 |
| Design Parameters for Dry Towers: | | | | | |
| Dry Bulb/Wet Bulb Temperatures, °F (°C) | 60/53 (15.6/11.7) | 40/36 (4.4/2.2) | 30/25 (-1.1/-3.9) | 20/15 (-6.7/-9.4) | 10/5 (-12.2/-15) |
| Cold Water Temperature, °F (°C) | 94.0 (34.4) | 90.0 (32.2) | 83.0 (28.3) | 84.0 (28.9) | 86.0 (30) |
| Cooling Range, °F (°C) | 17.0 ( 9.4) | 24.0 (13.3) | 26.0 (14.4) | 26.0 (14.4) | 26.0 (14.4) |
| Tower ITD, °F (°C) | 51.0 (28.3) | 74.0 (41.1) | 79.0 (43.9) | 90.0 (50.0) | 102.0 (56.7) |
| Condenser Heat Load, $10^9$ Btu/hr ($10^{12}$ J/hr) | 7.13 (7.52) | 7.14 (7.53) | 7.12 (7.51) | 7.12 (7.51) | 7.13 (7.52) |
| Design Parameters for Wet Helper Tower: | | | | | |
| Dry Bulb/Wet Bulb Temperatures, °F (°C) | 99/75 (37.2/23.9) | 99/75 (37.2/23.9) | 99/75 (37.2/23.9) | 99/75 (37.2/23.9) | 99/75 (37.2/23.9) |
| Tower Approach Temperature, °F (°C) | 20.0 (11.1) | 20.0 (11.1) | 19.2 (10.7) | 19.2 (10.7) | 19.3 (10.7) |
| Design and Maximum Operating Back Pressure $P_{max}$, in-HgA (mmHgA) | 5.00 (127.0) | 5.00 (127.0) | 4.00 (101.6) | 4.00 (101.6) | 4.00 (101.6) |
| Condenser Heat Load at $P_{max}$, $10^9$ Btu/hr ($10^{12}$ J/hr) | 7.25 (7.65) | 7.25 (7.65) | 7.18 (7.57) | 7.18 (7.57) | 7.18 (7.57) |
| Heat Load Distribution at $P_{max}$- Wet Tower/Dry Tower, % | 49.1/50.9 | 69.7/30.3 | 82.1/17.9 | 85.4/14.6 | 88.1/11.9 |
| Annual Make-up Water Requirement, $10^8$ gal ($10^6$ $m^3$) | 0.413 (0.156) | 4.49 (1.70) | 8.67 (3.28) | 12.9 (4.88) | 17.1 (6.47) |

TABLE E-13 (sheet 2 of 3)

DESIGN DATA FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS

SITE: MIDDLETOWN, U.S.A. TOWER: NATURAL SERIES - S1 MODE

| Variable | Percentage Make-up Requirement | | | | |
| --- | --- | --- | --- | --- | --- |
| | 1% | 10% | 20% | 30% | 40% |
| Condenser | | | | | |
| Surface Area, $10^3$ $ft^2$ ($10^3$ $m^2$) | 1287 (119.6) | 1091 (101.4) | 1063 (98.7) | 1060 (98.5) | 1054 (97.9) |
| Number of Tubes | 112,800 | 80,000 | 73,700 | 73,700 | 73,800 |
| Tube Length, ft (m) | 43.5 (13.3) | 52.0 (15.8) | 55.1 (16.8) | 54.9 (16.7) | 54.5 (16.6) |
| Circulating Water Flow & Pump | | | | | |
| Circulating Water Flow Rate, $10^3$ gpm ($m^3$ /min) | 838 (3172) | 594 (2249) | 547 (2071) | 547 (2071) | 548 (2074) |
| Number of Pumps | 5 | 4 | 4 | 4 | 4 |
| Pumping Head, ft (m) of Water | 47.2 (14.4) | 48.3 (14.7) | 50.5 (15.4) | 50.4 (15.4) | 50.2 (15.3) |
| Motor Rating, hp (kW) per pump | 2500 (1864) | 2500 (1864) | 2250 (1678) | 2250 (1678) | 2250 (1678) |
| Motor Brake Horsepower, hp (kW) per pump | 2249 (1677) | 2042 (1523) | 1963 (1464) | 1960 (1462) | 1953 (1456) |
| Flow & Booster Pump for Wet Tower | | | | | |
| Percentage of Circulating Water to Wet Helper Tower | 34 | 64 | 100 | 100 | 100 |
| Number of Pumps | 2 | 3 | 4 | 4 | 4 |
| Pumping Head, ft (m) of Water | 41.0 (12.5) | 41.0 (12.5) | 41.0 (12.5) | 41.0 (12.5) | 41.0 (12.5) |
| Motor Rating, hp (kW) per pump | 2000 (1491) | 1750 (1305) | 2000 (1491) | 2000 (1491) | 2000 (1491) |
| Motor Brake Horsepower, hp (kW) per pump | 1659 (1237) | 1486 (1108) | 1593 (1188) | 1594 (1189) | 1595 (1189) |

TABLE E-13 (sheet 3 of 3)

DESIGN DATA FOR THE OPTIMIZED WET/DRY COOLING SYSTEM

SITE: MIDDLETOWN, U.S.A. TOWER: NATURAL SERIES - S1 MODE

| Variable | Percentage Make-up Requirement | | | | |
|---|---|---|---|---|---|
| | 1% | 10% | 20% | 30% | 40% |
| **Circulating Water Pipelines** | | | | | |
| Condenser Intake: | | | | | |
| Number of Lines | 2 | 1 | 1 | 1 | 1 |
| Diameter/Length, in/ft (cm/m) | 120/1625 (305/495) | 144/1625 (366/495) | 138/1625 (351/495) | 138/1625 (351/495) | 138/1625 (351/495) |
| Condenser Discharge: | | | | | |
| Number of Lines | 2 | 1 | 1 | 1 | 1 |
| Diameter/Length, in/ft (cm/m) | 120/1140 (305/348) | 144/1140 (366/348) | 138/1140 (351/348) | 138/1140 (351/348) | 138/1140 (351/348) |
| Connecting Pipelines: | | | | | |
| Number of Lines | 2 | 1 | 1 | 1 | 1 |
| Diameter/Length, in/ft (cm/m) | 120/1380 (305/421) | 144/1380 (366/421) | 138/1380 (351/421) | 138/1380 (351/421) | 138/1380 (351/421) |
| **Cooling Tower** | | | | | |
| Size | | | | | |
| Dry Tower | | | | | |
| Diameter/Height, ft (m) | 424/460 (129/140) | 381/405 (116/123) | 355/378 (108/115) | 499/479 (152/146) | 434/396 (132/121) |
| Number of Towers | 3 | 2 | 2 | 1 | 1 |
| Number of Heat Exchangers per Tower | 258 | 232 | 216 | 304 | 254 |
| Wet Tower (Number of Cells) | 14 | 19 | 25 | 26 | 25 |

TABLE E-14

CAPITAL COST BREAKDOWN FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS ($$10^6$)

SITE: MIDDLETOWN, U.S.A. TOWER: NATURAL SERIES - S1 MODE YEAR: 1985

| Acct. No. | Equipment Item | | Percentage Make-up Requirement | | | | |
|---|---|---|---|---|---|---|---|
| | | | 1% | 10% | 20% | 30% | 40% |
| 218L | Circulating Water Pump Structures | (M | 1.115 | 0.984 | 0.953 | 0.953 | 0.953 |
| | | (L | 0.891 | 0.785 | 0.763 | 0.763 | 0.763 |
| | | (T | 2.006 | 1.769 | 1.716 | 1.716 | 1.716 |
| 232.211 | Circulating Water Pumps and Motors | (E | 4.884 | 4.540 | 4.784 | 4.784 | 4.784 |
| | | (M | 0.049 | 0.046 | 0.048 | 0.048 | 0.048 |
| | | (L | 0.369 | 0.369 | 0.421 | 0.421 | 0.421 |
| | | (T | 5.302 | 4.955 | 5.253 | 5.253 | 5.253 |
| 232.25 | Concrete Pipelines | (M | 5.317 | 4.143 | 3.868 | 3.868 | 3.868 |
| | | (L | 4.745 | 3.073 | 2.892 | 2.892 | 2.892 |
| | | (T | 10.062 | 7.216 | 6.760 | 6.760 | 6.760 |
| 232.3211 | Cooling Tower Basin and Foundation | (M | 1.352 | 1.478 | 1.845 | 1.845 | 1.807 |
| | | (L | 3.765 | 3.398 | 3.985 | 3.790 | 3.607 |
| | | (T | 5.117 | 4.876 | 5.830 | 5.635 | 5.414 |
| 232.3212 | Cooling Towers, Installed | (E | 54.543 | 34.631 | 33.614 | 27.015 | 23.355 |
| | | (M | 0.551 | 0.350 | 0.340 | 0.273 | 0.236 |
| | | (L | 44.993 | 27.877 | 26.597 | 21.649 | 18.202 |
| | | (T | 100.087 | 62.858 | 60.551 | 48.937 | 41.793 |
| 233.1 | Condensers, Installed | (E | 11.633 | 9.700 | 9.398 | 9.379 | 9.345 |
| | | (M | 0.058 | 0.049 | 0.047 | 0.047 | 0.047 |
| | | (L | 5.624 | 4.903 | 4.782 | 4.777 | 4.765 |
| | | (T | 17.315 | 14.652 | 14.227 | 14.203 | 14.157 |
| 24 | Electrical Equipment | (E | 0.744 | 0.775 | 0.922 | 0.936 | 0.936 |
| | | (M | 0.559 | 0.583 | 0.692 | 0.703 | 0.703 |
| | | (L | 0.531 | 0.607 | 0.742 | 0.758 | 0.758 |
| | | (T | 1.834 | 1.965 | 2.356 | 2.397 | 2.397 |
| | Direct Capital Cost of Cooling System | (E | 71.803 | 49.646 | 48.718 | 42.114 | 38.419 |
| | | (M | 9,003 | 7.632 | 7.793 | 7.737 | 7.662 |
| | | (L | 60.918 | 41.012 | 40.181 | 35.050 | 31.409 |
| | | (T | 141.724 | 98.290 | 96.692 | 84.901 | 77.490 |
| | Indirect Cost | | 35.430 | 23.943 | 24.173 | 21.225 | 19.372 |
| | Total Capital Cost | | 177.154 | 122.863 | 120.865 | 106.126 | 96.862 |

TABLE E-15

PENALTY BREAKDOWN AND COST SUMMARY FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS ($$10^6$)

SITE: MIDDLETOWN, U.S.A. TOWER: NATURAL SERIES - S1 MODE YEAR: 1985

| Item | Percentage Make-up Requirement | | | | |
|---|---|---|---|---|---|
| | 1% | 10% | 20% | 30% | 40% |
| Penalty Breakdown: | | | | | |
| Capacity Penalty | 27.363 | 27.363 | 14.458 | 14.458 | 14.458 |
| Replacement Energy Penalty | 4.484 | 14.614 | 10.114 | 12.786 | 13.914 |
| Circulating Water Pumping Power Penalty | 7.241 | 6.277 | 7.071 | 7.065 | 7.056 |
| Circulating Water Pumping Energy Penalty | 5.513 | 4.775 | 5.565 | 6.441 | 6.828 |
| Cooling Tower Fan Power Penalty | 1.186 | 1.644 | 2.182 | 2.232 | 2.270 |
| Cooling Tower Fan Energy Penalty | 0.020 | 0.245 | 0.542 | 0.782 | 0.997 |
| Make-up Water Purchase and Treatment Penalty | 0.061 | 0.666 | 1.285 | 1.917 | 2.533 |
| Cooling System Maintenance Penalty | 5.540 | 4.513 | 4.687 | 4.431 | 4.263 |
| Cost Summary: | | | | | |
| Total Penalty Cost | 51.409 | 60.095 | 45.904 | 50.112 | 52.319 |
| Total Capital Cost | 177.154 | 122.863 | 120.865 | 106.126 | 96.862 |
| Total Evaluated Cost | 228.563 | 182.958 | 166.769 | 156.238 | 149.181 |

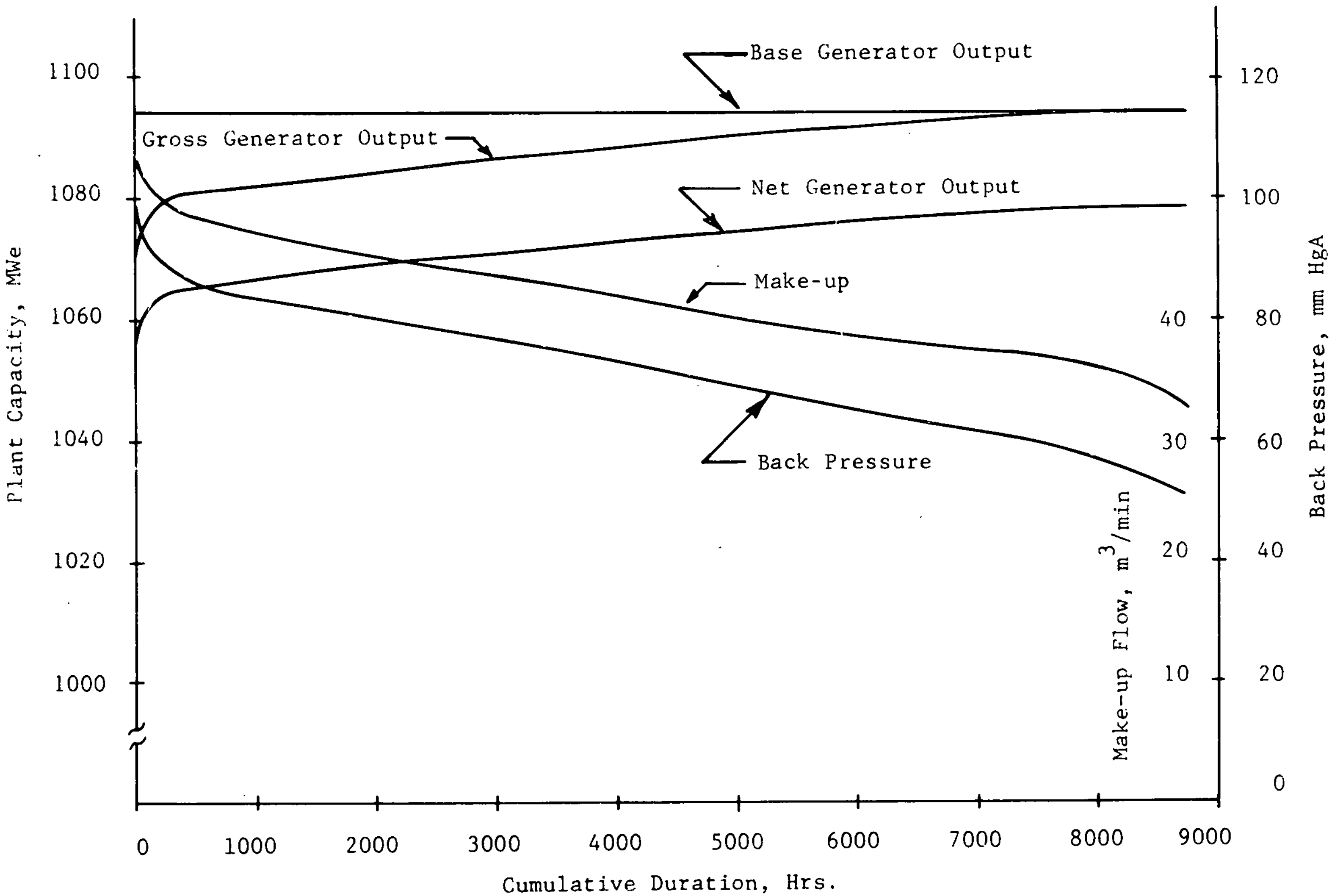


Figure E-1 Performance Curves For A Wet Cooling System
Middletown, U.S.A.

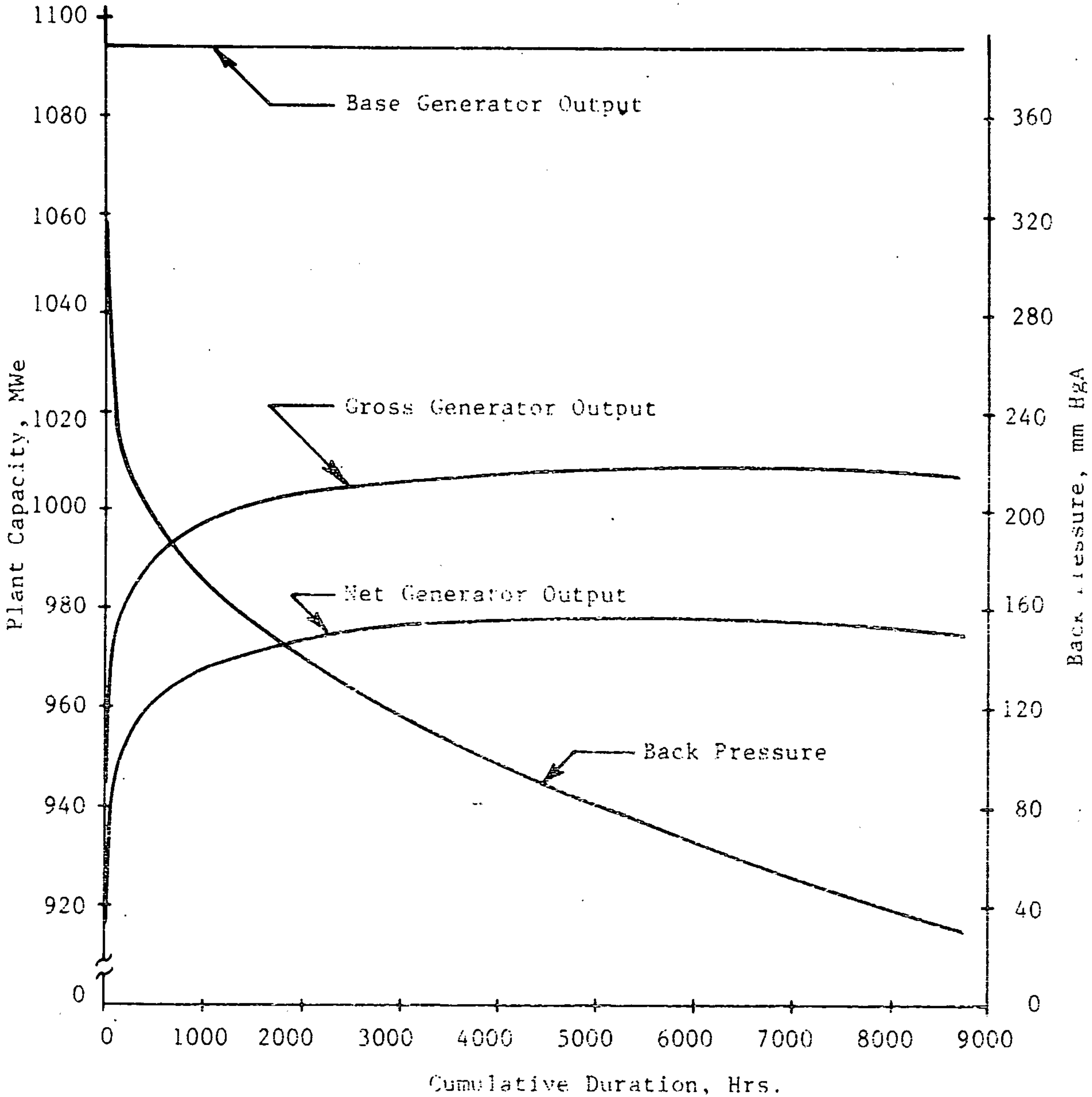


Figure E-2 Performance Curves For A Dry Cooling System Coupled With A High Back Pressure Turbine Middletown, U.S.A.

