EPA U.S. Environmental Protection Agency
Office of Research and Development

Industrial Environmental Research Laboratory
Research Triangle Park, North Carolina 27711

EPA-600/7-77-137
November 1977

WET/DRY COOLING SYSTEMS FOR FOSSIL-FUELED POWER PLANTS: WATER CONSERVATION AND PLUME ABATEMENT

Interagency
Energy-Environment
Research and Development
Program Report

RESEARCH REPORTING SERIES

Research reports of the Office of Research and Development, U.S. Environmental Protection Agency, have been grouped into seven series. These seven broad categories were established to facilitate further development and application of environmental technology. Elimination of traditional grouping was consciously planned to foster technology transfer and a maximum interface in related fields. The seven series are:

1. Environmental Health Effects Research
2. Environmental Protection Technology
3. Ecological Research
4. Environmental Monitoring
5. Socioeconomic Environmental Studies
6. Scientific and Technical Assessment Reports (STAR)
7. Interagency Energy-Environment Research and Development

This report has been assigned to the INTERAGENCY ENERGY-ENVIRONMENT RESEARCH AND DEVELOPMENT series. Reports in this series result from the effort funded under the 17-agency Federal Energy/Environment Research and Development Program. These studies relate to EPA's mission to protect the public health and welfare from adverse effects of pollutants associated with energy systems. The goal of the Program is to assure the rapid development of domestic energy supplies in an environmentally--compatible manner by providing the necessary environmental data and control technology. Investigations include analyses of the transport of energy-related pollutants and their health and ecological effects; assessments of, and development of, control technologies for energy systems; and integrated assessments of a wide range of energy-related environmental issues.

REVIEW NOTICE

This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

EPA-600/7-77-137
November 1977

WET/DRY COOLING SYSTEMS FOR FOSSIL-FUELED POWER PLANTS: WATER CONSERVATION AND PLUME ABATEMENT

by

M.C. Hu and G.A. Englesson

United Engineers and Constructors, Inc.
30 South 17th Street
Philadelphia, Pennsylvania 19101

Contract No. 68-03-2202
Program Element No. EHE624

EPA Project Officer: Theodore G. Brna

Industrial Environmental Research Laboratory
Office of Energy, Minerals, and Industry
Research Triangle Park, N.C. 27711

Prepared for

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Research and Development
Washington, D.C. 20460

ABSTRACT

The technical and economic feasibilities of wet/dry cooling towers for water conservation and vapor plume abatement are studied. Results of cost optimizations of wet/dry cooling for 1000-MWe fossil-fueled power plants are presented. Six sites (five in the western coal region and one in New York) are evaluated for water conservation, and four urban sites (Seattle, Cleveland, Newark, and Charlotte) are used in the plume abatement analyses.

Results are given as the total evaluated cost (TEC) of the cooling system. Separate cost components include initial capital cost, operating expenses and penalties for the cooling system operation capitalized over a plant life of forty years. The plant start-up date is 1985.

For the water conservation analyses, optimized wet and dry cooling towers are the reference systems. The wet/dry system has separated wet and dry mechanical draft towers. Costs are related to the make-up water requirement expressed as a percentage of the water required by a wet system. Parametric and sensitivity analyses show the effect of changing the system design and economic factors.

A parallel air-flow hybrid wet/dry tower is used in the plume abatement studies. Costs are presented for an allowable number of hours of fogging. A wet system, optimized solely for cost, serves as the reference.

CONTENTS

TABLES

Number		Page

FIGURES

TABLES IN APPENDICES

Number		Page

FIGURES IN APPENDICES

ACKNOWLEDGMENTS

"A Study of Wet/Dry Cooling Systems for Fossil Power Plants: Water Conservation and Plume Abatement" is a study directed to the development and understanding of the economic impact of wet/dry cooling systems on power plant operations. The project was completed under the direction of T. G. Brna, Project Officer for the U.S. Environmental Protection Agency (EPA), B. A. Tichenor and J. A. Chasse, former EPA Project Officers, G. A. Englesson, Project Manager for the United Engineers & Constructors Inc. (UE&C), and J. H. Crowley, Manager of the Advanced Engineering Department, UE&C Inc.

Principal contributors were: M. C. Hu, Principal Investigator; J. C. Bentz and N. H. Lee, evaluation of water conservation wet/dry towers; S. R. Buerkel and D. S. Wiggins, economic evaluation of wet/dry towers for plume abatement; J. E. Pinkerton and J. B. Robinson, plume analysis; F. P. Maiuri, water treatment analysis; D. E. Pennline, economic sensitivity analysis.

Acknowledgments are due to T. Thoem and G. Parker of EPA Region VIII, H. Lunenfeld of EPA Region II and W. F. Savage, Manager of Advanced Concepts Branch, U.S. Energy Research and Development Administration, for their interest and contributions to this study.

Acknowledgments are due to the following utilities and their representatives for providing data used in this study for various sites: R. S. Currie and K. A. Gulbrand of Southern California Edison Company; E. D. Kist and S. F. Anderson of Public Service Company of New Mexico; L. V. Hillier of Minnkota Power Cooperative, Inc.; R. J. Labrie of The Montana Power Company; and B. Z. Baxter, Jr. and R. H. Metzger of Orange and Rockland Utilities, Inc.

Acknowledgments are also due to the following cooling tower and turbine manufacturers and their representatives for providing data and consultation during this study; namely, M. W. Larinoff and E. C. Smith of Hudson Products; R. Landon and C. A. Baird of Marley Company; G. E. Collins and M. R. Lefevre of Research-Cottrel; J. A. Brown of Ecodyne; H. H. von Cleve and G. Hesse of GEA-Gesellschaft für Luftkondensation m.b.H.; P. J. Harris of GKN Birwelco Limited; J. E. Pugh of General Electric Company; and G. J. Silvestri, Jr. of Westinghouse Electric Corporation.

SECTION 1

INTRODUCTION

1.1 PURPOSE

The purpose of this report, prepared for the Environmental Protection Agency (EPA) by United Engineers & Constructors Inc. (UE&C) is twofold:

1. Document an economic and engineering evaluation of separate wet and dry cooling towers operating in combination to limit consumptive water use.
2. Document an economic and engineering evaluation of hybrid wet/dry cooling towers designed to minimize ground fogging.

This study is limited to an evaluation of wet/dry cooling for fossil-fueled generating stations with special emphasis on specific site conditions. Combination wet/dry systems for water conservation were evaluated at six locations (five in the coal areas of the Western United States and one in New York State) and hybrid wet/dry systems for plume abatement were evaluated at four urban sites (Seattle, WA; Cleveland, OH; Charlotte, NC; and Newark, NJ). A separate and complementary study of the use of wet/dry cooling for water conservation for light water reactor fueled stations was completed by UE&C for the Energy Research and Development Administration (ERDA)(1). In the ERDA study wet/dry cooling systems were evaluated at three hypothetical sites representing the Southwest, Southeast, and Northeast regions of the United States. This ERDA study included engineering and economic sensitivity analyses which formed the basis for the site specific analyses performed for the EPA. Both studies used the same basic analytic and evaluation tools.

1.2 BACKGROUND

The increasing use of evaporative (wet) cooling towers to dissipate power plant waste heat loads has focused attention on two inherent characteristics of such devices: consumptive water use and vapor plume emissions. Consumptive water use, because of its cumulative impact, is evolving as a major environmental concern in all parts of the United States. An immediate concern is the development of the coal resources of the Western United States. The limiting factor in this development may be the availability of water for cooling purposes.

Many efforts to determine the impacts of water consumption and energy production in the coal-rich regions of the Western United States have been initiated. One such effort reported in Reference 2, entitled "Western States Water Requirements for Energy Development to 1990", was prepared by the Western States Water Council (WSWC). Figure 1.1 taken from that report shows the cumulative capacity of projected installation of thermal electric power plants in the states which are members of the WSWC.

Figure 1.2 shows the quantity of water consumed by evaporative cooling in meeting those power plant projections.

The Western United States is an area of highly regulated water flow. Much of this flow has been allocated significantly into the future, and in drought years the annual allocation exceeds the annual stream flow. Development of the regional coal resources will require significant amounts of water. Since no new water sources are expected, existing water users may be required to change their patterns of use to accomodate energy development. Intense competition for the limited water resources between industrial, agricultural, recreational, urban, and energy segments of the economy as well as the in-stream flow needs of fish and wildlife will provide a major dilemma to local and regional planners.

The resolution of these conflicts will not be based on a conventional price/demand relationship. The WSWC believes that an increased price of water would not have a significant effect on the amount of water used for energy production. Even if the price was to increase substantially, the percentage of water cost to total cost of generation would remain low. This lack of cost sensitivity does not apply to all water users. Agricultural and municipal growth would both be significantly impacted by changing water costs. In the introduction to its report the WSWC states, "Unless planners and administrators recognize the energy industry's needs for water and its small dollar incentive for water conservation, much of the water resource planning in the past and in the future could be for naught" (2). In the future, the problems associated with the consumptive use of water will not be confined to the Western United States.

Another potentially adverse impact associated with evaporative cooling systems is the creation of ground fog or the aggravation of natural fogging conditions. This can be an especially important consideration for power plants which are sited in urban areas and are required to operate on a closed-cycle system.

One technology which can virtually remove both of these site constraints is dry cooling. However, the application of dry cooling would require significantly greater capital expenditures and incur substantial losses in plant performance during high temperature periods as compared with wet systems. The costs associated with the construction and operation of a dry cooling system are approximately three times those associated with wet tower operation. Substitution of dry cooling for wet cooling as determined in this study could increase the total cost of generation by 10 to 15 percent.

Wet/dry cooling systems combine desirable features of wet and dry cooling towers into one operational unit. When a wet/dry system is designed for water conservation, the dry tower limits the quantity of water evaporated and the wet tower limits the losses in plant performance. When a wet/dry system is designed for plume abatement, the dry sections cause a reduction of the relative humidity of the plume from the tower and its fogging potential. With respect to economics, the combination of wet and dry operation presents the opportunity for numerous trade-offs between capital costs and operating penalties. In addition, these systems have significant implications for power plant site selection.

Two basic criteria for fossil plant site selection are fuel and water availability. Planners must evaluate the economic and environmental trade-offs of transporting coal and water to the plant and transmitting electrical energy to the load center. In this report, for the mine-mouth sites the cost of coal ranges from $0.47 to $1.10 per million Btu in 1985, while the fuel cost at the New Hampton, N.Y. site is projected to be $5.44 per million Btu. The cost of transporting make-up water to the plant site can also be large. To provide condenser cooling water for a wet cooling system at the Kaiparowits, Utah site (30 miles from and 3600 ft. in elevation above Lake Powell) would cost 35 million dollars in capital and pumping costs over the plant lifetime. Water transportation costs usually limit sites selected for power plants using evaporative cooling to areas within 25 to 30 miles of a major water source or require the construction of a major impoundment along a smaller waterway. The use of wet/dry cooling permits relaxation of the water supply criterion and greatly increases the number of possible sites. The use of wet/dry cooling may also enable power plant siting in sensitive areas (e.g., urban) which have a high potential for ground fog formation.

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.

1.3 REPORT ORGANIZATION

The general system description and cost evaluation method are given in Section 3. The comparative results for six sites evaluated for water conservation are given in Section 4. Section 5 presents the results of a detailed engineering and economic sensitivity analysis at one water conservation site. The model which was used for plume analysis is described in Section 6 and the results of the system optimization for plume abatement at four sites are given in Section 7.

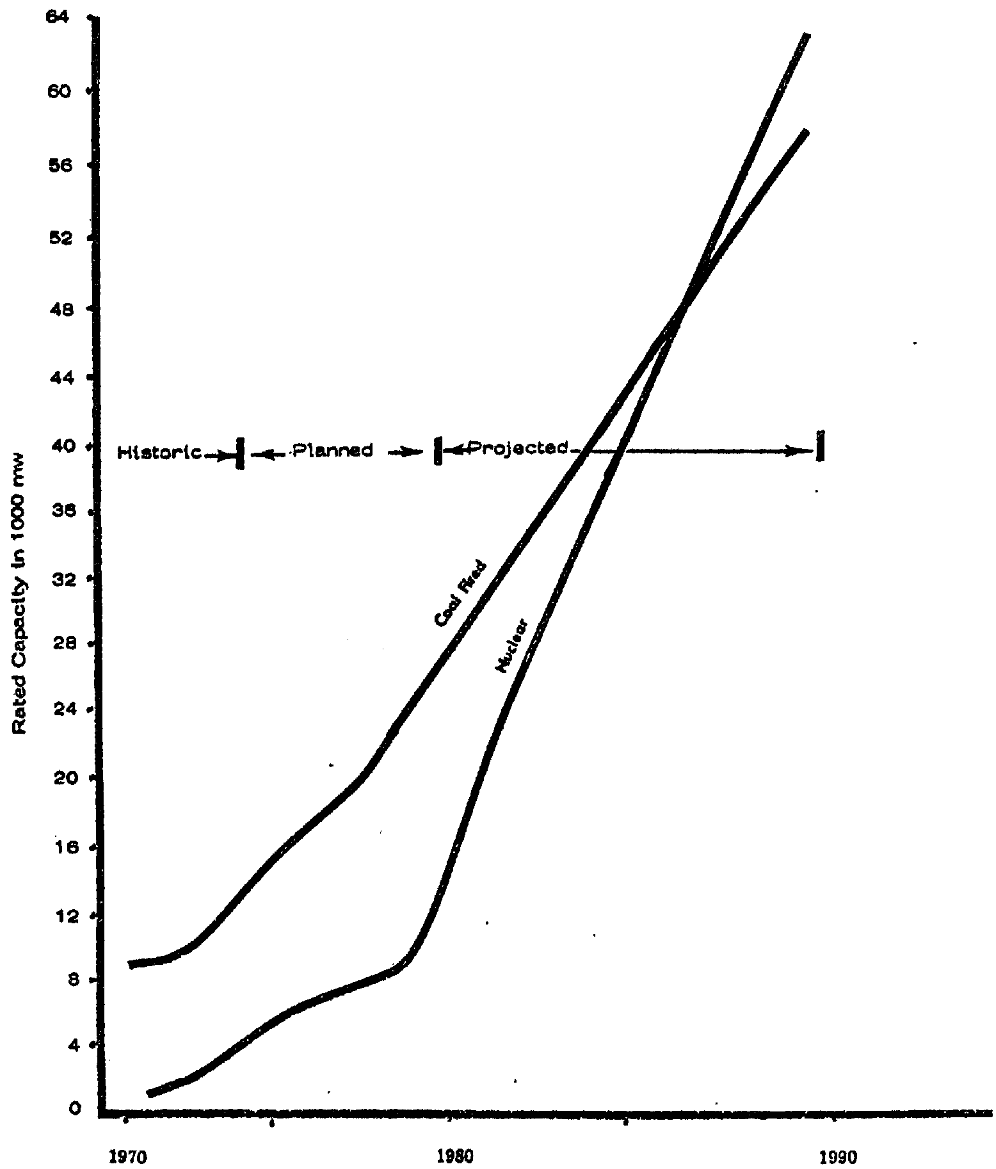


Figure 1.1 Scheduled and Projected Installation of Thermal Electric Power Plants in WSWC Member States Including Plants With Dry Cooling or Ocean Cooling (2)

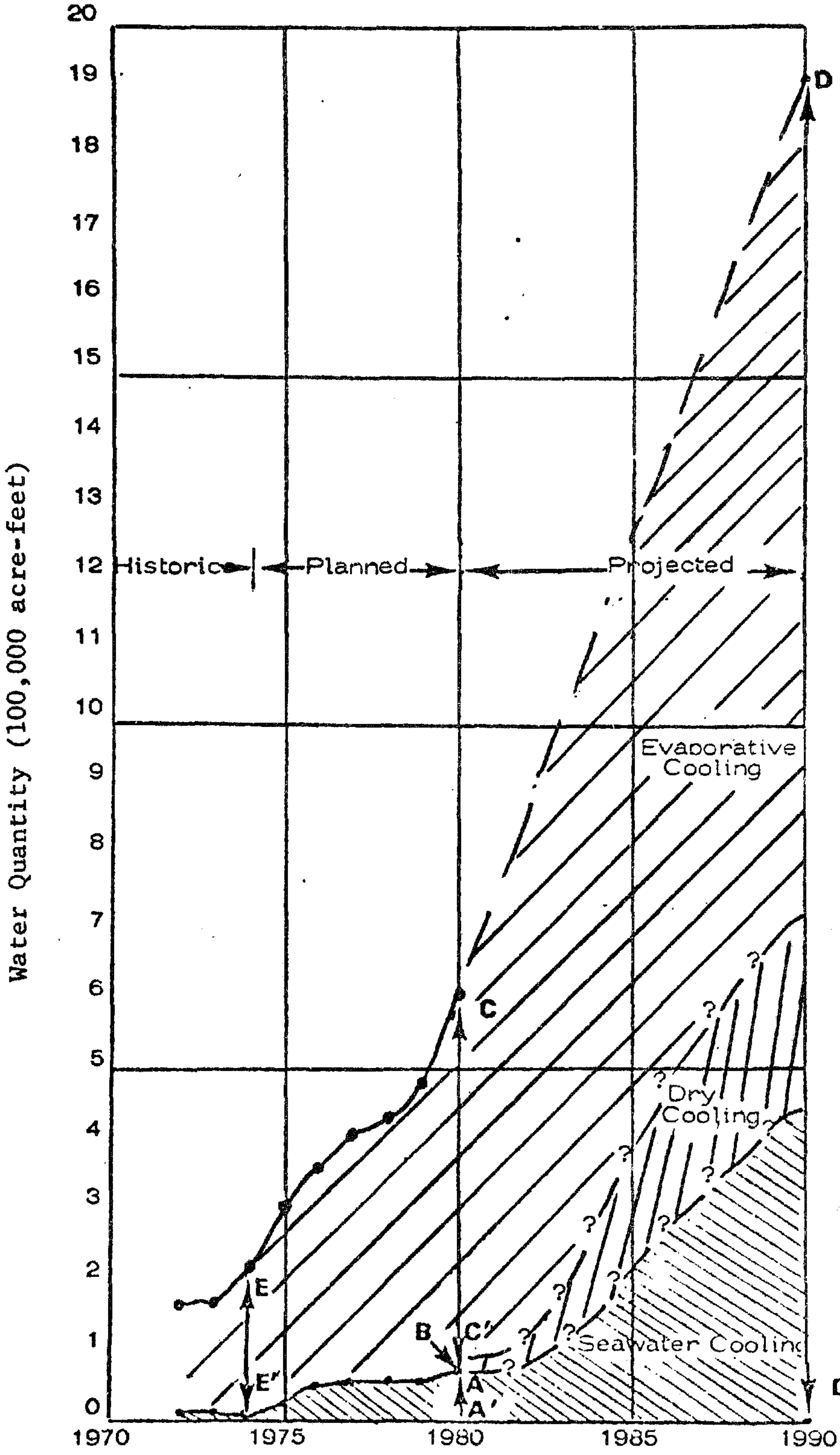


Figure 1.2 Cooling Water Needs for Scheduled and Projected Coal Fired and Nuclear Power Plants to 1990 (2)

SECTION 2

SUMMARY AND CONCLUSIONS

2.1 SUMMARY

This report presents the results of a design cost study for wet/dry cooling tower systems used in conjunction with 1000 MWe coal-fired power plants to reject waste heat while either conserving water or minimizing ground fogging. The purpose of this report, prepared for EPA by UE&C, is to document:

1. An economic and engineering evaluation of separate wet and dry cooling towers operating in combination to limit consumptive water use
2. An economic and engineering evaluation of wet/dry cooling towers designed to minimize ground fogging

The wet/dry cooling tower designed for water conservation is one which combines physically separated wet towers and dry towers into an operational system. In designing the wet/dry system, 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 systems are designed to operate with conventional low back-pressure turbines. The component wet and dry towers are state-of-the-art designs.

The wet/dry cooling tower designed for plume abatement is one which combines wet and dry heat exchanger modules into a single structure. In designing the wet/dry tower for plume abatement, the wet cooling tower is sized to carry the plant heat load at all ambient temperatures and separate dry modules are integrated into the cooling tower structure, physically oriented so that the air stream which cools the dry heat exchangers dries the wet plume.

The method used in the economic analysis is a fixed source-fixed demand method. A reference plant is assumed to have a constant energy input rate (fixed heat source) and a constant fixed demand for its output. It is against this fixed demand that each cooling system must be gauged. Inability to meet this demand is charged as a penalty cost which is added to the capital cost of the cooling system. Other penalty costs include the cost of supplying make-up water and the cooling system maintenance cost. The sum of the penalty costs and the capital cost of the cooling system is called the total evaluated cost (TEC).

The evaluations of wet/dry towers designed for water conservation were performed for five mine-mouth sites in the coal-rich Western United States and one Eastern site which will require coal shipment for operation. The evaluations of wet/dry towers designed for plume abatement were performed for four urban sites in the United States. The basic economic factors used to develop the system costs are shown below:

Plant Start-up Date	1985
Average Plant Capacity Factor	0.75
Annual Fixed Charge Rate	18%
Plant Life	40 years
Capacity Penalty Charge Rate	$485/kWe

2.2 CONCLUSIONS

1. Wet/dry cooling tower systems can be designed to provide a significant economic advantage over dry cooling, yet closely match the dry tower's ability to conserve water. The wet/dry systems which save as much as 98 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. Even where water supply is remote from the plant site, this advantage holds.

2. Where water is available, wet cooling will continue to be the economic choice in most circumstances. However, for sites with remote water supply sources, the advantage of wet cooling over wet/dry cooling may be small. In cases where resource limitations or environmental criteria make water costs excessive, wet/dry cooling can reach economic parity with wet cooling.

3. Ground fogging from low profile wet cooling towers can be significantly reduced by increasing the number of cells, thereby reducing the liquid water concentration in the plume. These design changes can be made without significantly increasing the total evaluated cost of the wet cooling tower. In cases of restrictive site conditions or fogging limitations, hybrid wet/dry cooling towers may be used effectively at costs which approximate those of enlarged wet towers.

SECTION 3

SYSTEM DESCRIPTION AND METHOD OF ECONOMIC EVALUATION

3.1 CHARACTERISTICS OF THE REFERENCE POWER PLANT

The reference power plant for the wet/dry cooling tower system evaluation is a nominal 1000 MWe coal-fired electric generating station. The power plant steam supply is assumed to be constant and fixed at 2541 MW thermal. This heat source may be coupled with either a conventional low back-pressure turbine, which has an operating limitation ranging from 5 to 6 in-HgA (127 to 152.4 mm-HgA) depending on the turbine manufacturer, or a high back-pressure turbine. When coupled with the conventional turbine, the generator for the reference plant delivers 1039 MWe at a back-pressure of 2 in-HgA (50.8 mm-HgA). This output, which is assumed equal to the constant fixed demand, is referred to as the base output of the reference plant. The selection of these quantities was based on a typical coal-fired plant design as described in Reference 3.

The high back-pressure turbine is of the intermediate annulus type with an operating limitation of 15 in-HgA (381 mm-HgA). This type of turbine is offered by the General Electric Company for fossil plants. A 330 MWe fossil unit with dry cooling towers, which is currently under construction at the Wyodak Station near Gillette, Wyoming, will utilize such a turbine. According to General Electric, the maximum rating commercially available is 750 MWe. In this study, the high back-pressure turbine is only used with dry towers.

The effect of cooling system performance on the turbine-generator output is calculated using the heat rate versus back-pressure curves shown in Figures 3.1 and 3.2. Figure 3.1 shows the typical heat rate curve for a steam plant in the 1000 MWe range coupled with a conventional turbine. Figure 3.2 shows a hypothetical heat rate curve projected for the same plant coupled with a high back-pressure turbine of the intermediate annulus type.

3.2 COOLING TOWER CONFIGURATIONS

3.2.1 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
3. Natural draft dry tower

All three towers are of conventional state-of-the-art designs. A description of these towers can be found in Appendix A.

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 configuration, 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 A.

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.

3.2.2 Wet/Dry Cooling Towers for Water Conservation

A number of possible arrangements exists for combining separate wet and dry towers into wet/dry towers which can conserve make-up water. Many of these wet/dry towers have been described in the literature (4,5). Evaluation of all possible arrangements is beyond the scope of this study. After preliminary evaluation and discussions with the EPA, 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 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 by means of a cooling water circuit which flows through the wet and dry towers in parallel.
3. Natural series wet/dry tower - This system combines separate natural draft dry towers and mechanical draft wet towers by means of a series water circuit.

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.

3.2.2.1 Design and Operation of Series Flow Wet/Dry Systems--

A schematic diagram for the series water flow towers is shown in Figure 3.3. 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 a specified limit. The other equipment sized at this design point are the condenser, and the circulating water pumps and pipeline. The performance of the dry tower is then evaluated at the peak ambient temperature and the specified limiting back pressure to determine the heat rejection capability of the dry tower at these conditions. This result is then used to size the wet helper tower needed to reject the remaining waste heat.

For the three wet/dry cooling systems evaluated, dry cooling is the basic heat rejection mechanism, and wet cooling is used to provide supplementary heat rejection. 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.

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 operated 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 3.4. When Point 3 is reached, all of the wet cells have been shutdown 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 as shown by Point 2 in Figure 3.4

Mode S1 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. The cost of this control system has not been included in the wet/dry cooling costs described in this study.

It should be noted that, for the S1 mode, the cut-off point for wet cooling is, in general, at a higher ambient temperature than the dry tower design temperature (Figure 3.4).

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 shutdown and the entire heat load is handled by the dry tower. A schematic of this system operation is presented in Figure 3.5. 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. Mode S2 is more energy conservative at the expense of higher water consumption than the same system operating in the S1 mode.

3.2.2.2 Design and Operation of Parallel Flow Wet/Dry Systems--

Figure 3.6 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. 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:

1. During wet/dry operation, the dry tower operates with partial water flow.
2. As the wet cells are sequentially shutdown, the water is diverted back through the dry cells.

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

1. During wet/dry operation, the dry tower operates with a constant partial water flow.
2. 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.

3.2.3 Wet/Dry Cooling Towers for Plume Abatement

The wet/dry cooling system for plume abatement is schematically depicted in Figure 3.7. The cooling tower design consists of a conventional evaporative fill section atop which are located dry heat exchangers.

The hot water from the condenser travels through the dry section and then falls through the evaporative fill. In many cases, due to size limitations of the heat exchanger and the design temperatures of the cooling system, only a portion of the total circulating water travels through the dry section. At all times during operation, however, the entire flow is cooled in the evaporative fill section.

Air flows in parallel streams through the wet and dry sections during wet/dry operation. In the fan stack, the saturated air from the wet section mixes with the hot dry air from the dry section before exiting from the tower. Air inlet louvers are provided to close off the air flow through the dry section during times when plume abatement is not required. With the air flow through the dry section blocked, the tower operates in an all wet mode and all of the air travels through the wet section.

Due to reduced efficiency during wet/dry operation, the wet/dry towers for plume abatement are designed to operate in the wet/dry mode only when plume fogging potential is great. This operation can be accomplished through the use of meteorological monitoring and a cooling tower control system connected to the computer control system for the plant. The cost of such a system has not been included in the wet/dry cooling system costs described in this report.

3.3 METHOD OF ECONOMIC EVALUATION

For a valid economic comparison of alternate cooling systems, the costs of different systems are assessed on a common basis. The method used in this study for the cooling tower system is consistent with that used in Reference 6. The method may be classified as a fixed source-fixed demand approach. It assumes that the reference plant has a fixed energy input rate and that there is a constant fixed demand for the plant output. The demand is fixed to establish a basis for system comparison. As the plant performance changes due to the change in cooling system performance, the plant output is compared to the fixed demand. Since the energy input rate to the plant is fixed, any deficit between output and demand is provided by an outside source. A penalty equivalent to an increase in capital cost of the outside source is added to the capital cost of the cooling system. A credit is taken if the plant operates above the demand. A penalty is also assessed for the cooling system power and energy requirements.

The treatment of the loss of plant performance is illustrated in Figure 3.8. The figure shows the typical gross plant output of the reference power plant as a function of ambient temperature over an annual cycle. 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 gross plant output $(\Delta kW)_{max}$, and the coincidental auxiliary power requirement, $(HP)_{aux}$. The hatched area in Figure 3.8 above the gross plant output curve represents the energy deficit caused by the changes in cooling system performance, whereas the hatched area between the gross plant output and the net plant output curves represents the energy requirement by the cooling system auxiliary equipment; e.g., pumps and fans.

In general, as the size of the cooling system becomes larger, its performance improves and its capital cost 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 and compare these optimum systems.

3.3.1 Economic Penalty Evaluation

The cost of a cooling system is composed of its capital cost plus the penalties which are assessed to reflect the cost associated with its operation. These penalties evaluated on an annual basis include degradation of plant performance, cooling system power and energy requirements, water supply costs, and system maintenance.

3.3.1.1 Capacity and Energy Penalties--

The equations used to evaluate the penalty costs associated with loss of plant output and cooling system operation are given below. In evaluating these penalties, it is assumed that the plant has an average capacity factor and operates at full capacity or is off-line.

Capacity Penalty (P_1):

$$P_1 = K \cdot afcr \cdot (\Delta kW)_{max} \tag{3-1}$$

Replacement Energy Penalty (P_2):

$$P_2 = CF \int_0^{8760} \left[OAM + F \cdot HR(T) \right] \Delta kW(T) dt \tag{3-2}$$

Cooling System Auxiliary Power (P_3):

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

Cooling System Auxiliary Energy (P_4):

$$P_4 = CF \int_0^{8760} \left[OAM + F \cdot HR(T) \right] HP(T) dt \tag{3-4}$$

where $(\Delta kW)_{max}$, $\Delta kW(T)$, $(HP)_{aux}$, and $HP(T)$ are shown in Figure 3.8 and:

afcr = annual fixed charge rate, %/100.

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

F	=	fuel cost for the generating unit used to make up the loss of energy, \$/Btu (\$/KJ).
$(HP)_{aux}$	=	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, 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 pumped 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, are 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.

The sources of capacity replacement which serve as the basis for the assessment of the associated economic factors K, F and OAM may include any of 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
4. purchased power from another utility system

The selection of the capacity replacement is dependent on economics and on the type of duty. 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 temperature change for the wet/dry and dry cooling concepts. Therefore, all the economic factors used in this study were assessed on the basis of base load units similar to the reference plant. A discussion of the economic factors is given in Appendix B; the numerical values of these factors are given in Table 4.1.

3.3.1.2 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. Annualized capital cost for the make-up water system which includes pipelines, pumps, and associated structures (C_1)
2. Pumping cost which includes both the capacity charge for the power required by the pumps and the energy charge for pumping the water (C_2)
3. Water purchase and treatment cost (C_3)

For the specific power plant sites considered in the study, all these component costs can be separately estimated.

Make-up Water Penalty (P_5):

$$P_5 = C_1 + C_2 + C_3 \qquad (3\text{-}5)$$

3.3.1.3 Cooling System Maintenance Cost Penalty--

The cooling system maintenance penalty is the cost charged to a cooling system for services which include periodic maintenance and replacement of parts. It is calculated on the basis of in-house engineering data, condenser tube cleaning costs and 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
4. Partial replacement of finned tubes for the heat exchangers in the dry towers
5. Cleaning of dry heat exchangers

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: condensers, pumps, and cooling towers.

Cooling System Maintenance Penalty (P_6):

$$P_6 = aC_c + bC_p + cC_T \qquad (3\text{-}6)$$

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; a=0.0075, b=0.0750, c_{dry}=0.0115, and c_{wet}=0.0122.

3.3.2 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 3-1 through 3-6. 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:

$$C_t = C + \frac{1}{afcr} \sum_{j=1}^{6} P_j \qquad (3\text{-}7)$$

where:

C_t = total evaluated cost, \$.

C = capital cost of cooling system, \$.

afcr = annual fixed charge rate, %/100.

P_j = annualized economic penalties, \$.

This total evaluated cost represents the lifetime capital cost of the cooling system and serves as the criterion for cooling system optimization and comparison.

3.4 OPTIMIZATION PROCEDURE

In this study, cooling system optimization is governed by one of two constraints: the amount of water consumed or the duration of ground fog produced. The particular design and optimization procedure is dependent upon the constraint applicable and details are provided in the sections on water conservation and plume abatement. 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. The parameters for sizing the water conservation wet/dry towers systems, for example, include:

    a) Turbine back-pressure for sizing the wet tower
    b) Dry bulb temperature for sizing the dry tower
    c) Condenser cooling range
    d) Dry tower initial temperature difference
    e) Wet tower approach
    f) Mode of operation of the wet/dry tower

    The definitions of temperatures in condensers and cooling towers are illustrated in Figure 3.9.

2. Evaluate the performance of the cooling system in response to ambient temperature changes during the annual cycle. The annual cycle is divided into a series of time intervals; each has a constant ambient dry bulb temperature and a coincident, constant wet bulb temperature.

3. Determine the impact of cooling system operation on the plant performance at the off-design conditions. For each time interval, the gross turbine output, the pump and fan capacity and energy requirements, and either the water consumption or fogging potential are evaluated.

4. Assess the penalties due to loss of performance, make-up supply, and cooling system maintenance. Penalties are calculated for each time interval, summed over the annual cycle, and then capitalized over the plant life.

5. Calculate the total evaluated cost of the cooling system which includes the capital cost as well as penalty costs.

6. Change the cooling tower and condenser design parameters and repeat the procedure until the design with the lowest total evaluated cost consistent with the system constraint is found.

The evaluation of the wet/dry cooling system for water conservation is described in Sections 4 and 5, and the evaluation of the wet/dry cooling system for plume abatement is described in Section 7. The evaluation includes the detailed design procedures used to obtain the optimized systems and the trade-offs among capital costs and penalty costs for representative systems.

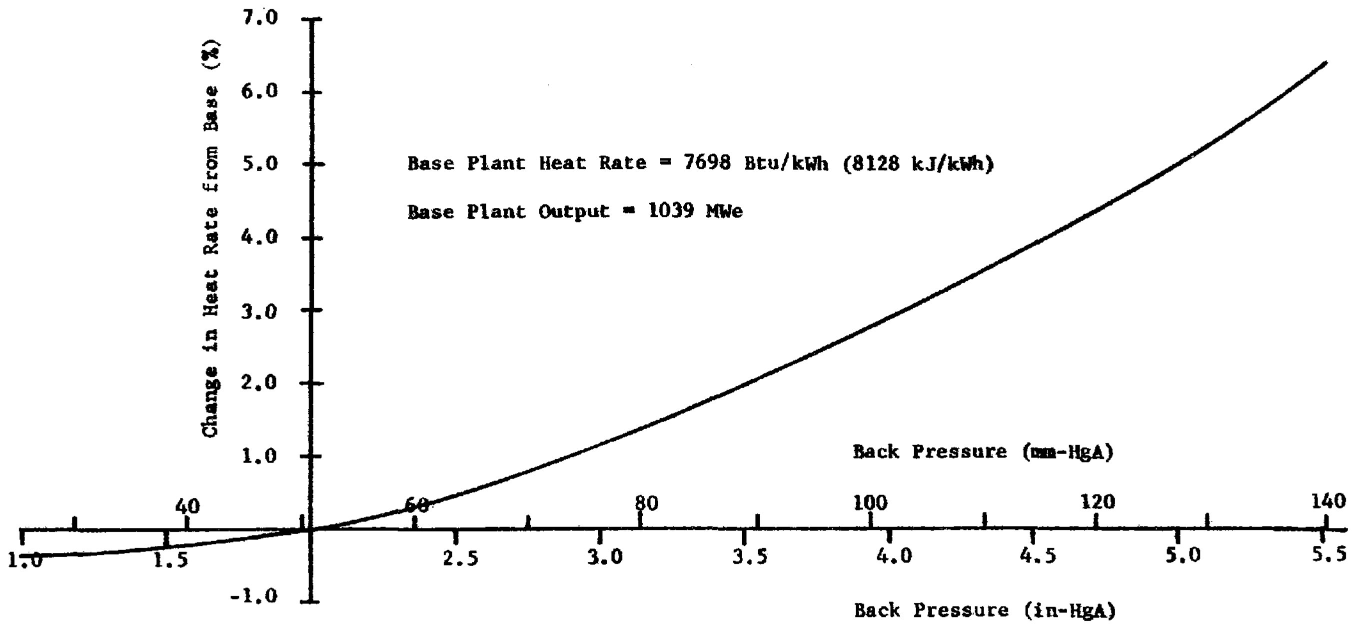


Figure 3.1 Heat Rate Correction Curve for a Plant with a Conventional Turbine

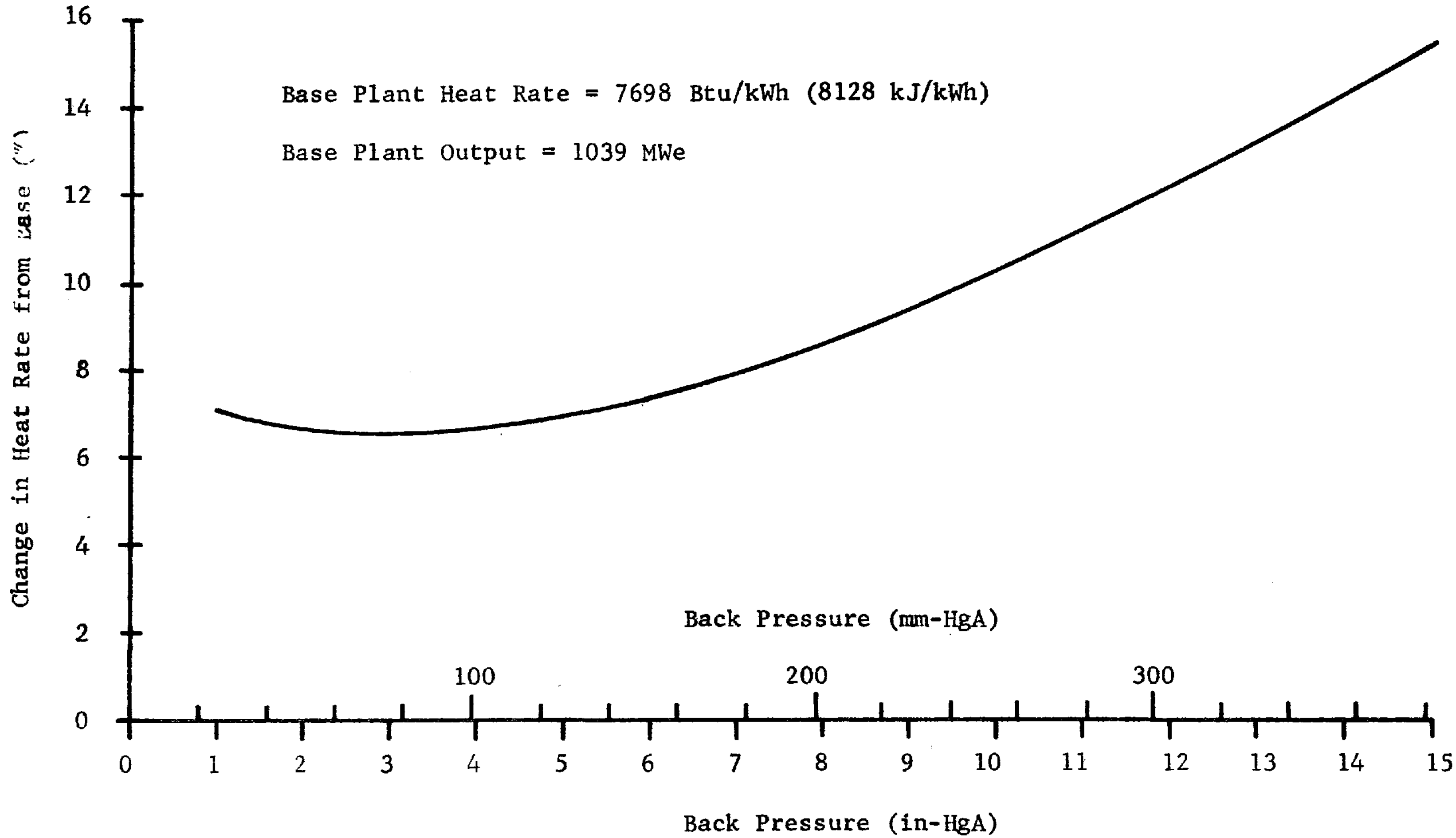


Figure 3.2 Heat Rate Correction Curve for a Plant with a High Back Pressure Turbine

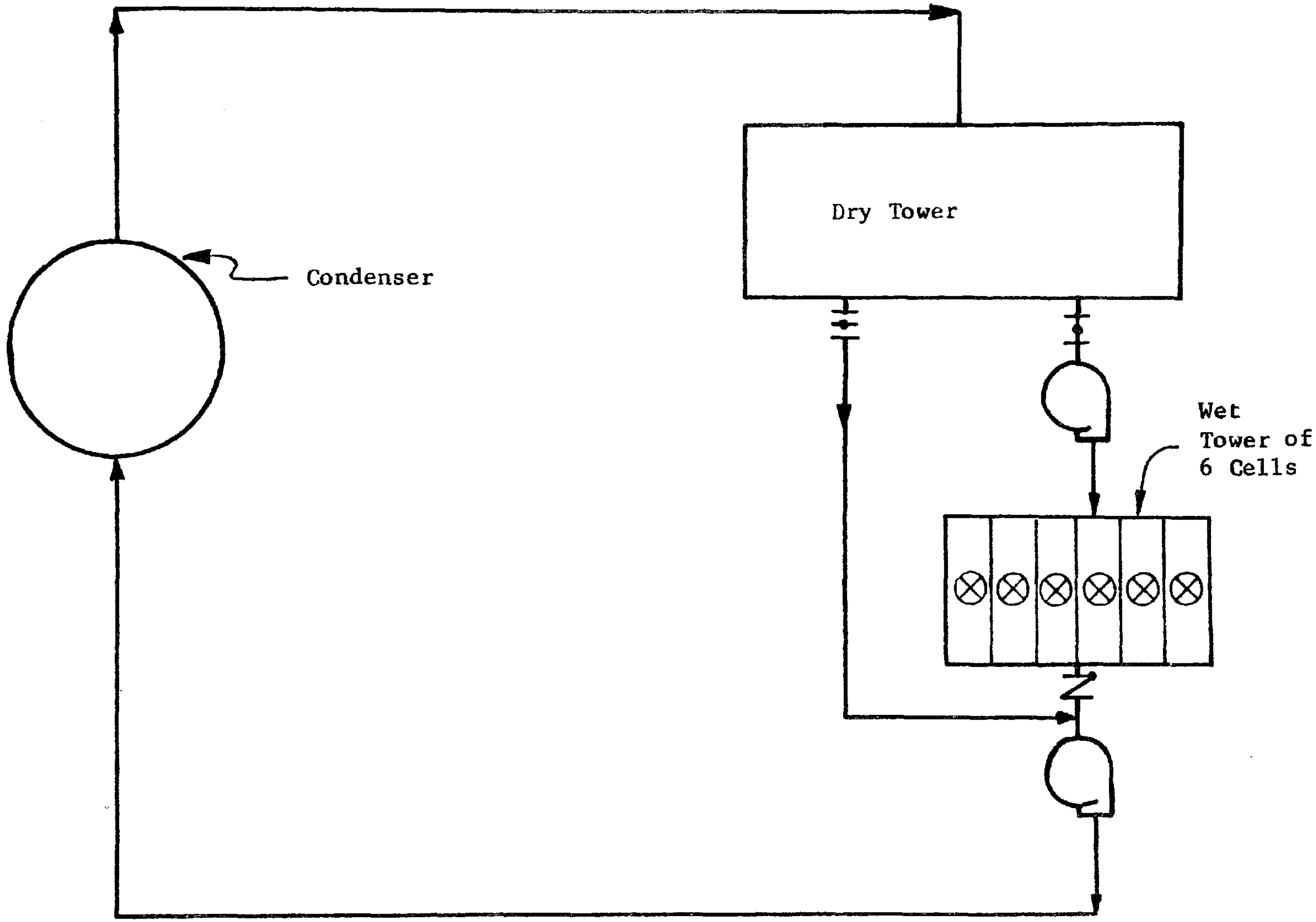


Figure 3.3 Series-Water Flow Wet/Dry Tower

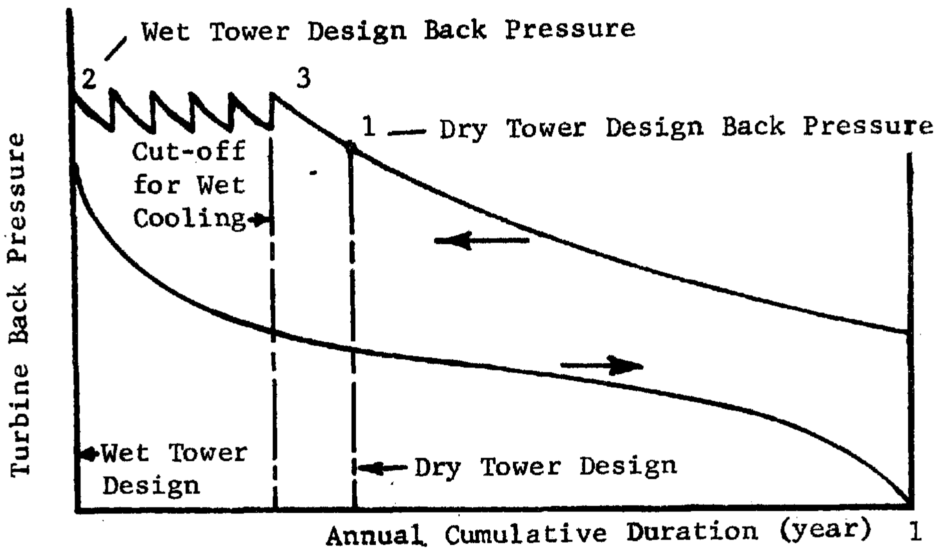


Figure 3.4 Wet/Dry Tower-Mode 1 Operation

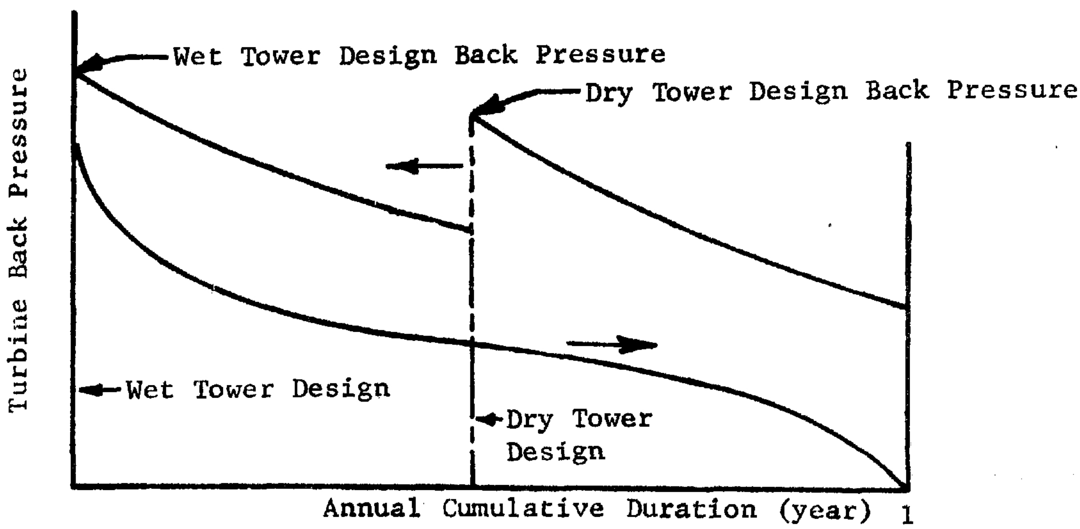


Figure 3.5 Wet/Dry Tower-Mode 2 Operation

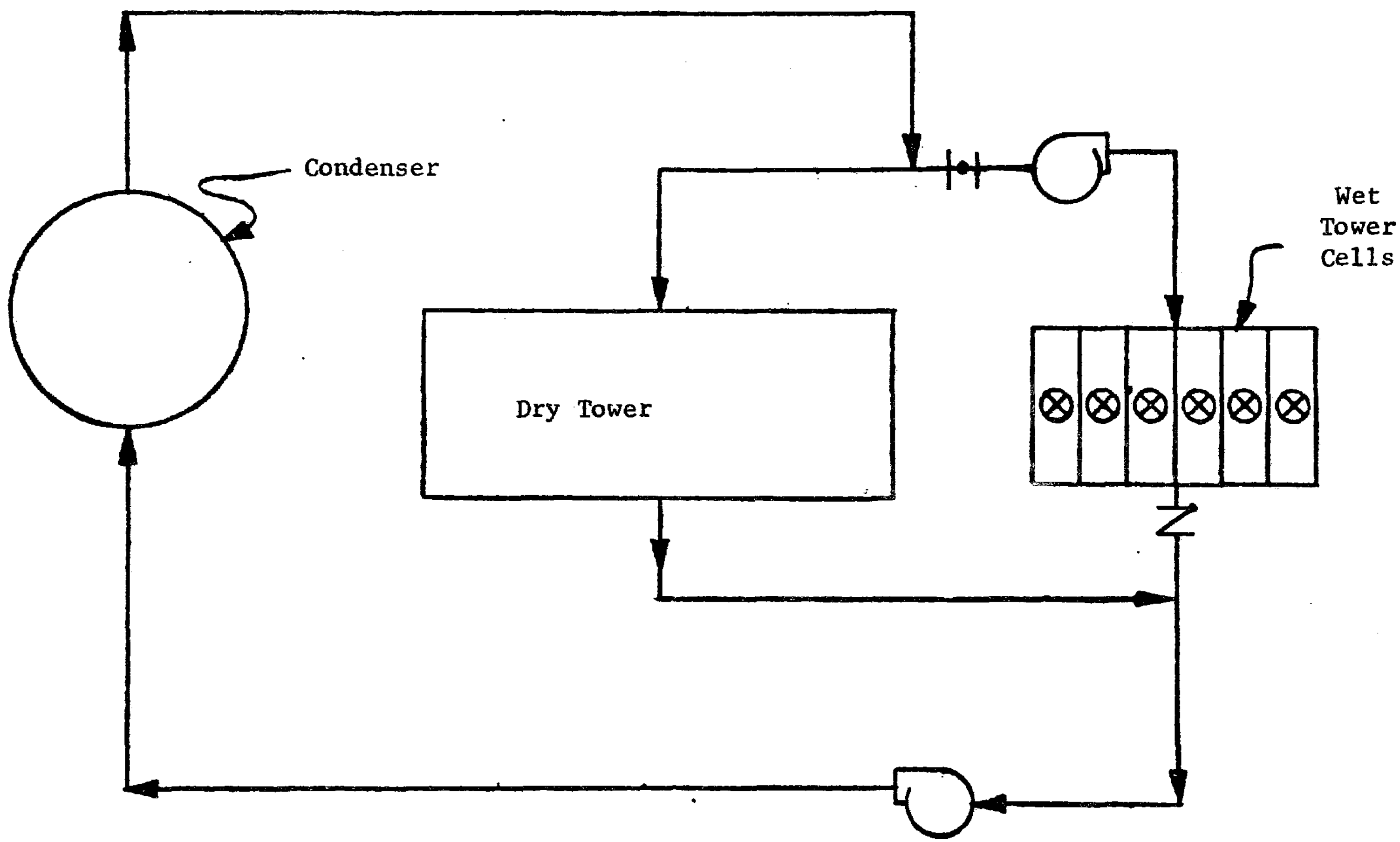


Figure 3.6 Parallel-Water Flow Wet/Dry Tower

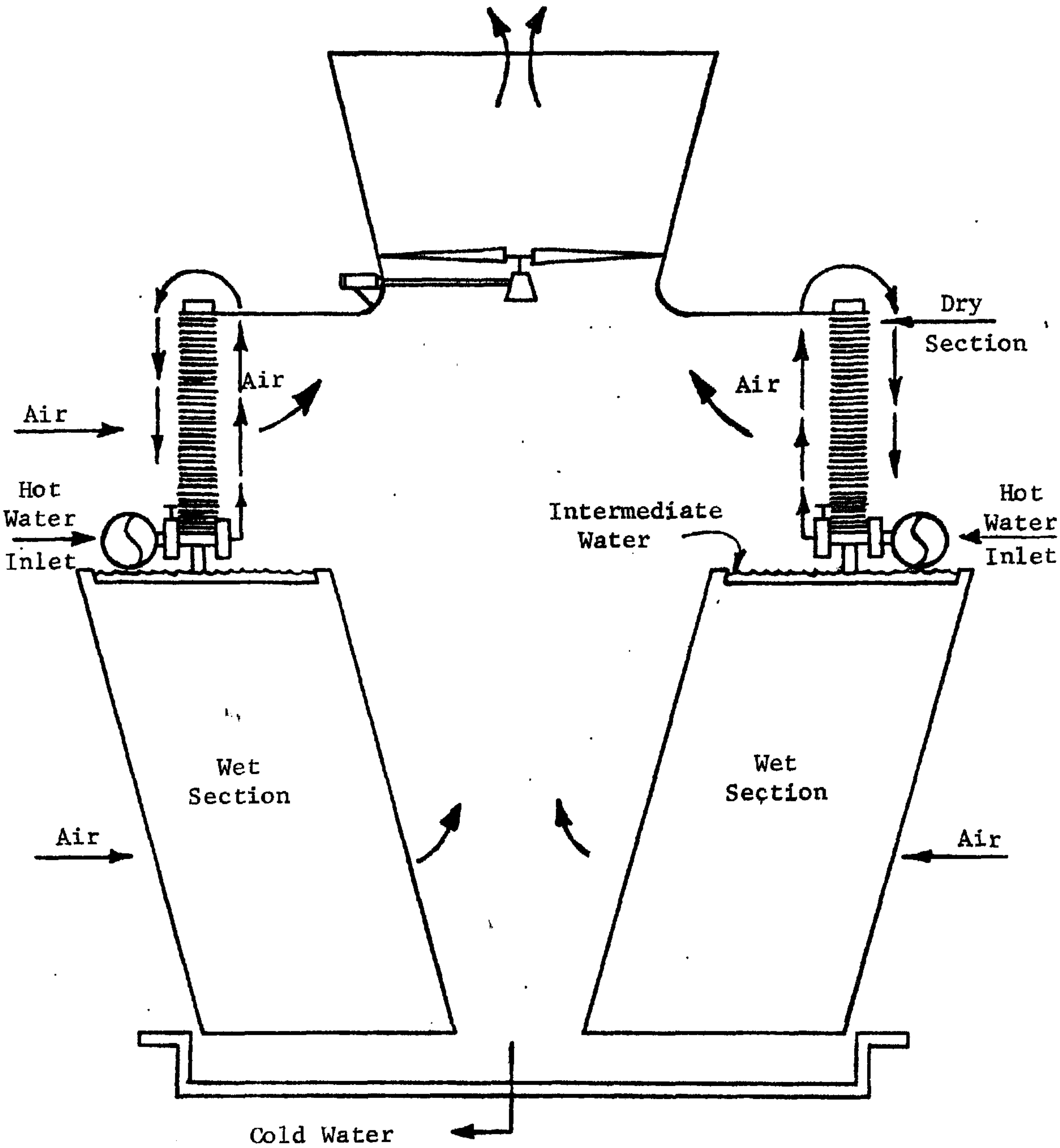


Figure 3.7 Parallel Path Wet/Dry Tower for Plume Abatement

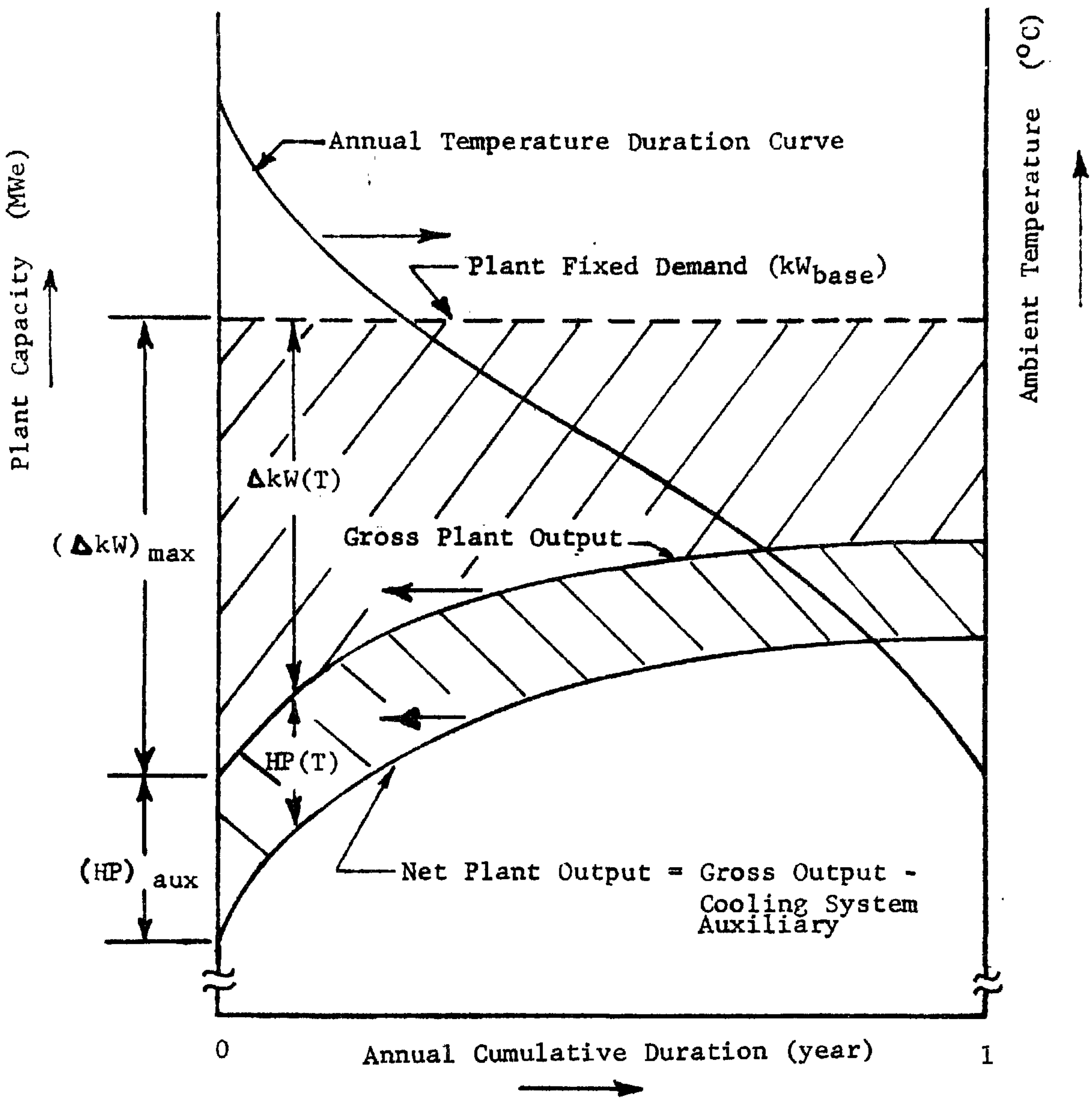
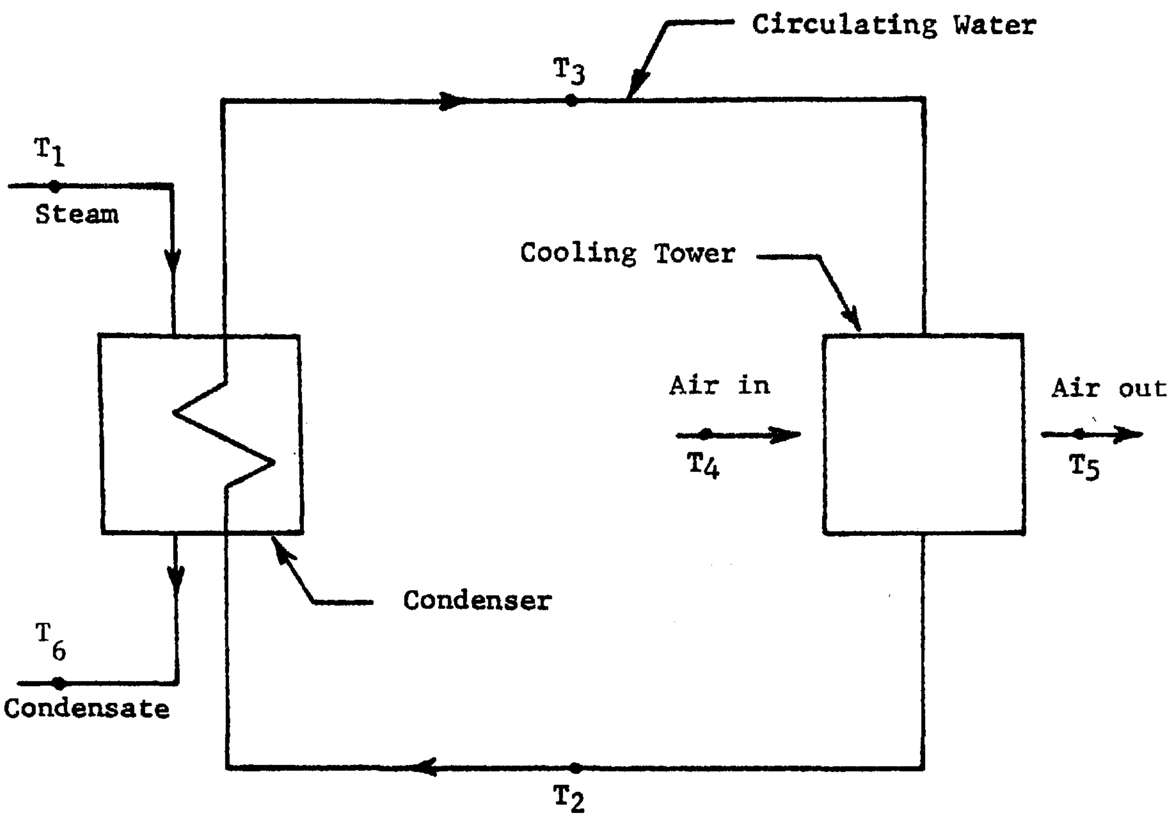


Figure 3.8 Ambient Temperature Duration and Corresponding Plant Performance



	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 ($T_1 = T_6$)	$T_1 - T_3$	$T_1 - T_3$

Figure 3.9 Definitions of Temperatures in the Cooling Systems

SECTION 4

RESULTS OF OPTIMIZATION OF WET/DRY TOWERS FOR WATER CONSERVATION

4.1 INTRODUCTION

The studies of wet/dry systems for water conservation involve evaluations at six specific sites, five of which are located in the coal-rich regions of the Western United States. One of these sites (Kaiparowits, Utah) was selected for more detailed parametric and sensitivity analyses. Those results are reported in Section 5. In this section, results are given for wet, dry, and mechanical series wet/dry (S1 mode) cooling systems at the six water conservation sites.

4.2 SITE LOCATION

Because the cooling water supply constraint is expected to be most severe for power plant sites in the West, the emphasis of these studies is on that region. In addition to the five sites in the Western United States, a sixth site in New York State was studied for comparison. The sites, which are shown in Figure 4.1, are:

Kaiparowits - Southern California Edison Company, Arizona Public Service Company and San Diego Gas & Electric Company were, until mid-1976, planning to build a 3000 MWe coal-fired plant on the west side of Lake Powell in Utah. This site was selected for more detailed economic sensitivity analyses.

San Juan - Public Service Company of New Mexico operates a plant at Farmington, New Mexico. The first water conservation wet/dry towers for utility application in the United States are planned to service two additional 450 MWe units at this site.

Colstrip - Montana Power Company operates a plant at this southeastern Montana location. Two units of 330 MWe are in operation; two additional 700 MWe units are planned for 1980 and 1981.

Young - Minnkota Power Cooperative, Inc. is operating a 250 MWe unit at Center, North Dakota.

Rock Springs - Pacific Power and Light Company operates a 1000 MWe plant at this southwest Wyoming location.

New Hampton - Orange and Rockland Utilities, Inc. has proposed a plant at this southeastern New York site.

Utilities operating, constructing, or planning power plants at these locations were contacted to obtain economic and site data for use in the evaluation. Some of these data are shown in Table 4.1. Data on make-up water quality are in Appendix D, and the annual coincident ambient wet and dry bulb temperature distributions are contained in Appendix O.

4.3 METHOD OF OPTIMIZATION

The general optimization procedure is given in Section 3.4. Specific examples of the procedure applied for the wet, dry and wet/dry (water conservation) cooling systems are provided in this section.

For the reference (wet and dry) cooling systems, different designs were obtained by systematically varying the range and approach temperatures. For each design, the capital cost and the capitalized operating penalties were determined. The system with the lowest total evaluated cost was selected as the optimum for a given set of design parameters. An example of the trade-off between the capital cost and penalty cost for a reference wet tower system is shown in Figure 4.2. This figure shows that, for a constant approach, as the range increases, the capital cost decreases and the penalty cost increases. These costs are added to identify the cooling system with the minimum total evaluated cost. This procedure is performed for a series of approach temperatures as shown in Figure 4.3. For the matrix of design parameters, the least cost system is identified.

For wet/dry systems designed to conserve water, it is not realistic to determine the optimum systems solely on the basis of economics. Therefore, the make-up water requirement was used as an additional optimization criterion. The make-up water requirement of a wet/dry system is defined as the percentage of the total annual make-up water needed by the optimum wet reference system. The method of optimization is as follows: by varying the design parameters listed in Section 3.4, wet/dry systems with a specific make-up are sized; from these systems the lowest total evaluated cost system is selected as the optimum system for that make-up water requirement. Figure 4.4 is an illustration of the total evaluated cost of a ten percent make-up system (10% of all-wet) as a function of range for a series of specified turbine back-pressures. The least cost systems for a set of design back-pressures are plotted on Figure 4.5 from which the optimum ten percent system is obtained.

4.4 OPTIMIZED SYSTEMS AT SELECTED SITES

Detailed engineering and economic evaluations given in Section 5 and Reference 1 have indicated that there is a slight economic advantage of the series-connected over the parallel-connected wet/dry systems and of the S1 mode over the S2 mode of operation. A larger economic advantage may be available if natural draft instead of mechanical draft dry towers are used in the wet/dry systems. For the analysis performed to compare the effects of site conditions, the mechanical series type wet/dry system was selected because there is no natural draft dry tower experience in this country.

4.4.1 Results for Kaiparowits

The results of the optimized wet/dry tower systems designed for various water make-up requirements and reference tower systems are shown in Tables 4.2 through 4.4. The make-up requirement is expressed as a percentage of the annual make-up required by an optimized wet tower system.

Table 4.2 shows a summary of the major design data for the optimized cooling systems. Included in this table are the number of tower modules and operating mode, the maximum operating back pressure, the gross generator output, the condenser or tower 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 S1.

These data indicate that dry cooling tower systems of manageable size can be designed for utility application by peak shaving the heat load with evaporative helper towers. The number of dry cells needed for the wet/dry option are comparable to or less than that required for the dry cooling system using the high back-pressure turbine. The data also show that the capacity deficit incurred with the dry tower and high back-pressure turbine (121.8 MWe) can be reduced more than 70 MWe even with the wet/dry system requiring two percent make-up.

Table 4.3 summarizes the major capital cost and the penalty cost elements for the tower systems described in Table 4.2. As previously discussed, the operating penalties are capitalized over the 40-year lifetime of the plant. For the wet/dry systems, the costs range between the dry and the wet systems and decrease monotonically as the make-up water requirement increases. The total evaluated costs for all of the wet/dry systems are significantly higher than those for the wet system, but significantly lower than that for the dry system. As shown in Table 4.3, the total evaluated cost for the 40 percent make-up wet/dry system is 40 percent higher than the cost of the wet system. The major capital and penalty cost elements are itemized in Table 4.4.

Additional design and cost details are included in Appendix F. The data indicate that the tower cost of each of the wet/dry systems constitutes approximately 30 to 40 percent of the capital cost of the cooling system and approximately 20 to 30 percent of the total evaluated cost. An examination of the elements of the penalty cost shows that, for the two percent make-up wet/dry system, the replacement energy cost is small. This occurs because the low percentage make-up systems require a larger number of dry tower cells to control water consumption. Operation of these dry tower cells at low ambient temperature conditions allows this system to attain low back-pressure and consequently high gross output.

4.4.1.1 Plant Performance--

An example of the change in plant output in response to changes in ambient temperatures during the year is shown in Figure 4.6 for the ten percent make-up wet/dry tower. The figure also shows the variation in turbine back-pressure and cooling tower make-up water flow rate.

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 and net plant outputs are at their lowest values. 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 at or 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 and the dry bulb temperature falls, the efficiency of the dry tower system increases, the back-pressure decreases, and the gross and net generator outputs increase.

4.4.1.2 Variation in Water Usage--

An important factor in the design of cooling systems is the make-up water requirement, whether determined on a daily, monthly, or annual basis. The annual make-up is determined as the summation of the water usage during each increment of an ambient temperature cycle.

Figures 4.7 and 4.8 show, for each month, the total amount of make-up required and the maximum flow rate for the San Juan site. The data were generated for San Juan and not for Kaiparowits for two reasons: (1) comparative data are available in Reference 1 for a nuclear plant of the same nominal capacity, and (2) monthly temperature distribution data were not available for Kaiparowits. The data are typical of water consumption expected for the western sites.

Although the annual make-up is small, the maximum flow rate can be large. For example, even for the two percent make-up systems, the maximum make-up flow rate is almost one-third that required by the wet system. The information such as that given in Figures 4.7 and 4.8 can be used to determine whether stream flow conditions match the make-up requirements, or to size a reservoir or impoundment. All water supply evaluations reported in this study used the maximum water flow conditions to size the water supply system.

There are many factors which influence the water supply costs for specific sites; among them are water quality, distance from supply to the site, elevation differences, 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.

In the design and evaluation of the wet/dry cooling system for a specific water make-up requirement, the optimization analysis is independent of the water supply. All of the systems designed for a specific water make-up quantity have essentially the same water supply cost. In this method of analysis, water treatment and supply costs can be determined for each make-up requirement. The water supply costs can then be added directly to the total evaluated costs of the wet and wet/dry cooling systems to permit a comparison. The capital and penalty costs are detailed in Table 4.5 to emphasize the water supply cost.

The make-up supply capital cost, pumping power and energy cost, and the water purchase and treatment cost are shown in Table 4.5. These three quantities are summed to determine the total make-up water penalty cost.

4.4.2 Site Comparisons

Major cost summaries for the other sites are given in Tables 4.6 through 4.15. Details of the design and costs are given in Appendices J through O.

4.4.2.1 Comparison Including Water Supply Costs--

A graphical comparison of the total evaluated costs for the six sites is presented in Figure 4.9. Costs at the New Hampton site are significantly greater than at the mine-mouth western sites primarily because of the higher fuel costs. The effect of fuel cost on system selection is further illustrated in the cost summaries for the six sites. At the mine-mouth sites, dry tower operation with a high back-pressure turbine is consistently less expensive than a dry tower optimized with a low back-pressure turbine. However, at New Hampton, with fuel costs five to ten times higher, the reverse is true because the high back-pressure turbine suffers significant fuel penalties in the low pressure (1 to 5 in-HgA) region.

The total evaluated costs in Figure 4.9 include the cost of transporting the make-up water from the source to the plant site. The water supply system is designed to meet the maximum flow requirements. The associated costs include the capital investment in pumps and pipelines and the operating charges. Additional economic advantages may be obtained by optimizing the water supply system (e.g., evaluating the trade-offs between on-site make-up storage and pipeline capacity).

The results presented in Figure 4.9 reflect the site-specific water supply conditions. For instance, the Kaiparowits cooling system is more expensive than comparable systems for the other western sites primarily because of costs associated with pumping water up 2600 ft (792 m) over 30 mi (48.3 km).

The general conclusion based on these results is that wet cooling maintains a significant cost advantage over the wet/dry option. It is apparent that the selection of wet/dry over wet cooling may be strongly influenced by water availability and/or legal restrictions rather than traditional market considerations.

Tables 4.6 through 4.15 break down the capital and penalty costs to emphasize the make-up water supply costs for sites other than Kaiparowits.

4.4.2.2 Comparison Excluding Water Supply Costs--

The results shown in Figure 4.10 remove some of the site specificity by excluding water supply costs. The water treatment and purchase costs shown in Table 4.1 are included.

With the water supply cost removed, the costs of comparable cooling systems at the western sites differ by less than 20 percent. Again, the New Hampton costs are significantly greater because of the fuel charges.

TABLE 4.1

MAJOR ECONOMIC AND SITE DATA

Plant Start-up Date:	1985
Annual Fixed Charge Rate:	18%
Plant Size (Gross Output):	1039 MWe
Average Plant Capacity Factor:	0.75
Plant Life:	40 years
Capacity Penalty Charge Rate:	\$485/kWe

	Kaiparowits, Utah	San Juan, New Mexico	Colstrip, Montana	Young, North Dakota	Rock Springs, Wyoming	New Hampton, New York
Levelized Coal Fuel Cost, ¢/MBtu (¢/GJ)	100 (94.7)	110 (104.2)	94 (89.0)	47 (44.5)	103.4 (97.9)	544 (515.2)
Operation and Maintenance Costs, Mills/kWhr	2.54	2.54	2.54	3.56	2.54	2.54
Make-up Water Purchase and Treatment Charge, \$/1000 gal (\$/m^3)	0.34 (0.090)	0.30 (0.079)	0.30 (0.079)	0.30 (0.079)	0.32 (0.085)	0.02 (0.005)
Site Elevation, ft (m)	6100 (1859)	5500 (1676)	3250 (991)	1960 (597)	6750 (2057)	400 (122)
Maximum Dry Bulb/Wet Bulb Temperatures, °F/°F (°C/°C)	103/77 (39.4/25.0)	102/63 (38.9/17.2)	102/67 (38.9/19.4)	104/70 (40.0/21.1)	93/56 (33.9/13.3)	99/75 (37.2/23.9)
Average Dry Bulb/Wet Bulb Temperatures, °F/°F (°C/°C)	45.7/39.2 (7.6/4.0)	57.4/42.5 (14.1/5.8)	52.6/40.7 (11.4/4.8)	46.8/37.6 (8.2/3.1)	47.7/35.7 (8.7/2.1)	54.3/46.3 (12.4/7.9)
Make-up Pipeline Length, mi (km)	30 (48.3)	5 (8.0)	30 (48.3)	13 (20.9)	40 (64.4)	25 (40.2)
Make-up Pipeline Elevation Change, ft (m)	2600 (792)	200 (61)	700 (213)	0 (0)	0 (0)	400 (122)
Cycles of Concentration for Circulating Water	9	10	9	12	12	10

TABLE 4.2

MAJOR DESIGN DATA FOR THE OPTIMIZED COOLING TOWER SYSTEMS

SITE: KAIPAROWITS, UTAH BASE OUTPUT: 1039 MWe WET/DRY TYPE: MECHANICAL SERIES (S1)

Item	Mech. Dry (H)*	Mech. Dry (L)†	Percentage Make-up Requirement# Mechanical Series Wet/Dry					Mech. Wet
			2	10	20	30	40	
Number of Tower Cells, Wet Tower/Dry Tower	0/113	0/290	9/126	13/93	16/77	17/61	19/52	22/0
Maximum Operating Back Pressure P_{max}, in-HgA (mm-HgA)	13.36 (339.3)	5.03 (127.8)	5.0 (127.0)	4.5 (114.3)	4.0 (101.6)	4.0 (101.6)	4.0 (101.6)	3.60 (91.4)
Gross Plant Output at P_{max}, MWe	914.3	989.0	989.8	999.1	1009.5	1009.5	1009.5	1017.4
Heat Load at P_{max}, 10^9 Btu/hr (10^{12} J/hr)	4.77 (5.03)	4.62 (4.88)	4.62 (4.88)	4.59 (4.84)	4.55 (4.80)	4.55 (4.80)	4.55 (4.80)	4.53 (4.78)
Heat Load Distribution at P_{max}, (Wet Tower/Dry Tower), %	0.0/ 100.0	0.0/ 100.0	51.6/ 48.4	69.8/ 30.2	78.8/ 21.2	82.3/ 17.7	84.7/ 15.3	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)	0.518 (0.196)	2.59 (0.98)	5.19 (1.97)	8.57 (3.24)	11.14 (4.22)	27.91 (10.57)

* H-High Back Pressure Turbine

† L-Conventional Low Back Pressure Turbine

\# Percentage of annual make-up required by optimized wet tower

TABLE 4.3

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

SITE: KAIPAROWITS, UTAH 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
			2	10	20	30	40	
Total Capital Cost (Direct & Indirect Capital Costs)	79.37	179.90	120.42	105.37	101.85	95.58	92.28	68.84
Total Capacity Penalty (Capacity & Auxiliary Power)	71.16	46.63	39.35	33.44	28.49	28.14	27.83	20.59
Total Operating Penalty (Replacement & Auxiliary Energies, Make-up Water & Maintenance)	38.56	22.17	17.78	20.46	21.22	23.97	25.08	15.37
Total Evaluated Cost (Sum of Capital & Penalty Costs)	189.09	248.70	177.55	159.27	151.56	147.69	145.19	104.80

* H-High Back Pressure Turbine

† L-Conventional Low Back Pressure Turbine

\# Percentage of annual make-up required by optimized wet tower

TABLE 4.4

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

SITE: KAIPAROWITS, UTAH YEAR: 1985 WET/DRY TYPE: MECHANICAL SERIES (S1)

	Mech. Dry (H)*	Mech. Dry (L)†	Percentage Make-up Requirement-Mech. Ser. Wet/Dry#					Mech. Wet
			2	10	20	30	40	
Capital Cost:								
Cooling Tower	39.42	101.06	49.23	40.07	36.26	31.30	29.34	12.98
Condenser	10.78	15.07	11.80	10.10	10.12	10.18	9.83	10.28
Circulating Water System	7.91	14.43	11.75	9.20	9.28	9.36	8.94	6.68
Make-up Facility	0.00	0.00	15.48	18.52	20.08	20.64	21.13	23.58
Electrical Equipment	5.39	13.27	8.08	6.41	5.74	4.98	4.58	1.56
Indirect Cost	15.87	35.97	24.08	21.07	20.37	19.12	18.46	13.76
Total Capital Cost	79.37	179.90	120.42	105.37	101.85	95.58	92.28	68.84
Penalty Cost:								
Capacity	60.48	24.27	24.00	19.34	14.30	14.30	14.30	10.49
Auxiliary Power	10.67	22.36	15.35	14.11	14.19	13.85	13.54	10.10
Replacement Energy	26.47	-0.76	3.29	8.11	8.53	10.54	11.26	1.31
Auxiliary Energy	8.29	14.32	9.35	7.68	7.75	8.15	8.20	6.94
Make-up Water	0.00	0.00	0.10	0.49	0.98	1.62	2.11	5.27
Cooling System Maintenance	3.81	8.61	5.04	4.18	3.95	3.67	3.52	1.84
Total Penalty	109.72	68.80	57.13	53.91	49.70	52.13	52.93	35.95

* H-High Back Pressure Turbine
† L-Conventional Low Back Pressure Turbine
# Percentage of annual make-up required by optimized wet tower

TABLE 4.5

BASE COOLING SYSTEM COST AND MAKE-UP WATER PENALTY COST COMPONENTS ($$10^6$)

SITE: KAIPAROWITS, UTAH YEAR: 1985 WET/DRY TYPE: MECHANICAL SERIES (S1)

	Mech. Dry (H)*	Mech. Dry (L)†	Percentage Make-up Requirement# Mechanical Series Wet/Dry					Mech. Wet
			2	10	20	30	40	
Capital Cost:								
Cooling Tower	39.42	101.06	49.23	40.07	36.26	31.30	29.34	12.98
Condenser	10.78	15.07	11.80	10.10	10.12	10.18	9.83	10.28
Circulating Water System	7.91	14.43	11.75	9.20	9.28	9.36	8.94	6.68
Electric Equipment	5.39	13.27	8.08	6.41	5.74	4.98	4.58	1.56
Indirect Cost	15.87	35.98	20.21	16.44	15.35	13.96	13.18	7.87
Total Capital Cost of Base Cooling System**	79.37	179.90	101.07	82.22	76.75	69.78	65.87	39.37
Penalty Cost:								
Capacity Loss	60.48	24.27	24.00	19.34	14.30	14.30	14.30	10.49
Power for Tower Fans & Circulating Water Pumps	9.67	22.36	12.96	10.88	10.52	10.02	9.57	5.43
Replacement Energy	26.47	-0.76	3.29	8.11	8.53	10.54	11.26	1.31
Fan Energy & Circulating Water Pumping Energy	8.29	14.32	9.30	7.42	7.23	7.28	7.08	4.17
Cooling System Maintenance	3.81	8.61	5.04	4.18	3.95	3.67	3.52	1.84
Total Penalty Cost of Base Cooling System**	109.72	68.80	54.59	49.92	44.53	45.58	45.71	23.25
Make-up Water Penalty Cost:								
Make-up Water Purchase & Treatment Cost	0.00	0.00	0.10	0.49	0.98	1.62	2.11	5.27
Capital Cost for Make-up Water Supply Facilities††	0.00	0.00	19.35	23.15	25.10	25.80	26.41	29.47
Power and Energy Cost for Pumping Make-up Water	0.00	0.00	2.44	3.50	4.20	4.70	5.10	7.44
Total Make-up Water Penalty Cost	0.00	0.00	21.89	27.14	30.28	32.11	33.62	42.18
Total Evaluated Cost of the Complete Cooling System	189.09	248.70	177.55	159.27	151.56	147.69	145.19	104.80

* H - High Back Pressure Turbine

† L - Low Back Pressure Turbine

\# Percentage of annual make-up required by optimized wet tower

** Base Cooling System - Cooling system without make-up and water treatment facilities

†† Including 25% direct capital cost as indirect capital cost

TABLE 4.6

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

SITE: SAN JUAN, NEW MEXICO 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
			2	10	20	30	40	
Total Capital Cost (Direct & Indirect Capital Costs)	79.43	168.75	122.74	101.92	92.43	87.90	81.33	47.63
Total Capacity Penalty (Capacity & Auxiliary Power)	68.70	47.64	39.36	31.81	25.84	20.99	19.84	12.04
Total Operating Penalty (Replacement & Auxiliary Energies, Make-up Water & Maintenance)	42.76	26.10	22.42	22.78	22.41	21.11	21.66	13.49
Total Evaluated Cost (Sum of Capital & Penalty Costs)	190.89	242.49	184.51	156.51	140.68	130.00	122.83	73.16

* H-High Back Pressure Turbine

† L-Conventional Low Back Pressure Turbine

\# Percentage of annual make-up required by optimized wet tower

TABLE 4.7

BASE COOLING SYSTEM COST AND MAKE-UP WATER PENALTY COST COMPONENTS ($$10^6$)

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

	Mech. Dry (H)*	Mech. Dry (L)†	Percentage Make-up Requirement# Mechanical Series Wet/Dry					Mech. Wet
			2	10	20	30	40	
Capital Cost:								
Cooling Tower	39.07	95.58	60.20	47.27	41.84	38.11	34.43	12.39
Condenser	11.26	14.46	12.07	10.81	10.12	10.14	9.66	10.13
Circulating Water System	7.86	12.51	11.70	10.26	9.16	9.40	8.82	6.50
Electric Equipment	5.36	12.45	9.81	7.60	6.62	6.01	5.29	1.52
Indirect Cost	15.88	33.75	23.45	18.98	16.92	15.91	14.55	7.63
Total Capital Cost of Base Cooling System**	79.43	168.75	117.23	94.92	84.66	79.57	72.75	38.17
Penalty Cost:								
Capacity Loss	57.54	24.27	24.01	19.37	14.30	9.64	9.64	6.48
Power for Tower Fans & Circulating Water Pumps	11.16	23.37	15.18	12.17	11.22	10.99	9.82	5.12
Replacement Energy	29.62	0.49	4.48	8.04	8.54	7.00	7.98	2.23
Fan Energy & Circulating Water Pumping Energy	9.23	17.45	12.19	9.52	8.62	8.51	7.82	4.23
Cooling System Maintenance	3.91	8.15	5.64	4.71	4.19	4.04	3.75	1.81
Total Penalty Cost of Base Cooling System**	111.46	73.73	61.50	53.81	46.88	40.18	39.01	19.87
Make-up Water Penalty Cost:								
Make-up Water Purchase & Treatment Cost	0.00	0.00	0.10	0.48	1.00	1.47	1.98	4.92
Capital Cost for Make-up Water Supply Facilities††	0.00	0.00	5.50	7.00	7.76	8.32	8.59	9.46
Power and Energy Cost for Pumping Make-up Water	0.00	0.00	0.18	0.30	0.38	0.45	0.50	0.74
Total Make-up Water Penalty Cost	0.00	0.00	5.78	7.78	9.14	10.24	11.07	15.12
Total Evaluated Cost of the Complete Cooling System	190.89	242.48	184.51	156.51	140.68	130.00	122.83	73.16

* H - High Back Pressure Turbine

† L - Low Back Pressure Turbine

\# Percentage of annual make-up required by optimized wet tower

** Base Cooling System - Cooling system without make-up and water treatment facilities

†† Including 25% direct capital cost as indirect capital cost

TABLE 4.8

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

SITE: COLSTRIP, MONTANA   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
			2	10	20	30	40	
Total Capital Cost (Direct & Indirect Capital Costs)	79.14	168.62	127.58	107.11	100.56	100.99	96.22	66.30
Total Capacity Penalty (Capacity & Auxiliary Power)	68.23	47.28	38.65	32.08	26.53	21.88	21.09	14.86
Total Operating Penalty (Replacement & Auxiliary Energies, Make-up Water & Maintenance)	37.38	22.94	18.64	20.09	20.59	19.32	19.63	13.60
Total Evaluated Cost (Sum of Capital & Penalty Costs)	184.75	238.84	184.87	159.28	147.68	142.19	136.94	94.76

* H-High Back Pressure Turbine

† L-Conventional Low Back Pressure Turbine

\# Percentage of annual make-up required by optimized wet tower

TABLE 4.9

BASE COOLING SYSTEM COST AND MAKE-UP WATER PENALTY COST COMPONENTS ($$10^6$)

SITE: COLSTRIP, MONTANA YEAR: 1985 WET/DRY TYPE: MECHANICAL SERIES (S1)

	Mech. Dry (H)*	Mech. Dry (L)†	Percentage Make-up Requirement# Mechanical Series Wet/Dry					Mech. Wet
			2	10	20	30	40	
Capital Cost:								
Cooling Tower	39.07	93.49	57.44	41.36	36.94	36.74	33.40	11.80
Condenser	10.82	14.46	11.26	10.81	10.10	9.85	9.63	10.44
Circulating Water System	8.06	14.65	11.06	10.43	9.48	9.02	8.90	7.43
Electric Equipment	5.36	12.30	9.34	6.75	5.93	5.66	4.99	1.55
Indirect Cost	15.83	33.72	22.27	17.33	15.62	15.32	14.22	7.82
Total Capital Cost of Base Cooling System**	79.14	168.62	111.37	86.68	78.07	76.59	71.14	39.04
Penalty Cost:								
Capacity Loss	57.43	24.27	23.98	19.34	14.30	9.65	9.65	7.41
Power for Tower Fans & Circulating Water Pumps	10.80	23.02	13.77	11.39	10.64	10.44	9.56	5.31
Replacement Energy	25.67	-0.13	3.38	7.32	8.08	6.43	6.92	1.75
Fan Energy & Circulating Water Pumping Energy	7.91	14.98	9.73	7.74	7.25	7.13	6.66	3.89
Cooling System Maintenance	3.79	8.09	5.42	4.38	3.99	3.92	3.65	1.95
Total Penalty Cost of Base Cooling System**	105.61	70.23	56.28	50.17	44.26	37.57	36.44	20.31
Make-up Water Penalty Cost:								
Make-up Water Purchase & Treatment Cost	0.00	0.00	0.09	0.51	1.01	1.45	1.91	4.78
Capital Cost for Make-up Water Supply Facilities ††	0.00	0.00	16.21	20.42	22.48	24.39	25.07	27.27
Power and Energy Cost for Pumping Make-up Water	0.00	0.00	0.92	1.50	1.86	2.19	2.38	3.36
Total Make-up Water Penalty Cost	0.00	0.00	17.22	22.43	25.35	28.03	29.36	35.41
Total Evaluated Cost of the Complete Cooling System	184.75	238.85	184.87	159.28	147.68	142.19	136.94	94.76

* H - High Back Pressure Turbine

† L - Low Back Pressure Turbine

\# Percentage of annual make-up required by optimized wet tower

** Base Cooling System - Cooling system without make-up and water treatment facilities

†† Including 25% direct capital cost as indirect capital cost

TABLE 4.10

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

SITE: YOUNG, NORTH DAKOTA 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
			2	10	20	30	40	
Total Capital Cost (Direct & Indirect Capital Costs)	78.89	171.16	113.63	90.39	90.75	82.68	76.66	53.45
Total Capacity Penalty (Capacity & Auxiliary Power)	68.61	48.13	37.71	34.74	25.35	24.19	23.86	14.81
Total Operating Penalty (Replacement & Auxiliary Energies, Make-up Water & Maintenance)	28.22	18.73	14.46	16.17	15.17	16.30	17.46	10.54
Total Evaluated Cost (Sum of Capital & Penalty Costs)	175.72	238.02	165.80	141.30	131.27	123.17	117.98	78.80