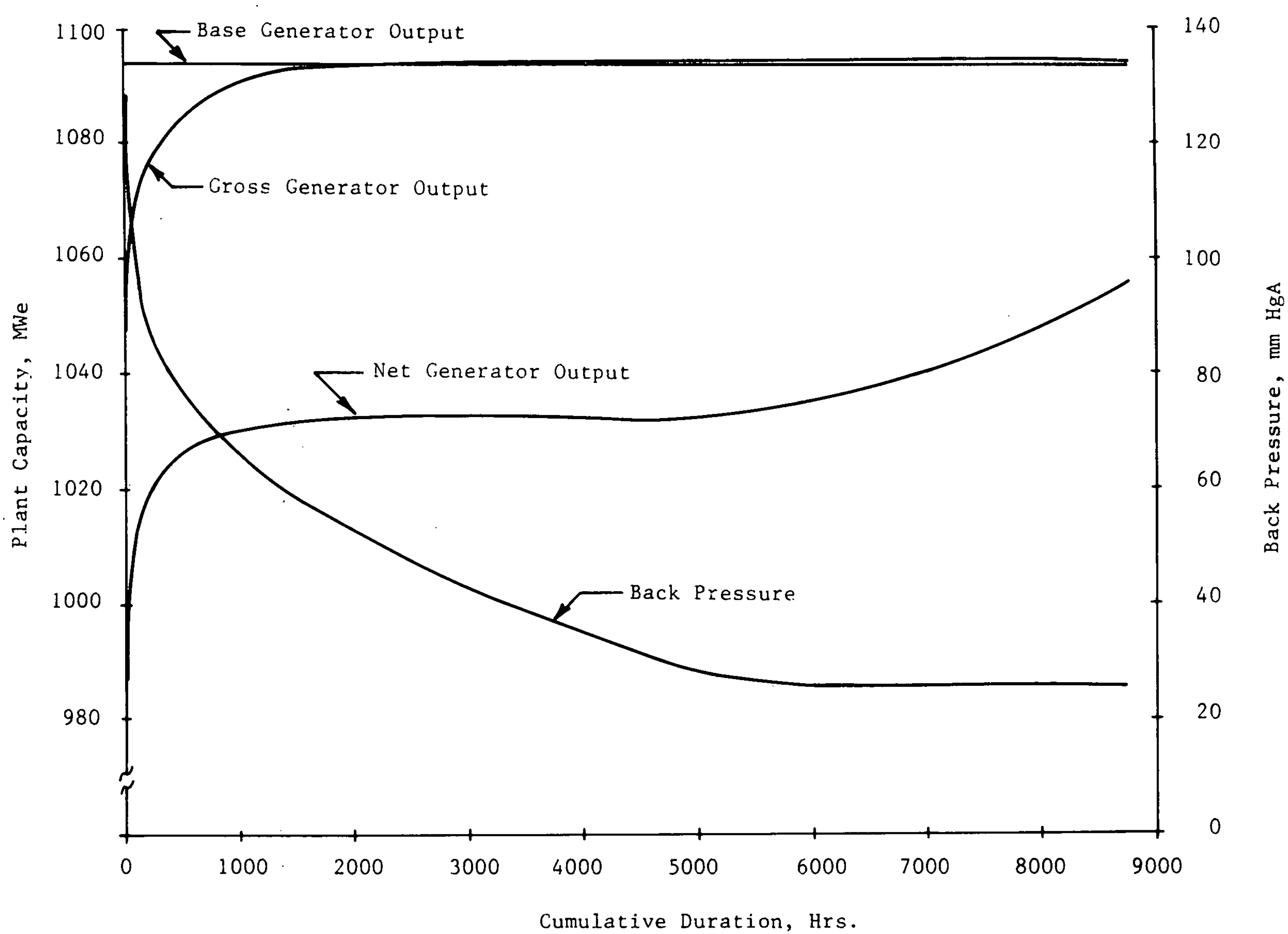


Figure E-3 Performance Curves for a Dry Cooling System
Coupled With A Low Back Pressure Turbine
Middletown, U.S.A.

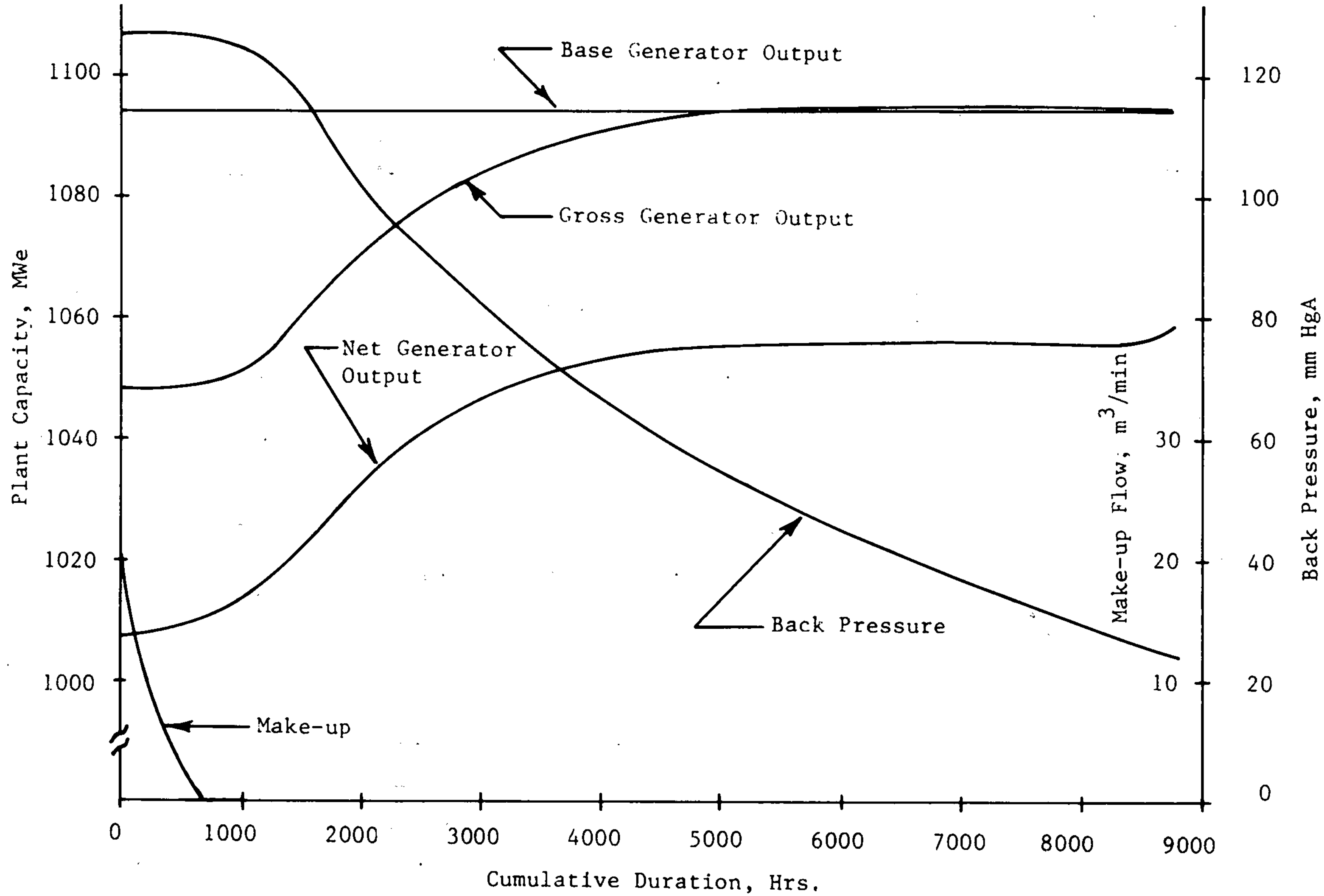


Figure E-4 Performance Curves For A 1% Mechanical Series Wet/Dry Cooling System Operating In The S1 Mode Middletown, U.S.A.

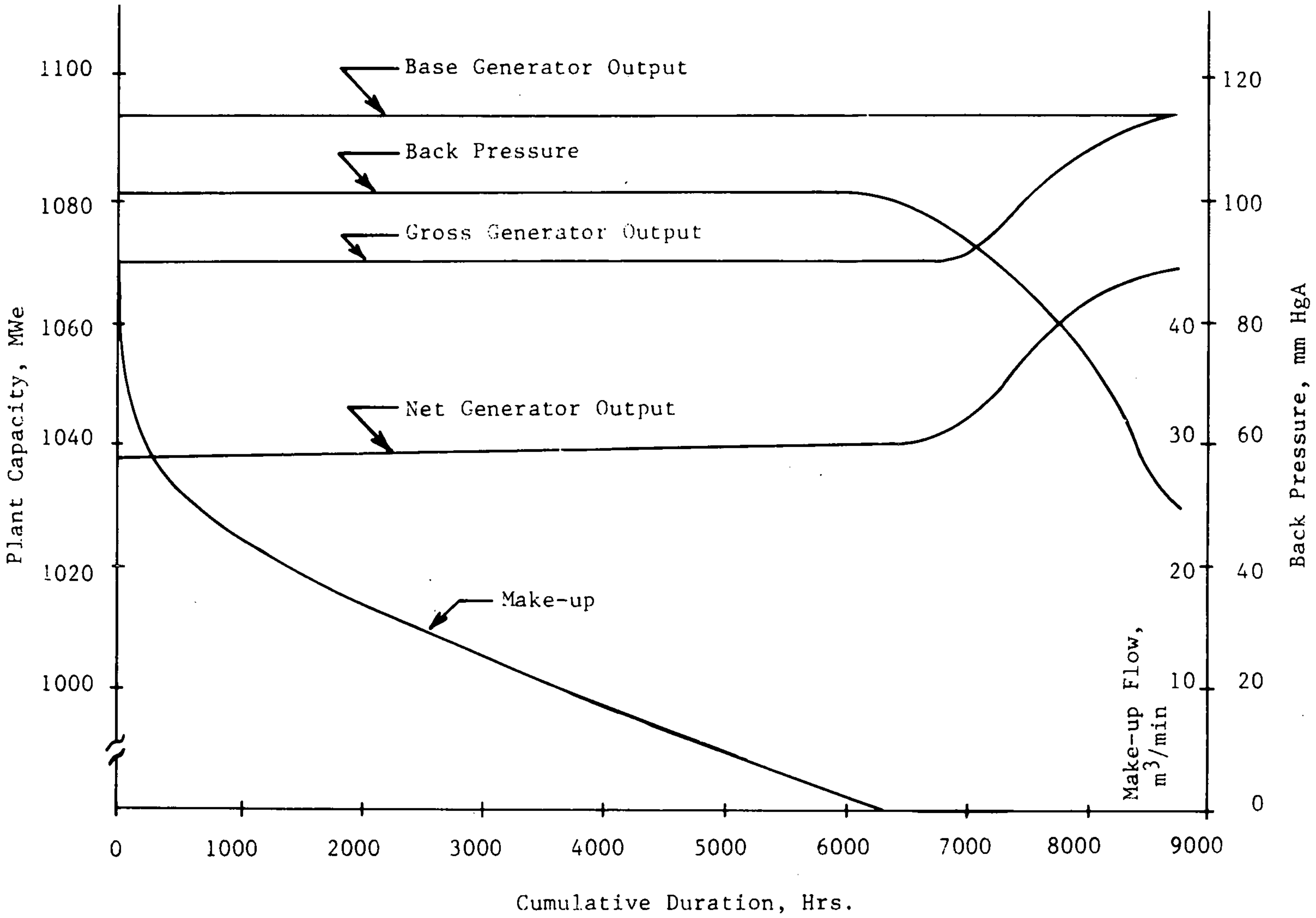


Figure E-5 Performance Curves For A 20% Mechanical Series Wet/Dry Cooling System Operating In The S1 Mode Middletown, U.S.A.

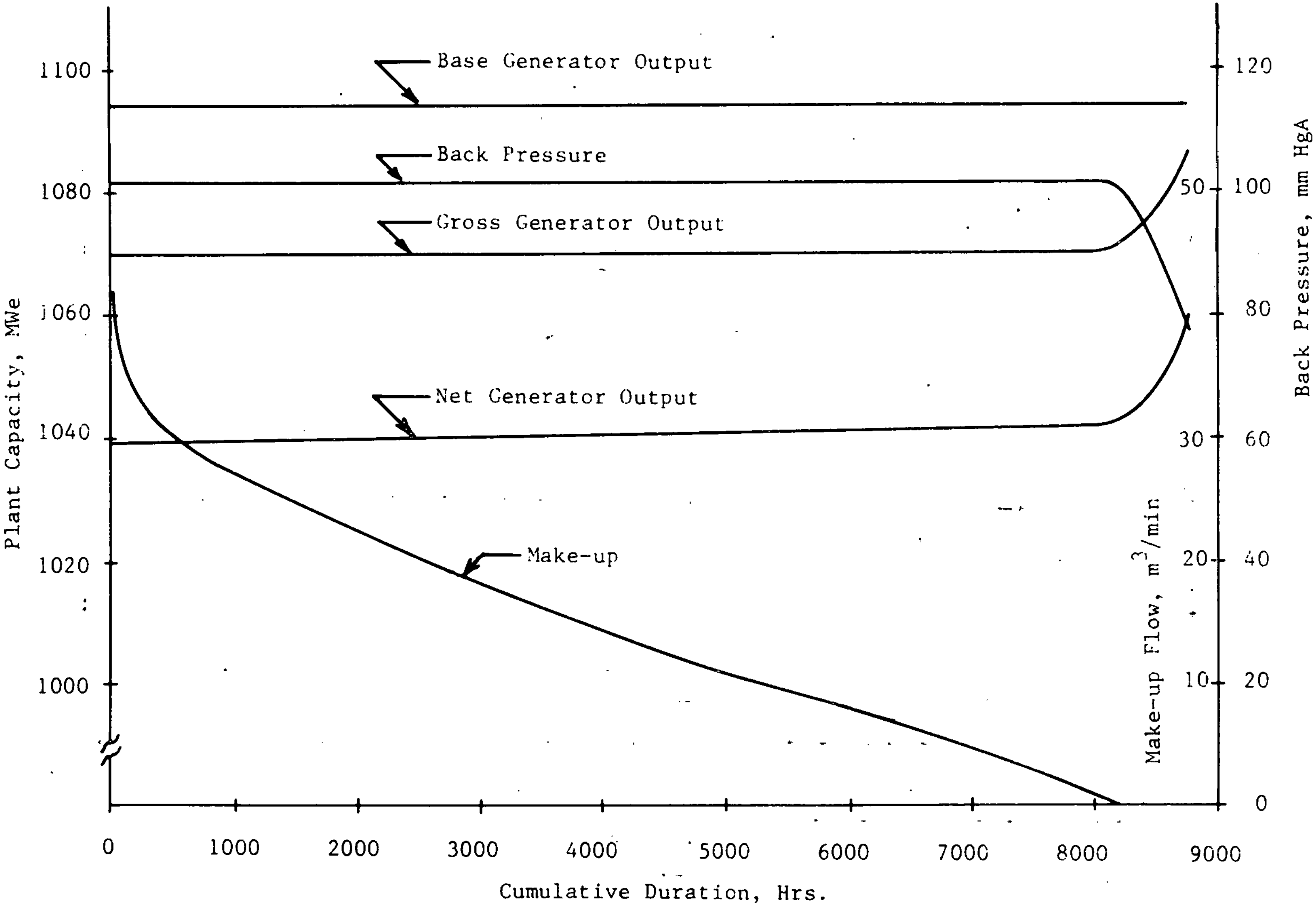


Figure E-6 Performance Curves For A 30% Mechanical Series Wet/Dry Cooling System Operating In The S1 Mode Middletown, U.S.A.

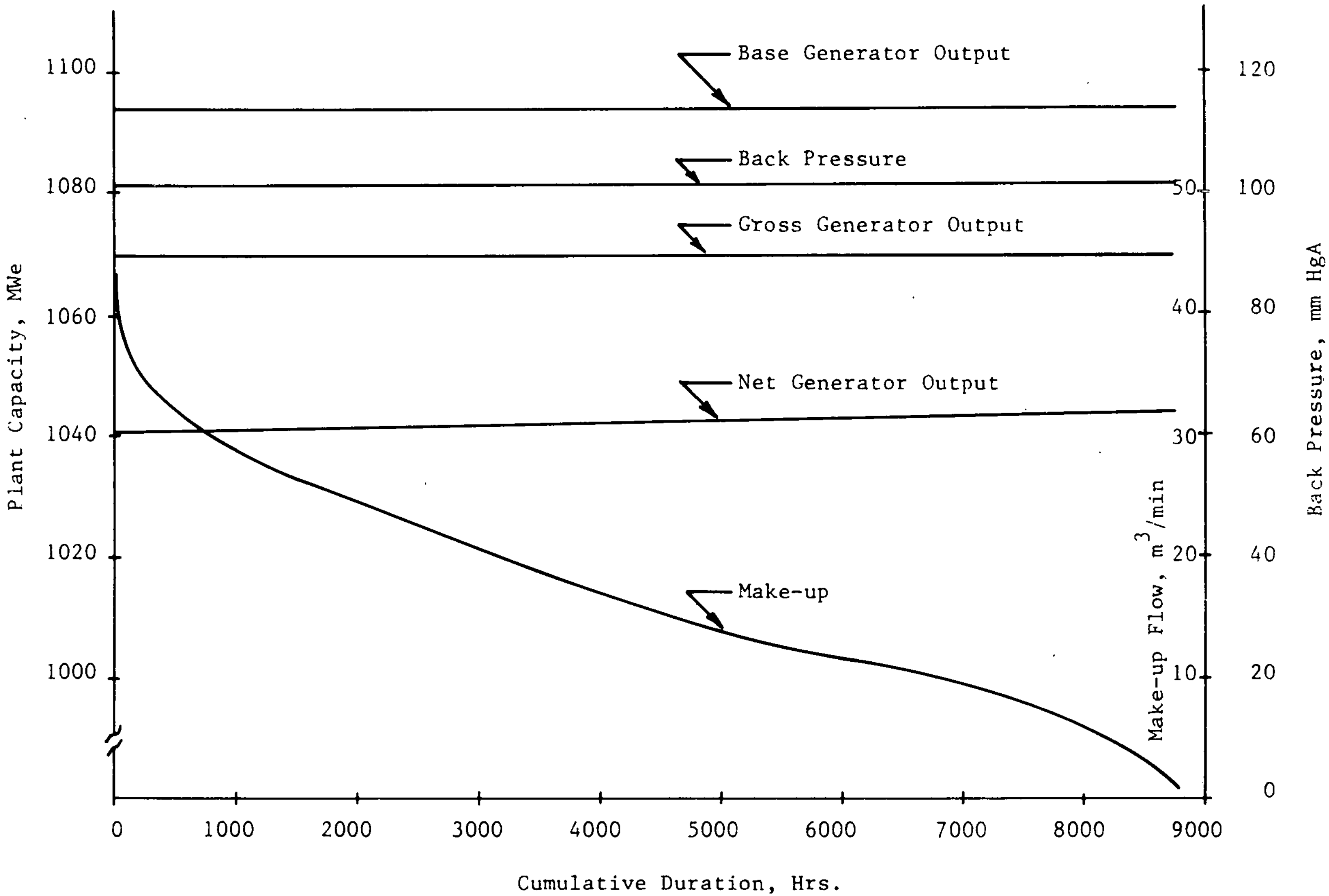


Figure E-7 Performance Curves For A 40% Mechanical Series Wet/Dry Cooling System Operating In The S1 Mode Middletown, U.S.A.