* H-High Back Pressure Turbine

† L-Conventional Low Back Pressure Turbine

Percentage of annual make-up required by optimized wet tower

TABLE 4.11

BASE COOLING SYSTEM COST AND MAKE-UP WATER PENALTY COST COMPONENTS ($$10^6$)

SITE: YOUNG, NORTH DAKOTA YEAR: 1985 WET/DRY TYPE: MECHANICAL SERIES (S1)

	Mech. Dry (H)*	Mech. Dry (L)†	Percentage Make-up Requirement# Mechanical Series Wet/Dry					Mech. Wet
			2	10	20	30	40	
Capital Cost:								
Cooling Tower	38.72	93.83	51.08	37.63	37.42	31.97	27.45	12.39
Condenser	11.23	15.77	11.79	10.09	9.87	9.59	9.63	10.11
Circulating Water System	7.85	14.80	11.62	9.16	8.94	8.83	8.91	6.50
Electric Equipment	5.32	12.52	8.41	6.13	5.91	4.92	4.28	1.52
Indirect Cost	15.77	34.24	20.72	15.75	15.53	13.81	12.56	7.63
Total Capital Cost of Base Cooling System**	78.89	171.16	103.62	78.76	77.67	69.12	62.83	38.15
Penalty Cost:								
Capacity Loss	57.49	24.27	23.90	23.86	14.30	14.30	14.30	9.05
Power for Tower Fans & Circulating Water Pumps	11.12	23.87	13.52	10.51	10.59	9.40	9.06	5.16
Replacement Energy	18.45	-0.35	2.48	6.57	5.09	6.64	7.53	1.32
Fan Energy & Circulating Water Pumping Energy	5.88	10.64	6.79	5.18	5.18	4.68	4.66	2.77
Cooling System Maintenance	3.89	8.44	5.08	3.96	3.99	3.59	3.34	1.81
Total Penalty Cost of Base Cooling System**	96.83	66.87	51.77	50.08	39.15	38.61	38.89	20.11
Make-up Water Penalty Cost:								
Make-up Water Purchase & Treatment Cost	0.00	0.00	0.10	0.44	0.86	1.32	1.82	4.40
Capital Cost for Make-up Water Supply Facilities††	0.00	0.00	10.02	11.62	13.08	13.56	13.84	15.31
Power and Energy Cost for Pumping Make-up Water	0.00	0.00	0.29	0.40	0.51	0.56	0.60	0.83
Total Make-up Water Penalty Cost	0.00	0.00	10.41	12.46	14.45	15.44	16.26	20.54
Total Evaluated Cost of the Complete Cooling System	175.72	238.02	165.80	141.30	131.27	123.17	117.98	78.80

* H - High Back Pressure Turbine

† L - Low Back Pressure Turbine

\# Percentage of annual make-up required by optimized wet tower

** Base Cooling System - Cooling system without make-up and water treatment facilities

†† Including 25% direct capital cost as indirect capital cost

TABLE 4.12

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

SITE: ROCK SPRINGS, WYOMING 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
			2	10	20	30	40	
Total Capital Cost (Direct & Indirect Capital Costs)	76.32	146.01	115.75	110.18	103.63	98.92	94.00	69.95
Total Capacity Penalty (Capacity & Auxiliary Power)	62.84	43.92	36.71	26.71	21.54	20.52	19.74	11.93
Total Operating Penalty (Replacement & Auxiliary Energies, Make-up Water & Maintenance)	39.41	21.50	18.85	18.73	18.72	19.81	20.20	13.61
Total Evaluated Cost (Sum of Capital & Penalty Costs)	178.57	211.44	171.30	155.62	143.88	139.25	133.94	95.49

* H-High Back Pressure Turbine

† L-Conventional Low Back Pressure Turbine

Percentage of annual make-up required by optimized wet tower

TABLE 4.13

BASE COOLING SYSTEM COST AND MAKE-UP WATER PENALTY COST COMPONENTS ($$10^6$)

SITE: ROCK SPRINGS, WYOMING   YEAR: 1985   WET/DRY TYPE: MECHANICAL SERIES (S1)

	Mech. Dry (H)*	Mech. Dry (L)†	Percentage Make-up Requirement# Mechanical Series Wet/Dry					Mech. Wet
			2	10	20	30	40	
Capital Cost:								
Cooling Tower	37.67	86.86	48.49	41.81	36.69	34.51	30.84	11.80
Condenser	10.79	11.18	11.28	10.84	10.22	9.25	8.90	10.15
Circulating Water System	7.40	7.74	10.86	10.33	9.40	7.98	7.87	6.50
Electric Equipment	5.19	11.02	7.97	6.87	5.94	5.36	4.64	1.48
Indirect Cost	15.26	29.20	19.65	17.47	15.56	14.27	13.06	7.47
Total Capital Cost of Base Cooling System**	76.32	146.01	98.25	87.32	77.81	71.37	65.31	37.40
Penalty Cost:								
Capacity Loss	52.39	24.26	23.86	14.30	9.64	9.64	9.64	5.14
Power for Tower Fans & Circulating Water Pumps	10.46	19.66	12.24	11.42	10.67	9.53	8.65	5.04
Replacement Energy	27.49	0.37	4.48	5.34	5.68	7.20	7.73	1.74
Fan Energy & Circulating Water Pumping Energy	8.22	14.30	9.41	8.36	7.76	7.13	6.62	3.99
Cooling System Maintenance	3.70	6.84	4.84	4.41	3.99	3.60	3.31	1.78
Total Penalty Cost of Base Cooling System**	102.25	65.43	54.83	43.83	37.74	37.10	35.95	17.69
Make-up Water Penalty Cost:								
Make-up Water Purchase & Treatment Cost	0.00	0.00	0.10	0.50	1.05	1.52	2.07	4.98
Capital Cost for Make-up Water Supply Facilities††	0.00	0.00	17.49	22.85	25.81	27.55	28.68	32.55
Power and Energy Cost for Pumping Make-up Water	0.00	0.00	0.63	1.12	1.47	1.71	1.92	2.87
Total Make-up Water Penalty Cost	0.00	0.00	18.22	24.47	28.33	30.78	32.67	40.40
Total Evaluated Cost of the Complete Cooling System	178.57	211.44	171.30	155.62	143.88	139.25	133.94	95.49

* H - High Back Pressure Turbine

† L - Low Back Pressure Turbine

\# Percentage of annual make-up required by optimized wet tower

** Base Cooling System - Cooling system without make-up and water treatment facilities

†† Including 25% direct capital cost as indirect capital cost

TABLE 4.14

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

SITE: NEW HAMPTON, NEW YORK 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
			2	10	20	30	40	
Total Capital Cost (Direct & Indirect Capital Costs)	75.34	141.14	115.22	110.83	107.49	99.31	92.95	68.92
Total Capacity Penalty (Capacity & Auxiliary Power)	64.70	44.54	37.74	27.78	22.80	21.80	21.43	13.64
Total Operating Penalty (Replacement & Auxiliary Energies, Make-up Water & Maintenance)	156.86	68.64	68.52	66.30	63.70	67.75	70.71	28.94
Total Evaluated Cost (Sum of Capital & Penalty Costs)	296.90	254.32	221.48	204.91	193.99	188.86	185.09	111.50

* H-High Back Pressure Turbine

† L-Conventional Low Back Pressure Turbine

Percentage of annual make-up required by optimized wet tower

TABLE 4.15

BASE COOLING SYSTEM COST AND MAKE-UP WATER PENALTY COST COMPONENTS ($$10^6$)

SITE: NEW HAMPTON, NEW YORK YEAR: 1985 WET/DRY TYPE: MECHANICAL SERIES (S1)

	Mech. Dry (H)*	Mech. Dry (L)†	Percentage Make-up Requirement# Mechanical Series Wet/Dry					Mech. Wet
			2	10	20	30	40	
Capital Cost:								
Cooling Tower	36.98	75.69	49.70	46.01	42.67	37.82	32.94	15.93
Condenser	10.79	14.39	11.82	10.82	10.45	10.15	10.17	10.83
Circulating Water System	7.40	12.67	11.63	10.58	10.53	9.48	9.56	7.53
Electric Equipment	5.11	10.16	8.20	7.42	6.77	5.73	5.04	1.92
Indirect Cost	15.06	28.23	20.33	18.71	17.60	15.79	14.42	9.06
Total Capital Cost of Base Cooling System**	75.34	141.14	101.68	93.54	88.02	78.97	72.13	45.27
Penalty Cost:								
Capacity Loss	54.29	24.72	23.99	14.30	9.65	9.65	9.64	5.99
Power for Tower Fans & Circulating Water Pumps	10.41	19.83	13.14	12.54	12.00	10.90	10.51	6.09
Replacement Energy	118.09	1.03	21.20	23.45	22.18	28.99	32.13	2.36
Fan Energy & Circulating Water Pumping Energy	35.11	60.62	42.24	37.66	36.00	33.46	33.11	20.16
Cooling System Maintenance	3.66	6.98	5.00	4.75	4.65	4.01	3.74	2.21
Total Penalty Cost of Base Cooling System**	221.56	113.18	105.57	92.70	84.48	87.01	89.13	36.81
Make-up Water Penalty Cost:								
Make-up Water Purchase & Treatment Cost	0.00	0.00	0.01	0.03	0.06	0.09	0.12	0.30
Capital Cost for Make-up Water Supply Facilities††	0.00	0.00	13.54	17.29	19.47	20.34	20.82	23.66
Power and Energy Cost for Pumping Make-up Water	0.00	0.00	0.68	1.35	1.96	2.45	2.89	5.46
Total Make-up Water Penalty Cost	0.00	0.00	14.23	18.67	21.49	22.88	23.83	29.42
Total Evaluated Cost of the Complete Cooling System	296.90	254.32	221.48	204.91	193.99	188.86	185.09	111.50

* H - High Back Pressure Turbine

† L - Low Back Pressure Turbine

\# Percentage of annual make-up required by optimized wet tower

** Base Cooling System - Cooling system without make-up and water treatment facilities

†† Including 25% direct capital cost as indirect capital cost

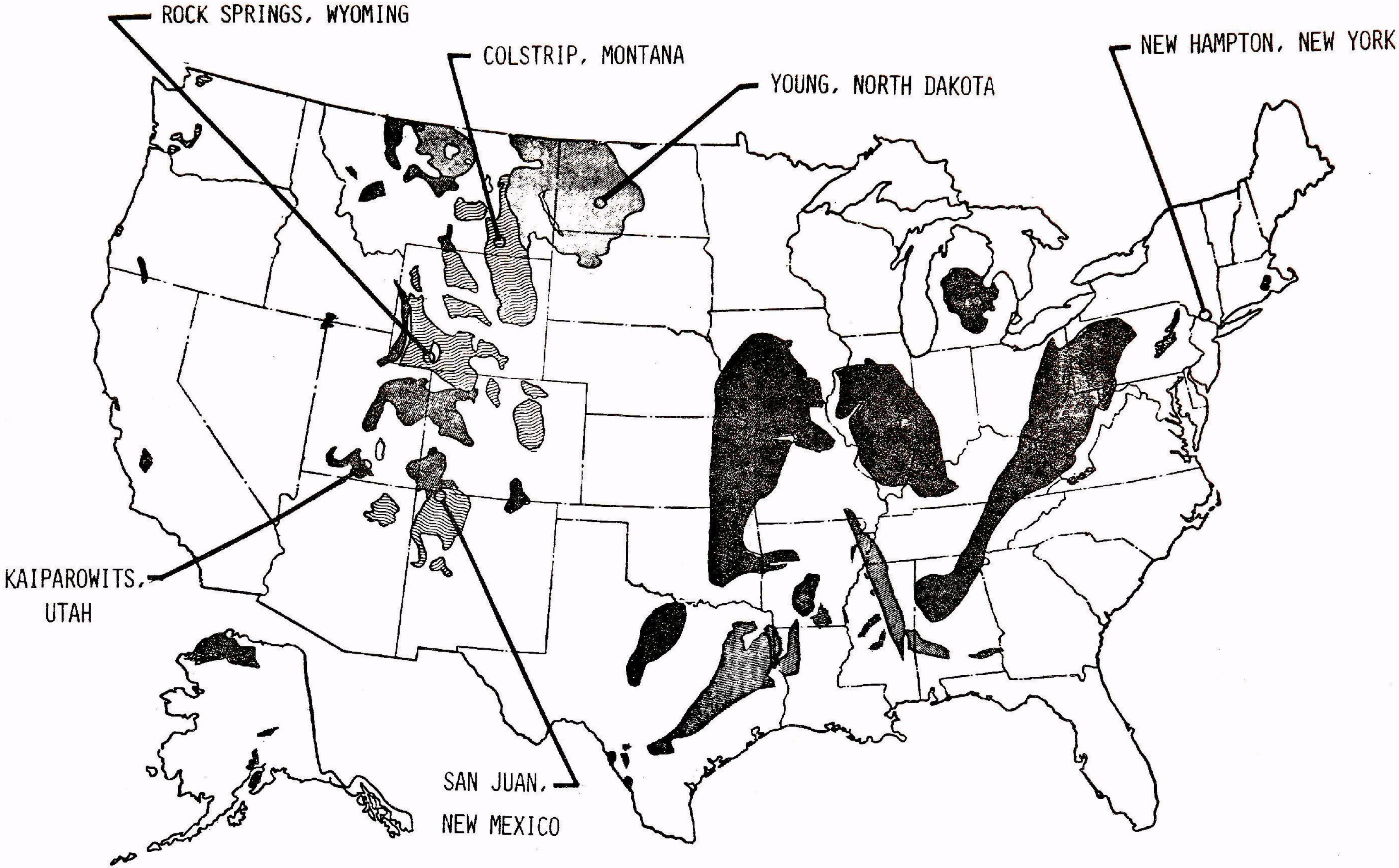


Figure 4.1 Coal Fields of the United States and Sites for the Water Conservation Analysis

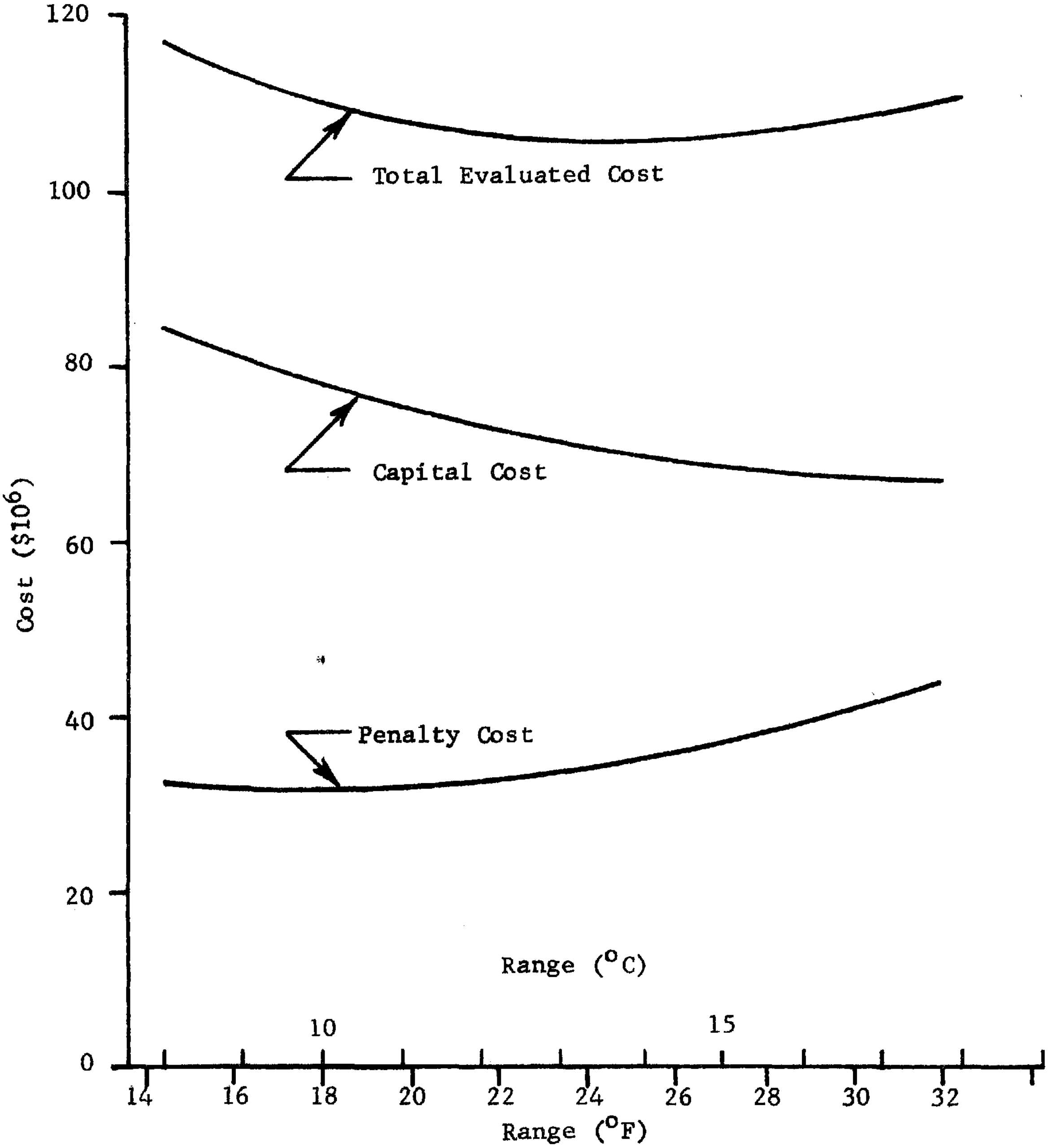


Figure 4.2 Typical Capital and Penalty Trade-off for Mechanical Wet Tower Systems (Kaiparowits, Constant Approach = 19°F (10.5°C))

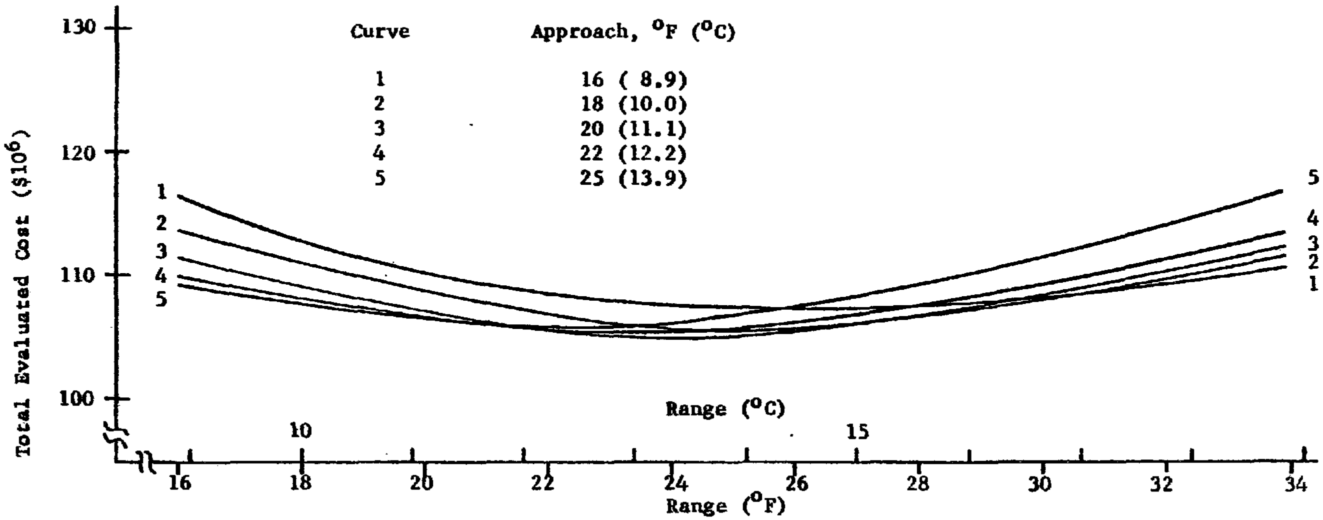


Figure 4.3 Effect of Approach Temperature on the Optimum Selection of the Wet Tower System (Kaiparowits, Mechanical Wet Tower, 1985)

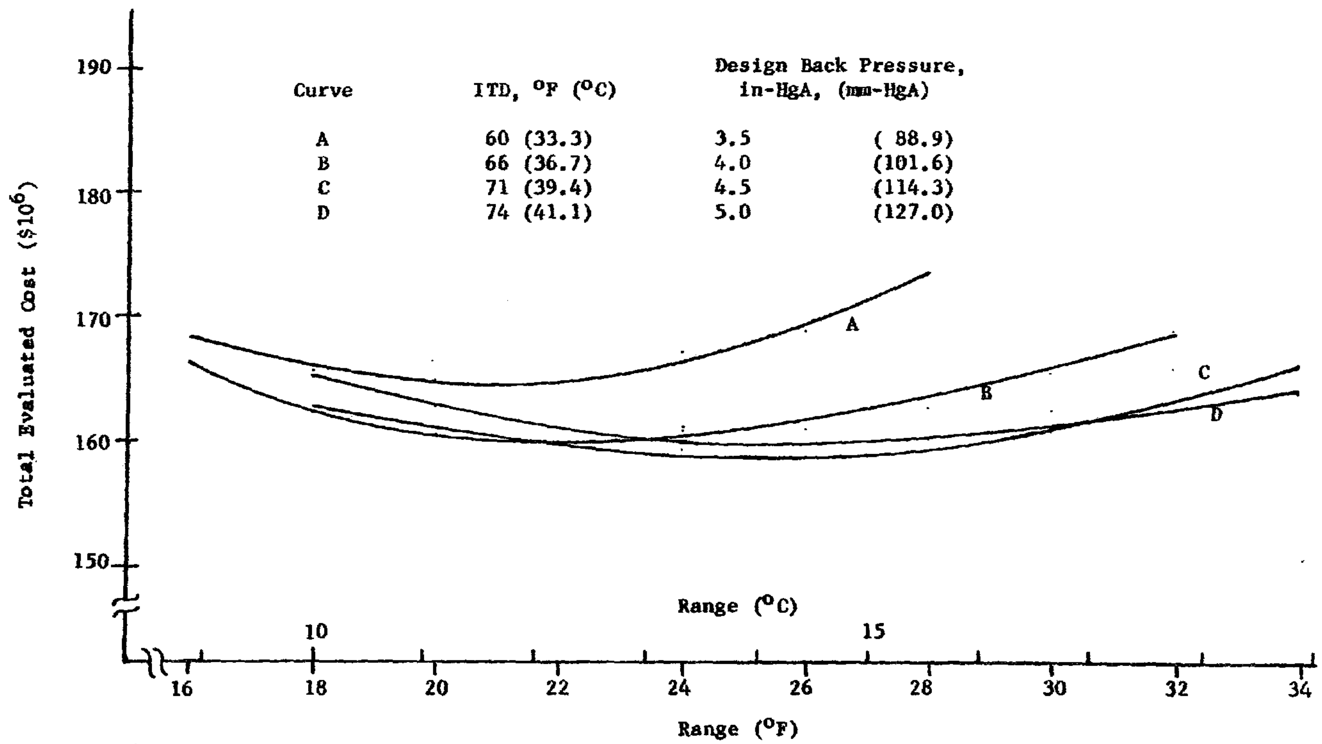


Figure 4.4 Optimization of a 10 Percent Wet/Dry System for a Series of Specified Design Back Pressures (Kaiparowits, Mechanical Series, S1 Mode)

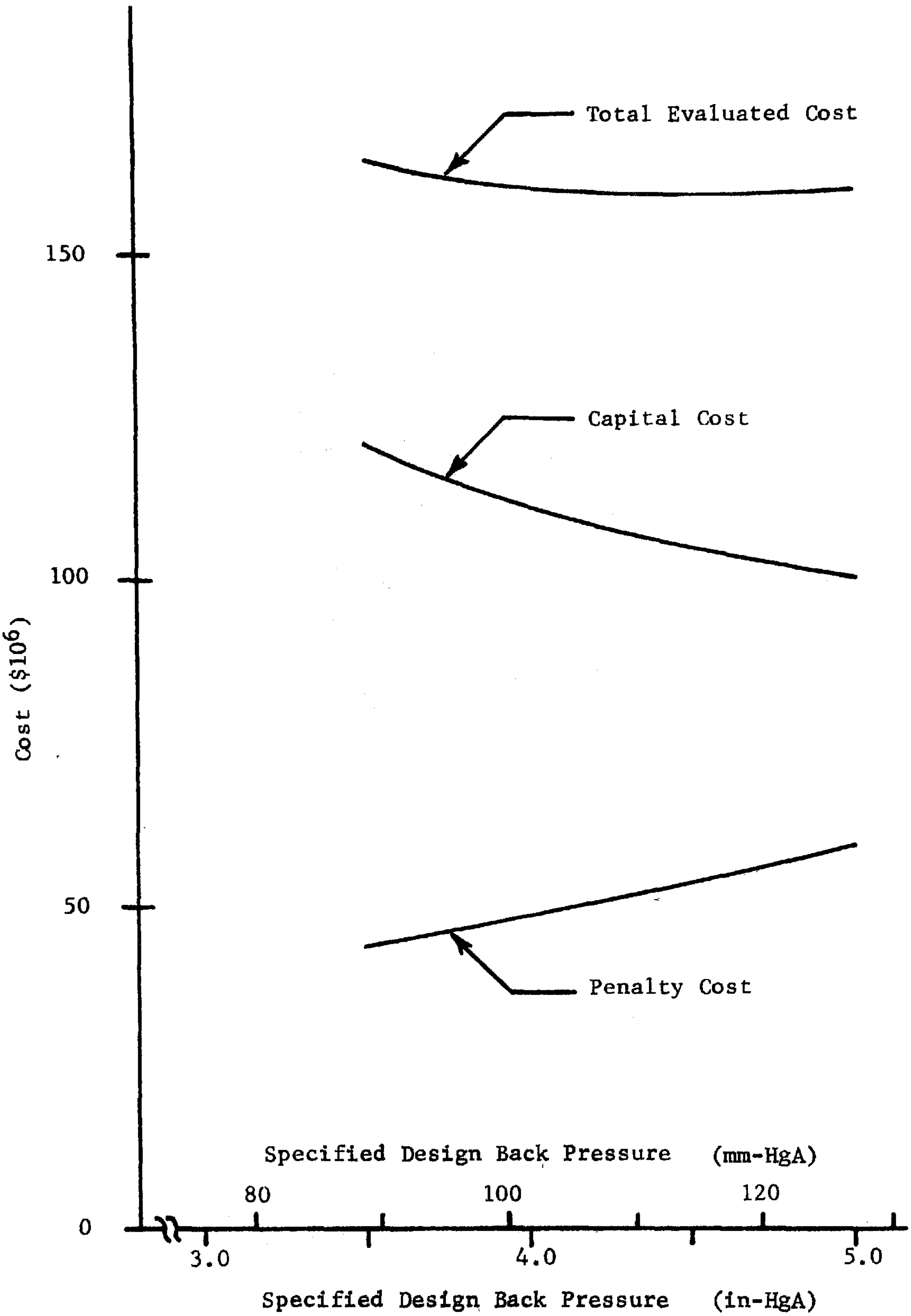


Figure 4.5 Optimum Selection and Economic Trade-offs of a 10 Percent Wet/Dry System (Kaiparowits, Mechanical Series, S1 Mode)

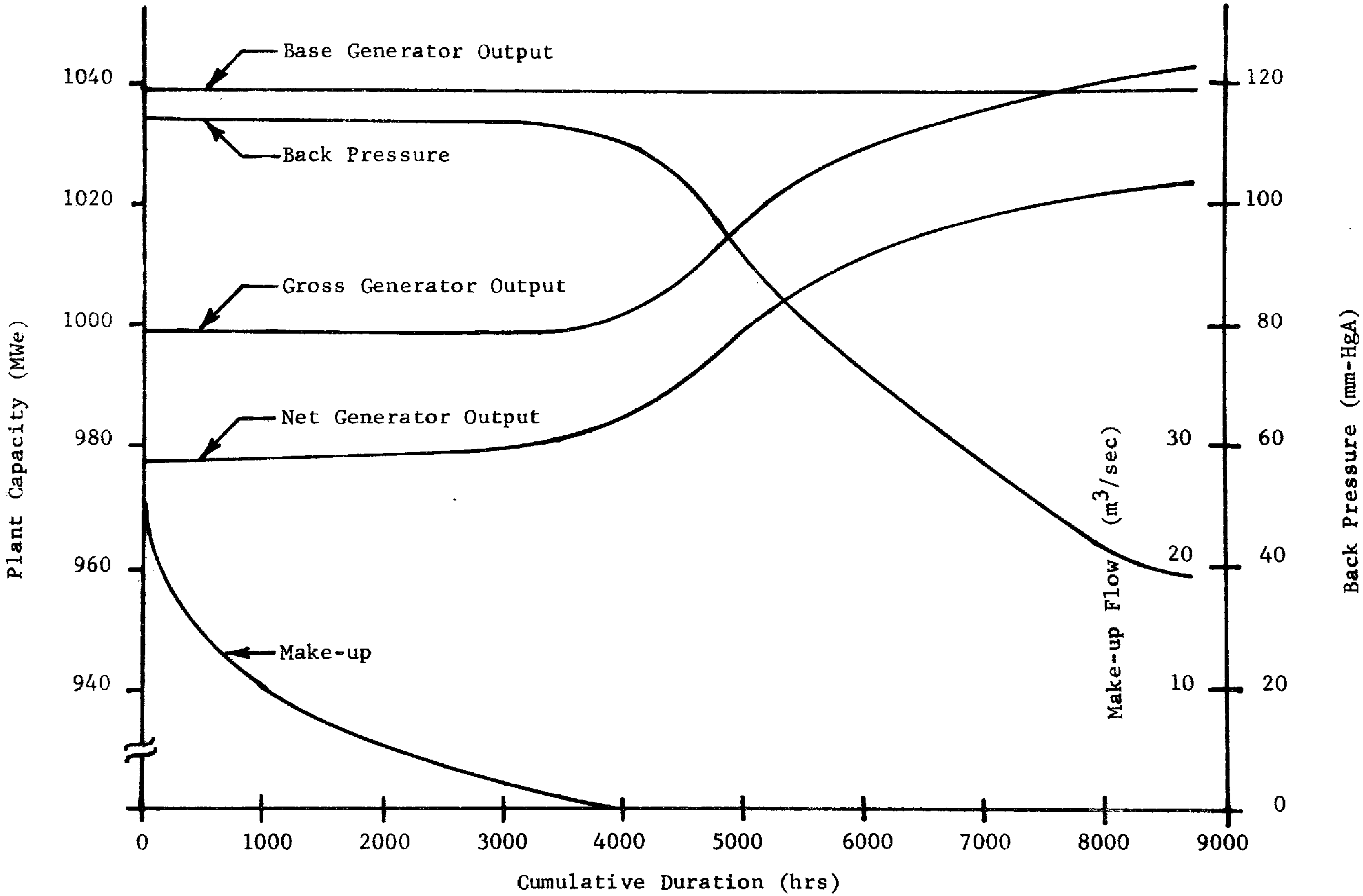


Figure 4.6 Performance Curves for a 10 Percent Mechanical Series Wet/Dry Cooling System at Kaiparowits, Utah

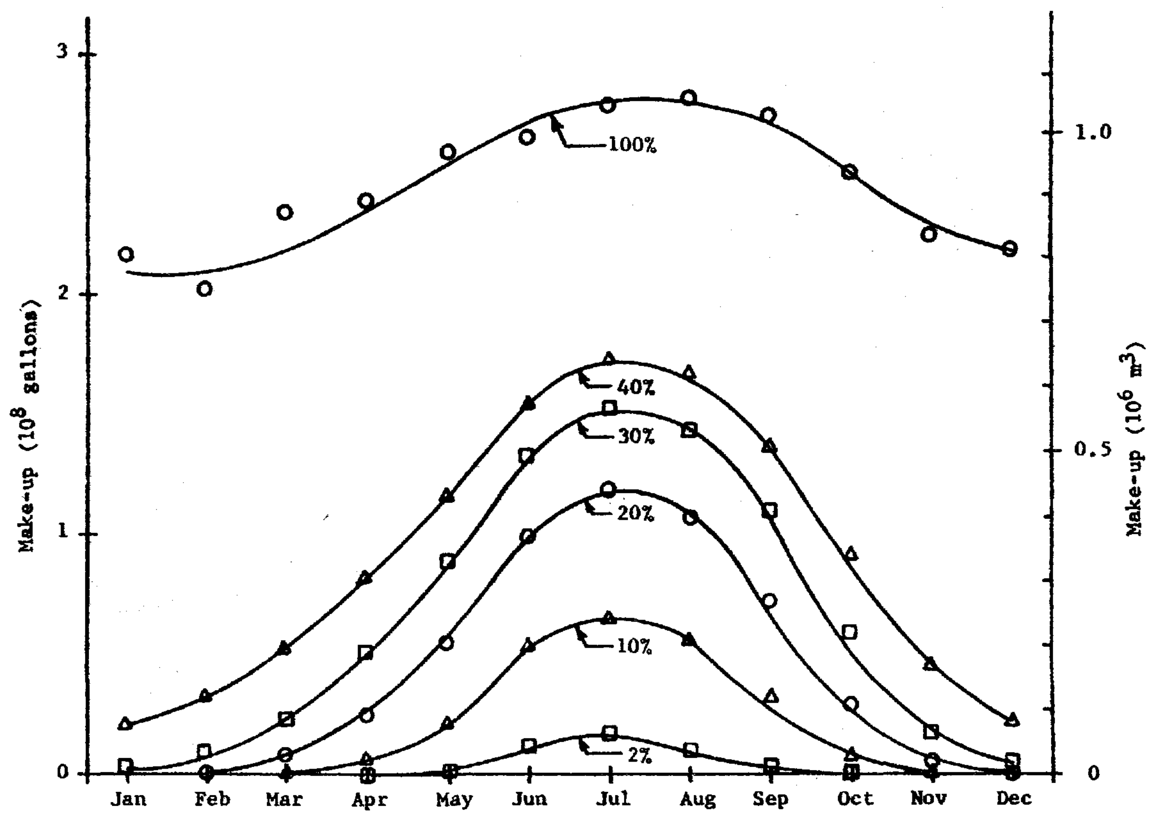


Figure 4.7 Total Make-up Requirement for Each Monthly Period at San Juan, New Mexico

NOTE: Curves are drawn through the discrete points to facilitate visual observation

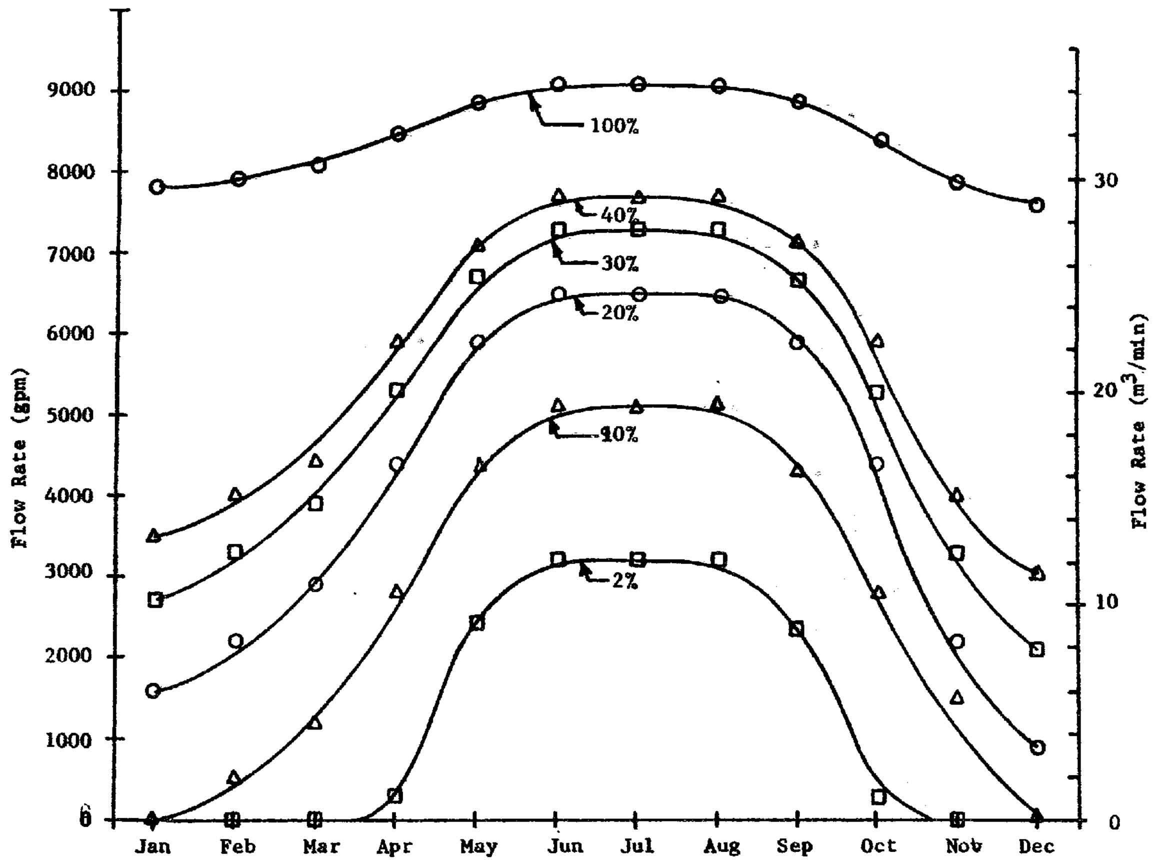


Figure 4.8 Maximum Make-up Flow Rate for Each Monthly Period at San Juan, New Mexico

NOTE: Curves are drawn through the discrete points to facilitate visual observation

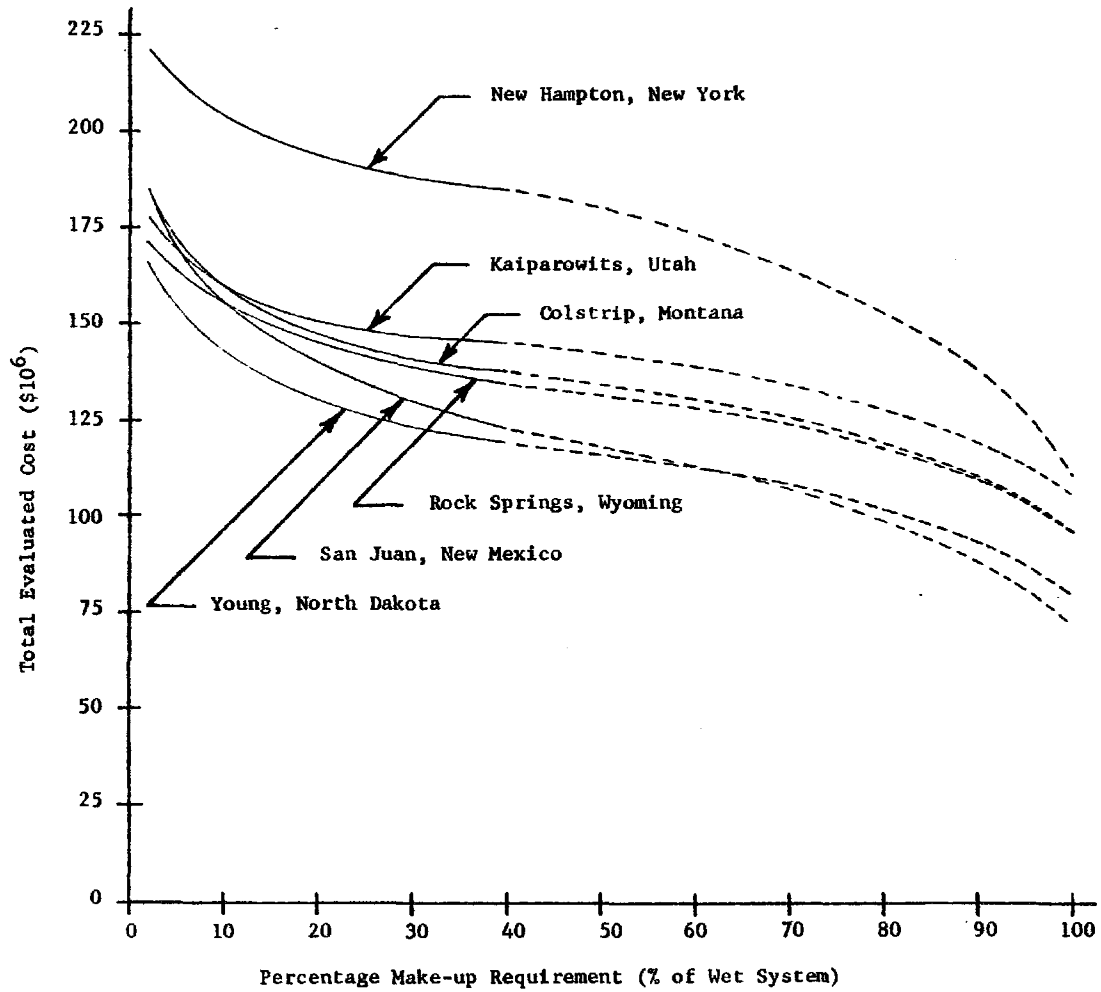


Figure 4.9 Comparison of Alternate Sites Including Water Supply Costs

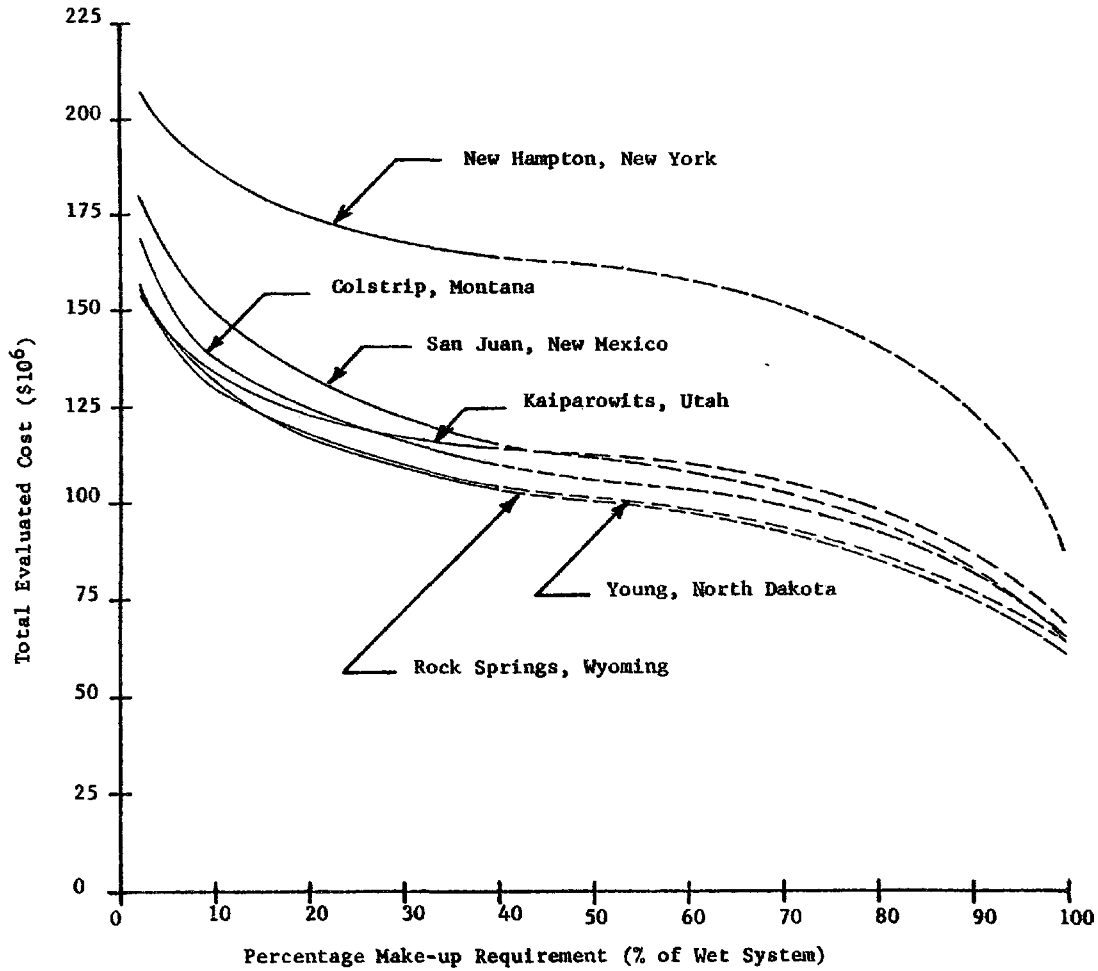


Figure 4.10 Comparison of Alternate Sites Excluding Water Supply Costs

SECTION 5

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

5.1 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 costs of the three types (see Section 3.2.2) of wet/dry tower systems. To accomplish these objectives, a systematic study of each of the three systems was performed using the Kaiparowits, Utah site conditions. Two operational modes, S1 and S2, were considered. Conventional low back-pressure turbines limited to 5 in-HgA (127 mm-HgA) were employed.

5.2 EVALUATION OF SYSTEM CONFIGURATION AND OPERATING MODE

This section presents the results of a cost comparison of the operating modes and the wet/dry system configurations (mechanical series, mechanical parallel, natural series). All comparisons are based on optimized systems.

5.2.1 Operating Mode

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

Figure 5.1 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 5.2 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 systems for the S1 mode are given in Tables 4.2 through 4.5 for the Kaiparowits site. The summary results of design, cost and penalty of the optimized systems for the S2 mode are given in Tables 5.1, 5.2 and 5.3 Detailed results are given in Appendices F and G.

Comparisons between the tabulated results for the S2 mode and the corresponding results for the S1 mode presented in Section 4 indicate for the same make-up percentage: 1) the system optimized for the S1 mode requires more wet cells and less dry cells than that for the S2 mode, and 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 5.3. The figure shows that except for the 40 percent system 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. For this reason, the optimized systems presented in Section 4 for the mechanical series are all designed to operate in the S1 mode.

5.2.2 Mechanical Series vs. Mechanical Parallel

Detailed calculations for the parallel water flow configurations were limited to Mode P1 because, analogous to series-connected wet/dry systems, this operational mode was consistently less expensive than Mode P2.

A summary of the data for the optimized systems is given in Tables 5.4 through 5.6. Detailed results are given in Appendix H. A direct comparison of the capital and penalty costs for the series and parallel systems is given in Figure 5.4.

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.

5.2.3 Mechanical Series vs. Natural Series

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 5.7 through 5.9. Detailed results are given in Appendix I. A direct comparison of capital, penalty, and total evaluated costs for the mechanical series and natural series systems is given in Figure 5.5. The comparison of total evaluated costs demonstrates an economic advantage of natural over mechanical series systems, for higher percentage make-up requirements.

This comparison clearly shows the trade-off of capital and auxiliary penalty costs between the two types of systems. For the twenty 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. This advantage increases with increasing percentage make-up requirement.

5.2.4 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 5.6. This comparison is included to better portray the relative economic advantages of the three systems.

While the natural draft system enjoys a cost advantage, the economic and performance data available from the manufacturers for natural draft dry towers are limited. 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 the airflow is controlled.

5.3 ECONOMIC SENSITIVITY ANALYSIS

The results presented in Sections 4 and 5.2 are projected 1985 costs based on one set of economic factors. The principal economic factors which influence the cooling system design 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). A comprehensive economic sensitivity analysis was completed to determine the effects that changes in the economic parameters will have on system size, capital cost, and the total evaluated cost.

All of the systems described so far 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 5.10. 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; and (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.

5.3.1 Results of Economic Sensitivity Analysis

The sensitivity of the total evaluated cost corresponding to the change in economics is shown in Table 5.11. 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.

The 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 5.7 through 5.10. 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 $1.00/MBtu [$0.95/GJ], replacement capacity of $485/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 ($0.50, $2.50 and $5/MBtu [$0.47, $2.37 and $4.74/GJ]).
5. Three sets of bars which represent the three replacement capacity charges ($225, $700 and $970/kWe).

By referring to the results shown in Figures 5.7 through 5.10, 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 slight difference in capital costs between the optimized systems and the "transferred" systems. Among the four factors studied, the trend is as follows:

   a) Capital costs escalations (material and labor) have the strongest effect of 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 minimal effect on the selection of optimum systems, resulting in almost the same costs for 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 five times the vase 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.

5.3.2 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. A similar economic sensitivity analysis performed for nuclear power plant cooling systems (1) has reached the same conclusion.

TABLE 5.1

MAJOR DESIGN DATA FOR THE OPTIMIZED COOLING TOWER SYSTEMS

SITE: KAIPAROWITS, UTAH BASE OUTPUT: 1039 MWe WET/DRY TYPE: MECHANICAL SERIES (S2)

Item	Mech. Dry (H)*	Mech. Dry (L)†	Percentage Make-up Requirement# Mechanical Series Wet/Dry				Mech. Wet
			10	20	30	40	
Number of Tower Cells, Wet Tower/Dry Tower	**	**	11/105	11/87	12/75	13/63	**
Maximum Operating Back Pressure P_{max}, in-HgA (mm-HgA)			5.00 (127.0)	5.00 (127.0)	5.00 (127.0)	5.00 (127.0)	
Gross Plant Output at P_{max}, MWe			989.8	989.8	989.8	989.8	
Heat Load at P_{max}, 10^9 Btu/hr (10^{12} J/hr)			4.62 (4.87)	4.62 (4.87)	4.62 (4.87)	4.62 (4.87)	
Heat Load Distribution at P_{max}, (Wet Tower/Dry Tower), %			59.5/ 40.5	65.7/ 34.3	70.4/ 29.6	74.8/ 25.2	
Annual Make-up Water for Wet Towers, 10^8 gal (10^6 m3)			2.85 (1.08)	5.55 (2.10)	8.37 (3.17)	10.99 (4.16)	

** Given in Table 4.2

* H-High Back Pressure Turbine

† L-Conventional Low Back Pressure Turbine

\# Percentage of annual make-up required by optimized wet tower

TABLE 5.2

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

SITE: KAIPAROWITS, UTAH 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
			10	20	30	40	
Total Capital Cost (Direct & Indirect Capital Costs)	**	**	109.94	101.15	94.88	89.02	**
Total Capacity Penalty (Capacity & Auxiliary Power)			38.40	37.76	36.85	36.39	
Total Operating Penalty (Replacement & Auxiliary Energies, Make-up Water & Maintenance)			16.76	16.74	16.50	17.09	
Total Evaluated Cost (Sum of Capital & Penalty Costs)			165.10	155.65	148.23	142.50	

* H-High Back Pressure Turbine

** Given in Table 4.3

† L-Conventional Low Back Pressure Turbine

Percentage of annual make-up required by optimized wet tower

TABLE 5.3

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

SITE: KAIPAROWITS, UTAH YEAR: 1985 WET/DRY TYPE: MECHANICAL SERIES (S2)

	Mech. Dry (H)*	Mech. Dry (L)†	Percentage Make-up Requirement-Mech. Ser. Wet/Dry#				Mech. Wet
			10	20	30	40	
Capital Cost:	**	**					**
Cooling Tower			43.08	36.79	33.23	29.60	
Condenser			10.88	10.48	9.80	9.32	
Circulating Water System			10.15	9.75	8.92	8.18	
Make-up Facility			16.83	17.84	18.60	19.35	
Electrical Equipment			7.01	6.06	5.35	4.77	
Indirect Cost			21.99	20.23	18.98	17.80	
Total Capital Cost			109.94	101.15	94.88	89.02	
Penalty Cost:							
Capacity			23.82	23.82	23.67	23.65	
Auxiliary Power			14.58	13.94	13.18	12.74	
Replacement Energy			3.31	3.49	3.33	3.62	
Auxiliary Energy			8.42	8.13	7.94	7.94	
Make-up Water			0.54	1.05	1.58	2.08	
Cooling System Maintenance			4.49	4.08	3.65	3.46	
Total Penalty			55.16	54.50	53.35	53.48	

* H-High Back Pressure Turbine

† L-Conventional Low Back Pressure Turbine

\# Percentage of annual make-up required by optimized wet tower

** Given in Table 4.4

TABLE 5.4

MAJOR DESIGN DATA FOR THE OPTIMIZED COOLING TOWER SYSTEMS

SITE: KAIPAROWITS, UTAH   BASE OUTPUT: 1039 MWe   WET/DRY TYPE: MECHANICAL PARALLEL (P1)

Item	Mech. Dry (H)*	Mech. Dry (L)†	Percentage Make-up Requirement# Mechanical Parallel Wet/Dry				Mech. Wet
			2	10	20	30	
Number of Tower Cells, Wet Tower/Dry Tower	**	**	9/123	11/88	16/77	17/64	**
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)	
Gross Plant Output at P_{max}, MWe			989.8	989.8	1009.5	1009.5	
Heat Load at P_{max}, 10^9 Btu/hr (10^{12} J/hr)			4.62 (4.87)	4.62 (4.87)	4.55 (4.80)	4.55 (4.80)	
Heat Load Distribution at P_{max}, (Wet Tower/Dry Tower), %			35.9/ 64.1	39.1/ 60.9	42.7/ 57.3	47.3/ 52.7	
Annual Make-up Water for Wet Towers, 10^8 gal (10^6 m^3)			0.607 (0.230)	2.78 (1.05)	5.21 (1.97)	8.35 (3.16)	

* H-High Back Pressure Turbine

† L-Conventional Low Back Pressure Turbine

\# Percentage of annual make-up required by optimized wet tower

** Given in Table 4.2

TABLE 5.5

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

SITE: KAIPAROWITS, UTAH YEAR: 1985 WET/DRY TYPE: MECHANICAL PARALLEL (P1)

Item	Mech. Dry (H)*	Mech. Dry (L)†	Percentage Make-up Requirement# Mechanical Parallel Wet/Dry				Mech. Wet
			2	10	20	30	
Total Capital Cost (Direct & Indirect Capital Costs)	**	**	120.87	104.31	108.22	102.24	**
Total Capacity Penalty (Capacity & Auxiliary Power)			39.28	37.63	29.51	28.92	
Total Operating Penalty (Replacement & Auxiliary Energies, Make-up Water & Maintenance)			18.08	22.17	21.35	23.70	
Total Evaluated Cost (Sum of Capital & Penalty Costs)			178.23	164.10	159.08	154.86	

** Given in Table 4.3

* H-High Back Pressure Turbine

† L-Conventional Low Back Pressure Turbine

Percentage of annual make-up required by optimized wet tower

TABLE 5.6

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

SITE: KAIPAROWITS, UTAH YEAR: 1985 WET/DRY TYPE: MECHANICAL PARALLEL (P1)

	Mech. Dry (H)*	Mech. Dry (L)†	Percentage Make-up Requirement-Mech. Para. Wet/Dry#				Mech. Wet
			2	10	20	30	
Capital Cost:	**	**					**
Cooling Tower			48.19	37.13	36.26	32.36	
Condenser			11.79	10.44	10.83	10.44	
Circulating Water System			12.31	10.59	12.03	11.73	
Make-up Facility			16.41	19.09	21.38	21.80	
Electrical Equipment			7.99	6.20	6.09	5.47	
Indirect Cost			24.17	20.86	21.64	20.45	
Total Capital Cost			120.87	104.31	108.22	102.24	
Penalty Cost:							
Capacity			23.86	23.86	14.30	14.30	
Auxiliary Power			15.42	13.77	15.21	14.63	
Replacement Energy			3.53	9.86	7.99	10.05	
Auxiliary Energy			9.32	7.45	7.73	7.62	
Make-up Water			0.12	0.52	0.98	1.58	
Cooling System Maintenance			5.10	4.33	4.65	4.44	
Total Penalty			57.36	59.80	50.86	52.62	

* H-High Back Pressure Turbine

† L-Conventional Low Back Pressure Turbine

\# Percentage of annual make-up required by optimized wet tower

** Given in Table 4.4

TABLE 5.7

MAJOR DESIGN DATA FOR THE OPTIMIZED COOLING TOWER SYSTEMS

SITE: KAIPAROWITS, UTAH BASE OUTPUT: 1039 MWe WET/DRY TYPE: NATURAL SERIES (S1)

Item	Mech. Dry (H)*	Mech. Dry (L)†	Percentage Make-up Requirement# Natural Series Wet/Dry					Mech. Wet
			2	10	20	30	40	
Number of Wet Tower Cells	**	**	10	12	17	18	18	**
Number of Dry Towers			2	1	1	1	1	
Number of Heat Exchangers per Tower			268	302	298	240	198	
Diameter/Height, ft (m)			441/449 (134/137)	497/495 (151/151)	490/442 (149/135)	395/400 (120/122)	326/352 (99/107)	
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			989.8	989.8	1009.5	1009.5	1009.5	
Heat Load at P_{max}, 10^9 Btu/hr (10^{12} J/hr)			4.62 (4.87)	4.62 (4.87)	4.55 (4.80)	4.55 (4.80)	4.55 (4.80)	
Heat Load Distribution at P_{max}, (Wet Tower/Dry Tower), %			61.6/ 38.4	76.1/ 23.9	87.1/ 12.9	89.7/ 10.3	92.0/ 8.0	
Annual Make-up Water for Wet Towers, 10^8 gal (10^6 m^3)			0.583 (0.221)	2.75 (1.04)	5.40 (2.04)	8.23 (3.12)	11.51 (4.36)	

* H-High Back Pressure Turbine

† L-Conventional Low Back Pressure Turbine

\# Percentage of annual make-up required by optimized wet tower

** Given in Table 4.2

TABLE 5.8

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

SITE: KAIPAROWITS, UTAH YEAR: 1985 WET/DRY TYPE: NATURAL SERIES (S1)

Item	Mech. Dry (H)*	Mech. Dry (L)†	Percentage Make-up Requirement# Natural Series Wet/Dry					Mech. Wet
			2	10	20	30	40	
Total Capital Cost (Direct & Indirect Capital Costs)	**	**	144.97	111.92	111.40	103.12	96.32	**
Total Capacity Penalty (Capacity & Auxiliary Power)			31.45	31.90	23.32	23.46	23.57	
Total Operating Penalty (Replacement & Auxiliary Energies, Make-up Water & Maintenance)			9.63	15.66	14.94	17.82	20.23	
Total Evaluated Cost (Sum of Capital & Penalty Costs)			186.05	159.48	149.65	144.40	140.13	

* H-High Back Pressure Turbine

† L-Conventional Low Back Pressure Turbine

\# Percentage of annual make-up required by optimized wet tower

** Given in Table 4.3

TABLE 5.9

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

SITE: KAIPAROWITS, UTAH YEAR: 1985 WET/DRY TYPE: NATURAL SERIES (S1)

	Mech. Dry (H)*	Mech. Dry (L)†	Percentage Make-up Requirement-Nat. Ser. Wet/Dry					Mech. Wet
			2	10	20	30	40	
Capital Cost:	**	**						**
Cooling Tower			72.19	46.37	46.91	46.01	40.37	
Condenser			12.41	11.25	10.15	10.13	10.10	
Circulating Water System			12.90	11.06	9.21	9.21	9.22	
Make-up Facility			17.09	19.48	21.34	21.76	22.08	
Electrical Equipment			1.40	1.37	1.50	1.54	1.54	
Indirect Cost			29.00	22.38	22.28	20.63	19.26	
Total Capital Cost			144.97	111.92	111.40	103.12	96.32	
Penalty Cost:								
Capacity			23.86	23.86	14.30	14.30	14.31	
Auxiliary Power			7.59	8.05	9.02	9.16	9.27	
Replacement Energy			2.94	9.29	7.65	9.60	10.84	
Auxiliary Energy			2.48	2.63	3.20	3.74	4.42	
Make-up Water			0.11	0.52	1.02	1.55	2.17	
Cooling System Maintenance			4.10	3.21	3.07	2.92	2.79	
Total Penalty			41.08	47.56	38.26	41.27	43.81	

* H-High Back Pressure Turbine

† L-Conventional Low Back Pressure Turbine

** Given in Table 4.4

TABLE 5.10

FACTORS USED FOR ECONOMIC SENSITIVITY ANALYSIS*

Variable		BASE 1985			
Replacement Capacity, $/kWe		485	225	700	970
Fuel Cost, ¢/MBtu (¢/GJ)		100 (95)	50 (47)	250 (237)	500 (474)
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%)

* The economic sensitivity analysis is performed by holding any three of the Base 1985 values constant and changing the fourth value.

TABLE 5.11

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

Sensitivity Parameters		Percentage Change from Base Optimum, %						
		Mech. Dry*	Percentage Make-up Requirement - Mechanical Series Wet/Dry					Mech. Wet
			2%	10%	20%	30%	40%	
Annual Fixed Charge Rate, %	= 12.5	+ 9.0	+ 4.4	+ 5.7	+ 6.2	+ 7.1	+ 7.3	+ 6.9
[18] **	= 25.0	- 5.7	- 2.8	- 3.6	- 3.9	- 4.5	- 4.8	- 3.7
Fuel Cost, $/MBtu ($/GJ)	= 0.50 (0.47)	- 7.0	- 2.7	- 3.8	- 4.1	- 4.8	- 5.1	- 2.4
[1.00 (0.95)] **	= 2.50 (2.37)	+ 21.1	+ 8.1	+ 10.5	+ 12.2	+ 12.4	+ 13.1	+ 9.0
	= 5.00 (4.74)	+ 56.2	+ 21.4	+ 26.6	+ 29.6	+ 32.0	+ 33.8	+ 22.9
Replacement Capacity Cost, $/kW	= 225	- 20.6	- 11.9	- 12.0	- 10.4	- 10.2	- 10.3	- 10.6
[485] **	= 700	+ 16.0	+ 9.8	+ 9.1	+ 8.3	+ 8.1	+ 8.1	+ 8.5
	= 970	+ 34.5	+ 22.2	+ 19.4	+ 18.8	+ 17.3	+ 17.4	+ 18.4
Escalation Multiplier (Material/Labor)	= 1.1/1.1	- 20.7	- 33.2	- 32.6	- 32.5	- 32.7	- 32.2	- 32.3
[1.91/2.29] **	= 3.30/4.75	+ 35.1	+ 58.6	+ 55.7	+ 56.4	+ 56.1	+ 55.8	+ 58.4
	= 5.75/6.75	+ 85.4	+140.8	+130.9	+128.3	+128.3	+123.7	+126.9

* High back pressure turbine
** Base economic value

	Mech. Dry*	Percentage Make-up Requirement - Mechanical Series Wet/Dry					Mech. Wet
		2%	10%	20%	30%	40%	
Base Total Evaluated Cost, $$10^6$	189.09	177.55	159.27	151.56	147.69	145.19	104.81

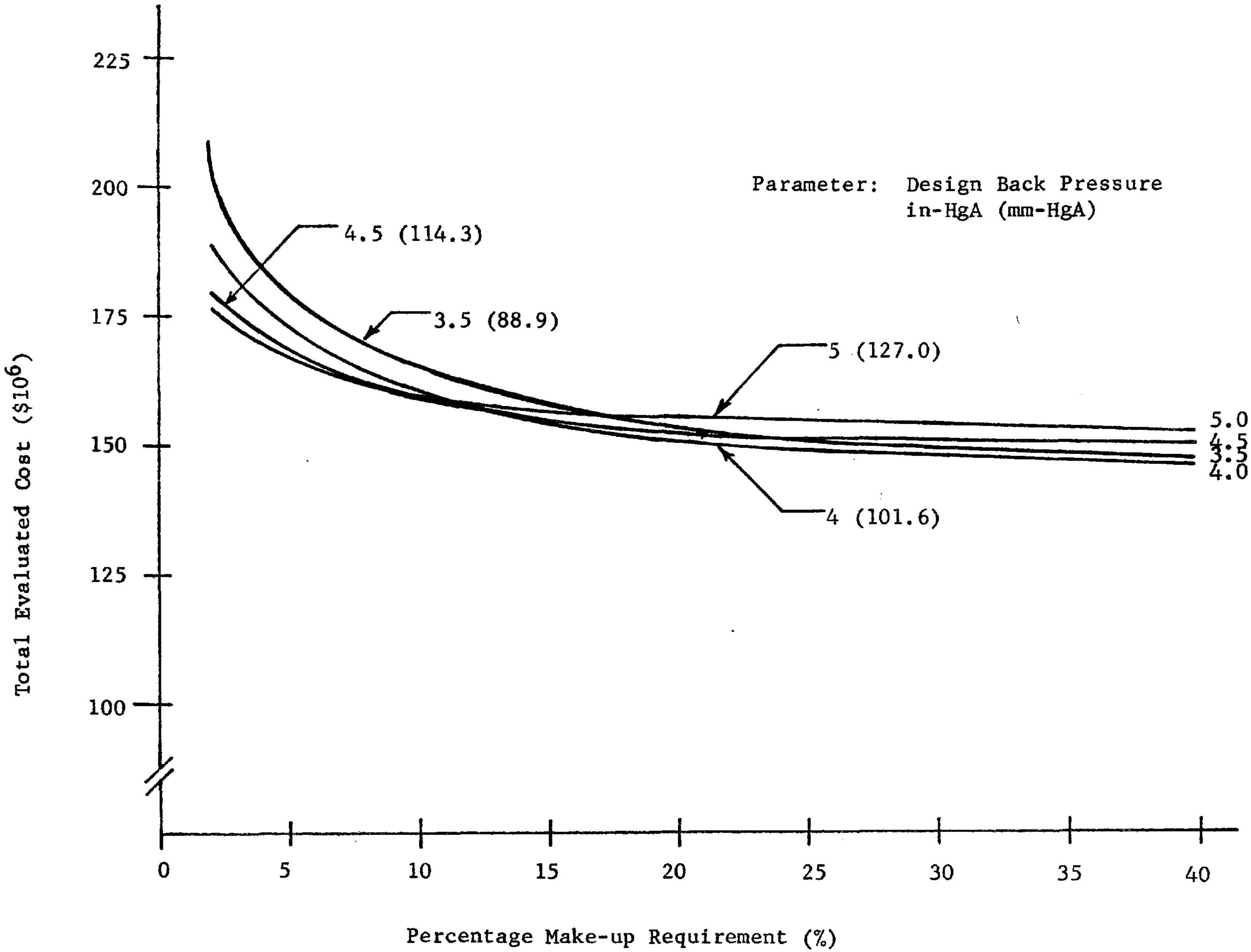


Figure 5.1 Total Evaluated Costs of Optimized Wet/Dry Systems Operating in S1 Mode for Various Specified Design Back Pressures (Kaiparowits, Mechanical Series, 1985)

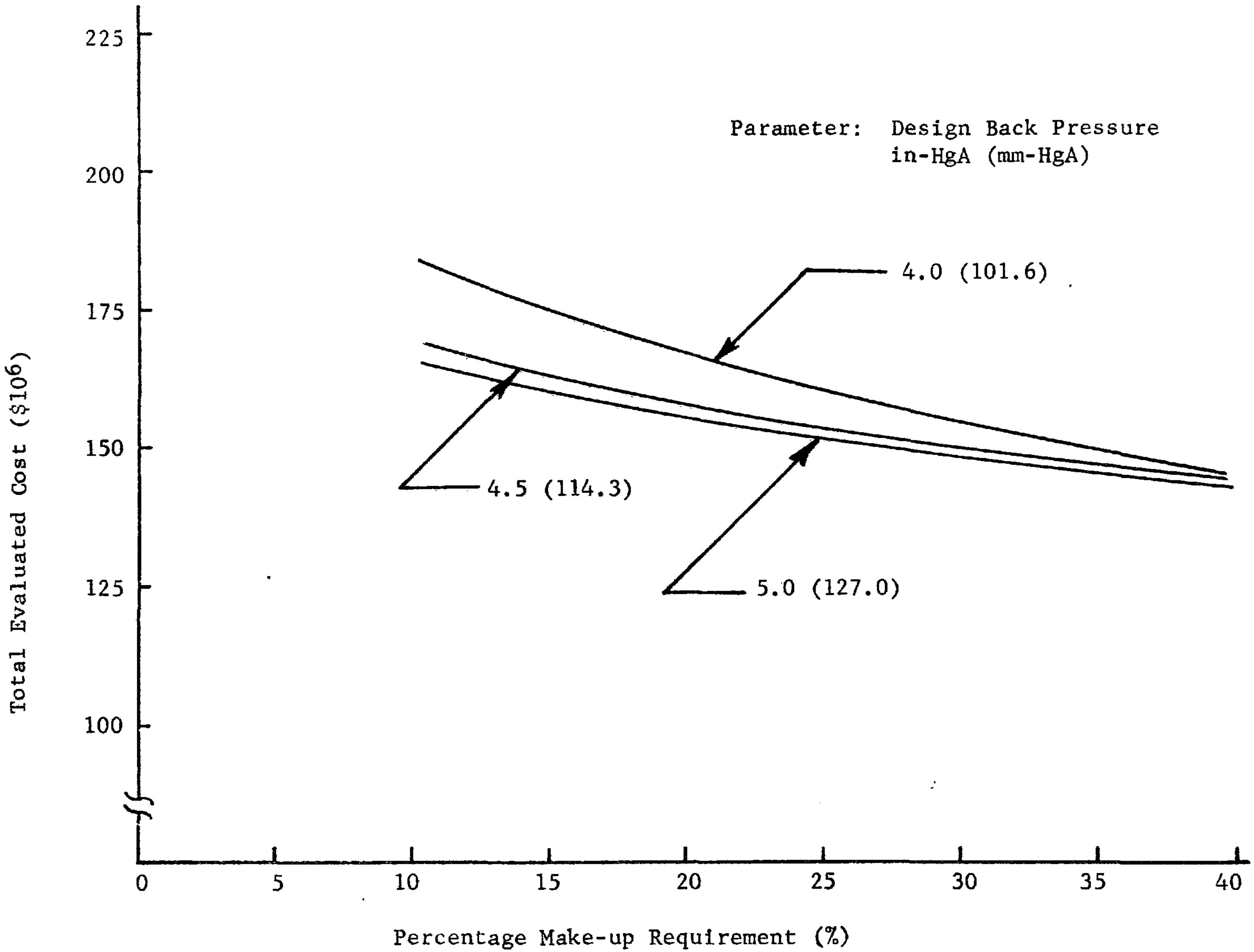


Figure 5.2 Total Evaluated Costs of Optimized Wet/Dry Systems Operating in S2 Mode for Various Specified Design Back Pressures (Kaiparowits, Mechanical Series, 1985)

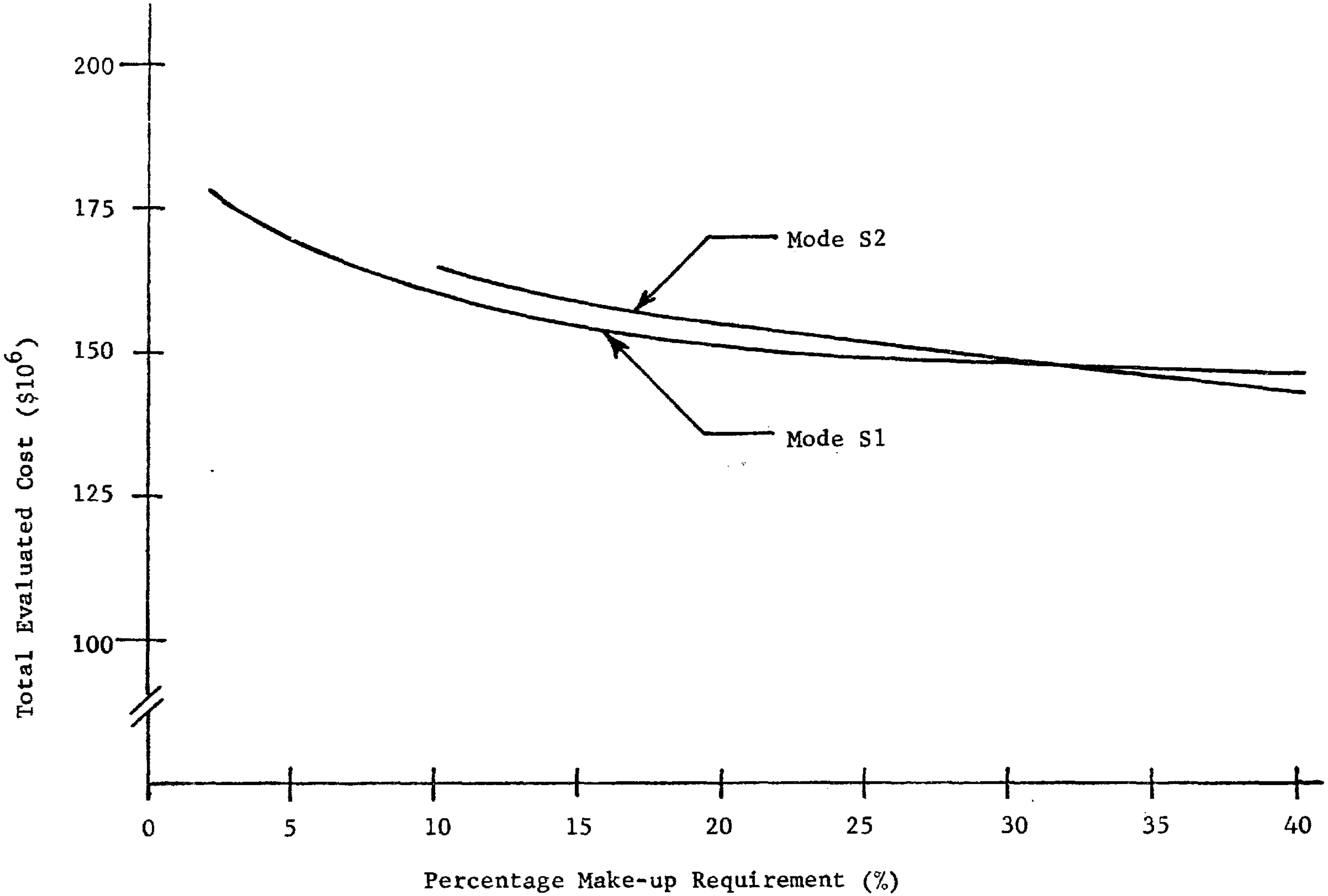


Figure 5.3 Comparison of the Optimized Systems Operating in the S1 and S2 Modes (Kaiparowits, Mechanical Series, 1985)

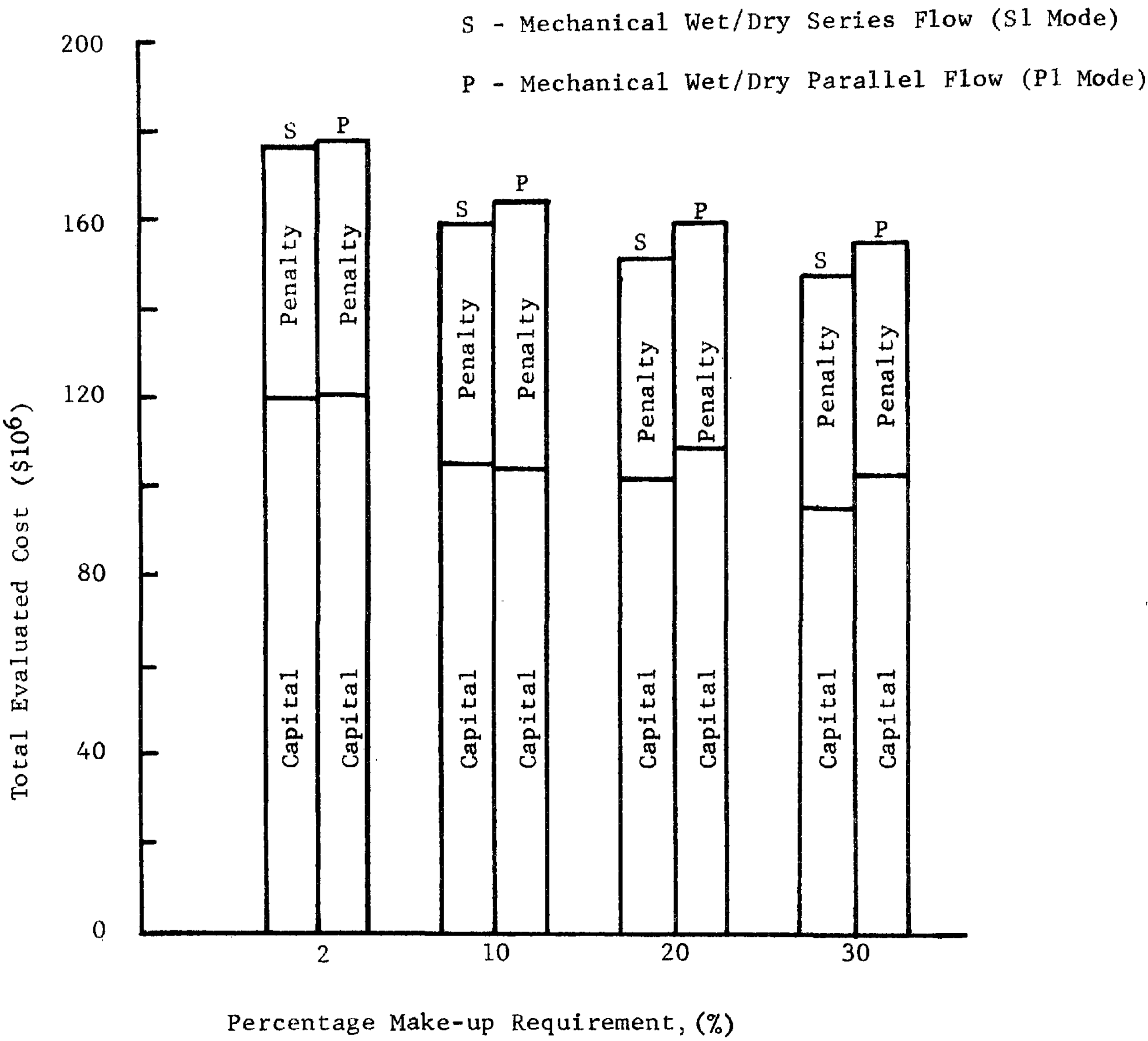


Figure 5.4 Comparison of Series (S1) and Parallel (P1) Mechanical Wet/Dry Cooling Tower Systems (Kaiparowits)

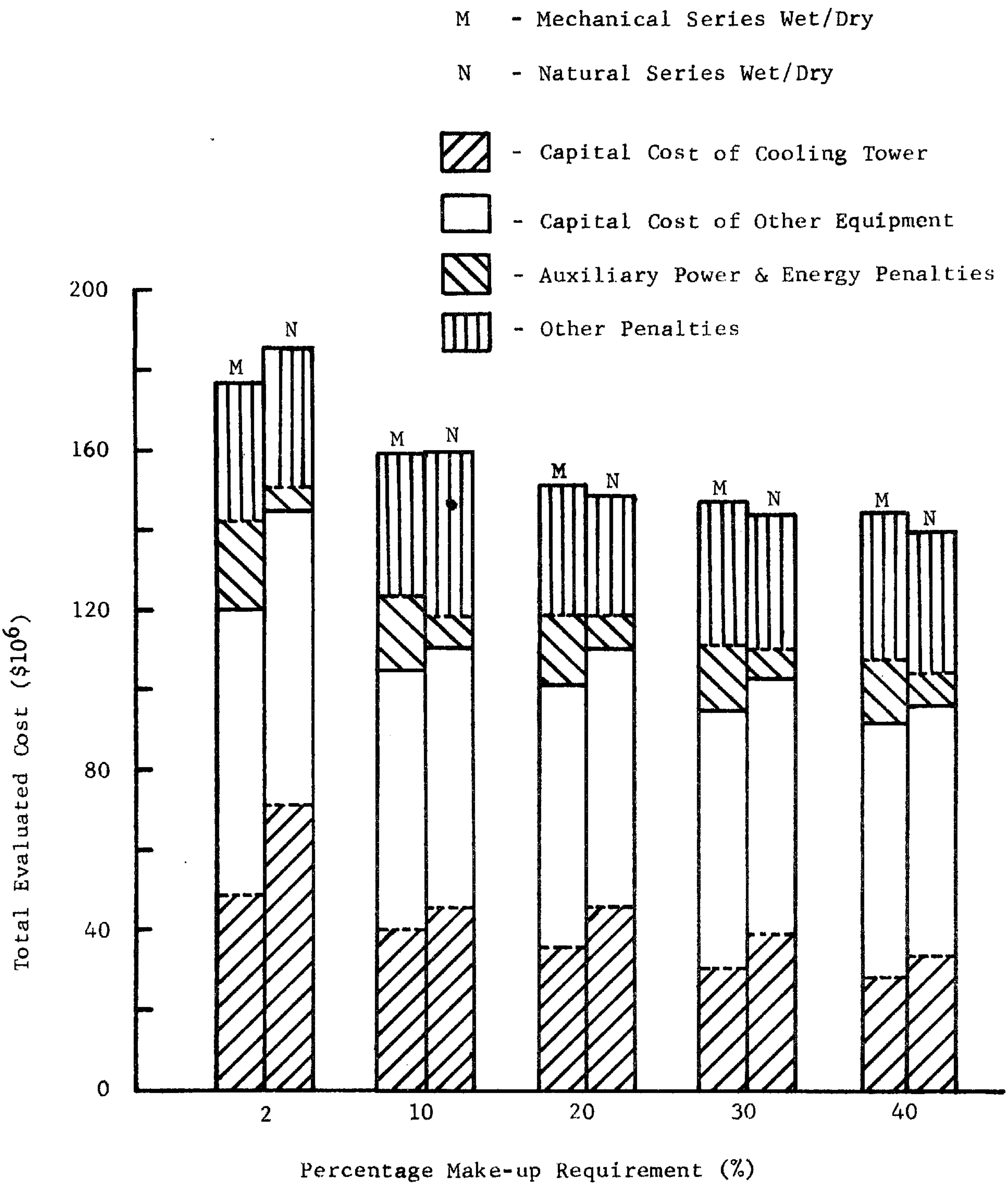


Figure 5.5 Comparison of Natural Series and Mechanical Series Wet/Dry Cooling Tower Systems (Kaiparowits, S1 Mode)

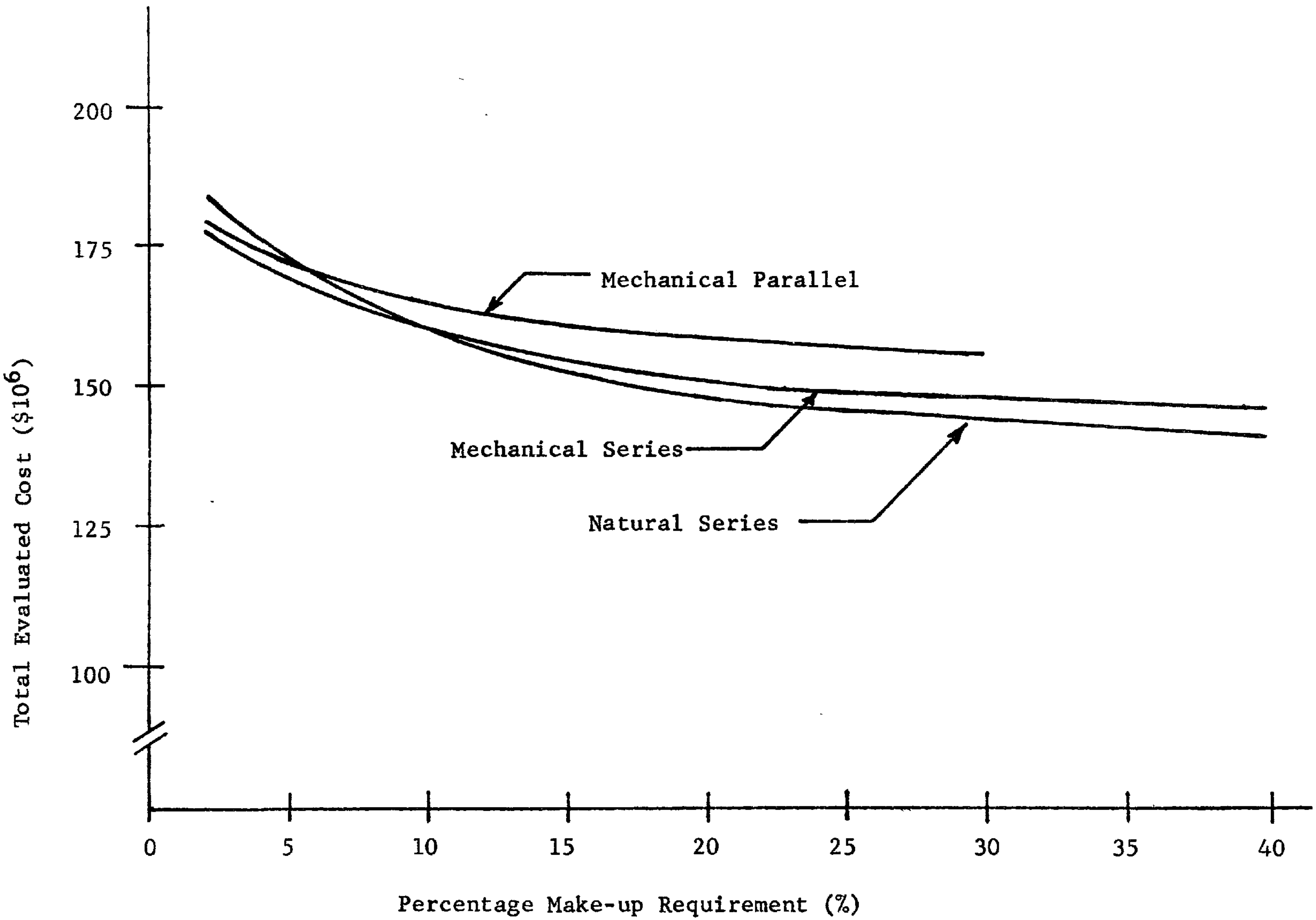


Figure 5.6 Comparison of Three Types of Wet/Dry Systems (Kaiparowits, 1985)

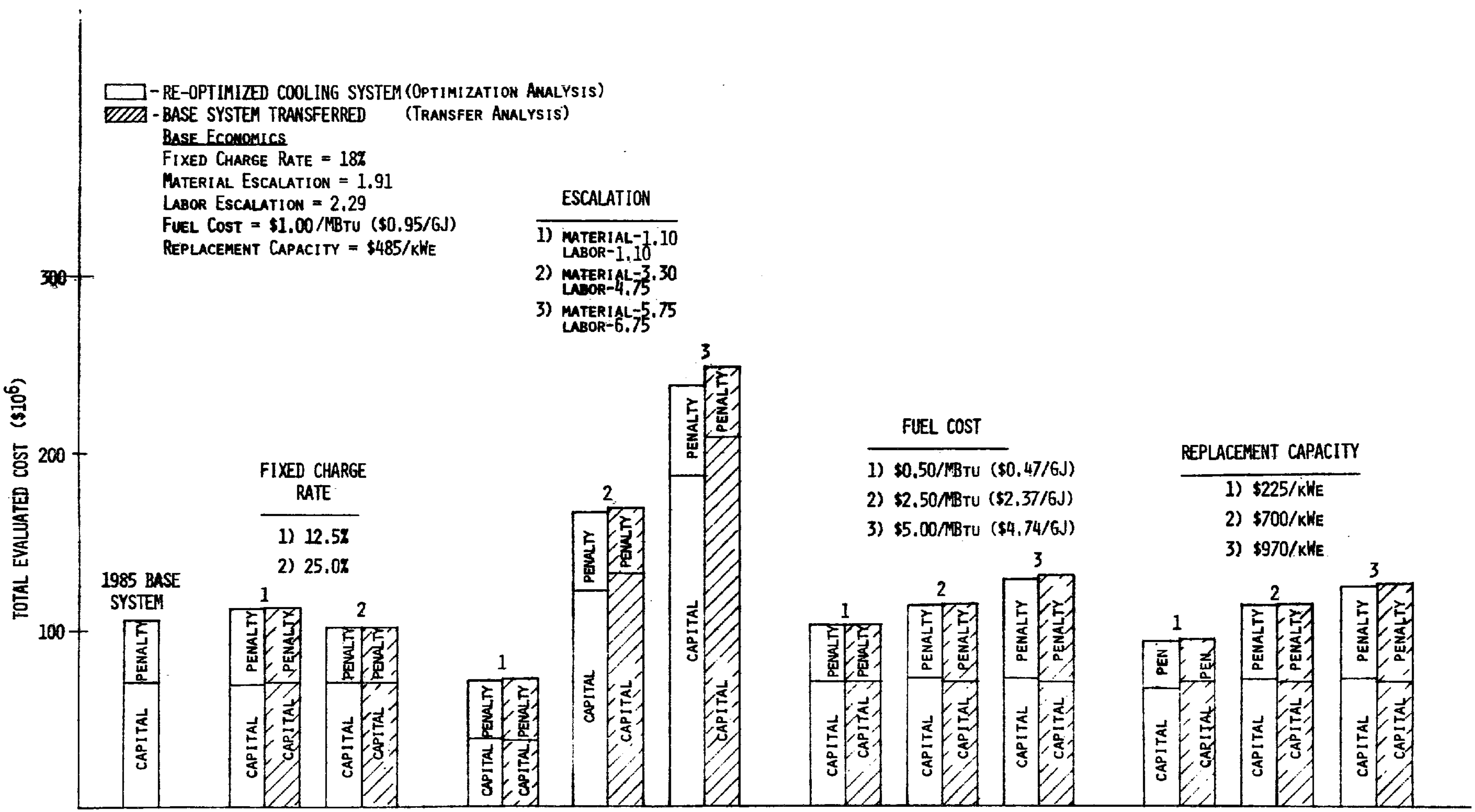


Figure 5.7 Effect of Economic Factors on Costs Obtained by Optimization and Transfer Analyses (Kaiparowits, Mechanical Wet)