# APPENDIX F

## DETAILED DATA FOR ATLANTA, GEORGIA SITE

This appendix contains data for cooling systems interfaced with LWR power plants sited at Atlanta, Georgia. Detailed design data, capital cost breakdowns and penalty breakdowns are presented for the reference cooling systems and mechanical series wet/dry cooling systems.

Tables F-1 through F-3 present data for the reference cooling systems.

Tables F-4 through F-6 present data for the mechanical series wet/dry cooling systems operating in the S1 mode.

Tables F-7 through F-9 present data for the mechanical series wet/dry cooling systems operating in the S2 mode.

Figures F-1 and F-2 provide information on the total monthly make-up requirement and the maximum make-up flow rate for each month for the wet cooling system and mechanical series wet/dry cooling systems operating in the S1 mode.

TABLE F-1 (sheet 1 of 3)

DESIGN DATA FOR THE OPTIMIZED REFERENCE COOLING SYSTEMS

SITE: ATLANTA, GEORGIA

| Variable | Mechanical Dry (High BP Turbine) | Mechanical Dry (Low BP Turbine) | Mechanical Wet (Low BP Turbine) |
|---|---|---|---|
| General Design Data | | | |
| Design Temperatures, $^{o}F$ ($^{o}C$): | | | |
| Dry Bulb | 95.0 (35.0) | 96.0 (35.6) | 95.0 (35.0) |
| Wet Bulb | 73.0 (27.8) | 75.0 (23.9) | 73.0 (27.8) |
| Cold Water | 134.0 (56.7) | 114.0 (45.6) | 91.0 (32.8) |
| Cooling Range | 24.0 (13.3) | 12.0 ( 6.7) | 26.0 (14.4) |
| ITD (Dry Tower) or Approach (Wet Tower) | 63.0 (35.0) | 30.0 (16.7) | 18.0 (10.0) |
| Design Turbine Back Pressure, in-HgA (mm-HgA) | 10.37 (263.4) | 4.65 (118.1) | 3.64 (92.5) |
| Maximum Operating Back Pressure, in-HgA (mm-HgA) | 11.59 (294.4) | 5.07 (128.8) | 3.69 (93.7) |
| Design Heat Load, $10^9$ Btu/hr ($10^{12}$ J/hr) | 7.53 ( 7.94) | 7.23 ( 7.62) | 7.16 ( 7.55) |
| Plant Capacity at Cooling System Design Point, MWe | 968 | 1056 | 1077 |
| Annual Make-up Water Requirement, $10^8$ gal. ($10^6$ $m^3$) | 0.0 | 0.0 | 46.26 (17.51) |

TABLE F-1 (sheet 2 of 3)

DESIGN DATA FOR THE OPTIMIZED REFERENCE COOLING SYSTEMS

SITE: ATLANTA, GEORGIA

| Variable | Mechanical Dry (High BP Turbine) | Mechanical Dry (Low BP Turbine) | Mechanical Wet (Low BP Turbine) |
|---|---|---|---|
| Condenser | | | |
| Surface Area, $10^3$ $ft^2$ ($10^3$ $m^2$) | 1139 (105.8) | 1522 (141.4) | 1046 (97.2) |
| Number of Tubes | 84,400 | 162,100 | 74,100 |
| Tube Length, ft (m) | 51.2 (15.6) | 35.9 (10.9) | 53.9 (16.4) |
| Circulating Water Flow & Pump | | | |
| Circulating Water Flow Rate, $10^3$ gpm ($m^3$/min) | 627 (2373) | 1204 (4555) | 550 (2081) |
| Number of Pumps | 4 | 7 | 4 |
| Pumping Head, ft (m) of Water | 58.4 (17.8) | 51.5 (15.7) | 86.3 (26.3) |
| Motor Rating, hp (kW) per pump | 3000 (2237) | 3000 (2237) | 4000 (2983) |
| Motor Brake Horsepower, hp (kW) per pump | 2598 (1937) | 2513 (1874) | 3369 (2512) |

TABLE F-1 (sheet 3 of 3)

DESIGN DATA FOR THE OPTIMIZED REFERENCE COOLING SYSTEMS

SITE: ATLANTA, GEORGIA

| Variable | Mechanical Dry (High BP Turbine) | Mechanical Dry (Low BP Turbine) | Mechanical Wet (Low BP Turbine) |
|---|---|---|---|
| Circulating Water Pipelines | | | |
| Condenser Intake: | | | |
| Number of Lines | 1 | 2 | 1 |
| Diameter/Length, in/ft (cm/m) | 144/1720 (366/524) | 144/1270 (366/524) | 138/1390 (351/423) |
| Condenser Discharge: | | | |
| Number of Lines | 1 | 2 | 1 |
| Diameter/Length, in/ft (cm/m) | 144/1080 (366/329) | 144/1080 (366/329) | 138/1010 (351/308) |
| Cooling Tower | | | |
| Size (Number of Cells): | | | |
| Dry Tower | 170 | 346 | - |
| Wet Tower | - | - | 33 |

TABLE F-2

CAPITAL COST BREAKDOWN FOR THE OPTIMIZED REFERENCE COOLING SYSTEMS ($$10^6$)

SITE: ATLANTA, GEORGIA TOWER: Mech. Wet and Dry Towers YEAR: 1985

| Acct. No. | Equipment Item | | Mechanical Dry (High BP Turbine) | Mechanical Dry* (Low BP Turbine) | Mechanical Wet (Low BP Turbine) |
|---|---|---|---|---|---|
| 218L | Circulating Water Pump Structures | (M | 1.003 | 1.276 | 0.955 |
| | | (L | 0.802 | 1.019 | 0.763 |
| | | (T | 1.805 | 2.295 | 1.718 |
| 232.211 | Circulating Water Pumps and Motors | (E | 2.995 | 5.242 | 2.988 |
| | | (M | 0.030 | 0.053 | 0.030 |
| | | (L | 0.211 | 0.369 | 0.211 |
| | | (T | 3.236 | 5.664 | 3.229 |
| 232.25 | Concrete Pipelines | (M | 2.903 | 5.806 | 2.416 |
| | | (L | 2.077 | 4.154 | 1.674 |
| | | (T | 4.980 | 9.960 | 4.090 |
| 232.3211 | Cooling Tower Basin and Foundation | (M | 0.520 | 1.056 | 2.141 |
| | | (L | 0.934 | 1.901 | 3.852 |
| | | (T | 1.454 | 2.957 | 5.993 |
| 232.3212 | Cooling Towers, Installed | (E | 51.350 | 104.513 | 8.110 |
| | | (M | 0.519 | 1.056 | 0.082 |
| | | (L | 5.980 | 12.170 | 5.290 |
| | | (T | 57.849 | 117.739 | 13.482 |
| 233.1 | Condensers, Installed | (E | 10.089 | 14.219 | 9.293 |
| | | (M | 0.051 | 0.071 | 0.047 |
| | | (L | 5.038 | 6.595 | 4.754 |
| | | (T | 15.178 | 20.885 | 14.094 |
| 24 | Electrical Equipment | (E | 2.247 | 4.461 | 1.006 |
| | | (M | 1.683 | 3.351 | 0.755 |
| | | (L | 4.076 | 8.244 | 0.680 |
| | | (T | 8.011 | 16.056 | 2.441 |
| | Direct Capital Cost of Cooling System | (E | 66.681 | 128.435 | 21.397 |
| | | (M | 6.714 | 12.669 | 6.426 |
| | | (L | 19.118 | 34.452 | 17.224 |
| | | (T | 92.513 | 175.556 | 45.047 |
| | Indirect Cost | | 23.128 | 43.889 | 11.262 |
| | Total Capital Cost | | 115.641 | 219.445 | 56.309 |

*This is not an optimized system.

TABLE F-3

PENALTY BREAKDOWN AND COST SUMMARY FOR THE OPTIMIZED REFERENCE COOLING SYSTEMS ($$10^6$)

SITE: ATLANTA, GEORGIA YEAR: 1985

| Item | Mechanical Dry (High BP Turbine) | Mechanical Dry (Low BP Turbine) | Mechanical Wet (Low BP Turbine) |
|---|---|---|---|
| Penalty Breakdown: | | | |
| Capacity Penalty | 83.362 | 28.400 | 10.911 |
| Replacement Energy Penalty | 58.201 | 2.137 | 4.840 |
| Circulating Water Pumping Power Penalty | 5.166 | 8.745 | 6.698 |
| Circulating Water Pumping Energy Penalty | 5.427 | 8.471 | 6.514 |
| Cooling Tower Fan Power Penalty | 14.330 | 28.673 | 2.994 |
| Cooling Tower Fan Energy Penalty | 13.938 | 26.246 | 2.828 |
| Make-up Water Purchase and Treatment Penalty | 0.000 | 0.000 | 6.862 |
| Cooling System Maintenance Penalty | 5.673 | 10.746 | 2.843 |
| Cost Summary: | | | |
| Total Penalty Cost | 186.097 | 113.418 | 44.490 |
| Total Capital Cost | 115.641 | 219.445 | 56.309 |
| Total Evaluated Cost | 301.738 | 332.863 | 100.799 |

TABLE F-4 (sheet 1 of 3)

DESIGN DATA FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS

SITE: ATLANTA, GEORGIA TOWER: MECHANICAL SERIES

| Variable | Percentage Make-up Requirement | | | | |
|---|---|---|---|---|---|
| | 1% | 10% | 20% | 30% | 40% |
| General Design Data | | | | | |
| Mode of Wet/Dry Tower Operation | S1 | S1 | S1 | S1 | S1 |
| Design Parameters for Dry Towers: | | | | | |
| Dry Bulb/Wet Bulb Temperatures, °F (°C) | 70.0/62.0 (21.1/16.7) | 55.0/50.0 (12.8/10.0) | 45.0/40.0 (7.2/4.4) | 40.0/36.0 (4.4/2.2) | 30.0/26.0 (-1.1/-3.3) |
| Cold Water Temperature, °F (°C) | 95.0 (35.0) | 93.0 (33.9) | 87.0 (30.6) | 87.0 (30.6) | 89.0 (31.7) |
| Cooling Range, °F (°C) | 16.0 (8.9) | 22.0 (12.2) | 26.0 (14.4) | 28.0 (15.6) | 28.0 (15.6) |
| Tower ITD, °F (°C) | 41.0 (22.8) | 60.0 (33.3) | 68.0 (37.8) | 75.0 (41.7) | 87.0 (48.3) |
| Condenser Heat Load, $10^9$ Btu/hr ($10^{12}$ J/hr) | 7.13 (7.52) | 7.14 (7.54) | 7.14 (7.53) | 7.15 (7.54) | 7.16 (7.55) |
| Design Parameters for Wet Helper Tower: | | | | | |
| Dry Bulb/Wet Bulb Temperatures, °F (°C) | 99.0/74.0 (37.2/23.3) | 99.0/74.0 (37.2/23.3) | 99.0/74.0 (37.2/23.3) | 99.0/74.0 (37.2/23.3) | 99.0/74.0 (37.2/23.3) |
| Tower Approach Temperature, °F (°C) | 20.0 (11.1) | 20.0 (11.1) | 20.0 (11.1) | 18.3 (10.2) | 18.3 (10.2) |
| Design and Maximum Operating Back Pressure $P_{max}$, in-HgA (mmHgA) | 5.0 (127.0) | 5.0 (127.0) | 4.5 (114.3) | 4.0 (101.6) | 4.0 (101.6) |
| Condenser Heat Load at $P_{max}$, $10^9$ Btu/hr ($10^{12}$ J/hr) | 7.25 (7.65) | 7.25 (7.65) | 7.21 (7.61) | 7.18 (7.57) | 7.18 (7.57) |
| Heat Load Distribution at $P_{max}$ - Wet Tower/ Dry Tower, % | 29.1/70.9 | 51.6/48.4 | 62.6/37.4 | 71.7/28.3 | 75.5/24.5 |
| Annual Make-up Water Requirement, $10^8$ gal ($10^6$ $m^3$) | 0.44 (0.17) | 5.05 (1.91) | 9.42 (3.57) | 14.1 (5.34) | 18.3 (6.94) |

TABLE F-4 (sheet 2 of 3)

DESIGN DATA FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS

SITE: ATLANTA, GEORGIA TOWER: MECHANICAL SERIES - S1 MODE

| Variable | Percentage Make-up Requirement | | | | |
|---|---|---|---|---|---|
| | 1% | 10% | 20% | 30% | 40% |
| Condenser | | | | | |
| Surface Area, $10^3$ $ft^2$ ($10^3$ $m^2$) | 1324 (123.0) | 1137 (105.6) | 1053 (97.8) | 1012 (94.0) | 1008 (93.7) |
| Number of Tubes | 119,900 | 87,400 | 73,900 | 68,700 | 68,800 |
| Tube Length, ft (m) | 42.2 (12.9) | 49.7 (15.1) | 54.4 (16.6) | 56.3 (17.2) | 56.0 (17.1) |
| Circulating Water Flow & Pump | | | | | |
| Circulating Water Flow Rate, $10^3$ gpm ($m^3$ /min) | 891 (3372) | 650 (2459) | 549 (2078) | 510 (1932) | 511 (1935) |
| Number of Pumps | 5 | 4 | 4 | 3 | 3 |
| Pumping Head, ft (m) of Water | 59.4 (18.1) | 66.8 (20.4) | 65.8 (20.1) | 68.6 (20.9) | 75.7 (23.1) |
| Motor Rating, hp (kW) per pump | 3500 (2610 ) | 3500 (2610 ) | 3000 (2237 ) | 4000 (2983 ) | 4000 (2983 ) |
| Motor Brake Horsepower, hp (kW) per pump | 3004 (2240) | 3078 (2295) | 2563 (1911) | 3311 (2469) | 3660 (2729) |
| Flow & Booster Pump for Wet Tower | | | | | |
| Percentage of Circulating Water to Wet Helper Tower, % | 20 | 48 | 79 | 100 | 100 |
| Number of Pumps | 2 | 2 | 3 | 3 | 3 |
| Pumping Head, ft (m) of Water | 41.0 (12.5) | 41.0 (12.5) | 41.0 (12.5) | 41.0 (12.5) | 41.0 (12.5) |
| Motor Rating, hp (kW) per pump | 1500 (1119 ) | 2500 (1864 ) | 2000 (1491 ) | 2500 (1864 ) | 2500 (1864 ) |
| Motor Brake Horsepower, hp (kW) per pump | 1060 (791) | 1820 (1357) | 1673 (1248) | 1979 (1476) | 1982 (1478) |

TABLE F-4 (sheet 3 of 3)

DESIGN DATA FOR THE OPTIMIZED WET/DRY COOLING SYSTEM

SITE: ATLANTA, GEORGIA TOWER: MECHANICAL SERIES - S1 MODE

| Variable | Percentage Make-up Requirement | | | | |
|---|---|---|---|---|---|
| | 1% | 10% | 20% | 30% | 40% |
| Circulating Water Pipelines | | | | | |
| Condenser Intake: | | | | | |
| Number of Lines | 2 | 2 | 1 | 1 | 1 |
| Diameter/Length, in/ft (cm/m) | 126/1310 (320/399) | 108/1310 (274/399) | 138/1310 (351/399) | 132/1310 (335/399) | 132/1310 (335/399) |
| Condenser Discharge: | | | | | |
| Number of Lines | 2 | 2 | 1 | 1 | 1 |
| Diameter/Length, in/ft (cm/m) | 126/1010 (320/308) | 108/1010 (274/308) | 138/1010 (351/308) | 132/1010 (335/308) | 132/1010 (335/308) |
| Connecting Pipelines: | | | | | |
| Number of Lines | 2 | 2 | 1 | 1 | 1 |
| Diameter/Length, in/ft (cm/m) | 126/1350 (320/412) | 108/1350 (274/412) | 138/1350 (351/412) | 132/1350 (335/412) | 132/1350 (335/412) |
| Cooling Tower | | | | | |
| Size (Number of Cells): | | | | | |
| Dry Tower | 244 | 162 | 145 | 130 | 107 |
| Wet Tower | 9 | 15 | 19 | 24 | 25 |

TABLE F-5

CAPITAL COST BREAKDOWN FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS ($$10^6$)