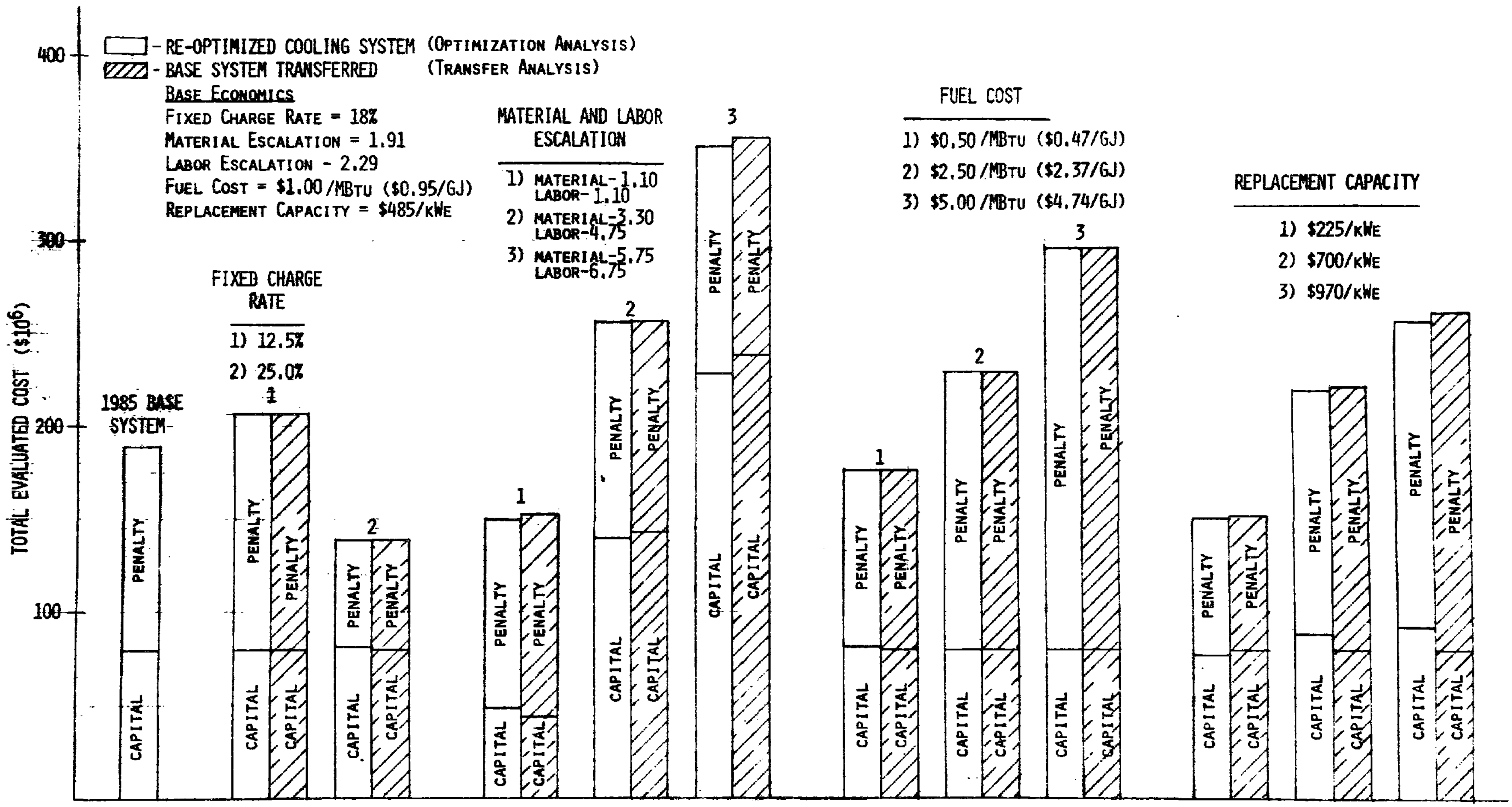


Figure 5.8 Effect of Economic Factors on Costs Obtained by Optimization and Transfer Analyses (Kaiparowits, Mechanical Dry)

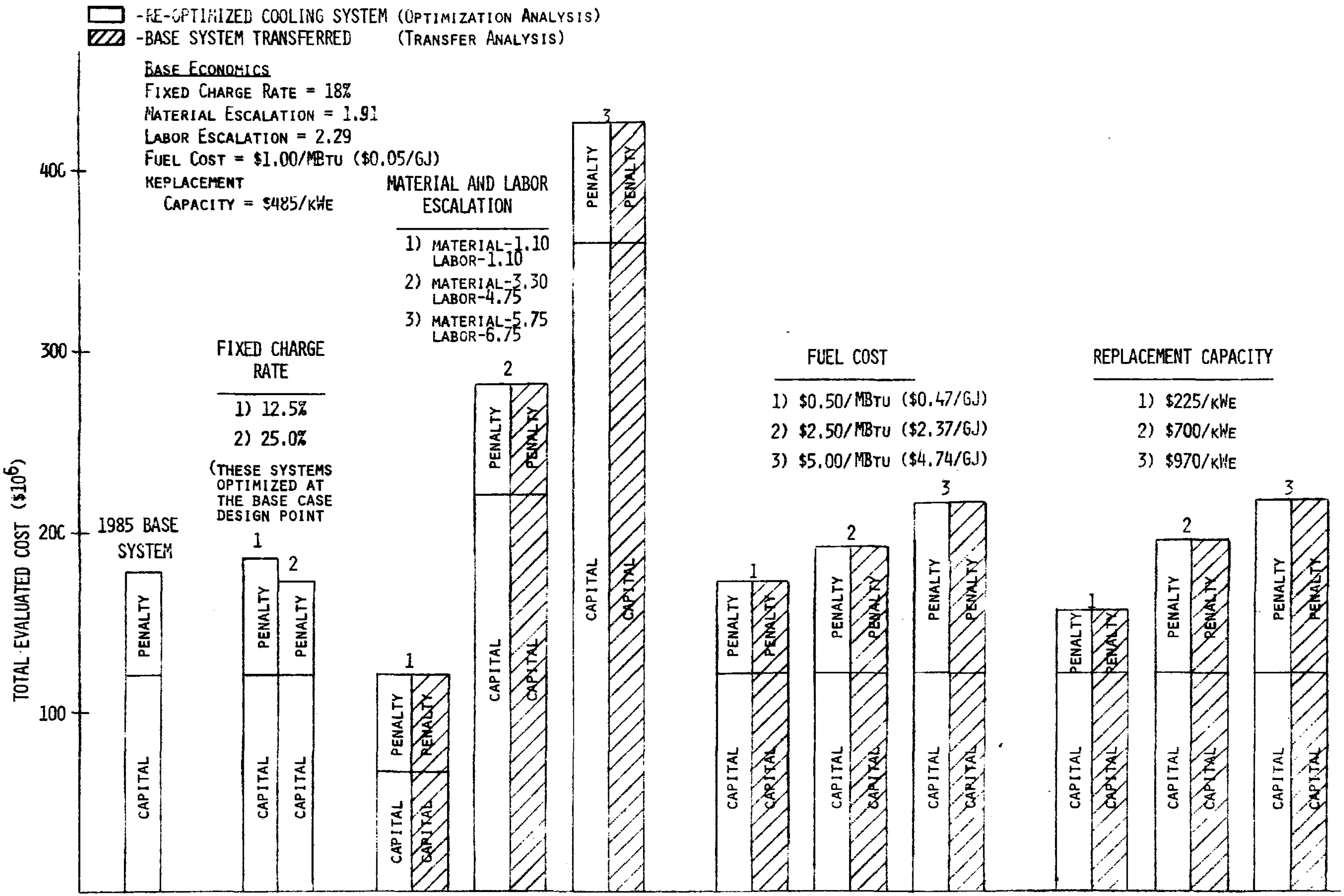


Figure 5.9 Effect of Economic Factors on Costs Obtained by Optimization and Transfer Analyses (Kaiparowits, 2% Wet/Dry)

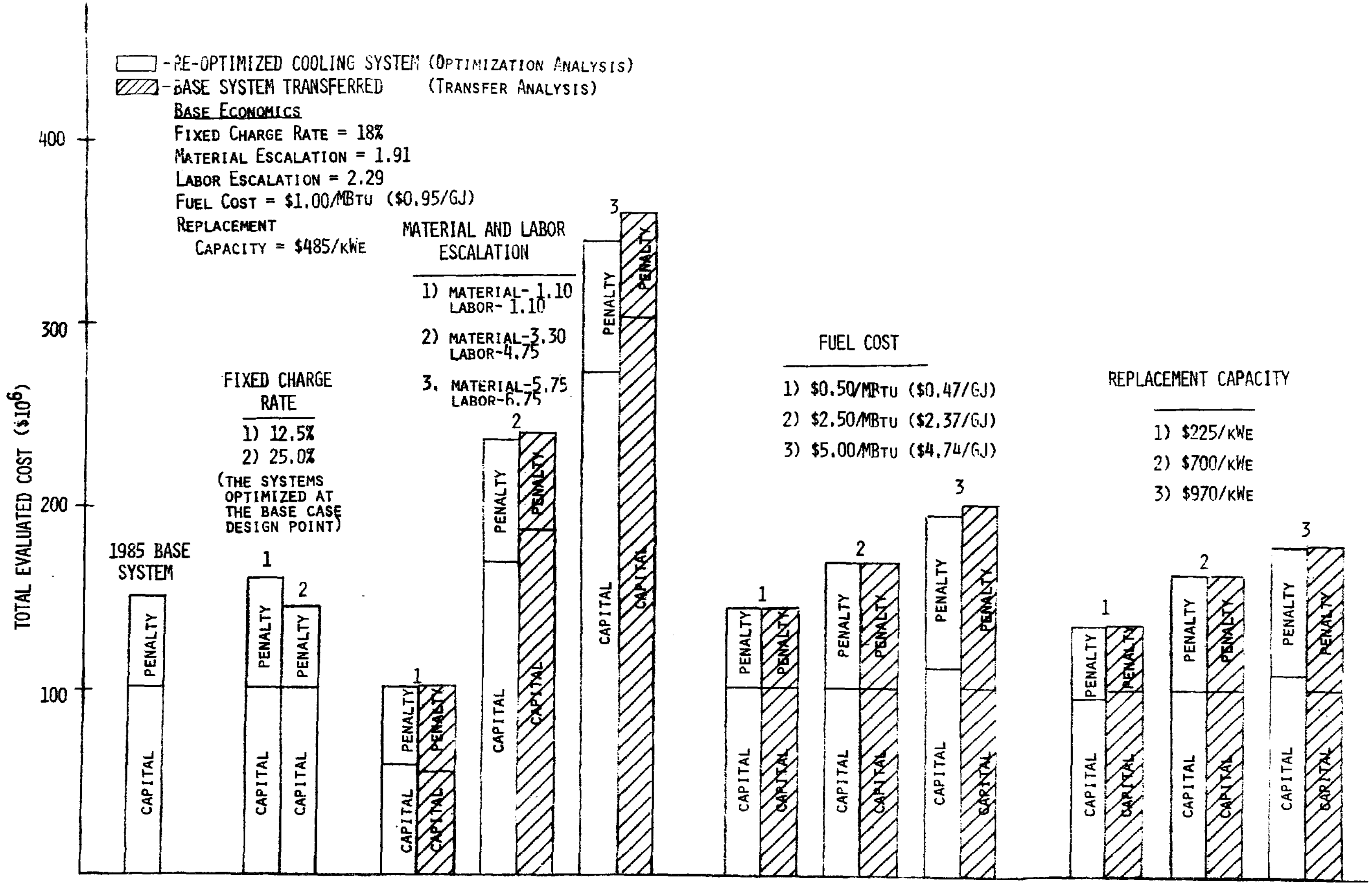


Figure 5.10 Effect of Economic Factors on Costs Obtained by Optimization and Transfer Analyses (Kaiparowits, 20% Wet/Dry)

SECTION 6

MATHEMATICAL MODEL FOR PLUME ABATEMENT ANALYSIS

6.1 INTRODUCTION

Fog from cooling towers occurs when a visible vapor plume containing liquid water vapor droplets impacts the ground and reduces ambient visibility. Two methods can be used to minimize this occurrence: (1) raise the height of the visible plume centerline, or (2) reduce the moisture content of the plume.

The purpose of the plume abatement study was to assess the economic impact of adding dry cooling sections on top of low profile mechanical draft cooling towers to reduce the frequency of ground fogging. A tower designed with both dry and wet sections contained in one structure and functioning as a single unit is termed a hybrid wet/dry cooling tower and is shown in Figure 3.7.

In this section, the mathematical model for evaluating the plume impact of cooling towers is presented. The optimization analysis which combines the fogging evaluation and economic evaluation of the hybrid wet/dry tower is presented in Section 7.

6.2 PLUME RISE AND DISPERSION

In order to determine whether the plume from an evaporative cooling tower will touch the ground and cause surface fogging, the final height of the plume, and the length, spread and density of the visible plume must be evaluated.

6.2.1 Plume Rise

Cooling tower plumes have been observed to be highly turbulent (8). One explanation for this highly turbulent nature is that the energy released in the form of latent heat enhances convective mixing within the plume and does not significantly contribute to the overall rise of the plume. Following this line of reasoning, only the sensible heat portion of the total heat in the plume was used in the plume rise calculation. This same assumption has been used by several investigators of plume rise from cooling towers (9, 10). The calculated plume rises which result from the use of sensible heat alone represent conservative values because the predicted final rise of the plume is lower than would be predicted by including the latent heat. This lower final plume rise increases the probability that the plume will impact the ground causing fog.

One of the more widely accepted formulae for predicting plume rise has been proposed by Briggs (11) and is stated as follows:

$$\Delta h = 1.6\, F^{1/3}\, X^{2/3}\, U^{-1} \qquad (6\text{-}1)$$

where:

Δh = plume rise above stack, ft (m).

F = buoyancy flux parameter, ft^4/s^3 (m^4/s^3).

= $(1 - \rho_o/\rho)\, g W_o r_o^2$.

ρ_o = density of plume at tower exit, lb/ft^3 (g/m^3).

ρ = density of ambient air, lb/ft^3 (g/m^3).

g = acceleration due to gravity, ft/s^2 (m/s^2).

W_o = plume exit velocity, ft/s (m/s).

r_o = radius of tower at top, ft (m).

U = average wind speed at top of tower, ft/s (m/s).

X = horizontal distance downwind of tower, ft (m).

Equation 6-1 expresses the plume rise as a function of downwind distance in a neutral or unstable atmosphere. The maximum plume rise occurs at a downwind distance X_{max}. Briggs reports this distance to be $119F^{2/5}$ for neutral and unstable conditions.

Under stable conditions, Briggs recommends the following formula for the maximum rise of the plume centerline (11):

$$\Delta h_{max} = 2.9 \left(\frac{F}{US}\right)^{1/3} \qquad (6\text{-}2)$$

where:

S = restoring acceleration per unit vertical displacement for adiabatic motion in the atmosphere (s^{-2}).

$$S = \frac{g}{T}\left(\frac{\partial \theta}{\partial Z}\right)$$

θ = potential temperature of the atmosphere, ^oR (^oK).

T = absolute temperature of the atmosphere, ^oR (^oK).

Z = elevation above ground, ft (m).

The constant 1.6 in Equation 6-1 is associated with an entrainment parameter of $\gamma = 0.6$, which has been postulated for chimney plumes (12) as indicated below:

$$C_1 = \left[\frac{3}{2\gamma^2}\right]^{1/3} \qquad (6\text{-}3)$$

$$C_1 = 1.6 \text{ when } \gamma = 0.6$$

In both plume rise formulae 6-1 and 6-2, the constants are proportional to $\gamma^{-2/3}$.

It has been noted that a cooling tower plume is highly turbulent and it should be expected that this turbulence is accompanied by increased entrainment as compared with a chimney-stack plume. This expectation has been supported by observational evidence of cooling tower plumes presented by Slawson et al. (10). Slawson found best agreement between observed and calculated plume rises by assuming a constant of 1.0 or 1.5 in Equation 6-1. An entrainment parameter of $\gamma = 0.8$ corresponds to a constant of 1.3, and is a reasonable fit to data reported by Slawson.

As a result, an entrainment parameter of $\gamma = 0.8$ has been assumed for the cooling tower plume rise. This results in a reduction of estimated plume rise, and Equations 6-1 and 6-2 now become:

$$\Delta h = 1.3 F^{1/3} X^{2/3} U^{-1} \qquad (6\text{-}4)$$

$$\Delta h_{max} = 2.4 \left(\frac{F}{US}\right)^{1/3} \qquad (6\text{-}5)$$

For natural draft towers, the entire amount of sensible heat in the plume is assumed to contribute to plume rise. For the rectangular (line) induced draft towers, the sensible heat from two cells is used to simulate the rise of the plume from a bank of cells. This assumption is supported by an analysis of a bank of seven mechanical draft towers as reported by the Applied Physics Laboratory of Johns Hopkins University (12).

This study concluded that the seven-port plume trajectory was best predicted by assuming: (1) the exit conditions and buoyancy flux of a single-port plume, and (2) an entrainment constant of $\gamma = 0.55$. This is approximately equivalent to using the buoyancy flux (F) for two cells and an entrainment parameter of 0.8. Hence, the use of the sensible heat emitted from two cells in Equations 6-4 and 6-5 is compatible with the conclusion of the Johns Hopkins Study (12).

At present there have been no studies published which describe the behavior of plumes from very large installations of mechanical draft towers. It is recognized that the cooling towers studied in this report (25 to 40 cells) are significantly larger than the seven-cell tower studied by Meyer (12). However, based upon common design practice, the number of cells per bank has been limited to less than 13 in this study. For the 25-cell cooling tower, one bank of 12 cells and one of 13 cells were assumed. The 40-cell tower is assumed to have four banks of ten cells each. A distance of one-half of the length of a bank is provided between banks. For example, approximately 230 feet separate the two banks of the 25-cell tower. Due to this large initial separation of the plumes, it is reasonable to assume that the plumes grow independently. The extrapolation of the results from a seven-cell cooling tower study to a 10-to 13-cell bank utilizes the best data available for the prediction of cooling tower plume behavior.

6.2.2 Length and Spread of the Visible Plume

The length of the visible plume is a function of tower operating conditions: ambient saturation deficit, wind speed, and the rate of entrainment of ambient air into the cooling tower plume. At the end of the visible plume, a sufficient amount of drier ambient air has been mixed with the moist cooling tower effluent to reduce the water content of the plume to a level below the saturation value.

One method of estimating the spread of the plume is to express the radius of the plume as a function of the initial radius, exit velocity, wind speed, plume centerline heights, and entrainment parameter. This type of relationship has been used by Meyer et al. (12), and Hanna (13):

$$R = R_o \left(\frac{W_o}{U}\right)^{1/2} + \gamma_s (\Delta h) \qquad (6\text{-}6)$$

where:

R = radius of visible plume, ft (m).

R_o = initial radius of plume, ft (m).

W_o = exit velocity of plume, ft/s (m/s).

γ_s = entrainment parameter for plume spread.

Ideally, the value for Δh would be determined by using either Equation 6-4 or 6-5, depending on atmospheric stability. However, Equation 6-5 applies only to the maximum rise in the stable case, and would not describe the radius of the plume at distances other than point of maximum rise. For the stable case, Briggs has noted that the plume follows the "2/3 power law" to the point of maximum rise given by $X_{max} = \pi U S^{-\frac{1}{2}}$ (8). For this reason, the expansion of the plume under all atmospheric conditions is described by using Equation 6-4 to calculate Δh. Substituting this Equation 6-4 into 6-6 yields the following expression for the plume radius as a function of downwind distance X:

$$R_X = R_o \left(\frac{W_o}{U}\right)^{1/2} + \gamma_s \left(1.3\, F^{1/3} X^{2/3} U^{-1}\right) \qquad (6\text{-}7)$$

The maximum height of the centerline of the plume is given by Equation 6-4 with $X_{max} = 119F^{2/5}$ (neutral or unstable cases), or by Equation 6-5 (stable cases).

The visible plume is considered to continue expanding beyond the distance of maximum rise by Equation 6-7 for those situations where the plume is visible beyond X_{max}. It should be noted that for both natural draft and induced draft towers the entire buoyancy flux (F) of the plume was utilized in the analysis of the spread of the plume. This assumption is consistent with the results of the study performed by Meyer et al. (12), which concluded that the visible length was best handled by assuming entrainment into the plume from all seven cells.

Since the plume rise has been estimated from formulae where $\gamma = 0.8$, it might be assumed that $\gamma_s = 0.8$ should be substituted in Equation 6-7. It is noted, however, that Slawson obtained the best agreement with observed visible plumes by using a value of $\gamma_s = 0.3$. Likewise, Meyer et al. found it necessary to "tune" their model for visible plume length by introducing a "peak factor". The apparent inconsistency probably arises, as suggested by Meyer (12), from a model which assumes a uniform water vapor content across the entire visible plume, as opposed to a real condition of a concentration of water vapor toward the center of the plume. It is the edges of the plume which are eroded most by the ambient atmosphere.

The relative shielding of the plume core from the drier environmental air can be accounted for by assuming $\gamma_s = 0.3$ in Equation 6-7. However, possible plume impaction on the ground requires an almost saturated environment. Under such a condition the edge effect may be less predominant, i.e., $\gamma_s > 0.3$, than with lower relative humidities encountered in most field experiments. This consideration of the physical situation, and the observations summarized in References 9 and 10, led to an estimation of plume shapes from Equation 6-7 through the use of both $\gamma_s = 0.3$ and $\gamma_s = 0.6$. Possible ground impaction was calculated for these alternative values of γ_s.

The volumetric flow rate of the plume at distance X is:

$$V_X = \pi U R_X^2 \tag{6-8}$$

A water vapor balance for the plume yields the following expression for the water vapor in the plume at any downwind distance X:

$$d_X = \frac{V_o}{V_X}(d_o - d_e) + d_e \tag{6-9}$$

where:

d_X = water vapor density at distance X, lb/ft^3 (g/m^3).

d_o = water vapor density at tower exit, lb/ft^3 (g/m^3).

d_e = water vapor density of the ambient air, lb/ft^3 (g/m^3).

V_o = volumetric flow rate at tower exit, ft^3/s (m^3/s).

V_X = volumetric flow rate at distance X, ft^3/s (m^3/s).

Similarly the temperature of the plume at distance X is given by:

$$T_X = \frac{V_o}{V_X}(T_o - T_e) + T_e \qquad (6\text{-}10)$$

where:

T_X = temperature of plume at distance X, ^oR (^oK).

T_o = plume exit temperature, ^oR (^oK).

T_e = temperature of ambient air, ^oR (^oK).

In order for the plume to be visible at a given downwind distance X, the plume must be supersaturated, i.e., the water vapor content of the plume, d_X, must be greater than the saturation value at the plume temperature, d_s (T_X).

The difference between d_X and d_s in an estimate of the liquid water content of the plume. At the end of the visible plume, the liquid water content is assumed to be zero.

6.2.3 Criteria for Ground Level Fogging

In order for the tower plume to cause ground level fogging at a certain distance from the tower, it is assumed that two conditions must be met simultaneously:

1. The plume must be visible (contain liquid water droplets).
2. The radius of the plume must exceed the sum of the plume rise and tower height.

If the plume has been determined to impact the ground for a particular weather observation, the liquid water content of the plume and corresponding visibility reductions are calculated. An experimentally determined relationship developed by Radford and reported by George (14), is used to estimate the visibility in the plume from the liquid water content. Figure 6-1 gives the relationship in graphical form. The calculated visibility within the plume is then compared to the natural visibility to determine if (1) the plume has enhanced (thickened) any existing natural fog, or (2) if it has caused the occurrence of ground level fog.

The total number of occurrences or hours of fog caused or enhanced by the cooling tower within a radius of five kilometers of the tower under construction is used as a measure of the tower's "fogging potential". Each occurrence of fog is counted as three hours in the results presented in the next section because the meteorological data used in the fogging analysis were recorded at three-hour intervals.

6.3 METEOROLOGICAL DATA BASE FOR PLUME ABATEMENT ANALYSIS

In performing the plume abatement analysis, the following ambient meteorological information is needed:

1. Ambient dry bulb temperature
2. Relative humidity
3. Wind speed and direction
4. Visibility
5. Cloud cover
6. Ceiling height

This information is available from surface weather observations. Ten recent years of surface weather observations for each of the four geographical locations studied in this section were obtained on TD 1440 format tapes from the National Climatic Center, Asheville, North Carolina. Each ten-year record contains data for eight observations per day taken at three-hour intervals.

The number of ambient data points for ten years is too numerous to be considered in the calculations. Therefore, a two-step selection process is performed for each site to reduce the number of ambient data points for plume abatement analysis.

First, all weather observations with relative humidity less than 92 percent are eliminated. It has been often observed, with the use of the UE&C cooling tower fogging model, that cases of fogging seldom occur when the ambient relative humidity is less than about 92 percent.

Second, three years of ambient data with maximum fogging potential are selected from the ten-year data. This is done by performing the plume analysis for the optimized wet tower system with the data obtained in Step 1 and then selecting the three years which have the worst fogging conditions.

This selection process yields a different three year data base for each cooling tower location studied. The data bases are presented in Section 7.

In addition to the data selection process described above, the Pasquill Stability Class is estimated from the surface data and used in the plume rise portion of the model.

Since the wind speed recorded near the surface is not representative of the wind speed at the top of the cooling tower, the following power law adjustment is made:

$$U = U_o \left(\frac{H}{Z_o}\right)^{0.2}$$

where:

U = wind speed at tower exit height, ft/s (m/s).

U_o = measured wind speed, ft/s (m/s).

H = height of cooling tower, ft (m).

Z_o = height at which wind speed is measured, ft (m).

A minimum wind speed of 2 knots is assigned to those observations recorded as calm.

In order to better represent the ambient air entrained into the cooling tower plume, thre relative humidity is adjusted to account for its vertical gradient. In certain cases, the relative humidity at plume height will be greater than that recorded near the surface; in other cases it will be less.

When low clouds are present, the mean humidity between the surface and plume height is assumed to be the mean value of the surface relative humidity and 100 percent, the value assumed at the cloud base. This adjustment is made whenever the ceiling height is less than 900 feet.

Another special case which required an adjustment is the nighttime surface observation with clear sky or scattered clouds, high ground level relative humidity, and a stable atmosphere (E, F or G Pasquill Stability Category).

This condition usually occurs when the air near the ground is cooled by radiation and brought near the point of saturation. When this occurs, the air a few hundred feet above the ground is generally drier than the near-surface air. To more accurately represent the humidity of the entrained air, the surface relative humidity is reduced by three percent.

A similar adjustment of relative humidity is performed on those observations where the relative humidity is reported to be above 97 percent when the ceiling is greater than 800 feet. For these observations, an average relative humidity of 97 percent is assumed.

6.4 FOGGING DURING AERODYNAMIC DOWNWASH

A cooling tower structure presents an obstacle to the normal flow of the wind. As a result, a high pressure zone is created on the windward side of the tower while a low pressure zone in the form of a wake is present immediately downwind of the tower. When a large turbulent wake is formed, the vapor plume exiting from the top of the tower can be deflected downward and captured by the wake. This phenomenon is known as aerodynamic downwash. In certain cases, enough of the plume is drawn into the wake to cause fogging immediately downwind of the tower.

In general, the turbulent wake extends between 10 and 20 tower heights downwind. As a result, any occurrence of cooling tower fog caused by aerodynamic downwash is expected to be quite localized and limited to the plant site. The hours of fog presented in this report do not include downwash fogging. In order to evaluate the cooling tower impact on the area surrounding the plant site, the far-field model presented in Section 6.2 was utilized. Fogging impact was analyzed at distances ranging from 0.3 to 5 kilometers, and the 16 cardinal directions.

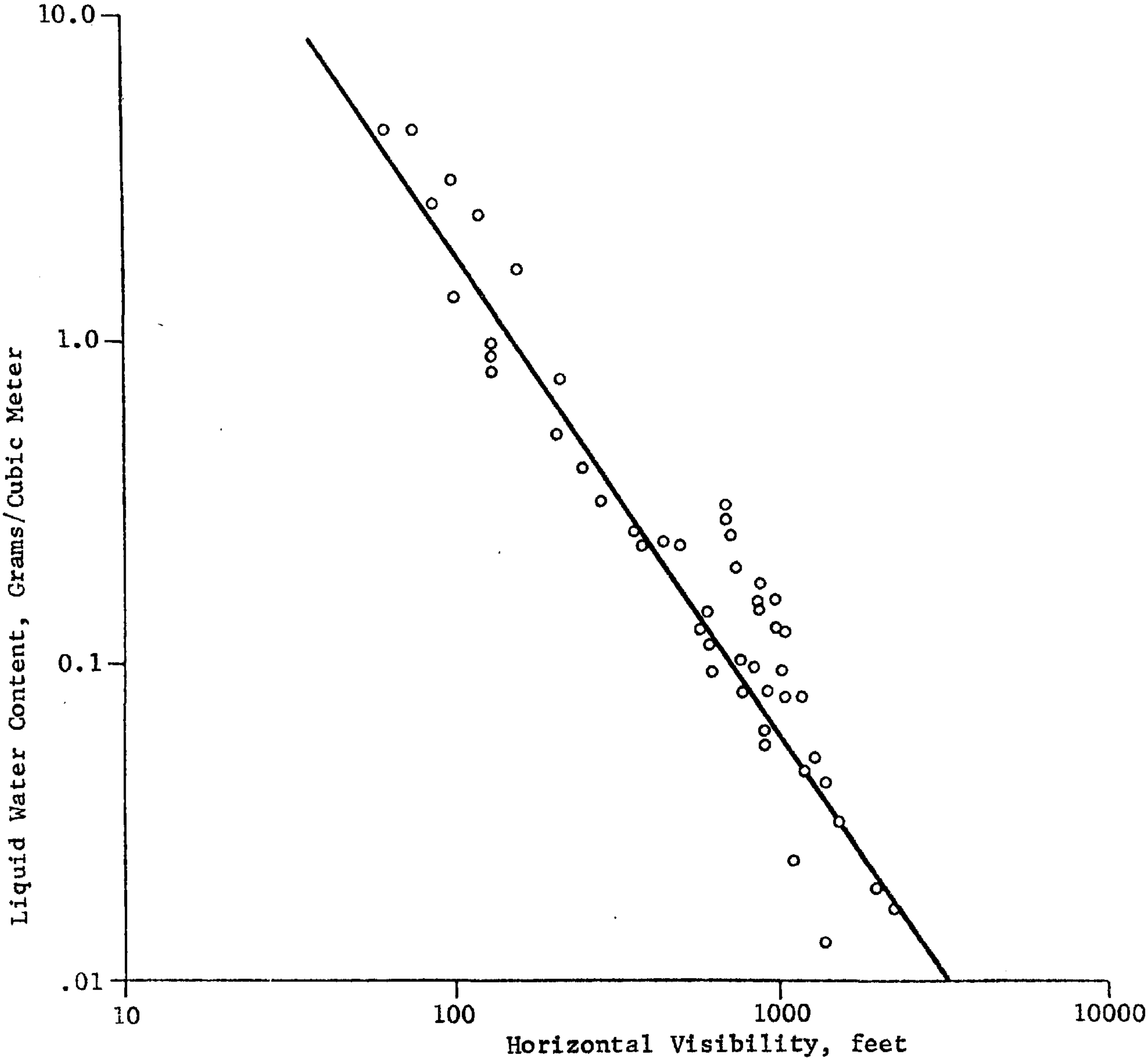


Figure 6.1 Relationship Between Liquid Water Content of Fogs and Visibility (12)

SECTION 7

ECONOMIC OPTIMIZATION OF WET/DRY TOWERS FOR PLUME ABATEMENT

7.1 INTRODUCTION

The optimization of wet/dry tower systems for plume abatement includes the following elements: (1) the determination of sizes and total evaluated costs of various cooling systems, (2) the determination of fogging potentials of these cooling systems during annual operation, and (3) the selection of minimum total evaluated cost systems from the systems with the same fogging potentials.

The scope of the plume abatement study includes the evaluation of both the mechanical draft wet and the mechanical draft hybrid wet/dry tower systems at four urban sites across the conterminous United States. The four sites are: Seattle, Washington; Cleveland, Ohio; Charlotte, North Carolina; and Newark, New Jersey. These sites are selected on the basis of potential fogging problems expected from the tower plume and geographic consideration of sites. A discussion of site selection is given in Appendix C.

Based on the selection process, described in Section 6, to determine the meteorological data base at each site, the following data bases are used in the analysis:

Location	Data Base Period
Seattle, Washington	1964, 1965, 1966
Cleveland, Ohio	1964, 1966, 1973
Charlotte, North Carolina	1968, 1972, 1973
Newark, New Jersey	1971, 1972, 1975

7.2 DESIGN AND OPTIMIZATION OF WET/DRY TOWERS FOR PLUME ABATEMENT

The design and operational characteristics of wet/dry towers for plume abatement are discussed in Section 3.2.3. These wet/dry towers are assumed to operate in the wet/dry mode only when the plume fogging potential is great. This controlled operation is accomplished through the use of meteorological and plume monitoring and control systems which are connected into the plant's computer system.

The wet/dry tower systems for plume abatement are optimized for specified fogging potential. The fogging potential is expressed in terms of the expected number of hours per year during which the visible plume impacts the ground and causes the natural visibility to be reduced to a quarter mile or less. The optimization analysis is performed in the following three steps.

In the first step, different wet tower systems are designed to handle the plant heat load by varying the wet tower approach and the cooling range. The tower systems are then evaluated for thermal performance, capital and penalty costs, and fogging potential. From these wet tower systems, all of the systems with the same fogging potential are identified, and the minimum cost system is selected as the optimized system for each specified fogging potential. An optimized wet tower system, selected solely on the basis of economics (Section 3), is referred to as the reference system.

For the economic penalty evaluation, the cumulative ambient dry bulb and coincident wet bulb temperature data are used to determine the thermal performance of the cooling systems. For the fogging potential, the meteorological data as discussed in Section 6 are used. The method of economic penalty evaluation is described in Section 3. The method of evaluating the fogging potential of a cooling system is described in Section 6.

In the second step, the hybrid wet/dry tower systems are evaluated in a similar manner with the exception that the plume abatement analyses are performed on the basis of wet/dry mode of operation. The analysis is performed for hybrid wet/dry towers with dry sections of 5-foot finned tube length increments, starting with a 5-foot section. The minimum cost hybrid wet/dry system is then identified for each specified fogging potential.

In the third and final step, the minimum cost systems obtained in the above two steps for wet and wet/dry systems for each specified fogging potential are compared, and the minimum cost is identified as the optimized system for the specified fogging potential.

7.3 OPTIMIZATION RESULTS FOR PLUME ABATEMENT TOWER SYSTEMS

7.3.1 Optimization Results for Seattle Site

Seattle has a climate which typically produces much more natural ground fog than the other sites. During these periods of natural fog, cooling tower operation in many instances enhances the natural ground fog, further reducing visibility. Of the total number of hours of cooling tower ground fogging at Seattle, approximately 75% are associated with the occurrence of natural ground fog. Results of this study at Seattle are presented in two sets of tables. One set contains design and cost information pertaining to wet mechanical draft tower systems, and the other set contains information on the wet/dry systems.

7.3.1.1 Mechanical Draft Wet Towers--

The optimized wet tower system selected solely on the basis of economics is referred to as the reference system in Tables 7.1 and 7.2. The cost and fogging potential of this reference system serve as the bases for comparison with respect to both cost and environmental impact. The total evaluated cost of the optimized mechanical draft cooling system is $70.52 million. This system operating at Seattle would produce 60 hours of ground fog per year. About 45 hours of this is enhanced ground fog.

This impact can be significantly mitigated by altering the design temperatures so that a larger cooling tower is required. Operation of this tower results in a lower exit temperature of the saturated plume in comparison to the reference tower. When analyzed for ground fogging, this "larger" tower creates less fog than the reference tower. The larger cooling system has a higher capital cost; however, a reduction in the operating penalties results from more efficient operation so that the total evaluated cost is not significantly affected.

The summary costs for the optimum wet systems that have specific degrees of ground fog are presented in Tables 7.1 and 7.2. Associated design data and detailed cost data for these systems are presented in Appendix P. The optimized reference wet system mentioned above has a cooling tower consisting of 26 cells. The design cold water temperature of this system is 82°F (27.8° C). By decreasing the design cold water temperature to 78°F (25.6°C), the required tower size increases to 33 cells and the ground fogging is reduced to 32 hours per year. The total evaluated cost of this system is $73.10 million.

Further reduction in ground fogging is obtained by decreasing the design cold water temperature and, consequently, increasing the required tower size. The economics of the wet systems, which result in 5, 10, 20 and 30 hours of ground fogging per year, are presented in Tables 7.1 and 7.2, and in Appendix P.

7.3.1.2 Mechanical Draft Wet/Dry Towers--

Three mechanical draft wet/dry towers are designed for plume abatement. As mentioned earlier, the cost associated with any control and/or monitoring systems required for this tower system have not been included in the total evaluated costs in the accompanying tables. The wet/dry tower cell of the three systems differ only in the cross section of the dry heat exchanger installed above the wet tower fill. The width of the heat exchanger is approximately the width of the cell; the variable cross section is obtained by varying the tube length of the exchanger. Tables 7.3 and 7.4 present the cost summaries of three wet/dry systems and a wet system having the same five hours per year of ground fogging. Figure 7.1 is a plot of the total evaluated cost as a function of the heat exchanger tube length for systems that create five hours of ground fog. This plot indicates that there is some savings associated with the wet/dry system if the criterion used is less than 13 hours per year of ground fog. If the ground fogging criterion is relaxed to 13 or more hours per year, the wet tower is preferred. These results are indicated in Figure 7.2 where the wet and wet/dry system costs are plotted as a function of ground fogging impact.

7.3.2 Optimization Results for Cleveland Site

Cleveland typically has much less natural ground fog than Seattle; almost all of the ground fog is produced by cooling tower operation. The reference wet mechanical draft cooling system, optimized solely on economics, has a total evaluated cost of $72.62 million and creates 38 hours per year of ground fog. This system costs more than the wet system at Seattle due to the higher ambient wet bulb temperatures characteristic of the site during the summer months. These higher temperatures result in higher turbine back pressures and, therefore, larger capacity and energy penalties.

Two sets of tables are presented for the systems designed for Cleveland. Tables 7.5 and 7.6 summarize the costs for the optimized wet systems. The costs of wet systems that create 5, 10, 20 and 30 hours of ground fog per year are tabulated. These systems are designed, as in the case at Seattle, by changing the design temperatures to increase the required tower size.

For the five hours per year ground fog criterion, mechanical draft wet/dry towers that are designed for Cleveland have a slight cost advantage over the wet system. Tables 7.7 and 7.8 present the summary of costs for these wet and wet/dry systems.

The total evaluated cost of wet and wet/dry systems as a function of ground fogging is plotted on Figure 7.3. The wet systems are less costly than the wet/dry systems when the ground fogging potential is greater than six hours per year.

7.3.3 Optimization Results for Newark Site

Cooling towers situated at Newark generate very little ground fogging in comparison to the other sites studied. The optimized mechanical draft wet cooling system has a total evaluated cost of $76.85 million and creates 16 hours per year of ground fog. This system and that designed for Charlotte are more expensive than the Seattle or Cleveland designs due to the high peak wet bulb temperature at these sites. Due to the low fogging potential of the optimized wet system, wet/dry towers do not offer any advantage at Newark.

Tables 7.9 and 7.10 present cost summaries for the optimized wet system and two wet systems having 5 and 10 hours of ground fogging. In addition, the wet/dry system having a fogging potential of five hours per year is included for comparison. This wet/dry system incorporates a heat exchanger with five-foot long tubes in the dry section.

Due to the nominal amount of ground fogging created by the optimum wet system, a reduction to five hours per year can easily be obtained by reducing the design cold water temperature to 86°F (30°C) and increasing the tower size from 25 to 31 cells. The cost of all the wet and wet/dry tower systems designed at Newark are graphed as a function of fogging potential in Figure 7.4.

7.3.4 Optimization Results for Charlotte Site

The optimized wet cooling system at Charlotte has a total evaluated cost of $75.32 million and impacts the site with 61 hours of ground fogging. Approximately two thirds of the ground fogging that occurs is enhanced fog. The wet systems at both Charlotte and Newark optimized at a lower condenser range

(22°F (12.2°C)) than the other sites studied and, consequently, have a larger capital cost. This increased capital cost is a result of the requirement for larger pumps, pipelines and condensers to handle the larger circulating water flowrate associated with the lower range. The replacement energy penalty at Charlotte is larger than at the other sites due to the higher wet bulb temperature characteristic of the site. These higher wet bulb temperatures result in higher turbine back pressures which result in less efficient operation of the plant throughout the year.

A summary of cost for four wet systems with varying degrees of ground fogging impact are presented in Tables 7.11 and 7.12. Figure 7.5 shows the costs of all the system designs at Charlotte as a function of ground fogging potential. As shown in Figures 7.2 to 7.4, there is little additional expense associated with reducing the potential from 61 to 20 or to 10 hours of ground fog.

7.4 PSYCHOMETRIC DISCUSSION

The wet systems can be designed at a number of different approach temperatures which result in different tower sizes, performance and fogging impact. The effect which a reduction in plume temperature has on visibility is illustrated by Figure 7.6. The amount of water present in the plume at various stages of dilution is given by a line which connects the tower exit condition with the ambient condition. The plume mixing line of the optimized mechanical draft system can be represented by Line A presented in Figure 7.6. The maximum excess water contained in this plume is given as distance 1 between this plume mixing line and the saturation line.

If another wet system is designed based on a lower approach temperature and/or range, a plume at a lower exit temperature will result. The plume mixing line for this tower is represented by Line B. There is a reduction of the maximum excess water (distance 2) contained in this tower plume when compared with the economically optimized system.

Figure 7.6 does not show the effects on fogging potential of the increased volumetric flowrate and the decreased plume height associated with the lower temperature system. However, it does indicate that there is some degree of control of the maximum excess water content in the plume through the variation of the design tower approach and range. The reduction of this excess water is one of the contributing factors which reduces the ground fog of the wet mechanical draft tower.

7.5 PLUME ABATEMENT CONCLUSIONS

Two major conclusions have been developed in this study.

1. Ground fogging from low profile wet mechanical draft towers can be significantly reduced by changing the design temperatures so that the required tower size increases.

   The intermediate results of the wet cooling tower optimization discussed in Section 4 are presented in Figure 4.3.

This figure shows that there are many wet cooling systems with different design conditions but with costs within one to two percent of the minimum. These systems all have different fogging potential. Systems with lower approach temperatures are larger and have higher capital cost but lower operating penalties. The resulting total evaluated cost can be slightly higher, but these systems would have much less fogging potential.

2. In most of the situations analyzed, the hybrid wet/dry cooling system is more expensive than a comparable wet tower and would not be recommended.

   Special site conditions, i.e., existing sites which must be backfitted to closed cycle cooling, may require some special treatment. For new sites, the development of the hybrid wet/dry cooling tower will, in general, not be necessary for the purpose of minimizing ground fogging from the tower.

TABLE 7.1

MAJOR COST SUMMARY FOR THE OPTIMIZED MECHANICAL WET COOLING SYSTEMS ($$10^6$)*

SITE: SEATTLE, WASHINGTON YEAR: 1985

Item	GROUND FOGGING HOURS - MECHANICAL WET TOWERS				
	5	10	20	30	Reference 60
Total Capital Cost (Direct & Indirect Capital Costs)	56.41	55.59	51.84	50.25	44.82
Total Capacity Penalty (Capacity & Auxiliary Power)	9.85	9.34	10.39	9.37	10.96
Total Operating Penalty (Replacement & Auxiliary Energies, Make-up Water & Maintenance)	13.92	13.72	14.01	13.48	14.74
Total Evaluated Cost (Sum of Capital & Penalty Costs)	80.18	78.65	76.24	73.10	70.52

* Design data for these systems are in Table P-1, p. 242.