SITE: ATLANTA, GEORGIA TOWER: MECHANICAL SERIES YEAR: 1985

| Acct. No. | Equipment Item | | Percentage Make-up Requirement | | | | |
|---|---|---|---|---|---|---|---|
| | | | 1% | 10% | 20% | 30% | 40% |
| 218L | Circulating Water Pump Structures | (M | 1.140 | 1.016 | 0.955 | 0.928 | 0.930 |
| | | (L | 0.911 | 0.811 | 0.763 | 0.742 | 0.742 |
| | | (T | 2.051 | 1.827 | 1.718 | 1.670 | 1.672 |
| 232.211 | Circulating Water Pumps and Motors | (E | 4.839 | 4.572 | 4.678 | 4.612 | 4.612 |
| | | (M | 0.049 | 0.046 | 0.047 | 0.047 | 0.047 |
| | | (L | 0.369 | 0.316 | 0.369 | 0.316 | 0.316 |
| | | (T | 5.257 | 4.934 | 5.094 | 4.975 | 4.975 |
| 232.25 | Concrete Pipelines | (M | 5.606 | 4.208 | 3.520 | 3.180 | 3.180 |
| | | (L | 4.500 | 3.630 | 2.560 | 2.402 | 2.402 |
| | | (T | 10.106 | 7.838 | 6.080 | 5.582 | 5.582 |
| 232.3211 | Cooling Tower Basin and Foundation | (M | 1.329 | 1.469 | 1.677 | 1.956 | 1.952 |
| | | (L | 2.393 | 2.643 | 3.018 | 3.520 | 3.511 |
| | | (T | 3.722 | 4.112 | 4.695 | 5.476 | 5.463 |
| 232.3212 | Cooling Towers, Installed | (E | 75.850 | 52.566 | 48.429 | 45.129 | 38.459 |
| | | (M | 0.766 | 0.531 | 0.489 | 0.456 | 0.388 |
| | | (L | 10.008 | 8.089 | 8.134 | 8.417 | 7.765 |
| | | (T | 86.624 | 61.186 | 57.052 | 54.002 | 46.612 |
| 233.1 | Condensers, Installed | (E | 12.015 | 10.139 | 9.331 | 8.976 | 8.955 |
| | | (M | 0.060 | 0.051 | 0.047 | 0.045 | 0.045 |
| | | (L | 5.769 | 5.068 | 4.763 | 4.630 | 4.626 |
| | | (T | 17.844 | 15.258 | 14.141 | 13.651 | 13.626 |
| 24 | Electrical Equipment | (E | 3.463 | 2.608 | 2.447 | 2.406 | 2.170 |
| | | (M | 2.602 | 1.959 | 1.839 | 1.808 | 1.631 |
| | | (L | 8.796 | 6.036 | 5.562 | 5.079 | 4.310 |
| | | (T | 14.861 | 10.603 | 9.848 | 9.293 | 8.111 |
| | Direct Capital Cost of Cooling System | (E | 96.167 | 69.885 | 64.885 | 61.123 | 54.196 |
| | | (M | 11.552 | 9.280 | 8.574 | 8.420 | 8.173 |
| | | (L | 32.746 | 26.593 | 25.169 | 25.106 | 23.672 |
| | | (T | 140.465 | 105.758 | 98.628 | 94.649 | 86.041 |
| | Indirect Cost | | 35.116 | 26.440 | 24.657 | 23.662 | 21.510 |
| | Total Capital Cost | | 175.581 | 132.198 | 123.285 | 118.311 | 107.551 |

TABLE F-6

PENALTY BREAKDOWN AND COST SUMMARY FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS ($$10^6$)

SITE: ATLANTA, GEORGIA TOWER: MECHANICAL SERIES YEAR: 1985

| Item | Percentage Make-up Requirement | | | | |
|---|---|---|---|---|---|
| | 1% | 10% | 20% | 30% | 40% |
| Penalty Breakdown: | | | | | |
| Capacity Penalty | 27.478 | 27.400 | 20.723 | 14.457 | 14.457 |
| Replacement Energy Penalty | 7.304 | 17.836 | 16.672 | 13.183 | 14.084 |
| Circulating Water Pumping Power Penalty | 7.465 | 7.930 | 7.591 | 7.889 | 8.414 |
| Circulating Water Pumping Energy Penalty | 7.344 | 6.847 | 6.625 | 7.292 | 8.190 |
| Cooling Tower Fan Power Penalty | 20.472 | 13.511 | 12.628 | 11.986 | 10.325 |
| Cooling Tower Fan Energy Penalty | 18.937 | 12.863 | 11.808 | 10.997 | 9.436 |
| Make-up Water Purchase and Treatment Penalty | 0.066 | 0.749 | 1.398 | 2.092 | 2.719 |
| Cooling System Maintenance Penalty | 8.481 | 6.626 | 6.388 | 6.132 | 5.660 |
| Cost Summary: | | | | | |
| Total Penalty Cost | 97.547 | 93.762 | 83.833 | 74.028 | 73.285 |
| Total Capital Cost | 175.581 | 132.198 | 123.285 | 118.311 | 107.551 |
| l Evaluated Cost | 273.128 | 225.960 | 207.118 | 192.339 | 1[illegible]36 |

TABLE F-7 (sheet 1 of 3)

DESIGN DATA FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS

SITE: ATLANTA, GEORGIA TOWER: MECHANICAL SERIES - S2 MODE

| Variable | Percentage Make-up Requirement | | |
|---|---|---|---|
| | 20% | 30% | 40% |
| General Design Data | | | |
| Mode of Wet/Dry Tower Operation | S2 | S2 | S2 |
| Design Parameters for Dry Towers: | | | |
| Dry Bulb/Wet Bulb Temperatures, °F (°C) | 55/50 (12.8/10.0) | 45/40 ( 7.2/ 4.4) | 35/31 ( 1.7/-0.6) |
| Cold Water Temperature, °F (°C) | 90.0 (32.2) | 84.0 (28.9) | 88.0 (31.1) |
| Cooling Range, °F (°C) | 18.0 (10.0) | 24.0 (13.3) | 26.0 (14.4) |
| Tower ITD, °F (°C) | 53.0 (29.4) | 63.0 (35.0) | 79.0 (43.9) |
| Condenser Heat Load, $10^9$ Btu/hr ($10^{12}$ J/hr) | 7.12 (7.51) | 7.12 (7.51) | 7.14 (7.53) |
| Design Parameters for Wet Helper Tower: | | | |
| Dry Bulb/Wet Bulb Temperatures, °F (°C) | 99/74 (37.2/23.3) | 99/74 (37.2/23.3) | 99/74 (37.2/23.3) |
| Tower Approach Temperature, °F (°C) | 20.0 (11.1) | 20.0 (11.1) | 20.0 (11.1) |
| Design and Maximum Operating Back Pressure $P_{max}$, in-HgA (mmHgA) | 4.98 (126.5) | 4.98 (126.5) | 4.98 (126.5) |
| Condenser Heat Load at $P_{max}$, $10^9$ Btu/hr ($10^{12}$ J/hr) | 7.25 (7.64) | 7.25 (7.64) | 7.25 (7.64) |
| Heat Load Distribution at $P_{max}$- Wet Tower/ Dry Tower, % | 45.7/54.3 | 54.3/45.7 | 63.4/36.6 |
| Annual Make-up Water Requirement, $10^8$ gal ($10^6$ $m^3$) | 9.34 (3.54) | 13.6 (5.15) | 18.8 (7.12) |

TABLE F-7 (sheet 2 of 3)

DESIGN DATA FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS

SITE: ATLANTA, GEORGIA TOWER: MECHANICAL SERIES - S2 MODE

| Variable | Percentage Make-up Requirement | | |
|---|---|---|---|
| | 20% | 30% | 40% |
| Condenser | | | |
| Surface Area, $10^3$ $ft^2$ ($10^3$ $m^2$) | 1259 (117.0) | 1106 (102.8) | 1050 ( 97.6) |
| Number of Tubes | 106,400 | 79,800 | 73,900 |
| Tube Length, ft (m) | 45.2 (13.8) | 52.9 (16.1) | 54.3 (16.6) |
| Circulating Water Flow & Pump | | | |
| Circulating Water Flow Rate, $10^3$ gpm ($m^3$ /min) | 791 (2994) | 593 (2245) | 549 (2078) |
| Number of Pumps | 5 | 4 | 4 |
| Pumping Head, ft (m) of Water | 71.2 (21.7) | 65.2 (19.9) | 73.0 (22.3) |
| Motor Rating, hp (kW) per pump | 3500 (2611) | 3000 (2238) | 3500 (2611) |
| Motor Brake Horsepower, hp (kW) per pump | 3197 (2385) | 2742 (2046) | 2846 (2123) |
| Flow & Booster Pump for Wet Tower | | | |
| Percentage of Circulating Water to Wet Helper Tower | 34 | 56 | 67 |
| Number of Pumps | 2 | 2 | 3 |
| Pumping Head, ft (m) of Water | 41.0 (12.5) | 41.0 (12.5) | 41.0 (12.5) |
| Motor Rating, hp (kW) per pump | 2000 (1492) | 2500 (1865) | 2000 (1492) |
| Motor Brake Horsepower, hp (kW) per pump | 1551 (1157) | 1942 (1449) | 1422 (1061) |

TABLE F-7 (sheet 3 of 3)

DESIGN DATA FOR THE OPTIMIZED WET/DRY COOLING SYSTEM

SITE: ATLANTA, GEORGIA TOWER: MECHANICAL SERIES - S2 MODE

| Variable | Percentage Make-up Requirement | | |
|---|---|---|---|
| | 20% | 30% | 40% |
| Circulating Water Pipelines | | | |
| Condenser Intake: | | | |
| Number of Lines | 2 | 1 | 1 |
| Diameter/Length, in/ft (cm/m) | 114/1310 (290/399) | 144/1310 (366/399) | 138/1310 (351/399) |
| Condenser Discharge: | | | |
| Number of Lines | 2 | 1 | 1 |
| Diameter/Length, in/ft (cm/m) | 114/1010 (290/308) | 144/1010 (366/308) | 138/1010 (351/308) |
| Connecting Pipelines: | | | |
| Number of Lines | 2 | 1 | 1 |
| Diameter/Length, in/ft (cm/m) | 114/1350 (290/411) | 144/1350 (366/411) | 138/1350 (351/411) |
| Cooling Tower | | | |
| Size (Number of Cells): | | | |
| Dry Tower | 178 | 155 | 118 |
| Wet Tower | 13 | 16 | 18 |

TABLE F-8

CAPITAL COST BREAKDOWN FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS ($\$10^6$)

SITE: ATLANTA, GEORGIA TOWER: MECHANICAL SERIES - S2 MODE

| Acct. No. | Equipment Item | | Percentage Make-up Requirement 20% | 30% | 40% |
|---|---|---|---|---|---|
| 218L | Circulating Water Pump Structures | (M | 1.093 | 0.982 | 0.955 |
| | | (L | 0.872 | 0.785 | 0.763 |
| | | (T | 1.965 | 1.767 | 1.718 |
| 232.211 | Circulating Water Pumps and Motors | (E | 5.119 | 4.413 | 4.593 |
| | | (M | 0.052 | 0.045 | 0.046 |
| | | (L | 0.369 | 0.316 | 0.369 |
| | | (T | 5.540 | 4.774 | 5.008 |
| 232.25 | Concrete Pipelines | (M | 4.529 | 3.770 | 3.520 |
| | | (L | 3.911 | 2.723 | 2.560 |
| | | (T | 8.440 | 6.493 | 6.080 |
| 232.3211 | Cooling Tower Basin and Foundation | (M | 1.389 | 1.513 | 1.530 |
| | | (L | 2.496 | 2.721 | 2.753 |
| | | (T | 3.885 | 4.234 | 4.283 |
| 232.3212 | Cooling Towers, Installed | (E | 56.941 | 50.690 | 40.009 |
| | | (M | 0.575 | 0.512 | 0.404 |
| | | (L | 8.329 | 8.010 | 7.023 |
| | | (T | 65.845 | 59.212 | 47.436 |
| 233.1 | Condensers, Installed | (E | 11.311 | 9.784 | 9.318 |
| | | (M | 0.057 | 0.049 | 0.047 |
| | | (L | 5.501 | 4.926 | 4.759 |
| | | (T | 16.869 | 14.759 | 14.124 |
| 24 | Electrical Equipment | (E | 2.834 | 2.480 | 2.204 |
| | | (M | 2.130 | 1.863 | 1.656 |
| | | (L | 6.600 | 5.814 | 4.624 |
| | | (T | 11.564 | 10.157 | 8.484 |
| | Direct Capital Cost of Cooling System | (E | 76.205 | 67.367 | 56.124 |
| | | (M | 9.825 | 8.734 | 8.158 |
| | | (L | 28.078 | 25.295 | 22.851 |
| | | (T | 114.108 | 101.396 | 87.133 |
| | Indirect Cost | | 28.527 | 25.349 | 21.783 |
| | Total Capital Cost | | 142.635 | 126.745 | 108.916 |

TABLE F-9

PENALTY BREAKDOWN AND COST SUMMARY FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS ($\$10^6$)

SITE: ATLANTA, GEORGIA TOWER: MECHANICAL SERIES - S2 MODE

| Item | Percentage Make-up Requirement | | |
|---|---|---|---|
| | 20% | 30% | 40% |
| Penalty Breakdown: | | | |
| Capacity Penalty | 27.173 | 27.116 | 27.152 |
| Replacement Energy Penalty | 5.163 | 6.327 | 7.806 |
| Circulating Water Pumping Power Penalty | 9.488 | 7.383 | 7.779 |
| Circulating Water Pumping Energy Penalty | 8.690 | 6.887 | 7.524 |
| Cooling Tower Fan Power Penalty | 15.419 | 14.092 | 11.435 |
| Cooling Tower Fan Energy Penalty | 14.450 | 13.130 | 10.629 |
| Make-up Water Purchase and Treatment Penalty | 1.386 | 2.017 | 2.795 |
| Cooling System Maintenance Penalty | 7.238 | 6.414 | 5.737 |
| Cost Summary: | | | |
| Total Penalty Cost | 89.007 | 83.366 | 80.857 |
| Total Capital Cost | 142.635 | 126.745 | 108.916 |
| Total Evaluated Cost | 231.642 | 210.111 | 189.773 |

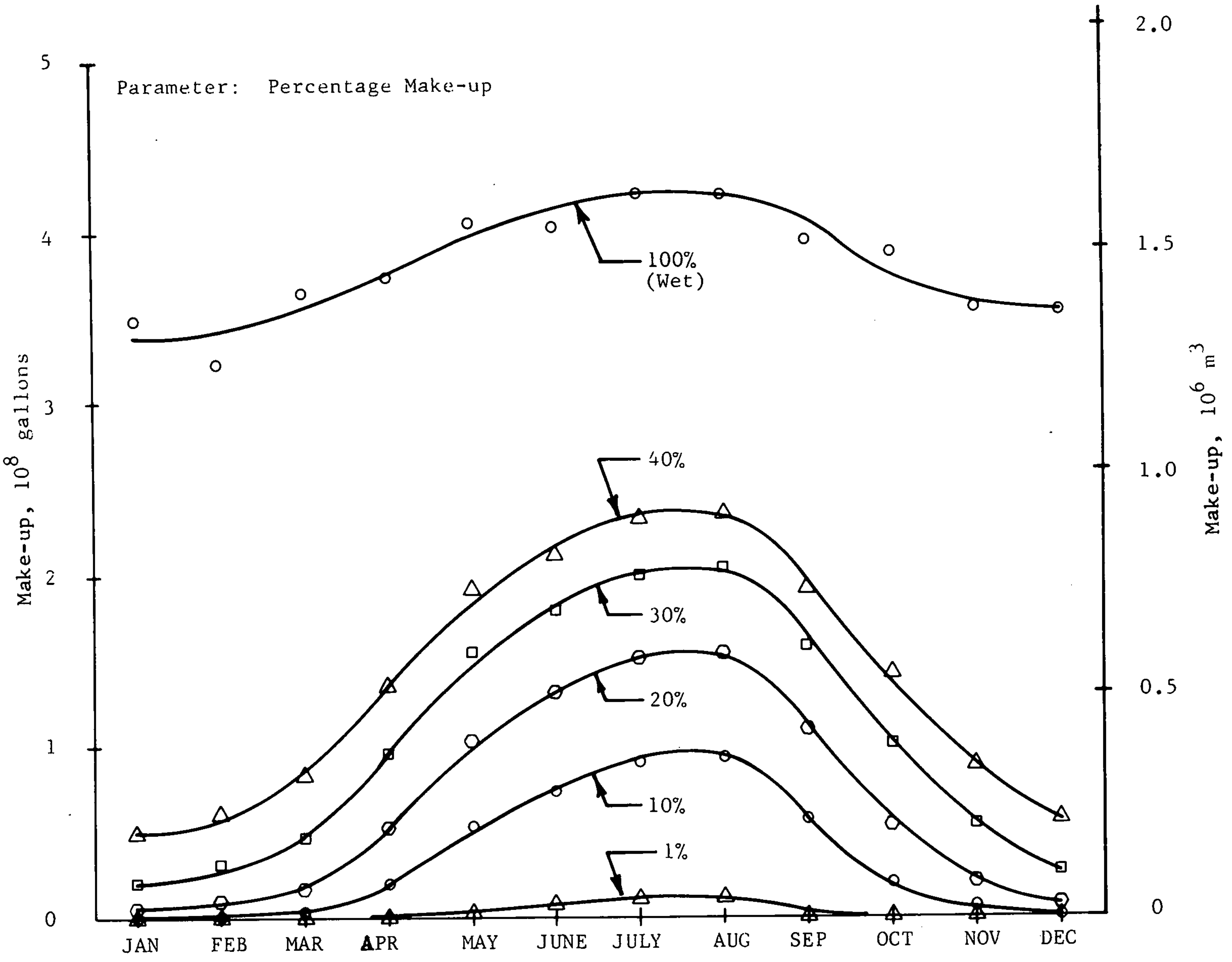


Figure F-1 Total Make-up Requirement for Each Monthly Period: Atlanta, Georgia
Mechanical Series Wet/Dry Cooling System - S1 Mode

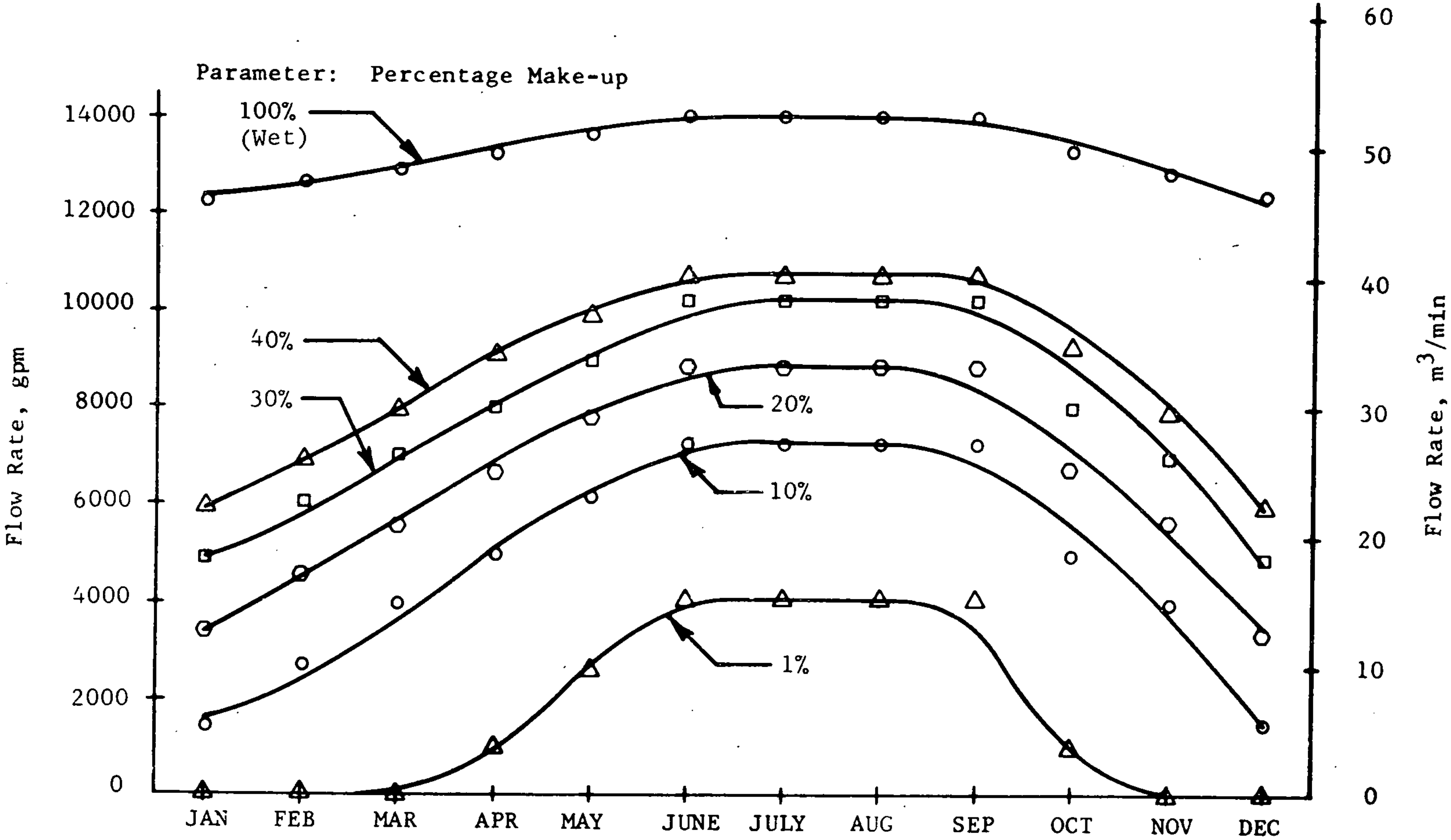


Figure F-2 Maximum Make-up Flow Rate for Each Monthly Period: Atlanta, Georgia Mechanical Series Wet/Dry Cooling System - S1 Mode

# APPENDIX G

## DETAILED DATA FOR SAN JUAN, NEW MEXICO SITE

This appendix contains data for cooling systems interfaced with LWR power plants sited at San Juan, New Mexico. Detailed design data, capital cost breakdowns, and penalty breakdowns are presented for reference cooling systems and mechanical series wet/dry cooling systems.

Tables G-1 through G-3 present data for the reference cooling systems.

Tables G-4 through G-6 present data for mechanical series wet/dry cooling system operating in the S1 mode.

Tables G-7 through G-9 present data for the mechanical series wet/dry cooling systems operating in the S2 mode.

Figures G-1 and G-2 provide information on the total monthly make-up requirement and the maximum make-up flow rate for each month for the wet cooling system and mechanical series wet/dry cooling systems operating in the S1 mode.

TABLE G-1 (sheet 1 of 3)

DESIGN DATA FOR THE OPTIMIZED REFERENCE COOLING SYSTEMS

SITE: SAN JUAN, NEW MEXICO

| Variable | Mechanical Dry (High BP Turbine) | Mechanical Dry (Low BP Turbine) | Mechanical Wet (Low BP Turbine) |
|---|---|---|---|
| **General Design Data** | | | |
| Design Temperatures, $^{o}F$ ($^{o}C$): | | | |
| Dry Bulb | 96.0 (35.6) | 102.0 (38.9) | 96.0 (35.6) |
| Wet Bulb | 62.0 (16.7) | 63.0 (17.2) | 62.0 (16.7) |
| Cold Water | 137.0 (58.3) | 117.0 (47.2) | 85.0 (29.4) |
| Cooling Range | 24.0 (13.3) | 12.0 (6.7) | 28.0 (15.6) |
| ITD (Dry Tower) or Approach (Wet Tower) | 65.0 (36.1) | 27.0 (15.0) | 23.0 (12.8) |
| Design Turbine Back Pressure, in-HgA (mm-HgA) | 11.12 (282.5) | 5.03 (127.8) | 3.26 (82.8) |
| Maximum Operating Back Pressure, in-HgA (mm-HgA) | 13.09 (332.5) | 5.03 (127.8) | 3.30 (83.8) |
| Design Heat Load, $10^9$ Btu/hr ($10^{12}$ J/hr) | 7.55 (7.96) | 7.26 (7.65) | 7.14 (7.53) |
| Plant Capacity at Cooling System Design Point, MWe | 960 | 1048 | 1083 |
| Annual Make-up Water Requirement, $10^8$ gal. ($10^6$ $m^3$) | 0.0 | 0.0 | 47.02 (17.80) |

TABLE G-1 (sheet 2 of 3)

DESIGN DATA FOR THE OPTIMIZED REFERENCE COOLING SYSTEMS

SITE: SAN JUAN, NEW MEXICO

| Variable | Mechanical Dry (High BP Turbine) | Mechanical Dry (Low BP Turbine) | Mechanical Wet (Low BP Turbine) |
|---|---|---|---|
| Condenser | | | |
| Surface Area, $10^3$ $ft^2$ ($10^3$ $m^2$) | 1143 (106.2) | 1529 (142.0) | 1017 (94.5) |
| Number of Tubes | 84,700 | 162,800 | 68,600 |
| Tube Length, ft (m) | 51.5 (15.7) | 35.9 (10.9) | 56.6 (17.3) |
| Circulating Water Flow & Pump | | | |
| Circulating Water Flow Rate, $10^3$ gpm ($m^3$/min) | 630 (2384) | 1209 (4576) | 510 (1930) |
| Number of Pumps | 4 | 7 | 3 |
| Pumping Head, ft (m) of Water | 59.6 (18.2) | 48.9 (14.9) | 87.2 (26.6) |
| Motor Rating, hp (kW) per pump | 3000 (2237) | 3000 (2237) | 4500 (3356) |
| Motor Brake Horsepower, hp (kW) per pump | 2660 (1984) | 2396 (1787) | 4201 (3133) |

TABLE G-1 (sheet 3 of 3)

DESIGN DATA FOR THE OPTIMIZED REFERENCE COOLING SYSTEMS

SITE: SAN JUAN, NEW MEXICO

| Variable | Mechanical Dry (High BP Turbine) | Mechanical Dry (Low BP Turbine) | Mechanical Wet (Low BP Turbine) |
|---|---|---|---|
| Circulating Water Pipelines | | | |
| Condenser Intake: | | | |
| Number of Lines | 1 | 2 | 1 |
| Diameter/Length, in/ft (cm/m) | 144/2090 (366/637) | 144/2090 (366/637) | 132/1160 (335/354) |
| Condenser Discharge: | | | |
| Number of Lines | 1 | 2 | 1 |
| Diameter/Length, in/ft (cm/m) | 144/1310 (366/399) | 144/1310 (366/399) | 132/1040 (335/317) |
| Cooling Tower | | | |
| Size (Number of Cells): | | | |
| Dry Tower | 175 | 431 | - |
| Wet Tower | - | - | 32 |

TABLE G-2

CAPITAL COST BREAKDOWN FOR THE OPTIMIZED REFERENCE COOLING SYSTEMS ($$10^6$)

SITE: SAN JUAN, NEW MEXICO YEAR: 1985

| Acct. No. | Equipment Item | | Mechanical Dry (High BP Turbine) | Mechanical Dry (Low BP Turbine) | Mechanical Wet (Low BP Turbine) |
|---|---|---|---|---|---|
| 218L | Circulating Water Pump Structures | (M | 1.005 | 1.278 | 0.928 |
| | | (L | 0.802 | 1.021 | 0.742 |
| | | (T | 1.807 | 2.299 | 1.670 |
| 232.211 | Circulating Water Pumps and Motors | (E | 2.995 | 5.242 | 2.604 |
| | | (M | 0.030 | 0.053 | 0.026 |
| | | (L | 0.211 | 0.369 | 0.158 |
| | | (T | 3.236 | 5.664 | 2.788 |
| 232.25 | Concrete Pipelines | (M | 3.398 | 6.796 | 2.032 |
| | | (L | 2.521 | 5.045 | 1.440 |
| | | (T | 5.919 | 11.841 | 3.472 |
| 232.3211 | Cooling Tower Basin and Foundation | (M | 0.535 | 1.316 | 2.076 |
| | | (L | 0.962 | 2.368 | 3.735 |
| | | (T | 1.497 | 3.684 | 5.811 |
| 232.3212 | Cooling Towers, Installed | (E | 52.860 | 130.188 | 7.864 |
| | | (M | 0.534 | 1.315 | 0.079 |
| | | (L | 6.154 | 15.159 | 5.130 |
| | | (T | 59.548 | 146.662 | 13.073 |
| 233.1 | Condensers, Installed | (E | 10.122 | 14.274 | 9.002 |
| | | (M | 0.051 | 0.072 | 0.045 |
| | | (L | 5.049 | 6.614 | 4.640 |
| | | (T | 15.222 | 20.960 | 13.687 |
| 24 | Electrical Equipment | (E | 2.301 | 5.388 | 0.908 |
| | | (M | 1.729 | 4.048 | 0.683 |
| | | (L | 4.191 | 10.190 | 0.621 |
| | | (T | 8.221 | 19.626 | 2.212 |
| | Direct Capital Cost of Cooling System | (E | 68.278 | 155.092 | 20.378 |
| | | (M | 7.282 | 14.878 | 5.869 |
| | | (L | 19.890 | 40.766 | 16.466 |
| | | (T | 95.450 | 210.736 | 42.713 |
| | Indirect Cost | | 23.862 | 52.684 | 10.678 |
| | Total Capital Cost | | 199.312 | 263.420 | 53.391 |

TABLE G-3

PENALTY BREAKDOWN AND COST SUMMARY FOR THE OPTIMIZED REFERENCE COOLING SYSTEMS ($\$10^6$)

SITE: SAN JUAN, NEW MEXICO YEAR: 1985

| Item | Mechanical Dry (High BP Turbine) | Mechanical Dry (Low BP Turbine) | Mechanical Wet (Low BP Turbine) |
|---|---|---|---|
| Penalty Breakdown: | | | |
| Capacity Penalty | 92.539 | 27.895 | 7.054 |
| Replacement Energy Penalty | 58.058 | 1.285 | 2.702 |
| Circulating Water Pumping Power Penalty | 5.288 | 8.339 | 6.266 |
| Circulating Water Pumping Energy Penalty | 5.554 | 8.066 | 6.074 |
| Cooling Tower Fan Power Penalty | 15.452 | 36.830 | 2.956 |
| Cooling Tower Fan Energy Penalty | 14.983 | 31.436 | 2.806 |
| Make-up Water Purchase and Treatment Penalty | 0.000 | 0.000 | 6.975 |
| Cooling System Maintenance Penalty | 5.784 | 12.595 | 2.615 |
| Cost Summary: | | | |
| Total Penalty Cost | 197.658 | 126.446 | 37.448 |
| Total Capital Cost | 199.312 | 263.420 | 53.391 |
| Total Evaluated Cost | 316.970 | 389.866 | 90.839 |

TABLE G-4 (sheet 1 of 3)

DESIGN DATA FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS

SITE: SAN JUAN, NEW MEXICO TOWER: MECHANICAL SERIES

| Variable | Percentage Make-up Requirement | | | | |
|---|---|---|---|---|---|
| | 1% | 10% | 20% | 30% | 40% |
| **General Design Data** | | | | | |
| Mode of Wet/Dry Tower Operation | S1 | S1 | S1 | S1 | S1 |
| Design Parameters for Dry Towers: | | | | | |
| Dry Bulb/Wet Bulb Temperatures, °F (°C) | 70.0/51.5 (21.1/10.8) | 55.0/42.0 (12.8/5.6) | 35.0/30.0 (1.7/-1.1) | 30.0/25.0 (-1.1/-3.9) | 20.0/16.5 (-6.7/-8.6) |
| Cold Water Temperature, °F (°C) | 95.0 (35.0) | 93.0 (33.9) | 82.0 (27.8) | 85.0 (29.4) | 84.0 (28.9) |
| Cooling Range, °F (°C) | 14.0 (7.8) | 24.0 (13.3) | 26.0 (14.4) | 28.0 (15.6) | 34.0 (18.9) |
| Tower ITD, °F (°C) | 39.0 (21.7) | 62.0 (34.4) | 73.0 (40.6) | 83.0 (46.1) | 98.0 (54.4) |
| Condenser Heat Load, $10^9$ Btu/hr ($10^{12}$ J/hr) | 7.12 (7.51) | 7.16 (7.55) | 7.12 (7.51) | 7.14 (7.53) | 7.16 (7.55) |
| Design Parameters for Wet Helper Tower: | | | | | |
| Dry Bulb/Wet Bulb Temperatures, °F (°C) | 102.0/63.0 (38.9/17.2) | 102.0/63.0 (38.9/17.2) | 102.0/63.0 (38.9/17.2) | 102.0/63.0 (38.9/17.2) | 102.0/63.0 (38.9/17.2) |
| Tower Approach Temperature, °F (°C) | 26.0 (14.4) | 26.0 (14.4) | 26.0 (14.4) | 26.0 (14.4) | 23.0 (12.8) |
| Design and Maximum Operating Back Pressure $P_{max}$, in-HgA (mmHgA) | 5.0 (127.0) | 5.0 (127.0) | 4.5 (114.3) | 4.0 (101.6) | 4.0 (101.6) |
| Condenser Heat Load at $P_{max}$ $10^9$ Btu/hr ($10^{12}$ J/hr) | 7.25 (7.65) | 7.25 (7.65) | 7.21 (7.61) | 7.18 (7.57) | 7.18 (7.57) |
| Heat Load Distribution at $P_{max}$- Wet Tower/Dry Tower, % | 33.4/66.6 | 57.8/42.2 | 69.6/30.4 | 78.2/21.8 | 81.7/18.3 |
| Annual Make-up Water Requirement, $10^8$ gal ($10^6$ $m^3$) | 0.494 (0.187) | 4.57 (1.73) | 9.11 (3.45) | 14.19 (5.37) | 18.78 (7.11) |

TABLE G-4 (sheet 2 of 3)

DESIGN DATA FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS

SITE: SAN JUAN, NEW MEXICO    TOWER: MECHANICAL SERIES

| Variable | Percentage Make-up Requirement | | | | |
|---|---|---|---|---|---|
| | 1% | 10% | 20% | 30% | 40% |
| Condenser | | | | | |
| Surface Area, $10^3$ $ft^2$ ($10^3$ $m^2$) | 1406 (130.6) | 1088 (101.1) | 1067 (99.1) | 1017 (94.5) | 891 (82.7) |
| Number of Tubes | 136,900 | 80,300 | 73,700 | 68,600 | 56,700 |
| Tube Length, ft (m) | 39.2 (11.9) | 51.8 (15.8) | 55.3 (16.9) | 56.6 (17.3) | 60.0 (18.3) |
| Circulating Water Flow & Pump | | | | | |
| Circulating Water Flow Rate, $10^3$ gpm ($m^3$ /min) | 1017 (3850) | 596 (2257) | 547 (2072) | 510 (1929) | 421 (1595) |
| Number of Pumps | 6 | 4 | 4 | 3 | 3 |
| Pumping Head, ft (m) of Water | 65.6 (20.0) | 67.4 (20.5) | 74.4 (22.7) | 77.4 (23.6) | 80.2 (24.5) |
| Motor Rating, hp (kW) per pump | 3500 (2610) | 3500 (2610) | 3500 (2610) | 4000 (2983) | 3500 (2610) |
| Motor Brake Horsepower, hp (kW) per pump | 3155 (2353) | 2851 (2126) | 2889 (2154) | 3731 (2782) | 3197 (23[illegible]) |
| Flow & Booster Pump for Wet Tower | | | | | |
| Percentage of Circulating Water to Wet Helper Tower | 16 | 48 | 66 | 87 | 100 |
| Number of Pumps | 2 | 2 | 3 | 3 | 3 |
| Pumping Head, ft (m) of Water | 41.0 (12.5) | 41.0 (12.5) | 41.0 (12.5) | 41.0 (12.5) | 41.0 (12.5) |
| Motor Rating, hp (kW) per pump | 2000 (1491) | 2000 (1491) | 2000 (1491) | 2000 (1491) | 2000 (1491) |
| Motor Brake Horsepower, hp (kW) per pump | 946 (705) | 1664 (1241) | 1400 (1044) | 1720 (1283) | 1633 (1218) |

TABLE G-4 (sheet 3 of 3)

DESIGN DATA FOR THE OPTIMIZED WET/DRY COOLING SYSTEM

SITE: SAN JUAN, NEW MEXICO TOWER: MECHANICAL SERIES - S1 MODE

| Variable | Percentage Make-up Requirement | | | | |
|---|---|---|---|---|---|
| | 1% | 10% | 20% | 30% | 40% |
| Circulating Water Pipelines | | | | | |
| Condenser Intake: | | | | | |
| Number of Lines | 2 | 1 | 1 | 1 | 1 |
| Diameter/Length, in/ft (cm/m) | 132/2170 (335/661) | 144/2170 (366/661) | 138/2170 (351/661) | 132/2170 (335/661) | 120/2170 (305/661) |
| Condenser Discharge: | | | | | |
| Number of Lines | 2 | 1 | 1 | 1 | 1 |
| Diameter/Length, in/ft (cm/m) | 132/1830 (335/558) | 144/1830 (366/558) | 138/1830 (351/558) | 132/1830 (335/558) | 120/1830 (305/558) |
| Connecting Pipelines: | | | | | |
| Number of Lines | 2 | 2 | 2 | 2 | 2 |
| Diameter/Length, in/ft (cm/m) | 132/1050 (335/320) | 102/1050 (259/320) | 96/1050 (244/320) | 96/1050 (244/320) | 84/1050 (213/320) |
| Cooling Tower | | | | | |
| Size (Number of Cells): | | | | | |
| Dry Tower | 263 | 170 | 138 | 119 | 102 |
| Wet Tower | 9 | 15 | 18 | 21 | 25 |