TABLE 7.2

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

SITE: SEATTLE, WASHINGTON

YEAR: 1985

	GROUND FOGGING HOURS - MECHANICAL WET TOWERS				
	5	10	20	30	Reference 60
Cost Breakdown:					
Cooling Tower	24.05	22.93	20.70	18.46	14.54
Condenser	10.29	10.69	10.30	10.95	10.87
Circulating Water System	6.16	6.27	6.16	6.63	6.63
Make-up Facility	2.32	2.30	2.26	2.22	2.15
Electrical Equipment	2.30	2.27	2.05	1.95	1.67
Indirect Cost	11.28	11.12	10.37	10.05	8.96
Total Capital Cost	56.41	55.59	51.84	50.25	44.82
Penalty Cost Breakdown:					
Capacity	4.00	3.40	4.95	3.82	5.89
Auxiliary Power	5.85	5.95	5.44	5.55	5.07
Replacement Energy	-0.22	-0.66	0.76	0.01	2.36
Auxiliary Energy	11.48	11.71	10.74	11.00	10.09
Make-up Water	0.39	0.39	0.39	0.39	0.40
Cooling System Maintenance	2.27	2.27	2.12	2.08	1.89
Total Penalty	23.77	23.06	24.40	22.85	25.70

TABLE 7.3

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

5 HOURS PER YEAR GROUND FOG

SITE: SEATTLE, WASHINGTON YEAR: 1985

Item	DRY HEAT EXCHANGER TUBE LENGTH			Mechanical Wet System
	15 ft	10 ft	5 ft	
Total Capital Cost (Direct & Indirect Capital Costs)	53.92	54.08	54.74	56.41
Total Capacity Penalty (Capacity & Auxiliary Power)	10.40	9.91	9.98	9.85
Total Operating Penalty (Replacement & Auxiliary Energies, Make-up Water & Maintenance)	14.95	14.39	14.17	13.92
Total Evaluated Cost (Sum of Capital & Penalty Costs)	79.27	78.38	78.89	80.18

TABLE 7.4

MAJOR CAPITAL AND PENALTY COST COMPONENTS FOR THE OPTIMIZED WET/DRY AND REFERENCE COOLING SYSTEMS ($\$10^6$)

5 HOURS PER YEAR GROUND FOG

SITE: SEATTLE, WASHINGTON

YEAR: 1985

	DRY HEAT EXCHANGER TUBE LENGTH			Mechanical Wet System
	15 ft	10 ft	5 ft	
Cost Breakdown:				
Cooling Tower	21.50	21.51	22.61	24.05
Condenser	10.90	10.93	10.64	10.29
Circulating Water System	6.71	6.71	6.27	6.16
Make-up Facility	2.18	2.20	2.24	2.32
Electrical Equipment	1.84	1.92	2.03	2.30
Indirect Cost	10.79	10.81	10.95	11.28
Total Capital Cost	53.92	54.08	54.74	56.41
Penalty Cost Breakdown:				
Capacity	4.82	4.29	4.35	4.00
Auxiliary Power	5.58	5.62	5.63	5.85
Replacement Energy	1.09	0.51	0.33	−0.22
Auxiliary Energy	11.10	11.15	11.13	11.48
Make-up Water	0.40	0.39	0.39	0.39
Cooling System Maintenance	2.36	2.34	2.32	2.27
Total Penalty	25.35	24.30	24.15	23.77

TABLE 7.5

MAJOR COST SUMMARY FOR THE OPTIMIZED MECHANICAL WET COOLING SYSTEMS ($$10^6$)*

SITE: CLEVELAND, OHIO YEAR: 1985

Item	GROUND FOGGING HOURS - MECHANICAL WET TOWERS				
	5	10	20	30	Reference 38
Total Capital Cost (Direct & Indirect Capital Costs)	54.75	51.73	47.88	47.02	44.80
Total Capacity Penalty (Capacity & Auxiliary Power)	10.51	10.25	11.07	11.02	12.10
Total Operating Penalty (Replacement & Auxiliary Energies, Make-up Water & Maintenance)	14.52	14.25	14.76	15.13	15.72
Total Evaluated Cost (Sum of Capital & Penalty Costs)	79.78	76.23	73.71	73.17	72.62

* Design data for these systems are in Table P-7, p. 252.

102

TABLE 7.6

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

SITE: CLEVELAND, OHIO YEAR: 1985

	GROUND FOGGING HOURS - MECHANICAL WET TOWERS				
	5	10	20	30	Reference 38
Cost Breakdown:					
Cooling Tower	22.38	19.57	16.78	15.10	14.54
Condenser	10.57	10.87	10.83	11.19	10.81
Circulating Water System	6.28	6.63	6.63	7.29	6.63
Make-up Facility	2.34	2.28	2.23	2.20	2.19
Electrical Equipment	2.23	2.03	1.83	1.84	1.67
Indirect Cost	10.95	10.35	9.58	9.40	8.96
Total Capital Cost	54.75	51.73	47.88	47.02	44.80
Penalty Cost Breakdown:					
Capacity	4.64	4.56	5.73	5.66	7.04
Auxiliary Power	5.87	5.69	5.34	5.36	5.06
Replacement Energy	0.39	0.55	1.82	1.99	3.38
Auxiliary Energy	11.50	11.18	10.55	10.63	10.05
Make-up Water	0.40	0.40	0.40	0.40	0.40
Cooling System Maintenance	2.24	2.12	1.99	2.11	1.89
Total Penalty	25.04	24.50	25.83	26.15	27.82

TABLE 7.7

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

5 HOURS PER YEAR GROUND FOG

SITE: CLEVELAND, OHIO YEAR: 1985

Item	DRY HEAT EXCHANGER TUBE LENGTH			Mechanical Wet System
	15 ft	10 ft	5 ft	
Total Capital Cost (Direct & Indirect Capital Costs)	52.14	53.36	53.06	54.75
Total Capacity Penalty (Capacity & Auxiliary Power)	11.78	10.85	10.74	10.51
Total Operating Penalty (Replacement & Auxiliary Energies, Make-up Water & Maintenance)	16.26	14.28	14.87	14.52
Total Evaluated Cost (Sum of Capital & Penalty Costs)	80.18	78.49	78.67	79.78

TABLE 7.8

MAJOR CAPITAL AND PENALTY COST COMPONENTS FOR THE OPTIMIZED WET/DRY AND REFERENCE COOLING SYSTEMS ($$10^6$)

5 HOURS PER YEAR GROUND FOG

SITE: CLEVELAND, OHIO YEAR: 1985

	DRY HEAT EXCHANGER LENGTH			Mechanical Wet System
	15 ft	10 ft	5 ft	
Cost Breakdown:				
Cooling Tower	20.02	20.82	20.67	22.38
Condenser	10.99	11.02	10.85	10.57
Circulating Water System	6.73	6.73	6.71	6.28
Make-up Facility	2.20	2.23	2.25	2.34
Electrical Equipment	1.77	1.89	1.97	2.23
Indirect Cost	10.43	10.67	10.61	10.95
Total Capital Cost	52.14	53.36	53.06	54.75
Penalty Cost Breakdown:				
Capacity	6.20	5.17	5.17	4.64
Auxiliary Power	5.58	5.68	5.58	5.87
Replacement Energy	2.54	1.32	1.20	0.39
Auxiliary Energy	11.09	10.25	11.00	11.49
Make-up Water	0.40	0.40	0.40	0.40
Cooling System Maintenance	2.23	2.31	2.26	2.24
Total Penalty	28.04	25.13	25.61	25.03

TABLE 7.9

MAJOR COST SUMMARY FOR THE OPTIMIZED WET/DRY AND MECHANICAL WET COOLING SYSTEMS ($$10^6$)*

SITE: NEWARK, NEW JERSEY YEAR: 1985

Item	Mechanical Wet/Dry Towers (5' Exchanger)** 5 Hours	MECHANICAL WET TOWER - (GROUND FOGGING)		
		5 Hours	10 Hours	Reference 16 Hours
Total Capital Cost (Direct & Indirect Capital Costs)	52.03	48.62	48.74	46.44
Total Capacity Penalty (Capacity & Auxiliary Power)	13.46	14.72	13.34	14.39
Total Operating Penalty (Replacement & Auxiliary Energies, Make-up Water & Maintenance)	15.64	15.38	15.18	16.02
Total Evaluated Cost (Sum of Capital & Penalty Costs)	81.13	78.72	77.26	76.85

* Design data for these systems are in Table P-13, p. 262.
** Dry heat exchanger tube length is 5-foot.

TABLE 7.10

MAJOR CAPITAL AND PENALTY COST COMPONENTS FOR THE OPTIMIZED WET/DRY AND MECHANICAL WET COOLING SYSTEMS ($$10^6$)

SITE: NEWARK, NEW JERSEY YEAR: 1985

	Mechanical Wet/Dry Towers (5' Exchanger) 5 hours	GROUND FOGGING HOURS-MECHANICAL WET TOWERS		
		5	10	Reference 16
Cost Breakdown:				
Cooling Tower	18.09	17.34	15.66	13.98
Condenser	11.59	10.81	11.59	11.58
Circulating Water System	7.77	6.63	7.65	7.65
Make-up Facility	2.21	2.25	2.21	2.19
Electrical Equipment	1.96	1.87	1.88	1.75
Indirect Cost	10.41	9.72	9.75	9.29
Total Capital Cost	52.03	48.62	48.74	46.44
Penalty Cost Breakdown:				
Capacity	7.63	9.25	7.63	8.89
Auxiliary Power	5.82	5.46	5.71	5.49
Replacement Energy	1.32	2.10	1.32	2.62
Auxiliary Energy	11.55	10.79	11.31	10.93
Make-up Water	0.40	0.40	0.40	0.40
Cooling System Maintenance	2.37	2.02	2.15	2.08
Total Penalty	29.09	30.10	28.52	30.41

TABLE 7.11

MAJOR COST SUMMARY FOR THE OPTIMIZED MECHANICAL WET COOLING SYSTEMS ($\$10^6$)*

SITE: CHARLOTTE, NORTH CAROLINA YEAR: 1985

Item	MECHANICAL WET TOWER - GROUND FOGGING			
	10	20	30	Reference 61
Total Capital Cost (Direct & Indirect Capital Costs)	51.73	50.10	47.88	46.45
Total Capacity Penalty (Capacity & Auxiliary Power)	11.33	11.17	12.24	12.00
Total Operating Penalty (Replacement & Auxiliary Energies, Make-up Water & Maintenance)	15.54	15.78	16.30	16.87
Total Evaluated Cost (Sum of Capital & Penalty Costs)	78.60	77.05	76.42	75.32

* Design data for these systems are in Table P-16, p. 267.

TABLE 7.12

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

SITE: CHARLOTTE, NORTH CAROLINA YEAR: 1985

	GROUND FOGGING HOURS-MECHANICAL WET TOWERS			
	10	20	30	Reference 61
Cost Breakdown:				
Cooling Tower	19.58	17.34	16.78	13.98
Condenser	10.85	11.19	10.82	11.58
Circulating Water System	6.63	7.29	6.63	7.65
Make-up Facility	2.30	2.26	2.25	2.19
Electrical Equipment	2.03	2.00	1.82	1.76
Indirect Cost	10.34	10.02	9.58	9.29
Total Capital Cost	51.73	50.10	47.88	46.45
Penalty Cost Breakdown:				
Capacity	5.67	5.56	6.91	6.56
Auxiliary Power	5.66	5.61	5.32	5.43
Replacement Energy	1.82	2.01	3.34	3.53
Auxiliary Energy	11.17	11.12	10.55	10.84
Make-up Water	0.43	0.43	0.43	0.43
Cooling System Maintenance	2.12	2.22	1.99	2.08
Total Penalty	26.87	26.95	28.54	28.87

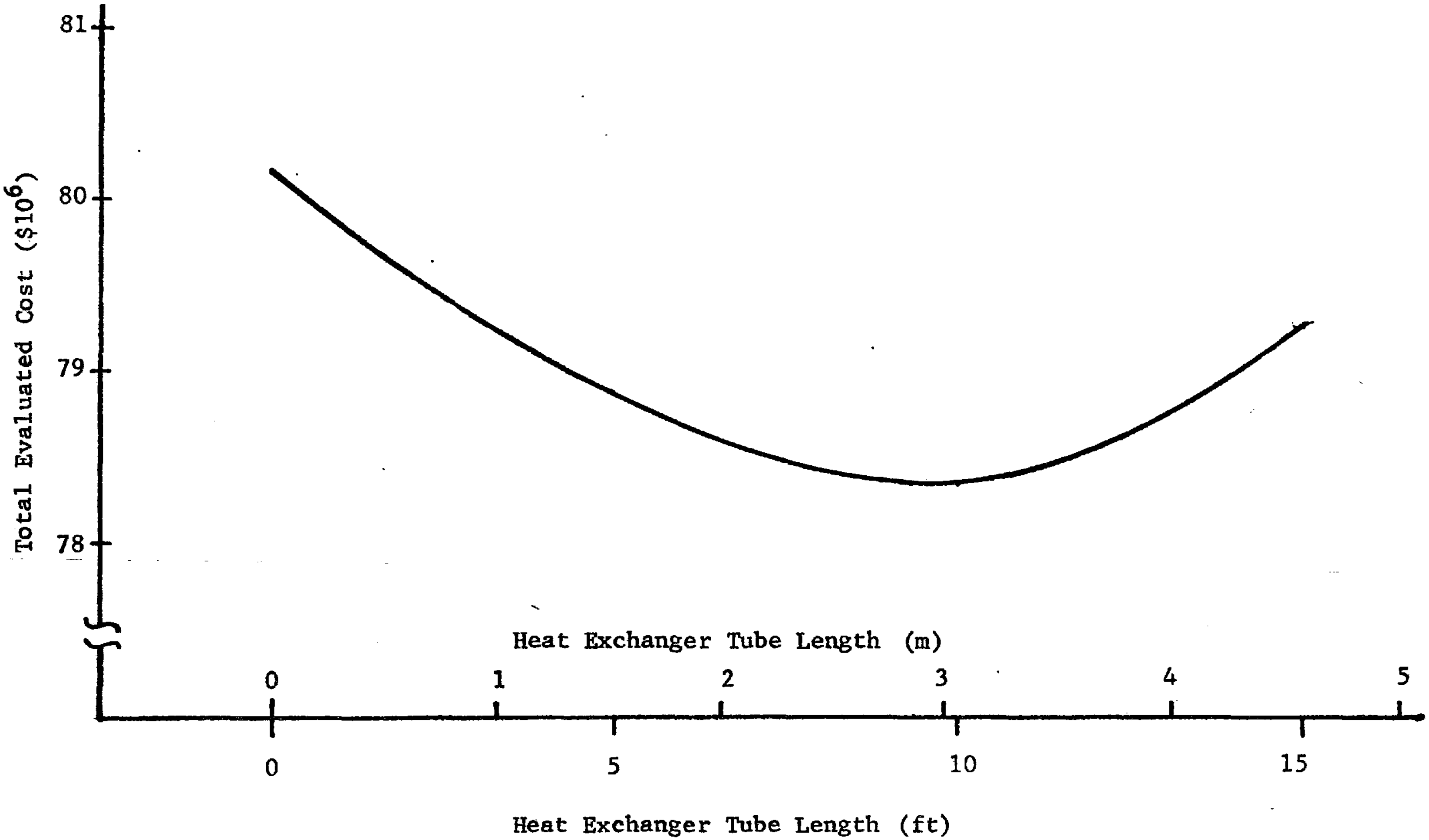


Figure 7.1 Total Evaluated Cost of Wet and Wet/Dry Cooling Systems Which Produce 5 Hours of Ground Fog as a Function of Heat Exchanger Size (Seattle, 1985)

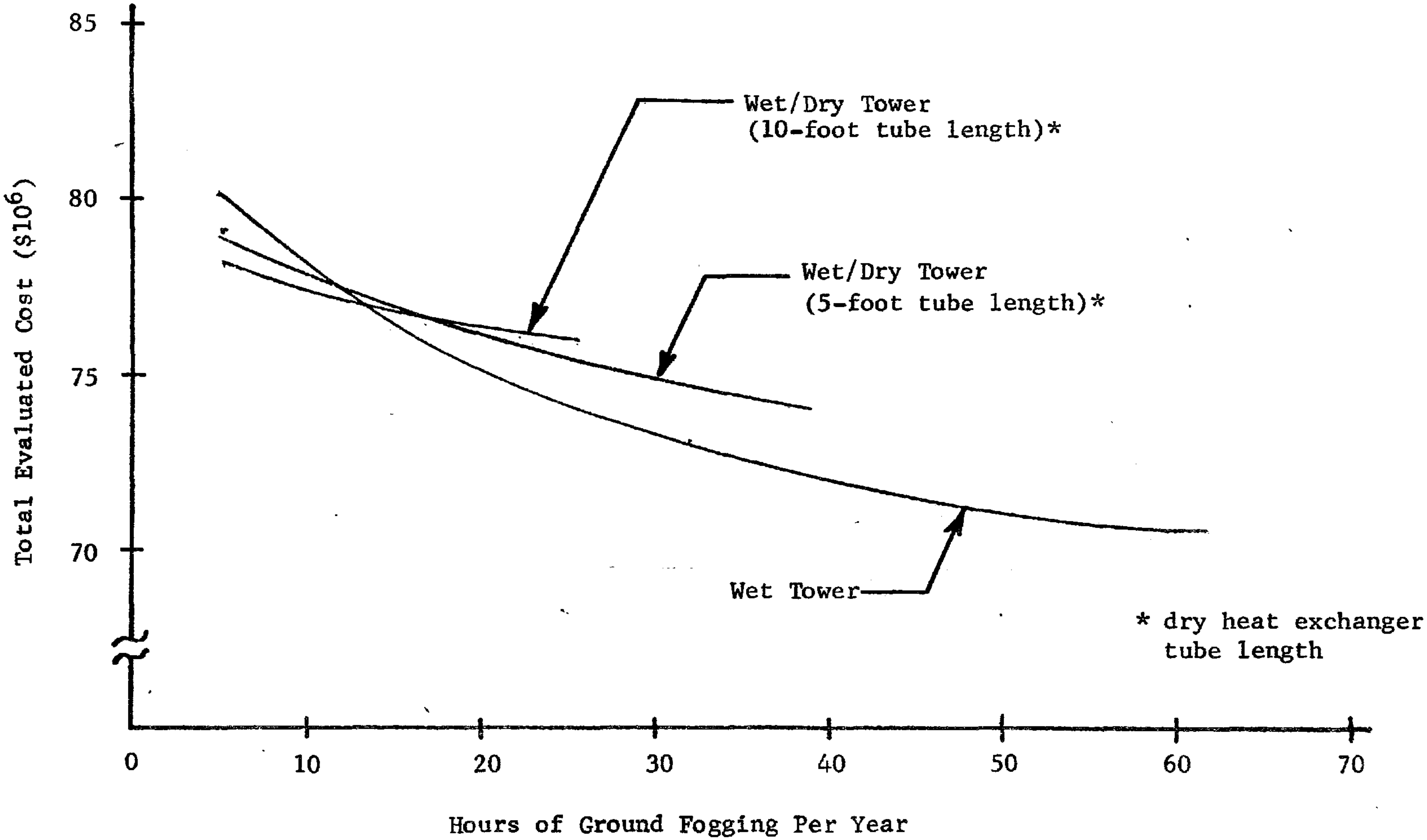


Figure 7.2 Total Evaluated Cost as a Function of Ground Fogging for Various Wet and Wet/Dry Cooling Towers (Seattle, 1985)

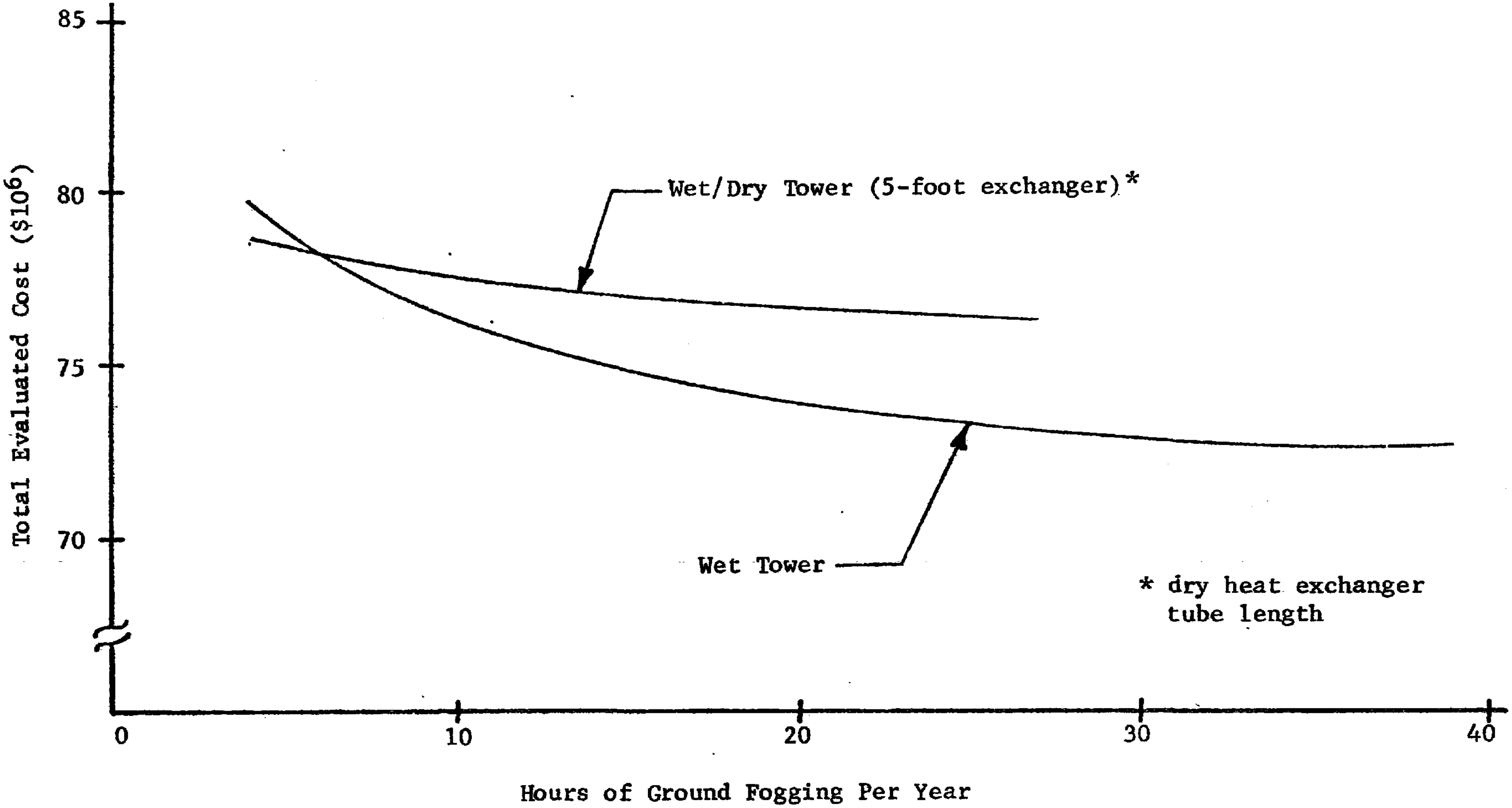


Figure 7.3 Total Evaluated Cost as a Function of Ground Fogging for Various Wet and Wet/Dry Cooling Towers (Cleveland, 1985)

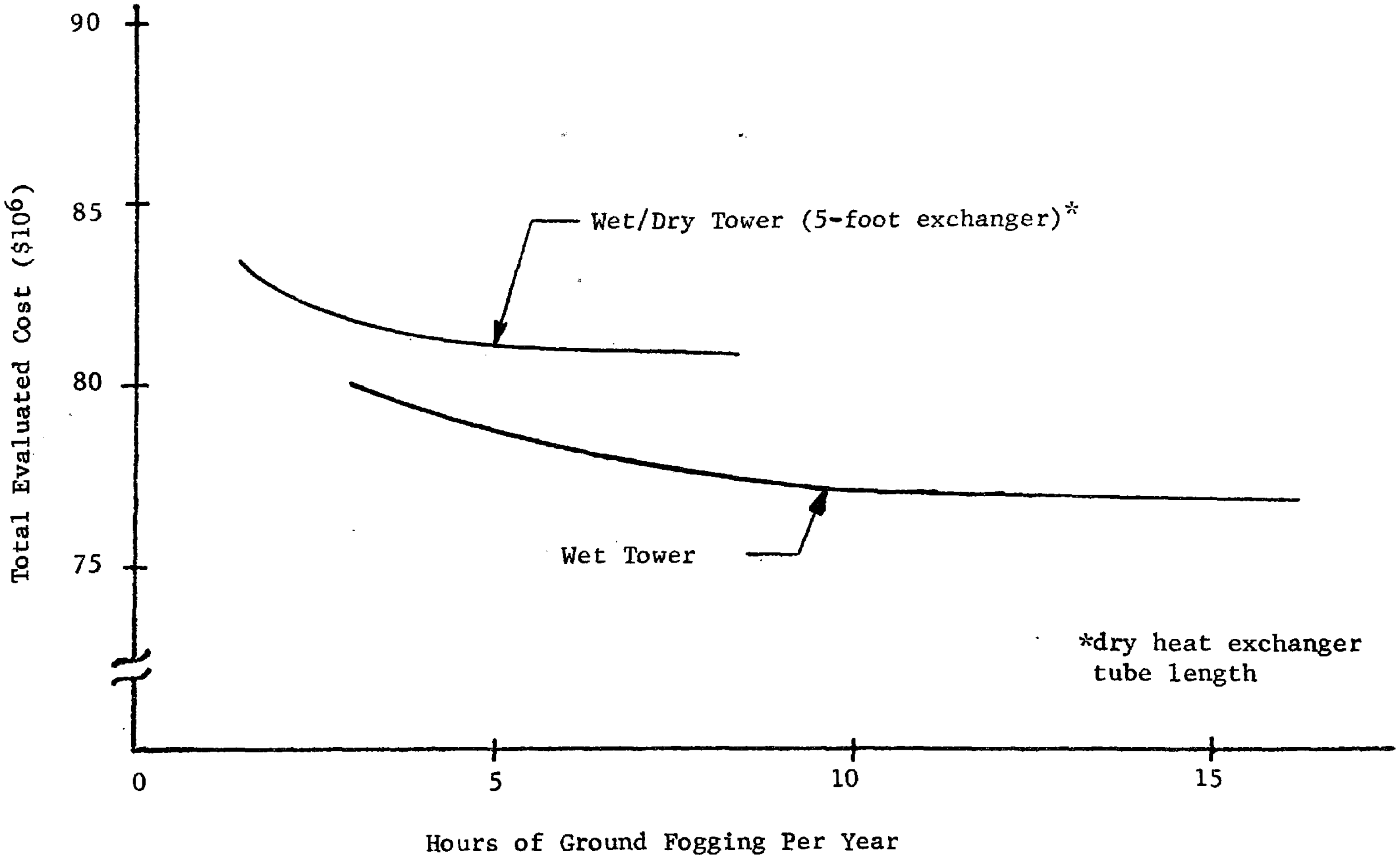


Figure 7.4 Total Evaluated Cost as a Function of Ground Fogging for Various Wet and Wet/Dry Cooling Towers (Newark, 1985)

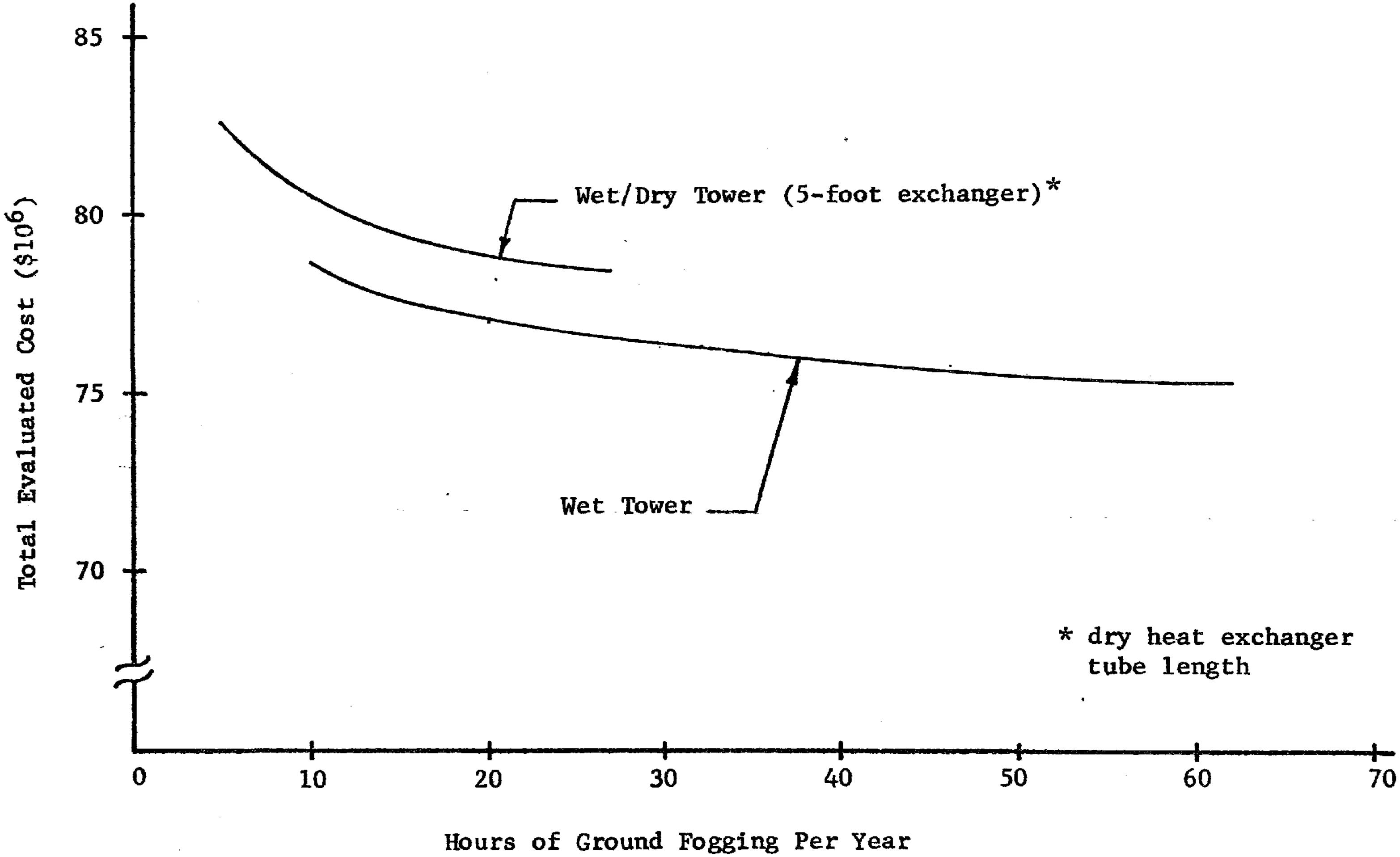


Figure 7.5 Total Evaluated Cost as a Function of Ground Fogging for Various Wet and Wet/Dry Cooling Towers (Charlotte, 1985)

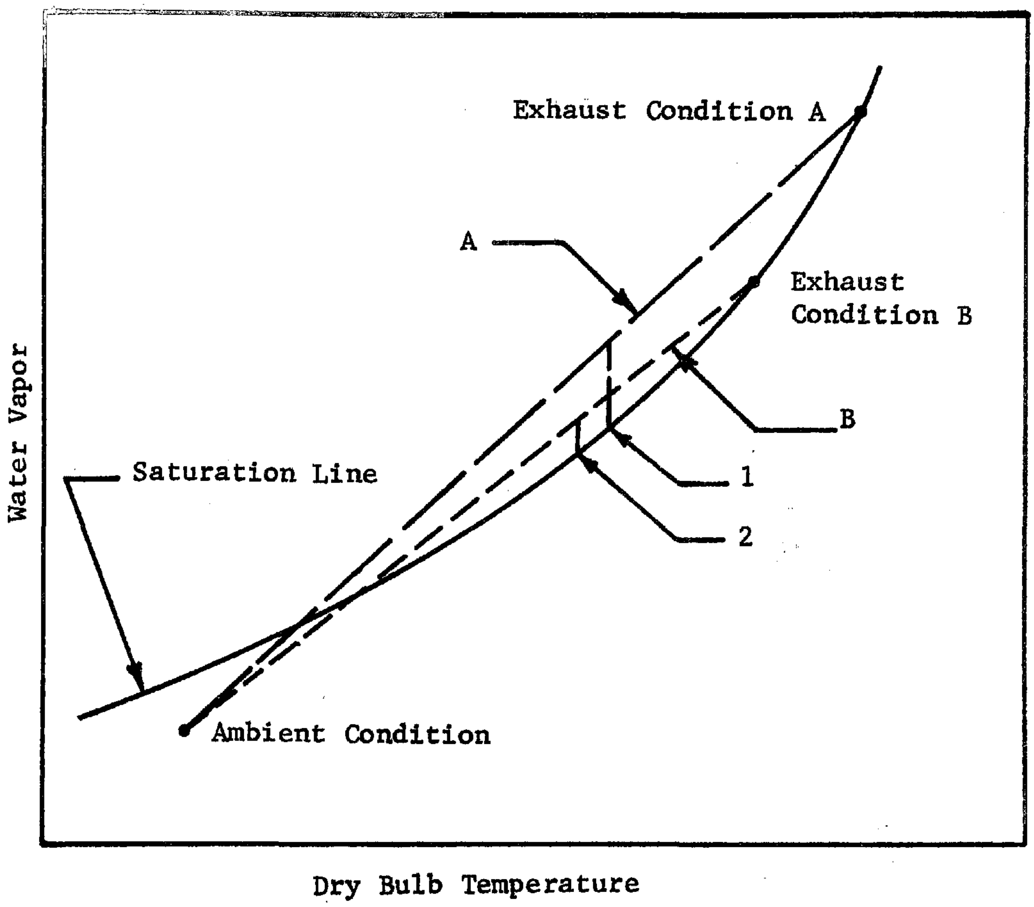


Figure 7.6 Psychrometric Chart for Two Plume Exhaust Conditions

REFERENCES

1. Engineering and Economic Evaluation of Wet/Dry Cooling Towers for Water Conservation, Report Number UE&C-ERDA-761130, United Engineers & Constructors Inc., Philadelphia, Pa., November 1976. (National Technical Information Service, Springfield, Virginia, COO-2442-1)

2. Western States Water Requirements for Energy Development to 1990, Western States Water Council, Salt Lake City, Utah, November 1974.

3. 1000 MWe Central Station Power Plants - Investment Cost Study, Volume III, WASH-1230, United Engineers & Constructors Inc., Philadelphia, Pa., 1972.

4. M. W. Larinoff, and L. L. Forster, "Dry and Wet-Peaking Tower Cooling Systems for Power Plant Application", Journal of Engineering for Power, Trans. ASME, Volume 98, Series A, pp. 335-348, 1976.

5. H. H. von Cleve, Comparison of Different Combinations of Wet and Dry Cooling Towers, ASME, 75-WA/Pwr-10.

6. Heat Sink Design and Cost Study for Fossil and Nuclear-Power Plants, WASH-1360, United Engineers & Constructors Inc., Philadelphia, Pa., December 1974.

7. Technical and Economic Assessment of the Direct-Cycle Gas-Cooled Reactor Plant, ERDA-109, United Engineers & Constructors Inc., Oak Ridge National Laboratory, and NASA-Lewis Research Center, October 1975.

8. G. J. Woffinden, P. R. Harrison, and J. A. Anderson, Cooling Tower Plume Survey, Volume 1, Technical Summary, Chalk Point Cooling Tower Project, Maryland Power Plant Siting Program, November 30, 1976.

9. G. W. Israel, and T. J. Overcamp, "Drift Deposition Model for Natural Draft Cooling Towers", Cooling Tower Environment - 1974, NTIS CONF 740302, pp. 614-628, 1975.

10. P. R. Slawson, J. H. Coleman, and J. W. Frey, "Some Observations on Cooling Tower Plume Behavior at the Paradise Steam Plant", Cooling Tower Environment - 1974, NTIS CONF 740302, pp. 147-160, 1975.

11. G. A. Briggs, Plume Rise, AEC Critical Review Series, 1969.

12. J. H. Meyer, *et al*., "Mechanical Draft Cooling Tower Visible Plume Behavior: Measurements, Models, Predictions", *Cooling Tower Environment - 1974*, NTIS CONF 740302, pp. 307-352, 1975.

13. S. R. Hanna, *Meteorological Effects of the Mechanical Draft Cooling Towers of the Oak Ridge Gaseous Diffusion Plant*, Environmental Research Laboratories, Air Resources, Atmospheric Turbulence and Diffusion Laboratory, NOAA, Oak Ridge, ATDL Contribution 89, 1974.

14. J. J. George, "Fog", *Compendium of Meteorology*, pp. 1179-1189, ed. T. F. Malone, American Meteorological Society, Boston, Massachusetts, 1951.

APPENDIX A

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 in (2.54 cm) O.D., 20 BWG gauge, 304 stainless steel tubes and a design water velocity of 7.0 ft/s (2.1 m/s). The condenser has two tube passes. Condenser design data for each cooling system can be found in Appendices F through N, and P.
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-hertz motors. The pumps have carbon steel casings with chrome steel shaft and bronze impeller. Pump design data for each system can be found in Appendices F through N, and P.
Cooling Towers	The following are descriptions of the cooling towers. The design data for each alternative can be found in Appendices F through N, and P.
1. 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 ft (12.5 m) fill height. Each cell has a fan; the fan has a diameter of 28 ft (8.6 m) and is driven by a 200 horsepower (149 KW) motor. The cell dimensions are 71 ft (21.6 m) wide, 36 ft (11.0 m) long, and 54 ft (16.5 m) high.
2. 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 four rows and two passes and is equipped with a 150 horsepower (111.9 KW) motor and a 28 ft (8.6 m) diameter fan. The overall cell dimensions are 41 ft (12.5 m) wide, 61 ft (18.6 m) long and 65 ft (19.8 m) high. The tubes are 1 in (2.54 cm) O.D. and 52 ft (15.8 m) long, admiralty tubes, with aluminum fins. The fin dimensions are 10 fins/

in (4 fins/cm) with a fin height of 0.625 in (1.59 cm).

3. Natural Draft Dry Tower — The natural draft tower has a hyperbolic concrete shell with a maximum base diameter of 500 ft (152.4 m) and a minimum thickness of 6 in (15.24 cm). The finned-tube heat exchanger modules are arranged vertically around the tower base. Each module has 264 tubes in 6 rows and 2 passes. The tubes are 1 in (2.54 cm) O.D. and 50 ft (15.2 m) long, admiralty tubes, with aluminum fins. The fin dimensions are 10 fins/in (4 fins/cm) with a fin height of 0.625 in (1.59 cm).

4. Mechanical Draft Wet/Dry Hybrid Cooling Tower — The mechanical draft wet/dry tower cells are induced draft with a 41 ft (12.5 m) cross-flow type fill of concrete construction. Atop the fill are located heat exchangers having 1 in (2.54 cm) O.D. admiralty tubes with 10 aluminum fins/inch (4 fins/cm) and a fin height of 0.625 in (1.59 cm) arranged in 4 rows and 2 passes. Each cell has a separate fan, and is driven by a 200 horsepower (149 KW) motor. The cell dimensions are 71 ft (21.6 m) wide and 36 ft (11.0 m) long.

APPENDIX B

ASSESSMENT OF ECONOMIC FACTORS

A brief economic analysis is 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 six percent is assumed. The fraction of capitalization is assumed for 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, F, are given by:

$$F = P + D + S + T \qquad \text{(B-1)}$$

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:

$$\text{Material:} \quad (1.06)^{9.5\text{ years}}\,(1.10)^{1.0\text{ year}} = 1.91 \qquad \text{(B-2)}$$

$$\text{Labor:} \quad (1.08)^{9.5\text{ years}}\,(1.10)^{1.0\text{ year}} = 2.29 \qquad \text{(B-3)}$$

CAPACITY PENALTY CHARGE RATE

For each base analysis presented in this report, an incremental base load plant cost of \$485/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 7.

FUEL COST

For the analyses reported in Sections 4 and 5, the fuel costs were obtained from the utilities. The fuel cost of 315¢/MBtu (298¢/GJ) used in Section 7 came from UE&C internal sources.

APPENDIX C

PLUME ABATEMENT SITES

The locations chosen for the plume abatement analysis were selected from a list of United States cities which was prepared by UE&C staff meteorologists.

Using rule of thumb criteria, such as overall regional estimations and ground rules assuming ambient temperatures less than 50°F (10°C), relative humidity near 100 percent, and wind speed 8 mph (3.58 m/s) or less, 13 sites were evaluated. Four of these were selected and studied in detail for geographic balance and different climatological data that represented distinct areas of the United States. The results of the analysis, listed by cities in descending order of fogging potential, are shown below:

1. Seattle, Washington
   Data period: 1951-1960
2. Cleveland, Ohio
   Data period: 1951-1960
3. Bedford, Massachusetts
   Data period: 1961-1970
4. Scranton, Pennsylvania*
   Data period: 1956-1960
5. Charlotte, North Carolina**
   Data period: 1951-1960
6. Chicago, Illinois
   Data period: 1951-1960
7. St. Louis, Missouri
   Data period: 1951-1960
8. Montgomery, Alabama
   Data period: 1951-1960
9. Fargo, North Dakota***
   Data period: 1951-1960
10. Atlanta, Georgia
    Data period: 1951-1960
11. Tuscon, Arizona
    Data period: 1956-1960
12. Miami, Florida
    Data period: 1951-1960
13. Newark, New Jersey
    Data period: 1951-1960

* Representing New Hampton, N.Y. for which there were no available data

** Representing Cliffside, N.C. for which there were no available data

*** Breakdown of the fogging criterion for extremely low temperature may mean that the fogging potential value here is much too low. The UE&C cooling tower model has not been examined for such extreme conditions

APPENDIX D

RAW WATER QUALITY FOR THE VARIOUS SITES AND WATER TREATMENT ANALYSIS FOR KAIPAROWITS, UTAH

SITE WATER QUALITY

The chemical constituent average values which are needed for a water analysis at each site are presented as ppm of $CaCO_3$.

	Kaiparowits	San Juan	Colstrip	Young	Rock Springs	New Hampton
Ca	232	165	115	{164}	142	53
Mg	135	37	70		86	20
Na	255	110	96	140	108	23
Cl	133	20	8	4	12	54
SO_4	359	174	140	146	178	19
HCO_3	129	118	127	154	156	50
SiO_2 (as SiO_2)	17	11	12	7	6	-

WATER TREATMENT ANALYSIS FOR KAIPAROWITS, UTAH

The raw water analysis for Kaiparowits is presented above. The raw water is treated by a cold lime-soda process to reduce the hardness by precipitation. After treatment, a chemical analysis of the effluent shows the following composition:

Ca - 35	Cl - 133	pH - 10.8
Mg - 33	SO_4 - 359	SiO_2 (as SiO_2) - 14
Na - 492	HCO_3 - 35	
TDS - 560	OH - 33	

All values except the SiO_2 are expressed as ppm of $CaCO_3$.

Sulfuric acid is added to the circulating cooling water for control of alkalinity and pH. If the circulating water is limited to nine cycles of concentration, precipitation will not occur in the cooling tower circulating water. At nine cycles of concentration with H_2SO_4 addition, the chemical analysis of the water gives a composition of:

Ca - 315	Cl - 1197	pH - 6.9
Mg - 297	SO_4 - 3813	SiO_2 (as SiO_2) - 126
Na - 4428	HCO_3 - 30	
TDS - 5040	OH - 0	

The nine cycles of concentration limitation is based upon the following rules: the product of SiO_2 (as SiO_2) and Mg (as $CaCO_3$) ionic concentrations should not exceed approximately 37,000, and the product of Ca (as Ca) and SO_4 (as SO_4) should not exceed approximately 400,000.

$$SiO_2 \text{ (as } SiO_2) \times Mg \text{ (as } CaCO_3)$$

$$126 \times 297 = 37,422$$

$$Ca \text{ (as Ca)} \times SO_4 \text{ (as } SO_4)$$

$$126 \times 3660 = 461,160$$

These products of the ionic concentrations are based upon standard industrial practice. Recent recommendations in the literature (1) have advocated using a range of 600,000 to 1,000,000 as the product of Ca and SO_4. Accordingly, a value of 461,160 for the product of Ca and SO_4 is 15 percent over the base value of 400,000, but is within recent acceptable limits.

The estimated required chemical dosages necessary for the water treatment are:

1. hydrated lime - 93% $Ca(OH)_2$ - 1.8 lbs/1000 gal
2. soda ash - 98% Na_2CO_3 - 2.1 lbs/1000 gal
3. sulfuric acid - 93% H_2SO_4 - 0.5 lbs/1000 gal
4. polyelectrolyte - 0.025 lbs/1000 gal

For a 1000 MWe fossil-fueled plant, the clarifier-softener for a wet cooling system would be designed to treat about 12,500 gpm of make-up water. This clarifier-softener would require approximately 700 to 1,000 lbs of chlorine in a 24 hour period. This chlorine requirement is based on a chlorine demand in the raw influent of 5 ppm. Additional chlorine is necessary to assure destruction of biological substances which can enter the circulating water through the air-water interface in the cooling tower. In addition, some chlorine residual is necessary to insure total destruction of biological substances. The residual level is generally pre-determined and serves as a control function to determine the end of the chlorination period.

The water treatment analysis for the other five sites is performed in a manner similar to the preceding discussion for Kaiparowits. The five sites in the western coal region require the cold lime-soda process for water treatment; the New Hampton site does not require this water treatment process.

---

(1) G. J. Crits, and G. Glover, "Cooling Blowdown in Cooling Towers", Water and Wastes Engineering, Volume 12, Number 4, pp. 45-52, April 1975.

APPENDIX E

DESCRIPTION OF CODES OF ACCOUNTS FOR CAPITAL COST ELEMENTS

This appendix contains the definitions of capital cost account numbers used to identify detailed capital cost data for the fossil power plants that are given in Appendices F through N, and P.

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)

118L Circulating Water Pump Structures

Circulating water pump house including concrete work, excavation and backfill, temporary sheeting, rip-rap, permanent sheet piling, and miscellaneous iron

132.2 Circulating Water System

1. Circulating water pumps and drives

2. Circulating water intake, discharge and connecting pipelines including excavation, backfill, supports, etc

132.3 Cooling Towers

1. Cooling tower basins and foundations including excavation and backfill, forms, reinforcing steel, concrete, concrete finish and miscellaneous iron

2. Cooling towers which are mechanical draft dry, mechanical draft wet, natural draft dry, mechanical draft hybrid wet/dry

133.1 Condensers

114 & 132.1 Make-up Facilities

1. Intake structures including excavation, concrete work, reinforcing steel, miscellaneous iron, cofferdam

2. Water intake facilities including traveling screens, trash racks, trash rakes, stop logs, pumps and drives

3. Intake lines including connections from pump discharges to cooling system, steel pipeline, excavation and backfill, coating and wrapping pipe, welding

4. Water treatment facilities including clarifier-softeners and chemical feeders

14 Electrical Equipment

1. Station service including switchgear and controls for traveling screens, trash rake, circulating water pumps, screen wash pumps and cooling tower fans

2. Station service and startup transformers which are the incremental transformer capacities involved

3. Cable trays and supports

4. Conduit

5. Station service power wiring

APPENDIX F

KAIPAROWITS, UTAH - REFERENCE AND MECHANICAL SERIES WET/DRY COOLING SYSTEMS

This appendix contains three different items for the Kaiparowits, Utah site:

1. Design data, capital investment and penalty breakdowns for the optimized reference cooling systems
2. Design data, capital investment and penalty breakdowns for the optimized mechanical series wet/dry cooling systems operating in the S1 mode
3. Performance curves for the optimized reference and wet/dry cooling systems

TABLE F-1. SUMMARY OF DESIGN DATA FOR THE OPTIMIZED REFERENCE COOLING SYSTEMS AT KAIPAROWITS, UTAH

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	90.0 (32.2)	103.0 (39.4)	90.0 (32.2)
Wet Bulb	66.0 (18.9)	75.0 (23.9)	66.0 (18.9)
Cold Water	130.0 (54.4)	118.0 (47.8)	86.0 (30.0)
Cooling Range	24.0 (13.3)	11.0 (6.1)	25.0 (13.9)
ITD (Dry Tower) or Approach (Wet Tower)	64.0 (35.6)	26.0 (14.4)	20.0 (11.1)
Design Turbine Back Pressure, in-HgA (mm-HgA)	9.43 (239.5)	5.03 (127.8)	3.08 (78.2)
Maximum Operating Back Pressure, in-HgA (mm-HgA)	13.36 (339.3)	5.03 (127.8)	3.60 (91.4)
Design Heat Load, 10^9 Btu/hr (10^{12} J/hr)	4.77 (5.03)	4.62 (4.87)	4.50 (4.75)
Plant Capacity at Cooling System Design Point, MWe	945.7	989.0	1026.2
Annual Make-up Water Requirement, 10^8 gal. (10^6 m^3)	0.0	0.0	27.91 (10.57)

* This is not an optimized system because of the turbine back pressure limitation.

TABLE F-1 (continued)

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)	722 (67.1)	1010 (93.8)	679 (63.1)
Number of Tubes	53,500	113,100	48,400
Tube Length, ft (m)	51.5 (15.7)	34.1 (10.4)	53.6 (16.3)
Circulating Water Flow & Pump			
Circulating Water Flow Rate, 10^3 gpm (m^3/min)	398 (1507)	841 (3184)	360 (1363)
Number of Pumps	4	5	2
Pumping Head, ft (m) of Water	61.4 (18.7)	49.3 (15.0)	92.1 (28.1)
Motor Rating, hp (kW) per pump	2000 (1491)	3000 (2237)	5000 (3729)
Motor Brake Horsepower, hp (kW) per pump	1732 (1292)	2352 (1754)	4697 (3503)

TABLE F-1 (continued)

Variable	Mechanical Dry (High BP Turbine)	Mechanical Dry* (Low BP Turbine)	Mechanical Wet (Low BP Turbine)
<u>Circulating Water Pipelines</u>			
Condenser Intake:			
Number of Lines	1	2	1
Diameter/Length, in/ft (cm/m)	114/1190 (290/363)	120/1190 (305/363)	108/1200 (274/366)
Condenser Discharge:			
Number of Lines	1	2	1
Diameter/Length, in/ft (cm/m)	114/1240 (290/378)	120/1240 (305/378)	108/1480 (274/451)
Connecting Pipelines:			
Number of Lines	2	2	1
Diameter/Length, in/ft (cm/m)	86/1060 (218/323)	120/1060 (305/323)	108/410 (274/125)
<u>Cooling Tower</u>			
Size (Number of Cells):			
Dry Tower	113	290	-
Wet Tower	-	-	22

TABLE F-2. SUMMARY OF CAPITAL INVESTMENT COST FOR THE OPTIMIZED REFERENCE COOLING SYSTEMS ($$10^6$) AT KAIPAROWITS, UTAH - 1985

Acct. No.	Equipment Item		Mechanical Dry (High BP Turbine)	Mechanical Dry* (Low BP Turbine)	Mechanical Wet (Low BP Turbine)
118L	Circulating Water Pump Structures	(M	0.846	1.117	0.816
		(L	0.676	0.893	0.653
		(T	1.522	2.010	1.469
132.211	Circulating Water Pumps and Motors	(E	1.951	3.774	1.815
		(M	0.020	0.038	0.018
		(L	0.211	0.263	0.105
		(T	2.182	4.045	1.938
132.25	Concrete Pipelines	(M	2.162	4.376	1.744
		(L	2.043	3.994	1.527
		(T	4.205	8.370	3.271
132.3211	Cooling Tower Basin and Foundation	(M	0.344	0.886	1.427
		(L	0.620	1.594	2.567
		(T	0.964	2.480	3.994
132.3212	Cooling Towers, Installed	(E	34.133	87.597	5.406
		(M	0.345	0.885	0.055
		(L	3.973	10.201	3.527
		(T	38.451	98.683	9.988
133.1	Condensers, Installed	(E	6.825	9.911	6.460
		(M	0.034	0.050	0.032
		(L	3.923	5.104	3.788
		(T	10.782	15.065	10.280
114 & 132.1	Make-up Facilities	(E	-	-	3.576
		(M	-	-	6.848
		(L	-	-	13.154
		(T	-	-	23.578
14	Electrical Equipment	(E	1.494	3.654	0.648
		(M	1.123	2.745	0.487
		(L	2.771	6.870	0.424
		(T	5.388	13.269	1.559
	Direct Capital Cost of Cooling System	(E	44.403	104.906	17.905
		(M	4.874	10.097	11.426
		(L	14.216	28.919	25.744
		(T	63.493	143.922	55.075
	Indirect Cost		15.873	35.980	13.769
	Total Capital Cost		79.366	179.902	68.844

* This is not an optimized system because of the turbine back pressure limitation.

TABLE F-3. PENALTY BREAKDOWN AND COST SUMMARY FOR THE OPTIMIZED REFERENCE COOLING SYSTEMS ($\$10^6$) AT KAIPAROWITS, UTAH - 1985

Item	Mechanical Dry (High BP Turbine)	Mechanical Dry* (Low BP Turbine)	Mechanical Wet (Low BP Turbine)
Penalty Breakdown:			
Capacity Penalty	60.484	24.267	10.490
Replacement Energy Penalty	26.466	-0.760	1.313
Penalty for Circulating Water Pumping Power Requirement	2.784	4.726	3.775
Penalty for Circulating Water Pumping Energy Requirement	2.257	3.636	2.916
Penalty for Cooling Tower Fan Power Requirement	7.889	17.633	1.657
Penalty for Cooling Tower Fan Energy Requirement	6.030	10.682	1.252
Make-up Water Purchase and Treatment Penalty	0.0	0.0	5.273
Make-up Water Pumping Energy and Capacity Penalty	0.0	0.0	7.443
Cooling System Maintenance Penalty	3.813	8.613	1.843
Cost Summary:			
Total Penalty Cost	109.723	68.797	35.962
Total Capital Cost	79.366	179.902	68.844
Total Evaluated Cost	189.089	248.699	104.806

* This is not an optimized system because of the turbine back pressure limitation.

TABLE F-4. SUMMARY OF DESIGN DATA FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS AT KAIPAROWITS, UTAH - MECHANICAL SERIES - S1 MODE

Variable	Percentage Make-up Requirement				
	2	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)	65.0/52.0 (18.3/11.1)	45.0/40.0 (7.2/4.4)	30.0/28.0 (-1.1/-2.2)	10.0/10.0 (-12.2/-12.2)	0.0/0.0 (-17.8/-17.8)
Cold Water Temperature, °F (°C)	99.0 (37.2)	90.0 (32.2)	85.0 (29.4)	81.0 (27.2)	85.0 (29.4)
Cooling Range, °F (°C)	18.0 (10.0)	26.0 (14.4)	26.0 (14.4)	26.0 (14.4)	28.0 (15.6)
Tower ITD, °F (°C)	52.0 (28.9)	71.0 (39.4)	81.0 (45.0)	97.0 (53.9)	113.0 (62.8)
Condenser Heat Load, 10^9 Btu/hr (10^{12} J/hr)	4.53 (4.78)	4.52 (4.77)	4.50 (4.74)	4.48 (4.73)	4.51 (4.75)
Design Parameters for Wet Helper Tower:					
Dry Bulb/Wet Bulb Temperatures, °F (°C)	103.0/77.0 (39.4/25.0)	103.0/77.0 (39.4/25.0)	103.0/77.0 (39.4/25.0)	103.0/77.0 (39.4/25.0)	103.0/77.0 (39.4/25.0)
Tower Approach Temperature, °F (°C)	20.0 (11.1)	20.0 (11.1)	17.1 (9.5)	17.0 (9.4)	15.1 (8.4)
Design and Maximum Operating Back Pressure P_{max}, in-HgA (mm-HgA)	5.0 (127.0)	4.5 (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)	4.62 (4.88)	4.59 (4.84)	4.55 (4.80)	4.55 (4.80)	4.55 (4.80)
Heat Load Distribution at P_{max}- Wet Tower/ Dry Tower, %	51.6/48.4	69.8/30.2	78.8/21.2	82.3/17.7	84.7/15.3
Annual Make-up Water Requirement, 10^8 gal (10^6 m^3)	0.518 (0.196)	2.59 (0.98)	5.190 (1.96)	8.57 (3.24)	11.14 (4.22)

TABLE F-4 (continued)

Variable	Percentage Make-up Requirement				
	2	10	20	30	40
Condenser					
Surface Area, 10^3 ft^2 (10^3 m^2)	793 (73.7)	662 (61.5)	667 (62.0)	674 (62.6)	642 (59.7)
Number of Tubes	67,700	46,800	46,500	46,400	43,300
Tube Length, ft (m)	44.7 (13.6)	54.0 (16.5)	54.7 (16.7)	55.5 (16.9)	56.6 (17.3)
Circulating Water Flow & Pump					
Circulating Water Flow Rate, 10^3 gpm (m^3 /min)	503 (1904)	348 (1317)	346 (1310)	345 (1306)	322 (1219)
Number of Pumps	3	2	2	2	2
Pumping Head, ft (m) of Water	63.7 (19.4)	69.9 (21.3)	76.6 (23.3)	88.6 (27.0)	97.2 (29.6)
Motor Rating, hp (kW) per pump	3500 (2610)	4000 (2983)	4500 (3356)	4500 (3356)	5000 (3729)
Motor Brake Horsepower, hp (kW) per pump	3031 (2260)	3447 (2570)	3758 (2802)	4333 (3231)	4440 (3311)
Flow & Booster Pump for Wet Tower					
Percentage of Circulating Water to Wet Helper Tower	41.5	93	100	100	100
Number of Pumps	2	2	2	2	2
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)	2500 (1864)	2500 (1864)	2500 (1864)
Motor Brake Horsepower, hp (kW) per pump	1213 (905)	1882 (1403)	2012 (1500)	2004 (1494)	1872 (1396)

TABLE F-4 (continued)

Variable	Percentage Make-up Requirement				
	2	10	20	30	40
Circulating Water Pipelines					
Condenser Intake:					
Number of Lines	1	1	1	1	1
Diameter/Length, in/ft (cm/m)	132/2000 (335/610)	108/2000 (274/610)	108/2000 (274/610)	108/2000 (274/610)	102/2000 (259/610)
Condenser Discharge:					
Number of Lines	1	1	1	1	1
Diameter/Length, in/ft (cm/m)	132/1600 (335/488)	108/1600 (274/488)	108/1600 (274/488)	108/1600 (274/488)	102/1600 (259/488)
Connecting Pipelines:					
Number of Lines	1	1	1	1	1
Diameter/Length, in/ft (cm/m)	132/650 (335/198)	108/650 (274/198)	108/650 (274/198)	108/650 (274/198)	102/650 (259/198)
Cooling Tower					
Size (Number of Cells):					
Dry Tower	126	93	77	61	52
Wet Tower	9	13	16	17	19

TABLE F-5. SUMMARY OF CAPITAL INVESTMENT COST FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS ($$10^6$)
AT KAIPAROWITS, UTAH - MECHANICAL SERIES - S1 MODE - 1985

Acct. No.	Equipment Item		Percentage Make-up Requirement 2	10	20	30	40
118L	Circulating Water Pump Structures	(M	0.924	0.806	0.804	0.804	0.783
		(L	0.737	0.643	0.643	0.641	0.625
		(T	1.661	1.450	1.447	1.445	1.408
132.211	Circulating Water Pumps and Motors	(E	3.462	3.075	3.154	3.233	3.233
		(M	0.035	0.031	0.032	0.033	0.033
		(L	0.263	0.211	0.211	0.211	0.211
		(T	3.760	3.317	3.397	3.477	3.477
132.25	Concrete Pipelines	(M	3.541	2.338	2.338	2.338	2.116
		(L	2.782	2.100	2.100	2.100	1.942
		(T	6.323	4.438	4.438	4.438	4.058
132.3211	Cooling Tower Basin and Foundation	(M	0.968	1.129	1.274	1.291	1.392
		(L	1.743	2.029	2.292	2.322	2.505
		(T	2.711	3.158	3.566	3.613	3.897
132.3212	Cooling Towers, Installed	(E	40.244	31.241	27.148	22.593	20.396
		(M	0.407	0.316	0.274	0.228	0.206
		(L	5.870	5.353	5.270	4.869	4.866
		(T	46.521	36.910	32.692	27.690	25.438
133.1	Condensers, Installed	(E	7.554	6.323	6.349	6.393	6.135
		(M	0.038	0.032	0.032	0.032	0.031
		(L	4.209	3.740	3.744	3.756	3.664
		(T	11.801	10.095	10.125	10.181	9.830
114 & 132.1	Make-up Facilities	(E	2.239	2.764	3.022	3.112	3.191
		(M	4.533	5.394	5.840	5.999	6.141
		(L	8.704	10.359	11.216	11.523	11.796
		(T	15.476	18.517	20.078	20.634	21.128
14	Electrical Equipment	(E	1.947	1.629	1.531	1.404	1.335
		(M	1.463	1.224	1.150	1.055	1.003
		(L	4.669	3.556	3.055	2.524	2.246
		(T	8.079	6.409	5.736	4.983	4.584
	Direct Capital Cost of Cooling System	(E	55.446	45.032	41.204	36.736	34.260
		(M	11.909	11.269	11.744	11.780	11.705
		(L	28.978	27.991	28.531	27.945	27.885
		(T	96.333	84.292	81.479	76.461	73.820
	Indirect Cost		24.084	21.073	20.370	19.115	18.456
	Total Capital Cost		120.417	105.365	101.849	95.576	92.276

TABLE F-6. PENALTY BREAKDOWN AND COST SUMMARY FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS ($$10^6$)
AT KAIPAROWITS, UTAH - MECHANICAL SERIES - S1 MODE - 1985

Item	Percentage Make-up Requirement				
	2	10	20	30	40
Penalty Breakdown:					
Capacity Penalty	23.996	19.335	14.297	14.297	14.297
Replacement Energy Penalty	3.289	8.110	8.533	10.538	11.257
Penalty for Circulating Water Pumping Power Requirement	4.629	4.283	4.637	5.093	5.072
Penalty for Circulating Water Pumping Energy Requirement	2.891	2.561	3.106	3.862	3.994
Penalty for Cooling Tower Fan Power Requirement	8.330	6.592	5.883	4.924	4.494
Penalty for Cooling Tower Fan Energy Requirement	6.406	4.856	4.123	3.417	3.081
Make-up Water Purchase and Treatment Penalty	0.098	0.489	0.980	1.618	2.105
Make-up Water Pumping Energy and Capacity Penalty	2.444	3.496	4.196	4.696	5.097
Cooling System Maintenance Penalty	5.045	4.182	3.953	3.670	3.515
Cost Summary:					
Total Penalty Cost	57.129	53.903	49.708	52.115	52.912
Total Capital Cost	120.417	105.365	101.849	95.576	92.276
Total Evaluated Cost	177.546	159.268	151.557	147.691	145.188

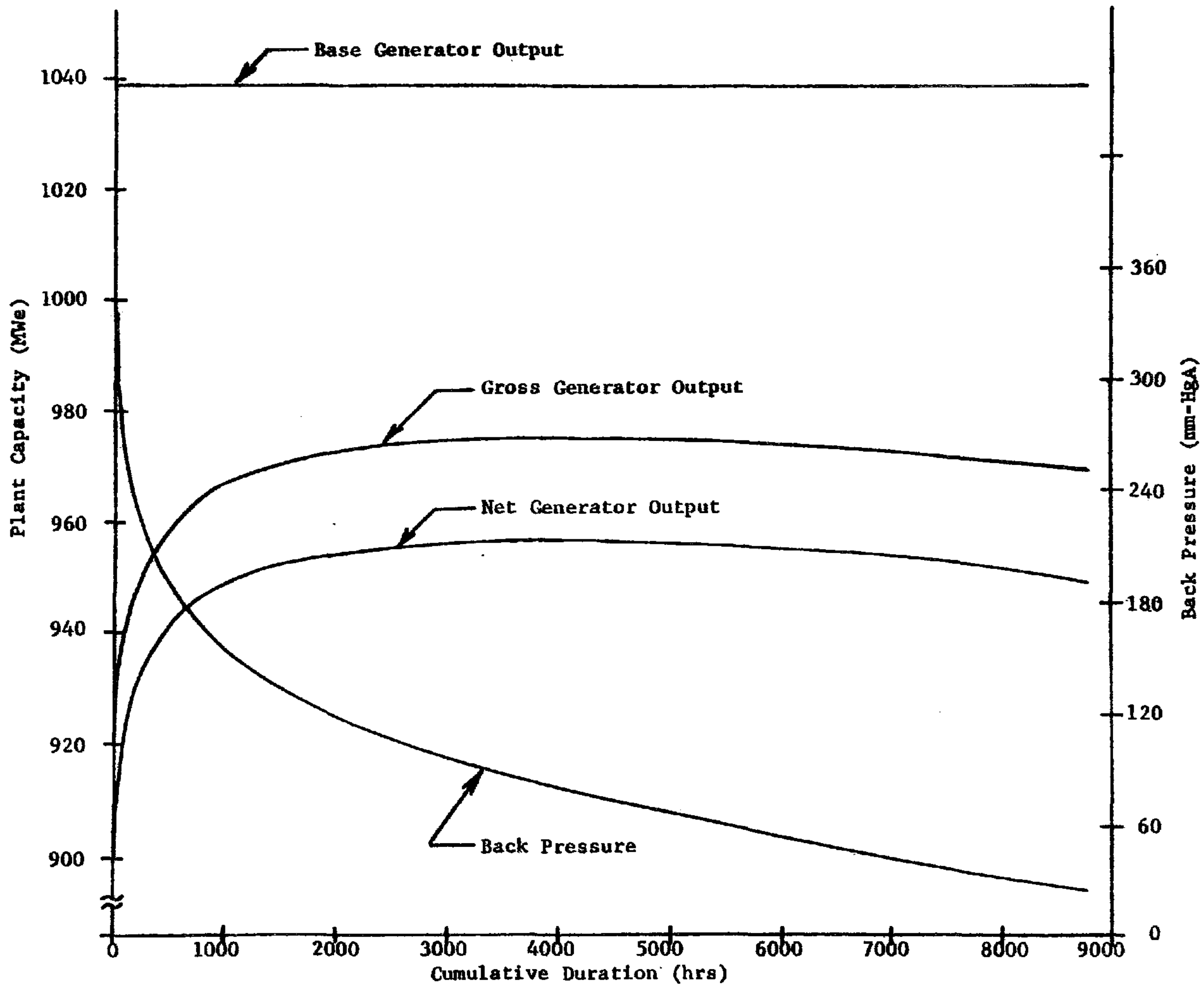


Figure F-1. Performance Curves for a High Back Pressure Mechanical Dry Cooling System at Kaiparowits, Utah

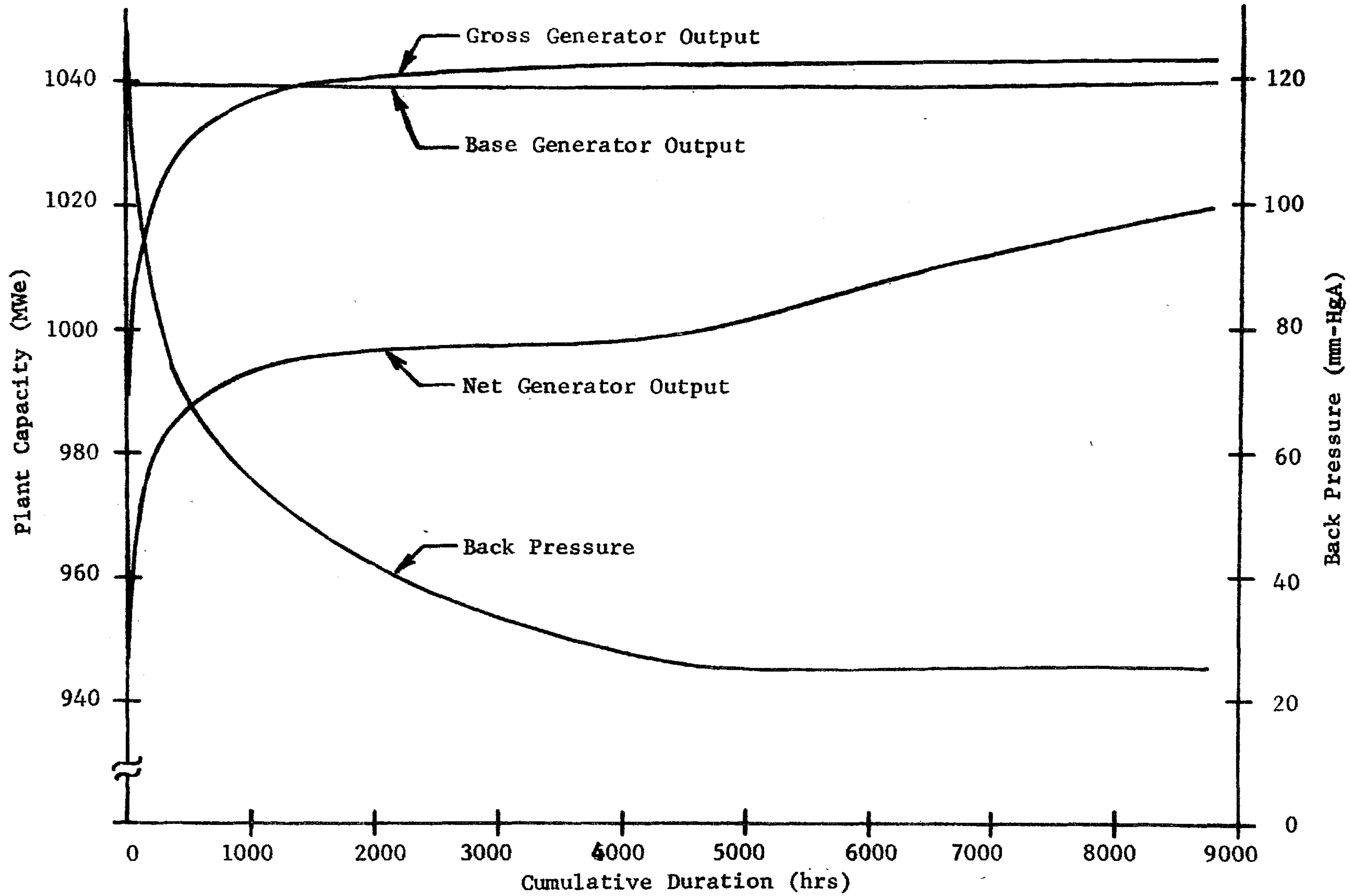


Figure F-2. Performance Curves for a Conventional Low Back Pressure Mechanical Dry Cooling System at Kaiparowits, Utah

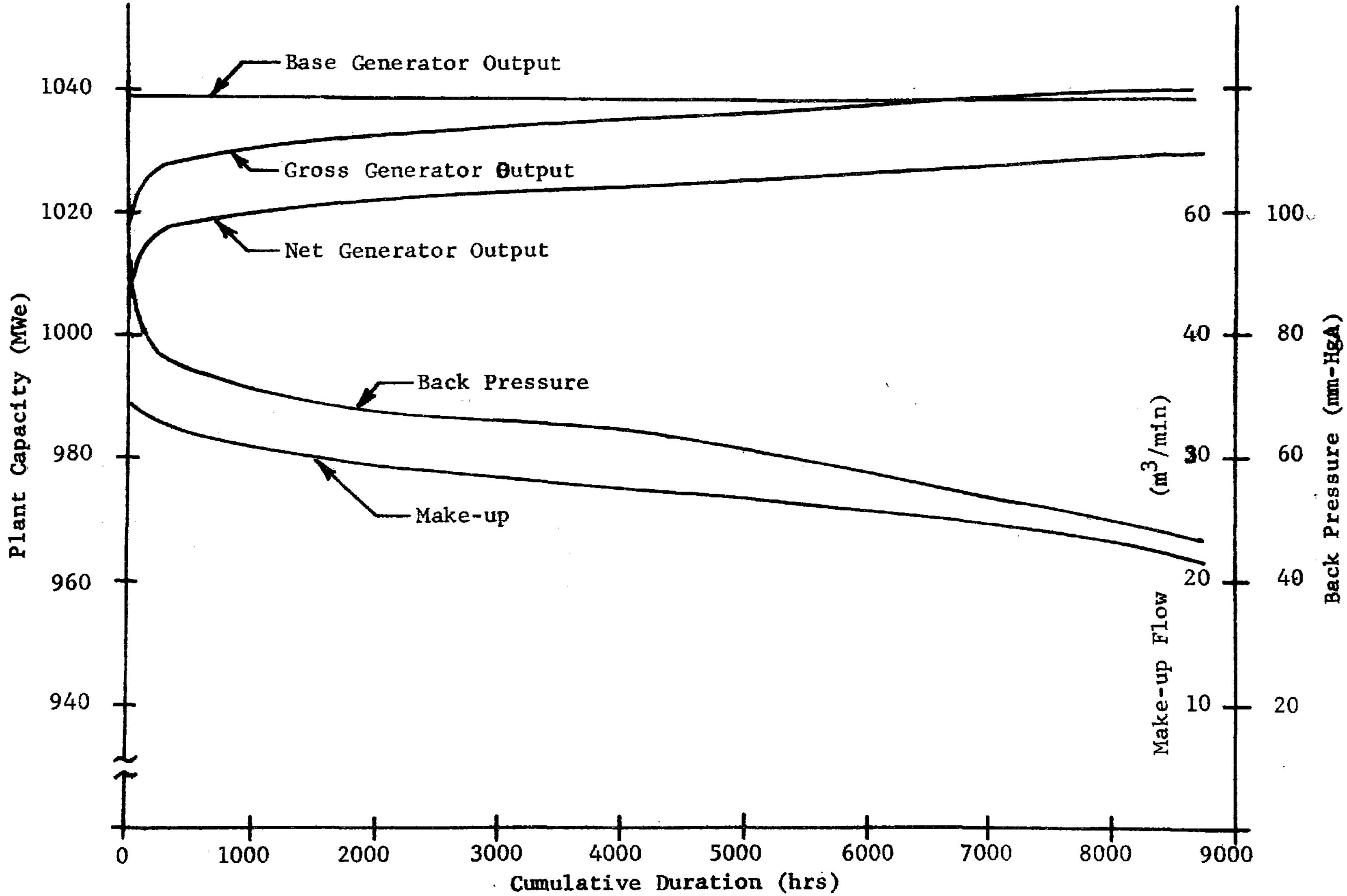


Figure F-3. Performance Curves for a Mechanical Wet Cooling System at Kaiparowits, Utah

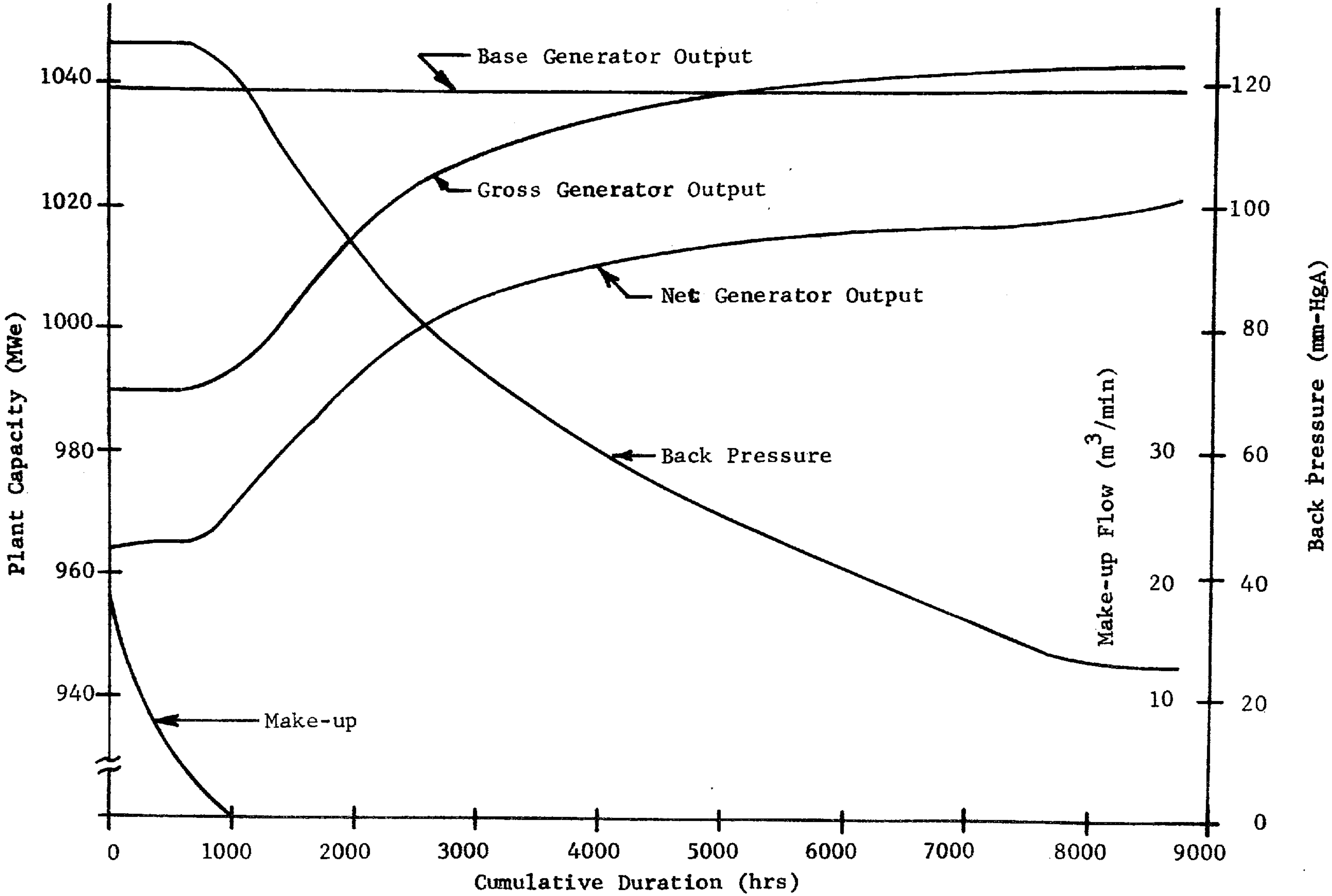


Figure F-4. Performance Curves for a 2% Mechanical Series Wet/Dry Cooling System at Kaiparowits, Utah

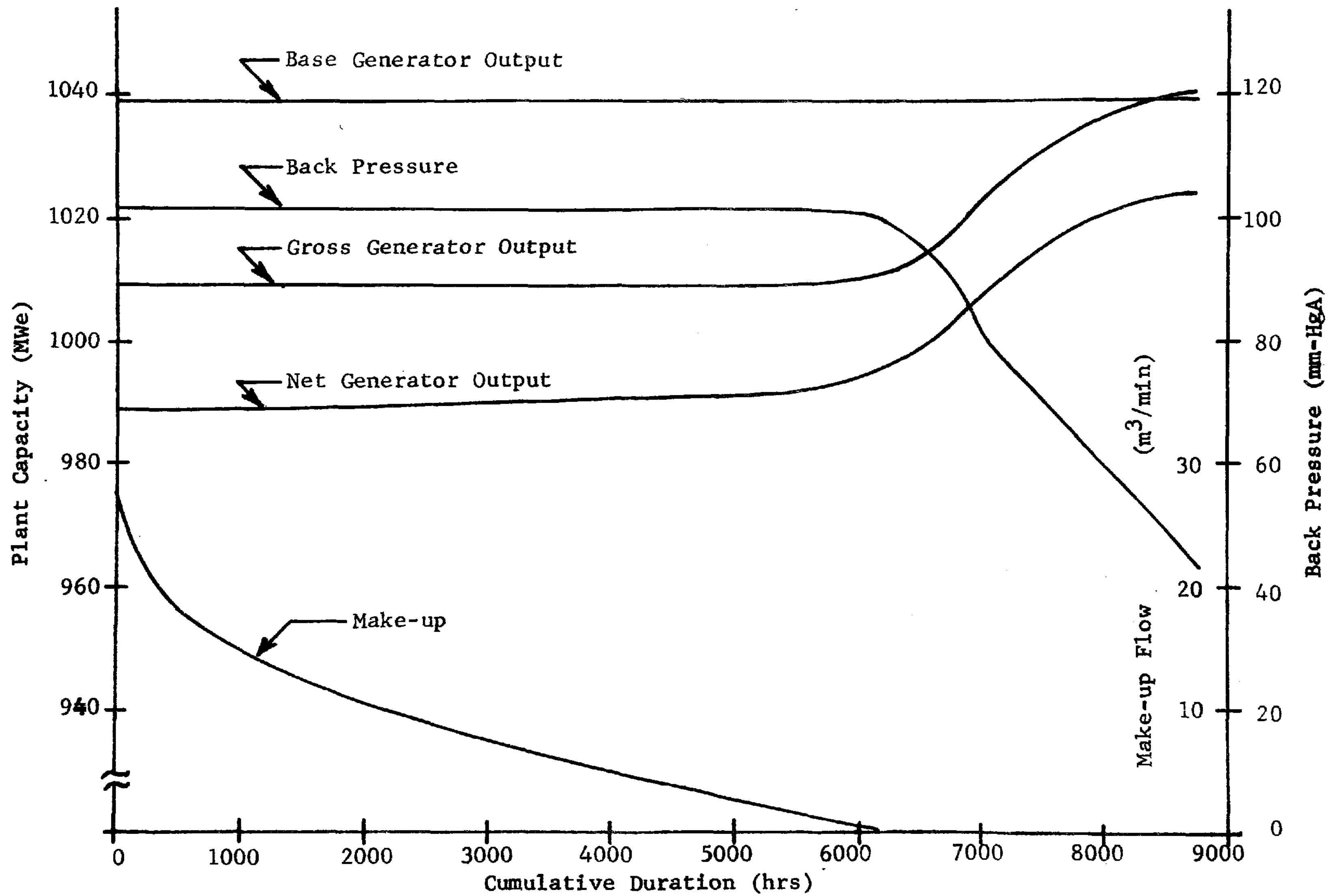


Figure F-5. Performance Curves for a 20% Mechanical Series Wet/Dry Cooling System at Kaiparowits, Utah

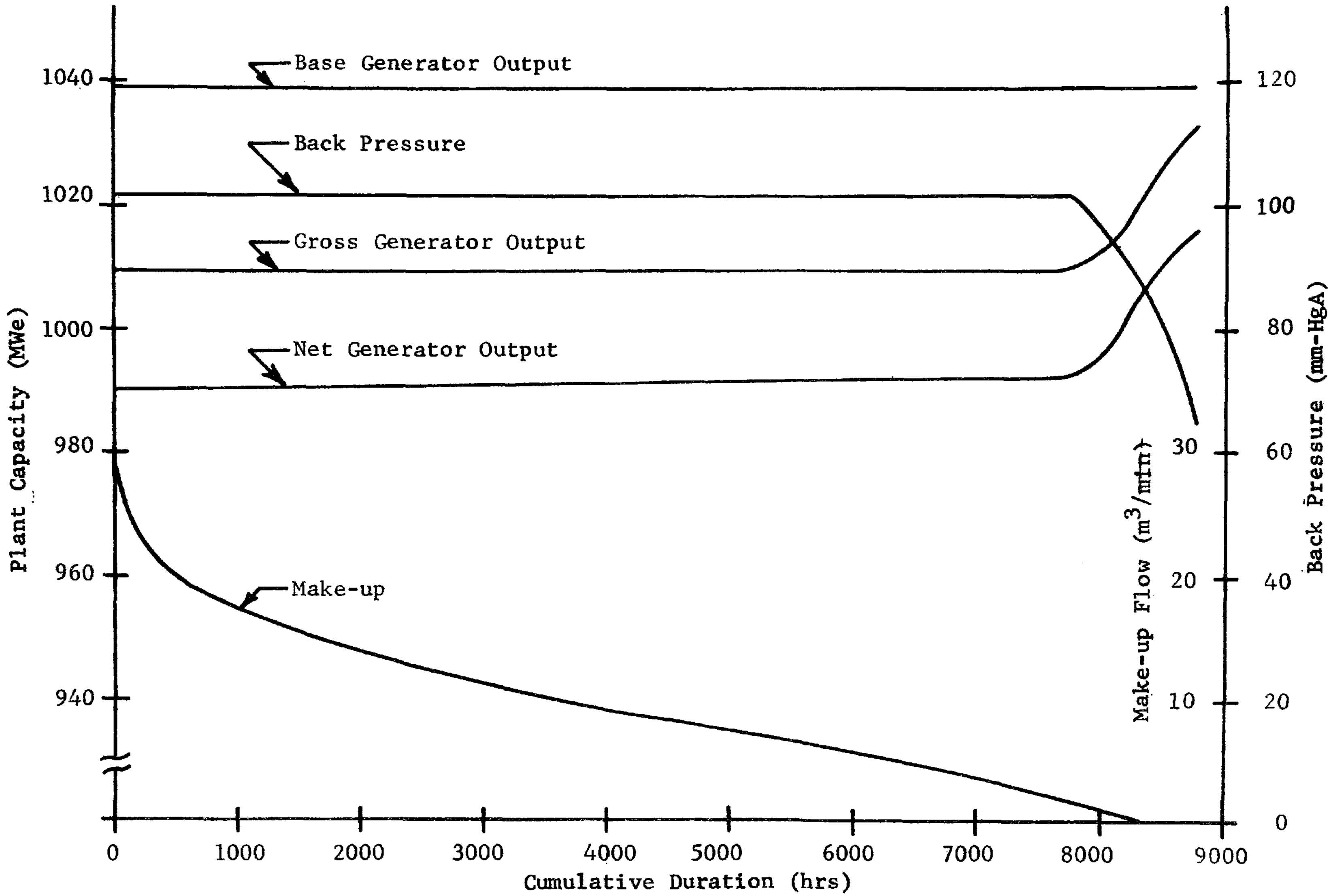


Figure F-6. Performance Curves for a 30% Mechanical Series Wet/Dry Cooling System at Kaiparowits, Utah

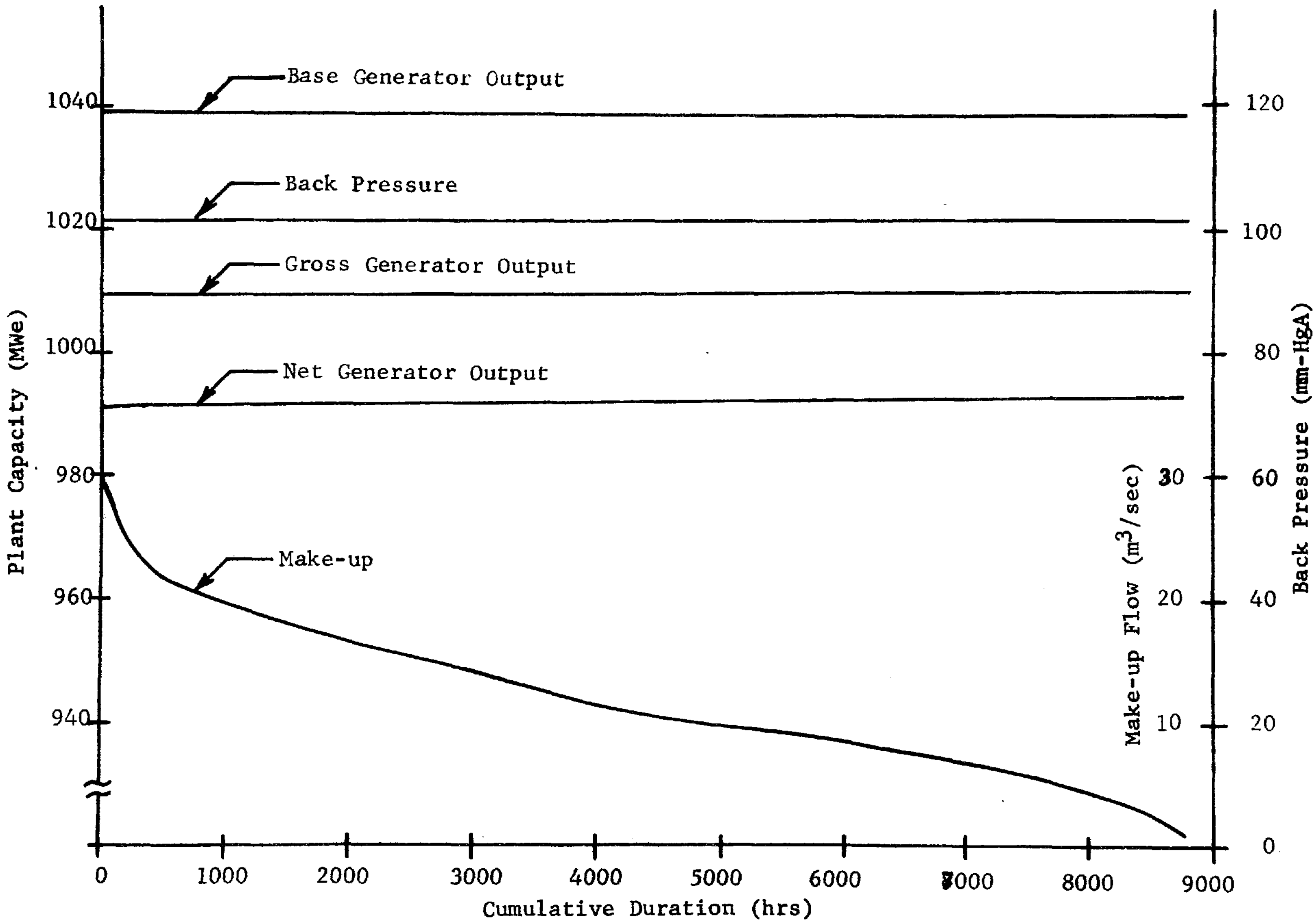


Figure F-7. Performance Curves for a 40% Mechanical Series Wet/Dry Cooling System at Kaiparowits, Utah

APPENDIX G

KAIPAROWITS, UTAH - MECHANICAL SERIES WET/DRY COOLING SYSTEMS: S2 MODE

This appendix contains design data, capital investment and penalty breakdowns for the optimized mechanical series wet/dry cooling systems operating in the S2 Mode at Kaiparowits, Utah.