TABLE G-5

## CAPITAL COST BREAKDOWN FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS ($\$10^6$)

SITE: SAN JUAN, NEW MEXICO TOWER: MECHANICAL SERIES - MODE S1 YEAR: 1985

| Acct. No. | Equipment Item | | Percentage Make-up Requirement | | | | |
|---|---|---|---|---|---|---|---|
| | | | 1% | 10% | 20% | 30% | 40% |
| 218L | Circulating Water Pump Structures | (M | 1.198 | 0.984 | 0.953 | 0.928 | 0.865 |
| | | (L | 0.958 | 7.785 | 0.763 | 0.742 | 0.692 |
| | | (T | 2.155 | 1.769 | 1.716 | 1.670 | 1.557 |
| 232.211 | Circulating Water Pumps and Motors | (E | 5.627 | 4.493 | 4.593 | 4.493 | 4.374 |
| | | (M | 0.057 | 0.045 | 0.046 | 0.045 | 0.044 |
| | | (L | 0.422 | 0.316 | 0.369 | 0.316 | 0.316 |
| | | (T | 6.106 | 4.854 | 5.008 | 4.854 | 4.734 |
| 232.25 | Concrete Pipelines | (M | 8.308 | 4.937 | 4.536 | 4.185 | 3.239 |
| | | (L | 6.614 | 3.927 | 3.675 | 3.504 | 3.030 |
| | | (T | 14.922 | 8.864 | 8.211 | 7.689 | 6.269 |
| 232.3211 | Cooling Tower Basin and Foundation | (M | 1.389 | 1.494 | 1.591 | 1.729 | 1.937 |
| | | (L | 2.496 | 2.686 | 2.862 | 3.108 | 3.483 |
| | | (T | 3.885 | 4.180 | 4.453 | 4.837 | 5.420 |
| 232.3212 | Cooling Towers, Installed | (E | 81.546 | 54.942 | 46.066 | 41.105 | 36.931 |
| | | (M | 0.824 | 0.555 | 0.465 | 0.415 | 0.373 |
| | | (L | 10.673 | 8.369 | 7.727 | 7.546 | 7.593 |
| | | (T | 93.043 | 63.866 | 54.258 | 49.066 | 44.896 |
| 233.1 | Condensers, Installed | (E | 12.912 | 9.683 | 9.419 | 9.002 | 7.980 |
| | | (M | 0.065 | 0.049 | 0.047 | 0.045 | 0.040 |
| | | (L | 6.105 | 4.898 | 4.788 | 4.640 | 4.273 |
| | | (T | 19.082 | 14.630 | 14.254 | 13.687 | 12.293 |
| 24 | Electrical Equipment | (E | 3.784 | 2.662 | 2.422 | 2.193 | 2.018 |
| | | (M | 2.843 | 2.000 | 1.820 | 1.648 | 1.516 |
| | | (L | 9.490 | 6.311 | 5.308 | 4.658 | 4.138 |
| | | (T | 16.117 | 10.973 | 9.550 | 8.499 | 7.672 |
| | Direct Capital Cost of Cooling System | (E | 103.869 | 71.780 | 62.500 | 56.793 | 51.303 |
| | | (M | 14.684 | 10.064 | 9.458 | 8.995 | 8.014 |
| | | (L | 36.757 | 27.292 | 25.492 | 24.514 | 23.525 |
| | | (T | 155.310 | 109.136 | 97.450 | 90.302 | 82.842 |
| | Indirect Cost | | 38.828 | 27.284 | 24.363 | 22.576 | 20.711 |
| | Total Capital Cost | | 194.138 | 136.420 | 121.813 | 112.878 | 103.553 |

## TABLE G-6

## PENALTY BREAKDOWN AND COST SUMMARY FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS ($\$10^6$)

SITE: SAN JUAN, NEW MEXICO TOWER: MECHANICAL SERIES - MODE S1 YEAR: 1985

| Item | Percentage Make-up Requirement | | | | |
|---|---|---|---|---|---|
| | 1% | 10% | 20% | 30% | 40% |
| Penalty Breakdown: | | | | | |
| Capacity Penalty | 27.490 | 27.382 | 20.723 | 14.457 | 14.444 |
| Replacement Energy Penalty | 4.855 | 14.174 | 15.064 | 12.945 | 14.191 |
| Circulating Water Pumping Power Penalty | 9.411 | 7.316 | 7.837 | 8.134 | 7.205 |
| Circulating Water Pumping Energy Penalty | 9.209 | 6.280 | 6.992 | 7.625 | 7.082 |
| Cooling Tower Fan Power Penalty | 22.757 | 14.490 | 12.328 | 11.183 | 10.161 |
| Cooling Tower Fan Energy Penalty | 20.895 | 13.947 | 11.544 | 10.284 | 9.346 |
| Make-up Water Purchase and Treatment Penalty | 0.073 | 0.678 | 1.351 | 2.105 | 2.786 |
| Cooling System Maintenance Penalty | 9.297 | 6.738 | 6.177 | 5.762 | 5.395 |
| Cost Summary: | | | | | |
| Total Penalty Cost | 103.992 | 91.005 | 82.016 | 72.495 | 70.610 |
| Total Capital Cost | 194.138 | 136.420 | 121.813 | 112.878 | 103.553 |
| [illegible]l Evaluated Cost | 298.130 | 227.425 | 203.829 | 185.373 | 17[illegible] 163 |

TABLE G-7 (sheet 1 of 3)

DESIGN DATA FOR THE OPTIMIZED WET/DRY COOLING SYSTEM

SITE: SAN JUAN, NEW MEXICO TOWER: MECHANICAL SERIES - S2 MODE

| Variable | Percentage Make-up Requirement | | |
|---|---|---|---|
| | 20% | 30% | 40% |
| General Design Data | | | |
| Mode of Wet/Dry Tower Operation | S2 | S2 | S2 |
| Design Parameters for Dry Towers: | | | |
| Dry Bulb/Wet Bulb Temperatures, °F (°C) | 55/42 (12.8/5.6) | 40/34 (4.4/1.1) | 30/25.5 (-1.1/-3.9) |
| Cold Water Temperature, °F (°C) | 88.0 (31.1) | 81.0 (27.2) | 83.0 (28.3) |
| Cooling Range, °F (°C) | 24.0 (13.3) | 26.0 (14.4) | 28.0 (15.6) |
| Tower ITD, °F (°C) | 57.0 (31.7) | 67.0 (37.2) | 81.0 (45.0) |
| Condenser Heat Load, $10^9$ Btu/hr ($10^{12}$ J/hr) | 7.13 (7.52) | 7.11 (7.50) | 7.13 (7.52) |
| Design Parameters for Wet Helper Tower: | | | |
| Dry Bulb/Wet Bulb Temperatures, °F (°C) | 102/63 (38.9/17.2) | 102/63 (38.9/17.2) | 102/63 (38.9/17.2) |
| Tower Approach Temperature, °F (°C) | 26.0 (14.4) | 26.0 (14.4) | 26.0 (14.4) |
| Design and Maximum Operating Back Pressure $P_{max}$, in-HgA (mmHgA) | 4.99 (126.7) | 4.98 (126.5) | 4.98 (126.5) |
| Condenser Heat Load at $P_{max}$, $10^9$ Btu/hr ($10^{12}$ J/hr) | 7.25 (7.64) | 7.25 (7.64) | 7.25 (7.64) |
| Heat Load Distribution at $P_{max}$- Wet Tower/Dry Tower, % | 54.5/45.5 | 61.4/38.6 | 68.1/31.9 |
| Annual Make-up Water Requirement, $10^8$ gal ($10^6$ $m^3$) | 9.19 (3.48) | 13.43 (5.09) | 18.13 (6.87) |

TABLE G-7 (sheet 2 of 3)

DESIGN DATA FOR THE OPTIMIZED WET/DRY COOLING SYSTEM

SITE: SAN JUAN, NEW MEXICO    TOWER: MECHANICAL SERIES - S2 MODE

| Variable | Percentage Make-up Requirement | | |
|---|---|---|---|
| | 20% | 30% | 40% |
| Condenser | | | |
| Surface Area, $10^3$ $ft^2$ ($10^3$ $m^2$) | 1095 (101.7) | 1071 (99.5) | 1022 (94.9) |
| Number of Tubes | 80,000 | 73,600 | 68,500 |
| Tube Length, ft (m) | 52.3 (15.9) | 55.5 (16.9) | 57.0 (17.4) |
| Circulating Water Flow & Pump | | | |
| Circulating Water Flow Rate, $10^3$ gpm ($m^3$ /min) | 594 (2249) | 547 (2071) | 509 (1927) |
| Number of Pumps | 4 | 4 | 3 |
| Pumping Head, ft (m) of Water | 65.2 (19.9) | 71.2 (21.7) | 76.5 (23.3) |
| Motor Rating, hp (kW) per pump | 3000 (2238) | 3500 (2611) | 4000 (2984) |
| Motor Brake Horsepower, hp (kW) per pump | 2748 (2050) | 2761 (2060) | 3683 (2748) |
| Flow & Booster Pump for Wet Tower | | | |
| Percentage of Circulating Water to Wet Helper Tower | 46 | 55 | 63 |
| Number of Pumps | 2 | 3 | 2 |
| Pumping Head, ft (m) of Water | 41.0 (12.5) | 41.0 (12.5) | 41.0 (12.5) |
| Motor Rating, hp (kW) per pump | 2000 (1492) | 1500 (1118) | 2500 (1864) |
| Motor Brake Horsepower, hp (kW) per pump | 1604 (1196) | 1756 (1309) | 1875 (1398) |

TABLE G-7 (sheet 3 of 3)

DESIGN DATA FOR THE OPTIMIZED WET/DRY COOLING SYSTEM

SITE: SAN JUAN, NEW MEXICO TOWER: MECHANICAL SERIES - S2 MODE

| Variable | Percentage Make-up Requirement | | |
|---|---|---|---|
| | 20% | 30% | 40% |
| Circulating Water Pipelines | | | |
| Condenser Intake: | | | |
| Number of Lines | 1 | 1 | 1 |
| Diameter/Length, in/ft (cm/m) | 144/2170 (366/661) | 138/2170 (351/661) | 132/2170 (335/661) |
| Condenser Discharge: | | | |
| Number of Lines | 1 | 1 | 1 |
| Diameter/Length, in/ft (cm/m) | 144/1830 (366/558) | 138/1830 (351/558) | 132/1830 (335/558) |
| Connecting Pipelines: | | | |
| Number of Lines | 2 | 2 | 2 |
| Diameter/Length, in/ft (cm/m) | 102/1050 (259/320) | 96/1050 (244/320) | 96/1050 (244/320) |
| Cooling Tower | | | |
| Size (Number of Cells): | | | |
| Dry Tower | 190 | 155 | 123 |
| Wet Tower | 15 | 17 | 18 |

TABLE G-8

CAPITAL COST BREAKDOWN FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS ($$10^6$)

SITE: SAN JUAN, NEW MEXICO TOWER: MECHANICAL SERIES - S2 MODE YEAR: 1985

| Acct. No. | Equipment Item | | Percentage Make-up Requirement | | |
|---|---|---|---|---|---|
| | | | 20% | 30% | 40% |
| 218L | Circulating Water Pump Structures | (M | 0.982 | 0.953 | 0.928 |
| | | (L | 0.785 | 0.763 | 0.742 |
| | | (T | 1.767 | 1.716 | 1.670 |
| 232.211 | Circulating Water Pumps and Motors | (E | 4.171 | 4.173 | 3.903 |
| | | (M | 0.042 | 0.042 | 0.039 |
| | | (L | 0.316 | 0.369 | 0.263 |
| | | (T | 4.529 | 4.584 | 4.205 |
| 232.25 | Concrete Pipelines | (M | 4.937 | 4.536 | 4.185 |
| | | (L | 3.927 | 3.675 | 3.504 |
| | | (T | 8.864 | 8.211 | 7.689 |
| 232.3211 | Cooling Tower Basin and Foundation | (M | 1.555 | 1.578 | 1.545 |
| | | (L | 2.796 | 2.837 | 2.780 |
| | | (T | 4.351 | 4.415 | 4.325 |
| 232.3212 | Cooling Towers, Installed | (E | 61.000 | 50.987 | 41.560 |
| | | (M | 0.616 | 0.515 | 0.420 |
| | | (L | 9.081 | 8.160 | 7.196 |
| | | (T | 70.697 | 59.662 | 49.176 |
| 233.1 | Condensers, Installed | (E | 9.721 | 9.441 | 9.037 |
| | | (M | 0.049 | 0.047 | 0.045 |
| | | (L | 4.907 | 4.795 | 4.649 |
| | | (T | 14.677 | 14.283 | 13.731 |
| 24 | Electrical Equipment | (E | 2.815 | 2.543 | 2.160 |
| | | (M | 2.115 | 1.911 | 1.623 |
| | | (L | 6.994 | 5.874 | 4.704 |
| | | (T | 11.924 | 10.328 | 8.487 |
| | Direct Capital Cost of Cooling System | (E | 77.707 | 67.144 | 56.660 |
| | | (M | 10.296 | 9.582 | 8.785 |
| | | (L | 28.806 | 26.473 | 23.838 |
| | | (T | 116.809 | 103.199 | 89.283 |
| | Indirect Cost | | 29.202 | 25.800 | 22.321 |
| | Total Capital Cost | | 146.011 | 128.999 | 111.604 |

TABLE G-9

PENALTY BREAKDOWN AND COST SUMMARY FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS ($\$10^6$)

SITE: SAN JUAN, NEW MEXICO TOWER: MECHANICAL SERIES - S2 MODE YEAR: 1985

| Item | Percentage Make-up Requirement | | |
|---|---|---|---|
| | 20% | 30% | 40% |
| Penalty Breakdown: | | | |
| Capacity Penalty | 27.180 | 27.127 | 27.116 |
| Replacement Energy Penalty | 4.094 | 4.632 | 5.666 |
| Circulating Water Pumping Power Penalty | 7.059 | 7.236 | 7.356 |
| Circulating Water Pumping Energy Penalty | 6.112 | 6.590 | 7.052 |
| Cooling Tower Fan Power Penalty | 17.107 | 14.612 | 12.239 |
| Cooling Tower Fan Energy Penalty | 15.968 | 13.505 | 11.338 |
| Make-up Water Purchase and Treatment Penalty | 1.363 | 1.992 | 2.690 |
| Cooling System Maintenance Penalty | 7.041 | 6.345 | 5.496 |
| Cost Summary: | | | |
| Total Penalty Cost | 85.924 | 82.039 | 78.953 |
| Total Capital Cost | 146.011 | 128.999 | 111.604 |
| Total Evaluated Cost | 231.935 | 211.038 | 190.557 |

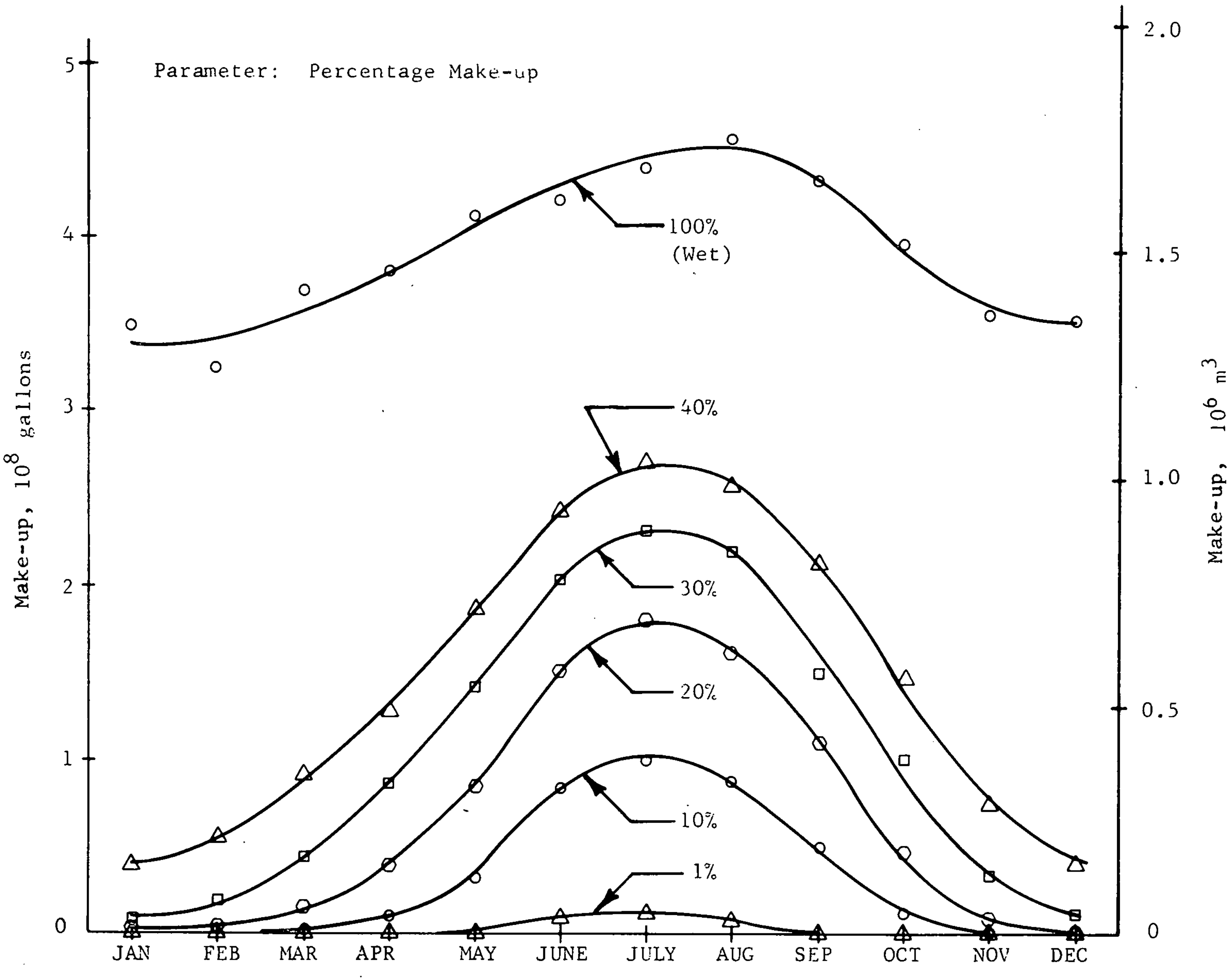


FIGURE G-1 Total Make-up Requirement for Each Monthly Period: San Juan, New Mexico
Mechanical Series Wet/Dry Cooling Systems - S1 Mode

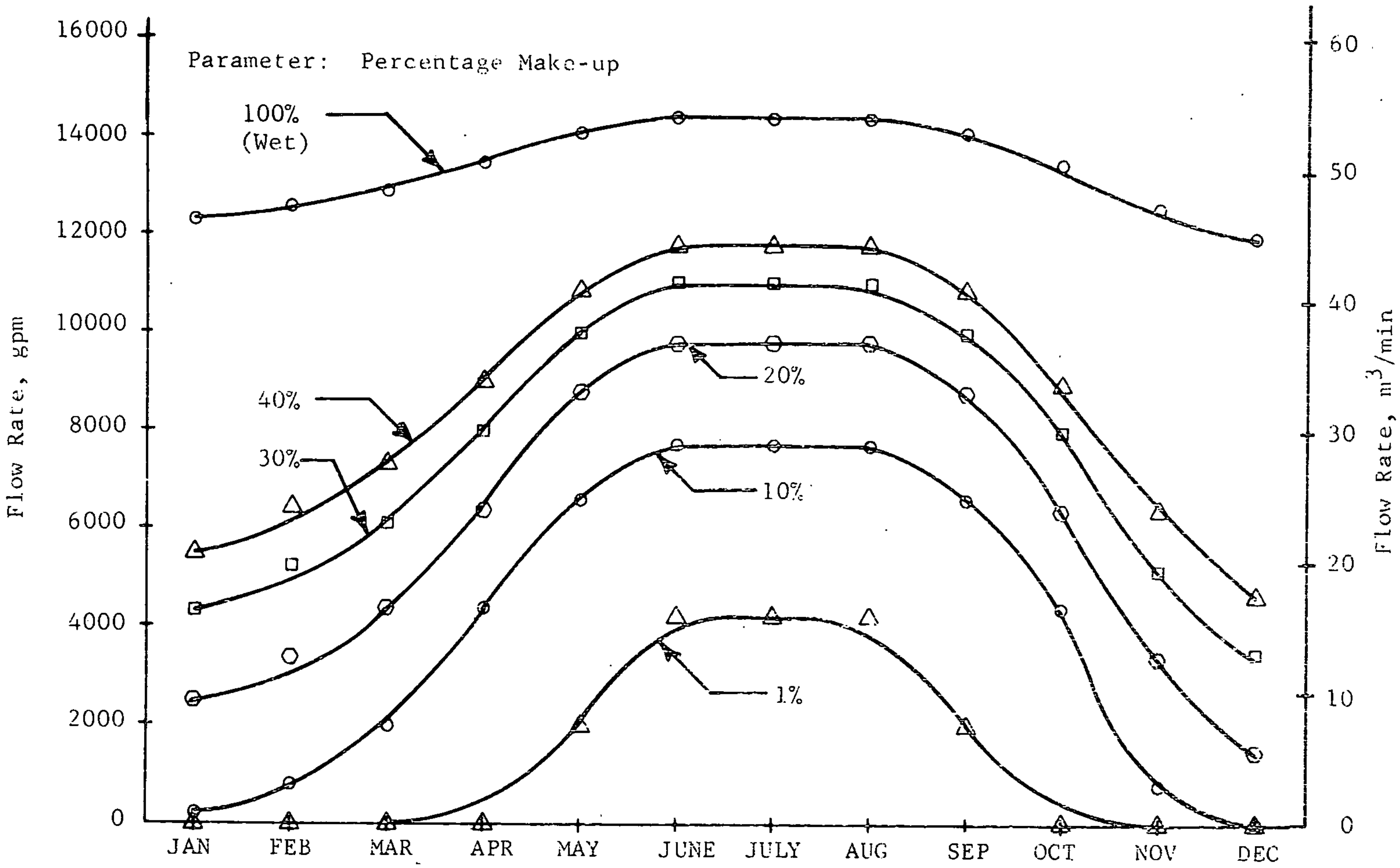


Figure G-2 Maximum Make-up Flow Rate for Each Monthly Period: San Juan, New Mexico Mechanical Series Wet/Dry Cooling Systems - S1 Mode

# APPENDIX H

## SENSITIVITY ANALYSIS RESULTS

This appendix presents results of the sensitivity analysis performed on the optimized reference cooling systems and the optimized mechanical series wet/dry cooling systems operating in the S1 mode.

Tables H-1 and H-2 show the impact of changing economics on the total evaluated cost for the Atlanta and San Juan sites.

Figures H-1 through H-3 present the cost comparisons of the transferred and optimized systems (10, 30, and 40 percent wet/dry systems) at Middletown.

## TABLE H-1

### IMPACT OF CHANGING ECONOMICS ON TOTAL EVALUATED COST (ATLANTA, MECHANICAL SERIES, S1 MODE)

| Sensitivity Parameters | | Percentage Change from Base System, % | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Mech. Dry* | Percentage Make-up Requirement - Mech. Series Wet/Dry - S1 Mode | | | | | Mech. Wet |
| | | | 1% | 10% | 20% | 30% | 40% | |
| Annual Fixed Charge Rate, % | = 12.5 | + 12.1 | + 6.8 | + 8.7 | + 8.8 | + 9.0 | + 9.4 | + 9.7 |
| [18] ** | = 25.0 | - 7.7 | - 4.3 | - 5.5 | - 5.8 | - 5.7 | - 6.1 | - 6.4 |
| Fuel Cost, $/MBtu ($/GJ) | = .76 ( .72) | - 12.4 | - 5.9 | - 8.0 | - 8.2 | - 8.2 | - 8.8 | - 7.3 |
| [1.53 (1.45)] ** | = 3.00 (2.84) | + 23.7 | + 11.3 | + 15.1 | + 14.3 | + 15.0 | + 16.1 | + 12.7 |
| | = 6.00 (5.68) | + 72.0 | + 34.3 | + 42.8 | + 42.3 | + 44.2 | + 44.8 | + 37.2 |
| Replacement Capacity Cost, $/kW | = 300 | - 17.9 | - 10.1 | - 10.8 | - 9.9 | - 9.2 | - 9.5 | - 11.3 |
| [600] ** | = 900 | + 16.8 | + 10.1 | + 10.8 | + 9.4 | + 8.9 | + 9.2 | + 9.9 |
| | = 1,200 | + 32.9 | + 20.3 | + 21.0 | + 18.2 | + 17.9 | + 18.4 | + 19.4 |
| Escalation Multiplier (Material/Labor) | = 1.1/1.1 | - 18.3 | - 30.2 | - 28.6 | - 29.8 | - 29.3 | - 29.1 | - 28.7 |
| [1.91/2.29] ** | = 3.30/4.75 | + 30.5 | + 54.4 | + 50.0 | + 49.4 | + 50.6 | + 48.9 | + 48.4 |
| | = 5.75/6.75 | + 73.5 | +134. | +122. | +119. | +118. | +117. | +108. |

* High back pressure turbine

** Base economic value

| | Mech. Dry* | Percentage Make-up Requirement - Mech. Series Wet/Dry - S1 Mode | | | | | Mech. Wet |
|---|---|---|---|---|---|---|---|
| | | 1% | 10% | 20% | 30% | 40% | |
| Base Total Evaluated Cost, $$10^6$ | 301.74 | 273.17 | 225.96 | 207.12 | 192.34 | 180.84 | 100.80 |

TABLE H-2

## IMPACT OF CHANGING ECONOMICS ON TOTAL EVALUATED COST (SAN JUAN, MECHANICAL SERIES, S1 MODE)

| Sensitivity Parameters | | Percentage Change from Base System, % | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Mech. Dry* | Percentage Make-up Requirement - Mech. Series Wet/Dry - S1 Mode | | | | | Mech. Wet |
| | | | 1% | 10% | 20% | 30% | 40% | |
| Annual Fixed Charge Rate, % | = 12.5 | + 11.7 | + 6.6 | + 8.0 | + 8.5 | + 9.0 | + 8.7 | + 10.5 |
| [18] ** | = 25.0 | - 7.5 | - 4.1 | - 5.1 | - 5.6 | - 5.7 | - 6.2 | - 6.7 |
| Fuel Cost, $/MBtu ($/GJ) | = .76 ( .72) | - 12.0 | - 5.5 | - 7.2 | - 7.8 | - 7.8 | - 8.3 | - 6.0 |
| [1.53 (1.45)] ** | = 3.00 (2.84) | + 22.8 | + 10.8 | + 13.7 | + 13.6 | + 14.4 | + 13.5 | + 11.5 |
| | = 6.00 (5.68) | + 69.4 | + 32.5 | + 39.1 | + 40.2 | + 40.4 | + 41.1 | + 35.0 |
| Replacement Capacity Cost, $/kW | = 300 | - 18.5 | - 9.9 | - 10.7 | - 9.9 | - 8.9 | - 9.0 | - 8.8 |
| [600] ** | = 900 | + 17.2 | + 10.0 | + 10.7 | + 9.3 | + 8.9 | + 7.8 | + 8.8 |
| | = 1,200 | + 33.7 | + 20.0 | + 20.3 | + 18.0 | + 17.5 | + 15.7 | + 17.6 |
| Escalation Multiplier (Material/Labor) | = 1.1/1.1 | - 18.4 | - 30.6 | - 29.5 | - 30.1 | - 30.3 | - 30.7 | - 28.2 |
| [1.91/2.29] ** | = 3.30/4.75 | + 30.5 | + 55.4 | + 51.7 | + 50.2 | + 51.9 | + 52.4 | + 50.1 |
| | = 5.75/6.75 | + 75.5 | +137. | +127. | +120. | +120. | +125. | +111. |

* High back pressure turbine.
** Base economic value

| | Mech. Dry* | Percentage Make-up Requirement - Mech. Series Wet/Dry - S1 Mode | | | | | Mech. Wet |
|---|---|---|---|---|---|---|---|
| | | 1% | 10% | 20% | 30% | 40% | |
| Base Total Evaluated Cost, $$10^6$ | 316.97 | 299.75 | 230.81 | 207.55 | 189.83 | 177.67 | 94.32 |

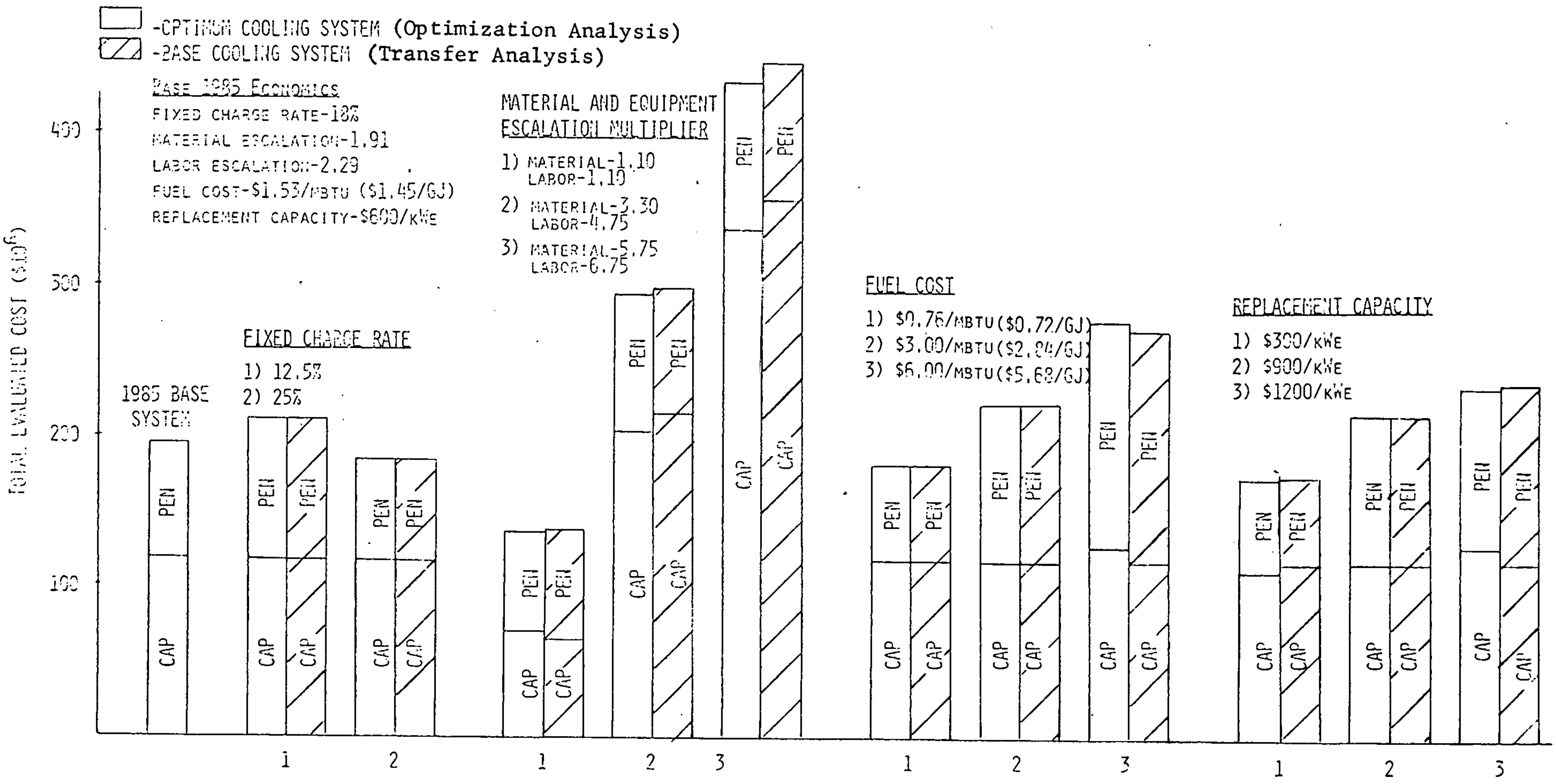


Figure H-1 Effect of Economic Factors on Costs Obtained by Optimization and Transfer Analyses (Middletown, 10% Wet/Dry)

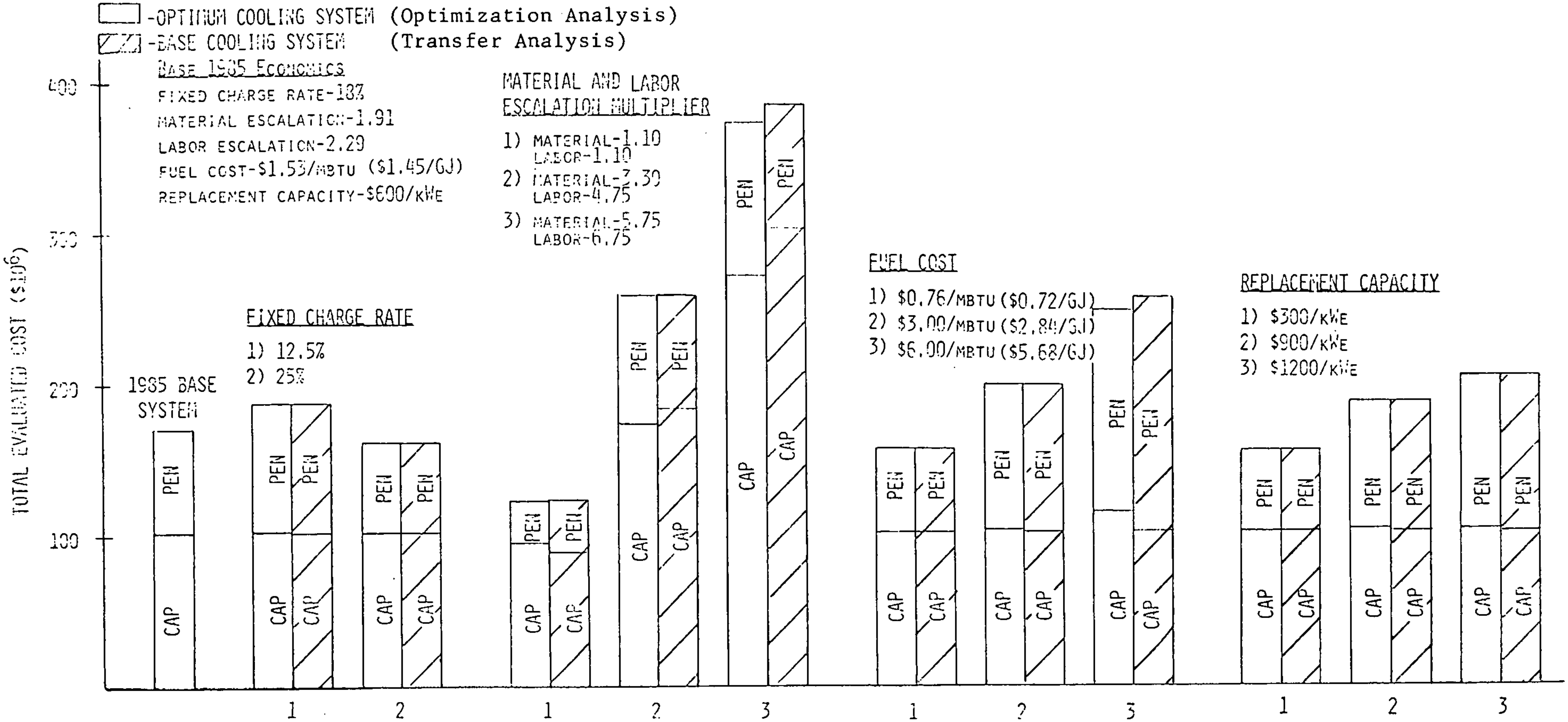


Figure H-2 Effect of Economic Factors on Costs Obtained by Optimization and Transfer Analysis (Middletown, 30% Wet/Dry)

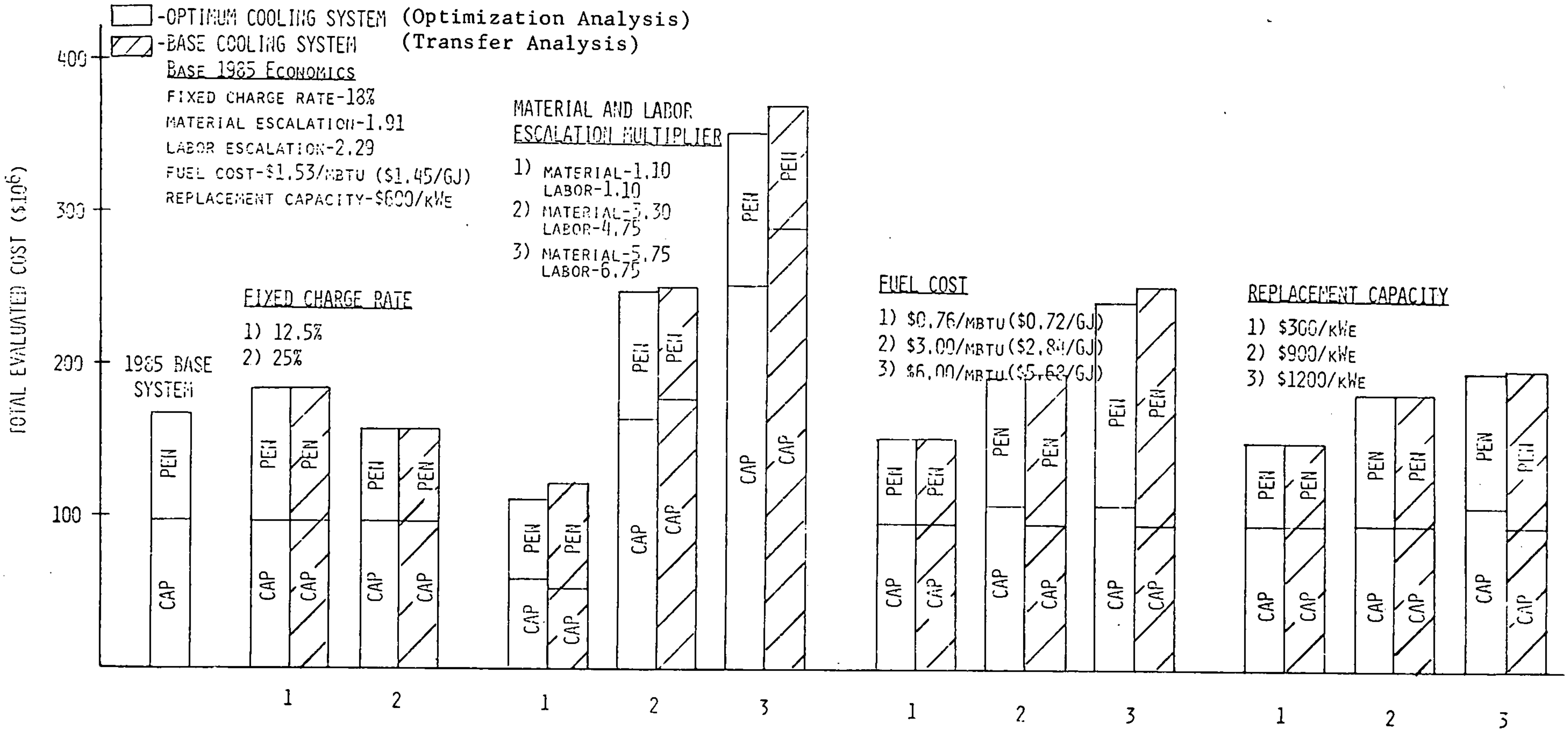


Figure H-3 Effect of Economic Factors on Costs Obtained by Optimization and Transfer Analysis (Middletown, 40% Wet/Dry)

## APPENDIX I

## A COST EVALUATION OF SUPPLYING MAKE-UP WATER

INTRODUCTION: In order to assess the impact of limited river flow for condenser make-up and inland plant siting on the economics of wet and wet/dry cooling systems, a study was completed using the Middletown cooling systems as a basis. A wet and three wet/dry tower systems were selected for comparative analysis. The three wet/dry systems have annual water requirements of 1, 10, and 40 percent of that required by the wet system. The wet/dry cooling systems are in a series arrangement operating in the S1 mode as described in Chapter 3.

One inland site was evaluated in conjunction with these cooling systems. This site is 29 miles (46.7 km) from the waterway and requires a 29 mile (46.7 km) make-up supply line.

The total evaluated cost was calculated for each case. The elements of the cost include the capital cost of the cooling towers, condensers, circulating water pumps and pipelines, electrical switchgear, structures, make-up pipelines, and impoundment pond costs, and the associated operating penalties including the cost of pumping water from the river to the site.

### ASSUMPTIONS

The analysis presented represents wet and wet/dry cooling systems at a hypothetical site. Certain assumptions and restrictions were stipulated that make this site rather unique, but nevertheless, the effect of make-up water restrictions and inland plant siting on the total evaluated cost of the cooling system can be seen.

The primary assumption made concerned the allowable make-up flow rate. Table I-1 indicates the monthly flow through the river supplying the plant. These flows are graphically illustrated in Figure I-1. This river serves a highly industrialized metropolitan area. Water quality restrictions limit the allowable water withdrawal for this plant to 0.1 percent of the river flow at any time. As shown on Figure I-1, this limitation will not allow continuous withdrawal for wet cooling tower make-up, although there is sufficient water available over the annual cycle. By building a reservoir, water impounded during the eight months from January to August can be used to supply the four water deficient months, September to December. The wet/dry systems described also required some on site impoundment to satisfy instantaneous system requirements and also as a precaution in the event of a make-up pump or pipeline failure. The impoundment for the wet/dry systems is sized to provide a two day supply at the maximum make-up rate. Pipeline costs for the four systems are given in Table I-3.

MAKE-UP SYSTEM DESCRIPTION

Make-up water is drawn from the river via an intake structure designed to satisfy a maximum water velocity in front of the traveling screens of ½ fps (0.15 m/s). The water is pumped through a steel pipeline to the impoundment pond. The pumps are sized and evaluated based only on frictions losses as the elevation difference between the intake and impoundment has been assumed to be zero. A liner has been included in the cost of the pond to eliminate any seepage losses. Pumps located at the edge of this pond pump the water directly to the cooling system. Information concerning the impoundment and the pipeline diameter is given on Table I-2.

## ESULTS

As expected, water supply costs for the wet cooling systems are greater than that of the wet/dry cooling systems. The economic choice in all cases, however, remains the wet system.

Increasing the distance from the plant to its make-up water supply may not significantly increase the system total evaluated cost.

One of the key factors which may greatly impact the system cost is the allowable make-up flow rate. In the situation presented here, a wet system would require a 153 acre (6.19 x $10^5$ $m^2$) impoundment to satisfy make-up requirements during low river flow periods. The capital cost of an impoundment this size could be on the order of $25 million (1985 dollars), depending on site conditions. With the use of wet/dry cooling, this cost would virtually be eliminated depending on the system chosen. A capital cost breakdown for the systems incorporating a 29 mile (46.7 km) make-up line is given on Table I-4.

TABLE I-1

WATER FLOWS AND REQUIREMENTS

| MONTH | RIVER FLOW, cfs ($m^3/s$) | ALLOWABLE MAKE-UP | | COOLING SYSTEM MAKE-UP REQUIREMENT, $10^8$ GALLONS ($10^6$ $m^3$) | | | |
|---|---|---|---|---|---|---|---|
| | | GPM ($m^3$/min) | $10^8$ gallons ($10^6$ $m^3$) | WET | 40% WET/DRY | 10% WET/DRY | 1% WET/DRY |
| January | 21,900 (620.2) | 9,830 (37.2) | 4.39 (1.66) | 3.15 (1.19) | 0.54 (0.20) | 0.01 (0.00) | 0.00 (0.00) |
| February | 24,250 (686.8) | 10,880 (41.2) | 4.39 (1.66) | 2.84 (1.08) | 0.52 (0.20) | 0.01 (0.00) | 0.00 (0.00) |
| March | 19,900 (563.6) | 8,930 (33.8) | 3.99 (1.51) | 3.33 (1.26) | 0.84 (0.32) | 0.02 (0.01) | 0.00 (0.00) |
| April | 26,250 (743.4) | 11,780 (44.6) | 5.09 (1.93) | 3.44 (1.30) | 1.22 (0.46) | 0.13 (0.05) | 0.01 (0.00) |
| May | 35,000 (991.2) | 15,710 (59.5) | 7.01 (2.65) | 3.80 (1.44) | 1.77 (0.67) | 0.52 (0.20) | 0.04 (0.02) |
| June | 33,250 (941.6) | 14,920 (56.5) | 6.44 (2.44) | 3.86 (1.46) | 2.13 (0.81) | 0.95 (0.36) | 0.13 (0.05) |
| July | 25,100 (710.8) | 11,270 (42.7) | 5.03 (1.90) | 4.09 (1.55) | 2.43 (0.92) | 1.26 (0.48) | 0.22 (0.08) |
| August | 19,200 (543.7) | 8,620 (32.6) | 3.85 (1.46) | 4.04 (1.53) | 2.32 (0.88) | 1.13 (0.43) | 0.17 (0.06) |
| September | 12,200 (345.5) | 5,480 (20.7) | 2.37 (0.90) | 3.76 (1.42) | 1.90 (0.72) | 0.70 (0.26) | 0.06 (0.02) |
| October | 9,900 (280.4) | 4,440 (16.8) | 1.98 (0.75) | 3.67 (1.39) | 1.50 (0.57) | 0.28 (0.01) | 0.01 (0.00) |
| November | 8,750 (247.8) | 3,930 (14.9) | 1.70 (0.64) | 3.37 (1.28) | 1.07 (0.41) | 0.07 (0.03) | 0.00 (0.00) |
| December | 14,000 (396.5) | 6,280 (23.8) | 2.80 (1.06) | 3.20 (1.21) | 0.62 (0.23) | 0.01 (0.00) | 0.00 (0.00) |
| | | | 49.04 (18.56) | 42.55 (16.11) | 16.86 (6.38) | 5.07 (1.92) | 0.63 (0.24) |

TABLE I-2

MAKE-UP SYSTEM DESIGN INFORMATION

| SYSTEM | Yearly Make-Up Requirement, $10^8$ gal ($10^6$ $m^3$) | Impoundment Size, Acres ($10^4$ $m^2$) | Impoundment Storage Capacity, Acre-ft ($10^4$ $m^3$) | Make-Up Pipeline Diameter, inches (cm) |
|---|---|---|---|---|
| WET | 42.34 (16.03) | 153 (61.92) | 2,295 (283.1) | 26 (66.0) |
| 40% WET/DRY | 16.35 ( 6.19) | 9 ( 3.64) | 135 ( 16.6) | 22 (55.9) |
| 10% WET/DRY | 4.40 ( 1.67) | 4 ( 1.62) | 60 ( 7.4) | 18 (45.7) |
| 1% WET/DRY | 0.435 (0.16) | 2 ( 0.81) | 30 ( 3.7) | 12 (30.5) |

TABLE I-3

SUMMARY OF COOLING SYSTEMS COSTS INCORPORATING EXTENDED
MAKE-UP WATER SUPPLY LINES AND IMPOUNDMENTS
1985 Dollars

| SYSTEM | Impound. Size, Acre-Feet ($10^4$ $m^3$) | Pipeline Lengths | | | | Base Systems (Chapter 5) |
|---|---|---|---|---|---|---|
| | | 1 Mile (1.6 km) | 10 Miles (16.1 km) | 20 Miles (32.2 km) | 29 Miles (46.7 km) | |
| WET | 2295 (283.1) | | | | | |
| Capital | | 88.96 | 94.71 | 102.06 | 110.38 | 54.44 |
| Penalties | | 43.75 | 44.23 | 44.78 | 45.29 | 43.66 |
| Total Evaluated Cost | | 132.71 | 138.94 | 146.84 | 155.67 | 98.10 |
| 40% WET/DRY | 135 (16.6) | | | | | |
| Capital | | 101.93 | 106.89 | 113.25 | 120.12 | 96.44 |
| Penalties | | 70.43 | 70.66 | 70.92 | 71.16 | 70.39 |
| Total Evaluated Cost | | 172.36 | 177.55 | 184.17 | 191.28 | 166.83 |
| 10% WET/DRY | 60 (7.4) | | | | | |
| Capital | | 122.91 | 127.11 | 132.83 | 138.69 | 118.96 |
| Penalties | | 76.95 | 77.03 | 77.11 | 77.19 | 76.94 |
| Total Evaluated Cost | | 199.86 | 204.14 | 209.94 | 215.88 | 195.90 |
| 1% WET/DRY | 30 (3.7) | | | | | |
| Capital | | 149.44 | 152.39 | 156.19 | 160.20 | 146.83 |
| Penalties | | 87.00 | 87.02 | 87.03 | 87.04 | 87.00 |
| Total Evaluated Cost | | 236.44 | 239.41 | 243.22 | 247.24 | 233.83 |

TABLE I-4

CAPITAL COST ($10^6) FOR A MAKE-UP SUPPLY SYSTEM WITH A 29 MILE (46.7 KM) PIPELINE AND IMPOUNDMENT

| Equipment Item | 1% Wet/Dry | 10% Wet/Dry | 40% Wet/Dry | Wet |
|---|---|---|---|---|
| Pipeline (Installed) | 7.825 | 11.690 | 13.460 | 15.959 |
| Intake Structure at River | 0.933 | 1.302 | 1.533 | 1.743 |
| Intake Pumps and Motors | 0.763 | 1.005 | 1.194 | 1.296 |
| Electrical Equipment | 0.327 | 0.413 | 0.451 | 0.530 |
| Impoundment Pond | 0.317 | 0.633 | 1.425 | 24.228 |
| Intake Structure, Pumps and Motors at Impoundment | 0.533 | 0.747 | 0.878 | 0.994 |
| Direct Capital Cost of Water Supply System | 10.698 | 15.790 | 18.941 | 44.750 |
| Indirect Cost | 2.675 | 3.948 | 4.735 | 11.188 |
| Total Capital Cost of Water Supply System | 13.373 | 19.738 | 23.676 | 55.938 |

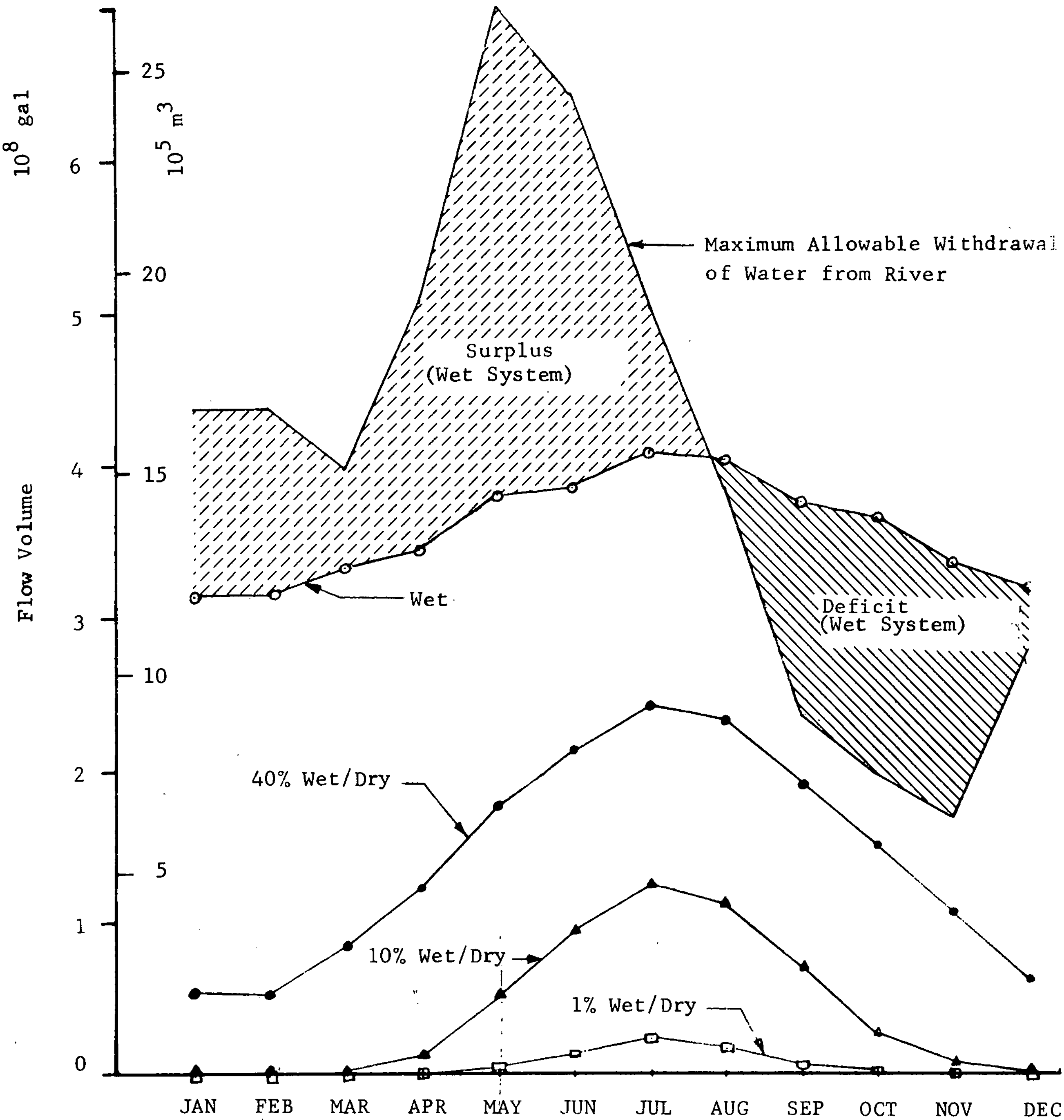


Figure I-1 Monthly Make-up Requirements

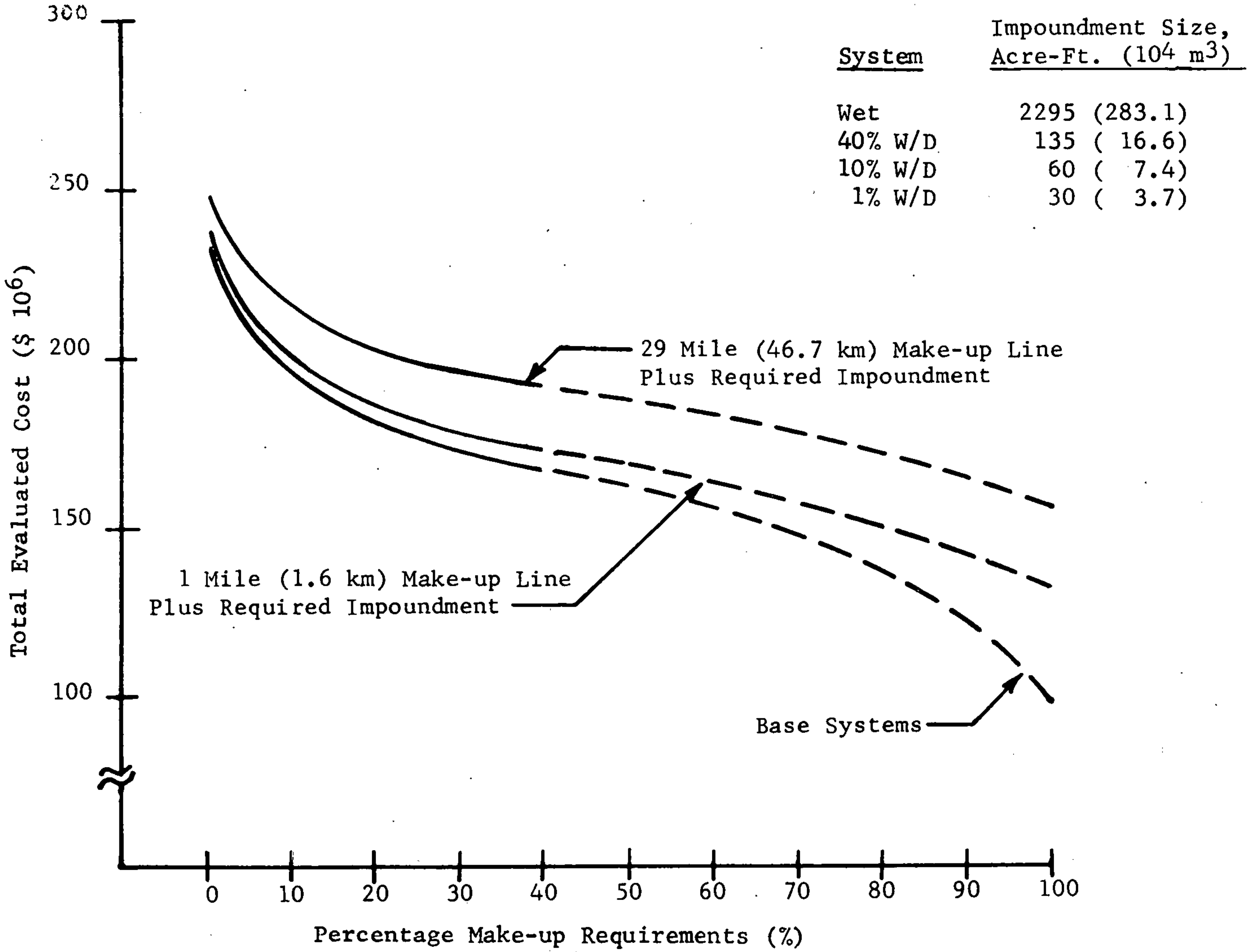


Figure I-2 Cooling System Costs Incorporating Extended Water Supply Lines and Impoundments



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