TABLE G-1. SUMMARY OF DESIGN DATA FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS AT KAIPAROWITS, UTAH - MECHANICAL SERIES - S2 MODE

Variable	Percentage Make-up Requirement			
	10	20	30	40
General Design Data				
Mode of Wet/Dry Tower Operation	S2	S2	S2	S2
Design Parameters for Dry Towers:				
Dry Bulb/Wet Bulb Temperatures, °F (°C)	60.0/50.0 (15.6/10.0)	50.0/44.0 (10.0/6.7)	35.0/33.0 (1.7/0.6)	20.0/20.0 (-6.7/-6.7)
Cold Water Temperature, °F (°C)	101.0 (38.3)	100.0 (37.8)	92.0 (33.3)	87.0 (30.6)
Cooling Range, °F (°C)	22.0 (12.2)	24.0 (13.3)	28.0 (15.6)	32.0 (17.8)
Tower ITD, °F (°C)	63.0 (35.0)	74.0 (41.1)	85.0 (47.2)	99.0 (55.0)
Condenser Heat Load, 10^9 Btu/hr (10^{12} J/hr)	4.57 (4.82)	4.58 (4.83)	4.55 (4.80)	4.54 (4.79)
Design Parameters for Wet Helper Tower:				
Dry Bulb/Wet Bulb Temperatures, °F (°C)	103.0/77.0 (39.4/25.0)	103.0/77.0 (39.4/25.0)	103.0/77.0 (39.4/25.0)	103.0/77.0 (39.4/25.0)
Tower Approach Temperature, °F (°C)	20.0 (11.1)	20.0 (11.1)	20.0 (11.1)	19.2 (10.7)
Design and Maximum Operating Back Pressure P_{max}, in-HgA (mmHgA)	4.99 (126.7)	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)	4.62 (4.87)	4.62 (4.87)	4.62 (4.87)	4.62 (4.87)
Heat Load Distribution at P_{max}- Wet Tower/ Dry Tower, %	59.5/40.5	65.7/34.3	70.4/29.6	74.8/25.2
Annual Make-up Water Requirement, 10^8 gal (10^6 m^3)	2.85 (1.08)	5.55 (2.10)	8.37 (3.17)	10.99 (4.16)

TABLE G-1 (continued)

Variable	Percentage Make-up Requirement			
	10	20	30	40
Condenser				
Surface Area, 10^3 ft^2 (10^3 m^2)	724 (67.3)	693 (64.4)	638 (59.3)	597 (55.5)
Number of Tubes	56,000	51,400	43,700	38,200
Tube Length, ft (m)	49.4 (15.1)	51.5 (15.7)	55.7 (17.0)	59.7 (18.2)
Circulating Water Flow & Pump				
Circulating Water Flow Rate, 10^3 gpm (m^3 /min)	416 (1575)	382 (1446)	325 (1230)	284 (1075)
Number of Pumps	3	3	2	3
Pumping Head, ft (m) of Water	66.3 (20.2)	72.0 (21.9)	72.7 (22.2)	82.0 (25.0)
Motor Rating, hp (kW) per pump	3000 (2238)	3000 (2238)	4000 (2984)	2500 (1865)
Motor Brake Horsepower, hp (kW) per pump	2606 (1944)	2598 (1938)	3352 (2501)	2201 (1642)
Flow & Booster Pump for Wet Tower				
Percentage of Circulating Water to Wet Helper Tower	58.2	67.9	85.9	100.0
Number of Pumps	2	2	2	2
Pumping Head, ft (m) of Water	41.0 (12.5)	41.0 (12.5)	41.0 (12.5)	41.0 (12.5)
Motor Rating, hp (kW) per pump	2000 (1492)	2000 (1492)	2000 (1492)	2000 (1492)
Motor Brake Horsepower, hp (kW) per pump	1408 (1050)	1507 (1124)	1623 (1211)	1651 (1232)

TABLE G-1 (continued)

Variable	Percentage Make-up Requirement			
	10	20	30	40
<u>Circulating Water Pipelines</u>				
Condenser Intake:				
Number of Lines	1	1	1	1
Diameter/Length, in/ft (cm/m)	120/2000 (305/610)	114/2000 (290/610)	108/2000 (274/610)	96/2000 (244/610)
Condenser Discharge:				
Number of Lines	1	1	1	1
Diameter/Length, in/ft (cm/m)	120/1600 (305/488)	114/1600 (290/488)	108/1600 (274/488)	96/1600 (244/488)
Connecting Pipelines:				
Number of Lines	1	1	1	1
Diameter/Length, in/ft (cm/m)	120/650 (305/198)	114/650 (290/198)	108/650 (274/198)	96/650 (244/198)
<u>Cooling Tower</u>				
Size (Number of Cells):				
Dry Tower	105	87	75	63
Wet Tower	11	11	12	13

TABLE G-2. SUMMARY OF CAPITAL INVESTMENT COST FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS ($$10^6$) AT KAIPAROWITS, UTAH - MECHANICAL SERIES - S2 MODE - 1985

Acct. No.	Equipment Item		Percentage Make-up Requirement 10	20	30	40
118L	Circulating Water Pump Structures	(M	0.861	0.835	0.787	0.749
		(L	0.687	0.666	0.627	0.598
		(T	1.548	1.501	1.414	1.346
132.211	Circulating Water Pumps and Motors	(E	3.179	3.179	2.833	2.921
		(M	0.032	0.032	0.029	0.030
		(L	0.263	0.263	0.211	0.263
		(T	3.474	3.474	3.072	3.214
132.25	Concrete Pipelines	(M	2.691	2.514	2.338	1.826
		(L	2.432	2.265	2.100	1.788
		(T	5.123	4.778	4.438	3.614
132.3211	Cooling Tower Basin and Foundation	(M	1.035	0.980	1.008	1.037
		(L	1.862	1.763	1.814	1.864
		(T	2.897	2.743	2.822	2.901
132.3212	Cooling Towers, Installed	(E	34.384	28.938	25.592	22.185
		(M	0.347	0.292	0.259	0.224
		(L	5.455	4.817	4.553	4.295
		(T	40.187	34.047	30.404	26.704
133.1	Condensers, Installed	(E	6.885	6.602	6.112	5.764
		(M	0.035	0.033	0.031	0.029
		(L	3.955	3.847	3.659	3.524
		(T	10.875	10.483	9.802	9.317
114 & 132.1	Make-up Facilities	(E	2.478	2.649	2.778	2.902
		(M	4.916	5.200	5.417	5.630
		(L	9.441	9.986	10.404	10.814
		(T	16.834	17.836	18.599	19.346
14	Electrical Equipment	(E	1.731	1.534	1.385	1.253
		(M	1.300	1.153	1.041	0.941
		(L	3.982	3.369	2.927	2.579
		(T	7.013	6.056	5.352	4.773
	Direct Capital Cost of Cooling System	(E	48.657	42.902	38.700	35.025
		(M	11.217	11.039	10.910	10.466
		(L	28.077	26.977	26.295	25.726
		(T	87.952	80.918	75.903	71.217
	Indirect Cost		21.988	20.230	18.976	17.804
	Total Capital Cost		109.940	101.148	94.879	89.021

TABLE G-3. PENALTY BREAKDOWN AND COST SUMMARY FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS ($$10^6$) AT KAIPAROWITS, UTAH - MECHANICAL SERIES - S2 MODE - 1985

Item	Percentage Make-up Requirement			
	10	20	30	40
Penalty Breakdown:				
Capacity Penalty	23.823	23.820	23.671	23.648
Replacement Energy Penalty	3.312	3.489	3.332	3.617
Penalty for Circulating Water Pumping Power Requirement	4.273	4.344	3.999	3.980
Penalty for Circulating Water Pumping Energy Requirement	2.631	2.851	2.798	2.971
Penalty for Cooling Tower Fan Power Requirement	7.539	6.552	5.929	5.295
Penalty for Cooling Tower Fan Energy Requirement	5.503	4.723	4.303	3.875
Make-up Water Purchase and Treatment Penalty	0.539	1.048	1.580	2.077
Make-up Water Pumping Energy and Capacity Penalty	3.050	3.596	4.091	4.563
Cooling System Maintenance Penalty	4.486	4.078	3.651	3.456
Cost Summary:				
Total Penalty Cost	55.157	54.501	53.354	53.482
Total Capital Cost	109.940	101.148	94.879	89.021
Total Evaluated Cost	165.097	155.649	148.233	142.503

APPENDIX H

KAIPAROWITS, UTAH - MECHANICAL PARALLEL WET/DRY COOLING SYSTEMS: P1 MODE

This appendix contains design data, capital investment and penalty breakdowns for the optimized mechanical parallel wet/dry cooling systems at Kaiparowits, Utah.

TABLE H-1. SUMMARY OF DESIGN DATA FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS AT KAIPAROWITS, UTAH - MECHANICAL PARALLEL - P1 MODE

Variable	Percentage Make-up Requirement			
	2	10	20	30
General Design Data				
Mode of Wet/Dry Tower Operation	P1	P1	P1	P1
Design Parameters for Dry Towers:				
Dry Bulb/Wet Bulb Temperatures, °F (°C)	55.0/46.0 (12.8/7.8)	40.0/37.0 (4.4/2.8)	30.0/28.0 (-1.1/-2.2)	20.0/20.0 (-6.7/-6.7)
Cold Water Temperature, °F (°C)	89.0 (31.7)	88.0 (31.1)	87.0 (30.6)	88.0 (31.1)
Cooling Range, °F (°C)	18.0 (10.0)	24.0 (13.3)	22.0 (12.2)	24.0 (13.3)
Tower ITD, °F (°C)	52.0 (28.9)	72.0 (40.0)	79.0 (43.9)	92.0 (51.1)
Condenser Heat Load, 10^9 Btu/hr (10^{12} J/hr)	4.48 (4.73)	4.50 (4.75)	4.49 (4.74)	4.50 (4.75)
Design Parameters for Wet Helper Tower:				
Dry Bulb/Wet Bulb Temperatures, °F (°C)	103.0/77.0 (39.7/25.0)	103.0/77.0 (39.7/25.0)	103.0/77.0 (39.7/25.0)	103.0/77.0 (39.7/25.0)
Tower Approach Temperature, °F (°C)	20.0 (11.1)	19.9 (11.1)	18.6 (10.3)	16.5 (9.17)
Design and Maximum Operating Back Pressure P_{max}, in-HgA (mmHgA)	5.0 (127.0)	5.0 (127.0)	4.0 (101.6)	4.0 (101.6)
Condenser Heat Load at P_{max}, 10^9 Btu/hr (10^{12} J/hr)	4.62 (4.87)	4.62 (4.87)	4.55 (4.80)	4.55 (4.80)
Heat Load Distribution at P_{max}- Wet Tower/ Dry Tower, %	35.9/64.1	39.1/60.9	42.7/57.3	47.3/52.7
Annual Make-up Water Requirement, 10^8 gal (10^6 m^3)	0.607 (0.230)	2.78 (1.05)	5.21 (1.97)	8.35 (3.16)

TABLE H-1 (continued)

Variable	Percentage Make-up Requirement			
	2	10	20	30
<u>Condenser</u>				
Surface Area, 10^3 ft^2 (10^3 m^2)	794 (73.8)	691 (64.2)	723 (67.2)	691 (64.2)
Number of Tubes	67,000	50,500	54,900	50,500
Tube Length, ft (m)	45.3 (13.8)	52.3 (15.9)	50.3 (15.3)	52.3 (15.9)
<u>Circulating Water Flow & Pump</u>				
Circulating Water Flow Rate, 10^3 gpm (m^3 /min)	498 (1885)	375 (1420)	408 (1544)	375 (1420)
Number of Pumps	3	3	3	3
Pumping Head, ft (m) of Water	67.9 (20.7)	75.0 (22.9)	81.8 (24.9)	90.6 (27.6)
Motor Rating, hp (kW) per pump	3500 (2611)	3000 (2238)	3500 (2611)	3500 (2611)
Motor Brake Horsepower, hp (kW) per pump	3194 (2383)	2661 (1985)	3156 (2354)	3213 (2397)
<u>Flow & Booster Pump for Wet Tower</u>				
Percentage of Circulating Water to Wet Helper Tower	33.7	57.1	79.2	81.2
Number of Pumps	9	11	16	17
Pumping Head, ft (m) of Water	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)	350 (261)
Motor Brake Horsepower, hp (kW) per pump	217 (162)	226 (169)	235 (175)	208 (155)

TABLE H-1 (continued)

Variable	Percentage Make-up Requirement			
	2	10	20	30
<u>Circulating Water Pipelines</u>				
Condenser Intake:				
Number of Lines	1	1	1	1
Diameter/Length, in/ft (cm/m)	132/2000 (335/610)	114/2000 (290/610)	120/2000 (305/610)	114/2000 (290/610)
Condenser Discharge:				
Number of Lines	1	1	1	1
Diameter/Length, in/ft (cm/m)	132/1500 (335/457)	114/1500 (290/457)	120/1500 (305/457)	114/1500 (290/457)
Connecting Pipelines:				
Number of Lines	2	2	2	2
Diameter/Length, in/ft (cm/m)	90/900 (229/274)	78/900 (198/274)	84/900 (213/274)	78/900 (198/274)
<u>Cooling Tower</u>				
Size (Number of Cells):				
Dry Tower	123	88	77	64
Wet Tower	9	11	16	17

TABLE H-2. SUMMARY OF CAPITAL INVESTMENT COST FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS ($$10^6$)
AT KAIPAROWITS, UTAH - MECHANICAL PARALLEL - P1 MODE - 1985

Acct. No.	Equipment Item		Percentage Make-up Requirement			
			2	10	20	30
118L	Circulating Water Pump Structures	(M	0.921	0.829	0.856	0.829
		(L	0.735	0.662	0.682	0.662
		(T	1.656	1.491	1.538	1.491
132.211	Circulating Water Pumps and Motors	(E	3.498	3.387	4.135	4.262
		(M	0.035	0.034	0.042	0.043
		(L	0.529	0.611	0.818	0.859
		(T	4.062	4.032	4.995	5.164
132.25	Concrete Pipelines	(M	3.606	2.630	2.857	2.630
		(L	2.986	2.441	2.638	2.441
		(T	6.592	5.071	5.495	5.071
132.3211	Cooling Tower Basin and Foundation	(M	0.961	0.984	1.274	1.301
		(L	1.727	1.768	2.292	2.338
		(T	2.687	2.752	3.566	3.639
132.3212	Cooling Towers, Installed	(E	39.350	29.233	27.148	23.508
		(M	0.397	0.295	0.274	0.237
		(L	5.757	4.851	5.270	4.974
		(T	45.505	34.379	32.692	28.720
133.1	Condensers, Installed	(E	7.545	6.572	6.857	6.572
		(M	0.038	0.033	0.034	0.033
		(L	4.204	3.833	3.939	3.833
		(T	11.787	10.438	10.830	10.438
114 & 132.1	Make-up Facilities	(E	2.404	2.859	3.231	3.298
		(M	4.797	5.556	6.212	6.334
		(L	9.212	10.671	11.932	12.167
		(T	16.414	19.086	21.375	21.800
14	Electrical Equipment	(E	1.922	1.544	1.605	1.490
		(M	1.444	1.160	1.206	1.119
		(L	4.626	3.492	3.275	2.860
		(T	7.991	6.197	6.086	5.469
	Direct Capital Cost of Cooling System	(E	54.719	43.595	42.976	39.130
		(M	12.199	11.521	12.755	12.526
		(L	29.776	28.329	30.846	30.134
		(T	96.694	83.445	86.577	81.790
	Indirect Cost		24.174	20.863	21.645	20.450
	Total Capital Cost		120.868	104.308	108.222	102.240

TABLE H-3. PENALTY BREAKDOWN AND COST SUMMARY FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS ($$10^6$)
AT KAIPAROWITS, UTAH - MECHANICAL PARALLEL - P1 MODE - 1985

Item	Percentage Make-up Requirement			
	2	10	20	30
Penalty Breakdown:				
Capacity Penalty	23.859	23.859	14.297	14.297
Replacement Energy Penalty	3.531	9.861	7.992	10.050
Penalty for Circulating Water Pumping Power Requirement	4.635	4.209	5.314	5.297
Penalty for Circulating Water Pumping Energy Requirement	3.005	2.597	3.156	3.305
Penalty for Cooling Tower Fan Power Requirement	8.140	6.172	5.858	5.171
Penalty for Cooling Tower Fan Energy Requirement	6.258	4.567	4.047	3.472
Make-up Water Purchase and Treatment Penalty	0.115	0.524	0.984	1.577
Make-up Water Pumping Energy and Capacity Penalty	2.711	3.676	4.566	5.005
Cooling System Maintenance Penalty	5.105	4.330	4.648	4.449
Cost Summary:				
Total Penalty Cost	57.358	59.797	50.862	52.622
Total Capital Cost	120.868	104.308	108.222	102.240
Total Evaluated Cost	178.227	164.104	159.084	154.862

APPENDIX I

KAIPAROWITS, UTAH - NATURAL SERIES WET/DRY COOLING SYSTEMS: S1 MODE

This appendix contains design data, capital investment and penalty breakdowns for the optimized natural series wet/dry cooling systems at Kaiparowits, Utah.

TABLE I-1. SUMMARY OF DESIGN DATA FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS AT KAIPAROWITS, UTAH - NATURAL SERIES - S1 MODE

Variable	Percentage Make-up Requirement				
	2	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)	60.0/50.0 (15.6/10.0)	40.0/37.0 (4.4/2.8)	30.0/28.0 (-1.1/-2.2)	20.0/20.0 (-6.7/-6.7)	10.0/10.0 (-12.2/-12.2)
Cold Water Temperature, °F (°C)	97.0 (36.1)	93.0 (33.9)	83.0 (28.3)	85.0 (29.4)	89.0 (31.7)
Cooling Range, °F (°C)	16.0 (8.89)	20.0 (11.1)	26.0 (14.4)	26.0 (14.4)	26.0 (14.4)
Tower ITD, °F (°C)	53.0 (29.4)	73.0 (40.6)	79.0 (43.9)	91.0 (50.6)	105.0 (58.3)
Condenser Heat Load, 10^9 Btu/hr (10^{12} J/hr)	4.51 (4.76)	4.51 (4.76)	4.49 (4.74)	4.50 (4.75)	4.52 (4.77)
Design Parameters for Wet Helper Tower:					
Dry Bulb/Wet Bulb Temperatures, °F (°C)	103.0/77.0 (39.4/25.0)	103.0/77.0 (39.4/25.0)	103.0/77.0 (39.4/25.0)	103.0/77.0 (39.4/25.0)	103.0/77.0 (39.4/25.0)
Tower Approach Temperature, °F (°C)	20.0 (11.1)	20.0 (11.1)	17.1 (9.5)	17.1 (9.5)	17.2 (9.6)
Design and Maximum Operating Back Pressure P_{max}, in-HgA (mmHgA)	5.0 (127.0)	5.0 (127.0)	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)	4.62 (4.87)	4.62 (4.87)	4.55 (4.80)	4.55 (4.80)	4.55 (4.80)
Heat Load Distribution at P_{max} - Wet Tower/ Dry Tower, %	61.6/38.4	76.1/23.9	87.1/12.9	89.7/10.3	92.0/8.0
Annual Make-up Water Requirement, 10^8 gal (10^6 m^3)	0.583 (0.221)	2.75 (1.04)	5.40 (2.04)	8.23 (3.12)	11.51 (4.36)

TABLE I-1 (continued)

Variable	Percentage Make-up Requirement				
	2	10	20	30	40
<u>Condenser</u>					
Surface Area, 10^3 ft^2 (10^3 m^2)	836 (77.7)	753 (70.0)	670 (62.2)	667 (62.0)	663 (61.6)
Number of Tubes	75,800	60,600	46,500	46,500	46,800
Tube Length, ft (m)	42.1 (12.8)	47.4 (14.4)	55.1 (16.8)	54.7 (16.7)	54.2 (16.5)
<u>Circulating Water Flow & Pump</u>					
Circulating Water Flow Rate, 10^3 gpm (m^3 /min)	563 (2131)	451 (1707)	345 (1306)	346 (1310)	347 (1314)
Number of Pumps	4	3	2	2	2
Pumping Head, ft (m) of Water	47.0 (14.3)	48.4 (14.8)	55.5 (16.9)	55.4 (16.9)	55.1 (16.8)
Motor Rating, hp (kW) per pump	2250 (1678)	2500 (1865)	3000 (2238)	3000 (2238)	3000 (2238)
Motor Brake Horsepower, hp (kW) per pump	1880 (1402)	2064 (1540)	2720 (2029)	2716 (2026)	2715 (2025)
<u>Flow & Booster Pump for Wet Tower</u>					
Percentage of Circulating Water to Wet Helper Tower	39.6	58.0	100.0	100.0	100.0
Number of Pumps	2	2	2	2	2
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	1750 (1306)	2000 (1492)	2500 (1865)	2500 (1865)	2500 (1865)
Motor Brake Horsepower, hp (kW) per pump	1297 (968)	1521 (1135)	2008 (1498)	2012 (1501)	2021 (1508)

TABLE I-1 (continued)

Variable	Percentage Make-up Requirement				
	2	10	20	30	40
Circulating Water Pipelines					
Condenser Intake:					
Number of Lines	1	1	1	1	1
Diameter/Length, in/ft (cm/m)	138/1870 (351/570)	126/1870 (320/570)	108/1870 (274/570)	108/1870 (274/570)	108/1870 (274/570)
Condenser Discharge:					
Number of Lines	1	1	1	1	1
Diameter/Length, in/ft (cm/m)	138/1440 (351/439)	126/1440 (320/439)	108/1440 (274/439)	108/1440 (274/439)	108/1440 (274/439)
Connecting Pipelines:					
Number of Lines	2	2	2	2	2
Diameter/Length, in/ft (cm/m)	96/890 (244/271)	90/890 (229/271)	78/890 (198/271)	78/890 (198/271)	78/890 (198/271)
Cooling Tower					
Dry Tower					
Diameter/Height, ft (m)	441/449 (134/137)	497/495 (151/151)	490/442 (149/135)	395/400 (120/122)	326/352 (99/107)
Number of Towers	2	1	1	1	1
Number of Heat Exchangers per Tower	268	302	298	240	198
Wet Tower					
Number of Cells	10	12	17	18	18

TABLE I-2. SUMMARY OF CAPITAL INVESTMENT COST FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS ($$10^6$)
AT KAIPAROWITS, UTAH - NATURAL SERIES - S1 MODE - 1985

Acct. No.	Equipment Item		Percentage Make-up Requirement				
			2	10	20	30	40
118L	Circulating Water Pump	(M	0.963	0.886	0.804	0.804	0.806
	Structures	(L	0.769	0.708	0.641	0.643	0.643
		(T	1.732	1.594	1.445	1.448	1.450
132.211	Circulating Water Pumps	(E	3.893	3.303	2.916	2.916	2.916
	and Motors	(M	0.039	0.033	0.029	0.029	0.029
		(L	0.316	0.263	0.211	0.211	0.211
		(T	4.249	3.600	3.156	3.156	3.156
132.25	Concrete Pipelines	(M	3.854	3.146	2.405	2.405	2.405
		(L	3.059	2.716	2.205	2.205	2.205
		(T	6.914	5.862	4.610	4.610	4.610
132.3211	Cooling Tower Basin	(M	0.934	0.944	1.241	1.287	1.268
	and Foundation	(L	2.535	2.189	2.652	2.677	2.579
		(T	3.469	3.133	3.893	3.964	3.847
132.3212	Cooling Towers, Installed	(E	37.510	23.565	23.736	19.940	16.945
		(M	0.379	0.238	0.240	0.201	0.171
		(L	30.833	19.436	19.040	15.748	13.156
		(T	68.722	43.239	43.016	35.889	30.272
133.1	Condensers, Installed	(E	7.989	7.155	6.368	6.349	6.327
		(M	0.040	0.036	0.032	0.032	0.032
		(L	4.376	4.058	3.749	3.744	3.740
		(T	12.406	11.249	10.149	10.125	10.098
114 &	Make-up Facilities	(E	2.522	2.924	3.226	3.292	3.343
132.1		(M	4.989	5.669	6.203	6.323	6.416
		(L	9.581	10.888	11.914	12.146	12.323
		(T	17.092	19.482	21.343	21.762	22.082
14	Electrical Equipment	(E	0.555	0.551	0.607	0.623	0.623
		(M	0.417	0.414	0.456	0.468	0.468
		(L	0.424	0.410	0.440	0.453	0.453
		(T	1.396	1.374	1.504	1.544	1.544
	Direct Capital Cost of	(E	52.469	37.498	36.853	33.120	30.154
	Cooling System	(M	11.615	11.366	11.410	11.549	11.595
		(L	51.893	40.688	40.852	37.827	35.310
		(T	115.977	89.532	89.115	82.496	77.059
	Indirect Cost		28.997	22.384	22.280	20.627	19.263
	Total Capital Cost		144.974	111.916	111.395	103.123	96.322

TABLE I-3. PENALTY BREAKDOWN AND COST SUMMARY FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS ($$10^6$)
AT KAIPAROWITS, UTAH - NATURAL SERIES - S1 MODE - 1985

Item	Percentage Make-up Requirement				
	2	10	20	30	40
Penalty Breakdown:					
Capacity Penalty	23.859	23.859	14.297	14.297	14.308
Replacement Energy Penalty	2.945	9.292	7.648	9.602	10.845
Penalty for Circulating Water Pumping Power Requirement	4.064	3.711	3.799	3.799	3.806
Penalty for Circulating Water Pumping Energy Requirement	2.403	2.271	2.447	2.604	2.851
Penalty for Cooling Tower Fan Power Requirement	0.691	0.833	1.192	1.210	1.220
Penalty for Cooling Tower Fan Energy Requirement	0.016	0.078	0.205	0.304	0.409
Make-up Water Purchase and Treatment Penalty	0.110	0.519	1.020	1.554	2.174
Make-up Water Pumping Energy and Capacity Penalty	2.895	3.785	4.576	4.982	5.406
Cooling System Maintenance Penalty	4.096	3.213	3.072	2.923	2.790
Cost Summary:					
Total Penalty Cost	41.078	47.561	38.256	41.274	43.808
Total Capital Cost	144.974	111.916	111.395	103.123	96.322
Total Evaluated Cost	186.052	159.477	149.651	144.397	140.130

APPENDIX J

SAN JUAN, NEW MEXICO
REFERENCE AND MECHANICAL SERIES WET/DRY COOLING SYSTEMS

This appendix contains two different items for San Juan, New Mexico:

1. Design data, capital investment and penalty breakdowns for the optimized reference cooling systems
2. Design data, capital investment and penalty breakdowns for the optimized mechanical series wet/dry cooling systems, S1 mode

TABLE J-1. SUMMARY OF DESIGN DATA FOR THE OPTIMIZED REFERENCE COOLING SYSTEMS AT 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, ^oF (^oC):			
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	22.0 (12.2)	12.0 (6.7)	26.0 (14.4)
ITD (Dry Tower) or Approach (Wet Tower)	63.0 (35.0)	27.0 (15.0)	23.0 (12.8)
Design Turbine Back Pressure, in-HgA (mm-HgA)	10.61 (269.5)	5.00 (127.0)	3.08 (78.2)
Maximum Operating Back Pressure, in-HgA (mm-HgA)	12.60 (320.0)	5.03 (127.8)	3.12 (79.2)
Design Heat Load, 10^9 Btu/hr (10^{12} J/hr)	4.80 (5.06)	4.62 (4.87)	4.50 (4.75)
Plant Capacity at Cooling System Design Point, MWe	935.8	989.0	1026.2
Annual Make-up Water Requirement, 10^8 gal. (10^6 m^3)	0.0	0.0	29.53 (11.18)

* This is not an optimized system because of the turbine back pressure limitation.

TABLE J-1 (continued)

Variable	Mechanical Dry (High BP Turbine)	Mechanical Dry* (Low BP Turbine)	Mechanical Wet (Low BP Turbine)
<u>Condenser</u>			
Surface Area, 10^3 ft^2 (10^3 m^2)	761 (70.7)	974 (90.5)	667 (62.0)
Number of Tubes	58,800	103,700	46,500
Tube Length, ft (m)	49.4 (15.1)	35.9 (10.9)	54.7 (16.7)
<u>Circulating Water Flow & Pump</u>			
Circulating Water Flow Rate, 10^3 gpm (m^3/min)	437 (1654)	770 (2915)	346 (1310)
Number of Pumps	3	5	2
Pumping Head, ft (m) of Water	63.6 (19.4)	50.5 (15.4)	90.4 (27.6)
Motor Rating, hp (kW) per pump	3000 (2237)	2500 (1864)	5000 (3729)
Motor Brake Horsepower, hp (kW) per pump	2626 (1958)	2209 (1647)	4434 (3306)

TABLE J-1 (continued)

Variable	Mechanical Dry (High BP Turbine)	Mechanical Dry* (Low BP Turbine)	Mechanical Wet (Low BP Turbine)
<u>Circulating Water Pipelines</u>			
Condenser Intake:			
Number of Lines	1	2	1
Diameter/Length, in/ft (cm/m)	120/1190 (305/363)	114/1190 (290/363)	108/1120 (274/341)
Condenser Discharge:			
Number of Lines	1	2	1
Diameter/Length, in/ft (cm/m)	120/540 (305/165)	114/540 (290/165)	108/940 (274/287)
Connecting Pipelines:			
Number of Lines	2	2	2
Diameter/Length, in/ft (cm/m)	84/1180 (213/360)	114/1180 (290/360)	78/710 (198/216)
<u>Cooling Tower</u>			
Size (Number of Cells):			
Dry Tower	112	274	-
Wet Tower	-	-	21

TABLE J-2. SUMMARY OF CAPITAL INVESTMENT COST FOR THE OPTIMIZED REFERENCE COOLING SYSTEMS ($$10^6$) AT SAN JUAN, NEW MEXICO - 1985

Acct. No.	Equipment Item		Mechanical Dry (High BP Turbine)	Mechanical Dry * (Low BP Turbine)	Mechanical Wet (Low BP Turbine)
118L	Circulating Water Pump Structures	(M	0.877	1.081	0.804
		(L	0.701	0.863	0.643
		(T	1.577	1.944	1.447
132.211	Circulating Water Pumps and Motors	(E	2.246	3.545	1.815
		(M	0.023	0.036	0.018
		(L	0.158	0.263	0.105
		(T	2.427	3.844	1.938
132.25	Concrete Pipelines	(M	2.032	3.621	1.641
		(L	1.821	3.101	1.472
		(T	3.853	6.722	3.113
132.3211	Cooling Tower Basin and Foundation	(M	0.342	0.837	1.362
		(L	0.614	1.505	2.450
		(T	0.956	2.342	3.812
132.3212	Cooling Towers, Installed	(E	33.831	82.764	5.160
		(M	0.342	0.836	0.052
		(L	3.940	9.638	3.366
		(T	38.113	93.238	8.578
133.1	Condensers, Installed	(E	7.172	9.472	6.349
		(M	0.036	0.048	0.032
		(L	4.053	4.937	3.744
		(T	11.261	14.457	10.125
114 & 132.1	Make-up Facilities	(E	-	-	2.030
		(M	-	-	1.929
		(L	-	-	3.608
		(T	-	-	7.567
14	Electrical Equipment	(E	1.516	3.397	0.634
		(M	1.139	2.552	0.476
		(L	2.702	6.504	0.408
		(T	5.357	12.453	1.517
	Direct Capital Cost of Cooling System	(E	44.765	99.179	15.989
		(M	4.790	9.011	6.314
		(L	13.988	26.810	15.797
		(T	63.543	135.000	38.100
	Indirect Cost		15.887	33.750	9.526
	Total Capital Cost		79.430	168.750	47.626

* This is not an optimized system because of the turbine back pressure limitation.

TABLE J-3. PENALTY BREAKDOWN AND COST SUMMARY FOR THE OPTIMIZED REFERENCE COOLING SYSTEMS ($$10^6$) AT SAN JUAN, NEW MEXICO - 1985

Item	Mechanical Dry (High BP Turbine)	Mechanical Dry* (Low BP Turbine)	Mechanical Wet (Low BP Turbine)
Penalty Breakdown:			
Capacity Penalty	57.535	24.267	6.480
Replacement Energy Penalty	29.617	0.489	2.234
Penalty for Circulating Water Pumping Power Requirement	3.166	4.439	3.564
Penalty for Circulating Water Pumping Energy Requirement	2.769	3.680	2.965
Penalty for Cooling Tower Fan Power Requirement	7.999	18.933	1.554
Penalty for Cooling Tower Fan Energy Requirement	6.458	13.770	1.265
Make-up Water Purchase and Treatment Penalty	0.0	0.0	5.579
Make-up Water Pumping Energy and Capacity Penalty	0.0	0.0	0.740
Cooling System Maintenance Penalty	3.913	8.156	1.809
Cost Summary:			
Total Penalty Cost	111.456	73.734	26.190
Total Capital Cost	79.430	168.750	47.626
Total Evaluated Cost	190.886	242.484	73.816

* This is not an optimized system because of the turbine back pressure limitation.

TABLE J-4. SUMMARY OF DESIGN DATA FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS AT SAN JUAN, NEW MEXICO - MECHANICAL SERIES - S1 MODE

Variable	Percentage Make-up Requirement				
	2	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)	60.0/45.0 (15.6/7.2)	45.0/36.5 (7.2/2.5)	35.0/30.0 (1.7/-1.1)	20.0/16.5 (-6.7/-8.6)
Cold Water Temperature, °F (°C)	95.0 (35.0)	95.0 (35.0)	86.0 (30.0)	84.0 (28.9)	78.0 (25.6)
Cooling Range, °F (°C)	17.0 (9.4)	22.0 (12.2)	26.0 (14.4)	26.0 (14.4)	30.0 (16.7)
Tower ITD, °F (°C)	42.0 (23.3)	57.0 (31.7)	67.0 (37.2)	75.0 (41.7)	88.0 (48.9)
Condenser Heat Load, 10^9 Btu/hr (10^{12} J/hr)	4.50 (4.75)	4.53 (4.78)	4.50 (4.75)	4.49 (4.74)	4.48 (4.73)
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)	22.3 (12.4)
Design and Maximum Operating Back Pressure P_{max}, in-HgA (mmHgA)	5.0 (127.0)	4.5 (114.3)	4.0 (101.6)	3.5 (88.9)	3.5 (88.9)
Condenser Heat Load at P_{max}, 10^9 Btu/hr (10^{12}J/hr)	4.62 (4.87)	4.59 (4.84)	4.55 (4.80)	4.52 (4.77)	4.52 (4.77)
Heat Load Distribution at P_{max}- Wet Tower/ Dry Tower, %	38.7/61.3	60.9/39.1	73.2/26.8	82.2/17.8	85.0/15.0
Annual Make-up Water Requirement, 10^8 gal (10^6 m^3)	0.625 (0.237)	2.90 (1.10)	5.97 (2.26)	8.85 (3.35)	11.90 (4.50)

TABLE J-4 (continued)

Variable	Percentage Make-up Requirement				
	2	10	20	30	40
Condenser					
Surface Area, 10^3 ft^2 (10^3 m^2)	812 (75.4)	719 (66.8)	666 (61.9)	669 (62.2)	632 (58.7)
Number of Tubes	71,300	55,400	46,600	46,500	40,200
Tube Length, ft (m)	43.5 (13.3)	49.6 (15.1)	54.6 (16.6)	54.9 (16.7)	60.0 (18.3)
Circulating Water Flow & Pump					
Circulating Water Flow Rate, 10^3 gpm (m^3 /min)	529 (2002)	412 (1560)	346 (1310)	345 (1306)	299 (1132)
Number of Pumps	3	3	2	2	2
Pumping Head, ft (m) of Water	62.5 (19.1)	66.3 (20.2)	71.5 (21.8)	76.3 (23.3)	80.5 (24.5)
Motor Rating, hp (kW) per pump	3500 (2610)	3000 (2237)	4000 (2983)	4000 (2983)	4000 (2983)
Motor Brake Horsepower, hp (kW) per pump	3128 (2333)	2583 (1926)	3512 (2619)	3740 (2789)	3413 (2545)
Flow & Booster Pump for Wet Tower					
Percentage of Circulating Water to Wet Helper Tower	23.2	50.2	79	98.2	100
Number of Pumps	2	2	2	2	2
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	1000 (746)	1500 (1119)	2000 (1491)	2500 (1864)	2000 (1491)
Motor Brake Horsepower, hp (kW) per pump	716 (534)	1202 (896)	1591 (1186)	1974 (1472)	1738 (1296)

TABLE J-4 (continued)

Variable	Percentage Make-up Requirement				
	2	10	20	30	40
Circulating Water Pipelines					
Condenser Intake:					
Number of Lines	1	1	1	1	1
Diameter/Length, in/ft (cm/m)	132/1980 (335/604)	120/1980 (305/604)	108/1980 (274/604)	108/1980 (274/604)	102/1980 (259/604)
Condenser Discharge:					
Number of Lines	1	1	1	1	1
Diameter/Length, in/ft (cm/m)	132/1490 (335/454)	120/1490 (305/454)	108/1490 (274/454)	108/1490 (274/454)	102/1490 (259/454)
Connecting Pipelines:					
Number of Lines	2	2	2	2	2
Diameter/Length, in/ft (cm/m)	96/760 (244/232)	84/760 (213/232)	78/760 (198/232)	78/760 (198/232)	72/760 (183/232)
Cooling Tower					
Size (Number of Cells):					
Dry Tower	161	117	98	84	70
Wet Tower	7	11	13	15	17

TABLE J-5. SUMMARY OF CAPITAL INVESTMENT COST FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS ($$10^6$)
AT SAN JUAN, NEW MEXICO - MECHANICAL SERIES - S1 MODE - 1985

Acct. No.	Equipment Item		Percentage Make-up Requirement				
			2	10	20	30	40
118L	Circulating Water Pump Structures	(M	0.942	0.858	0.804	0.804	0.762
		(L	0.751	0.584	0.643	0.643	0.609
		(T	1.693	1.543	1.447	1.447	1.371
132.211	Circulating Water Pumps and Motors	(E	3.182	3.099	2.833	3.075	2.995
		(M	0.032	0.031	0.029	0.021	0.030
		(L	0.263	0.263	0.211	0.211	0.211
		(T	3.477	3.393	3.073	3.317	3.236
132.25	Concrete Pipelines	(M	3.619	2.800	2.437	2.437	2.193
		(L	2.913	2.521	2.201	2.201	2.024
		(T	6.532	5.321	4.638	4.638	4.217
132.3211	Cooling Tower Basin and Foundation	(M	0.945	1.072	1.144	1.230	1.318
		(L	1.701	1.928	2.056	2.214	2.370
		(T	2.646	3.000	3.290	3.444	3.688
132.3212	Cooling Towers, Installed	(E	50.271	38.013	32.777	29.011	25.298
		(M	0.508	0.384	0.331	0.293	0.256
		(L	6.778	5.871	5.527	5.359	5.183
		(T	57.557	44.268	38.635	34.663	30.737
133.1	Condensers, Installed	(E	8.748	6.840	6.342	6.359	6.023
		(M	0.039	0.034	0.032	0.032	0.030
		(L	4.285	3.939	3.742	3.746	3.609
		(T	12.072	10.813	10.116	10.137	9.662
114 & 132.1	Make-up Facilities	(E	1.042	1.429	1.622	1.757	1.820
		(M	1.169	1.452	1.601	1.707	1.758
		(L	2.193	2.719	2.995	3.194	3.288
		(T	4.404	5.600	6.217	6.658	6.866
14	Electrical Equipment	(E	2.266	1.829	1.651	1.561	1.404
		(M	1.703	1.374	1.241	1.173	1.055
		(L	5.837	4.392	3.728	3.279	2.830
		(T	9.806	7.595	6.620	6.013	5.289
	Direct Capital Cost of Cooling System	(E	64.510	51.210	45.224	41.762	37.539
		(M	8.957	8.005	7.618	7.707	7.401
		(L	24.722	22.319	21.103	20.848	20.125
		(T	98.189	81.534	73.945	70.317	65.065
	Indirect Cost		24.548	20.384	18.487	17.579	16.266
	Total Capital Cost		122.737	101.918	92.432	87.896	81.331

TABLE J-6. PENALTY BREAKDOWN AND COST SUMMARY FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS ($\$10^6$) AT SAN JUAN, NEW MEXICO - MECHANICAL SERIES - S1 MODE - 1985

Item	Percentage Make-up Requirement				
	2	10	20	30	40
Penalty Breakdown:					
Capacity Penalty	24.007	19.373	14.297	9.638	9.638
Replacement Energy Penalty	4.479	8.039	8.544	6.995	7.982
Penalty for Circulating Water Pumping Power Requirement	3.771	4.079	4.101	4.592	4.140
Penalty for Circulating Water Pumping Energy Requirement	3.208	2.872	2.935	3.504	3.409
Penalty for Cooling Tower Fan Power Requirement	11.410	8.092	7.123	6.398	5.683
Penalty for Cooling Tower Fan Energy Requirement	8.979	6.643	5.684	5.007	4.419
Make-up Water Purchase and Treatment Penalty	0.104	0.483	0.995	1.474	1.983
Make-up Water Pumping Energy and Capacity Penalty	0.177	0.298	0.382	0.450	0.499
Cooling System Maintenance Penalty	5.641	4.710	4.191	4.044	3.743
Cost Summary:					
Total Penalty Cost	61.776	54.589	48.252	42.102	41.496
Total Capital Cost	122.737	101.918	92.432	87.896	81.331
Total Evaluated Cost	184.513	156.507	140.684	129.998	122.827

APPENDIX K

COLSTRIP, MONTANA - REFERENCE AND MECHANICAL SERIES WET/DRY COOLING SYSTEMS

This appendix contains two different items for Colstrip, Montana:

1. Design data, capital investment and penalty breakdowns for the optimized reference cooling systems
2. Design data, capital investment and penalty breakdowns for the optimized mechanical series wet/dry cooling systems, S1 mode

TABLE K-1. SUMMARY OF DESIGN DATA FOR THE OPTIMIZED REFERENCE COOLING SYSTEMS AT COLSTRIP, MONTANA

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	95.0 (35.0)	102.0 (38.9)	95.0 (35.0)
Wet Bulb	63.0 (17.2)	63.0 (17.2)	63.0 (17.2)
Cold Water	134.0 (56.7)	117.0 (47.2)	87.0 (30.6)
Cooling Range	24.0 (13.3)	12.0 (6.7)	24.0 (13.3)
ITD (Dry Tower) or Approach (Wet Tower)	63.0 (35.0)	27.0 (15.0)	24.0 (13.3)
Design Turbine Back Pressure, in-HgA (mm-HgA)	10.37 (263.4)	5.03 (127.8)	3.08 (78.2)
Maximum Operating Back Pressure, in-HgA (mm-HgA)	12.58 (319.6)	5.03 (127.8)	3.23 (82.0)
Design Heat Load, 10^9 Btu/hr (10^{12} J/hr)	4.80 (5.06)	4.62 (4.87)	4.50 (4.75)
Plant Capacity at Cooling System Design Point, MWe	937.9	989.0	1026.2
Annual Make-up Water Requirement, 10^8 gal. (10^6 m^3)	0.0	0.0	28.66 (10.85)

* This is not an optimized system because of the turbine back pressure limitation.

TABLE K-1 (continued)

Variable	Mechanical Dry (High BP Turbine)	Mechanical Dry* (Low BP Turbine)	Mechanical Wet (Low BP Turbine)
<u>Condenser</u>			
Surface Area, 10^3 ft^2 (10^3 m^2)	726 (67.4)	974 (90.4)	692 (64.3)
Number of Tubes	53,800	103,700	50,400
Tube Length, ft (m)	51.5 (15.7)	35.9 (10.9)	52.4 (16.0)
<u>Circulating Water Flow & Pump</u>			
Circulating Water Flow Rate, 10^3 gpm (m^3/min)	400 (1514)	770 (2915)	375 (1420)
Number of Pumps	3	6	3
Pumping Head, ft (m) of Water	64.0 (19.6)	53.5 (16.3)	89.2 (27.2)
Motor Rating, hp (kW) per pump	3000 (2238)	2250 (1678)	3500 (2611)
Motor Brake Horsepower, hp (kW) per pump	2420 (1805)	1949 (1454)	3160 (2357)

TABLE K-1 (continued)

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)	114/2090 (290/637)	114/2090 (290/637)	114/1680 (290/512)
Condenser Discharge:			
Number of Lines	1	2	1
Diameter/Length, in/ft (cm/m)	114/1820 (290/555)	114/1820 (290/555)	114/1530 (290/466)
Cooling Tower			
Size (Number of Cells):			
Dry Tower	112	268	-
Wet Tower	-	-	20

TABLE K-2. SUMMARY OF CAPITAL INVESTMENT COST FOR THE OPTIMIZED REFERENCE COOLING SYSTEMS ($$10^6$) AT COLSTRIP, MONTANA - 1985

Acct. No.	Equipment Item		Mechanical Dry (High BP Turbine)	Mechanical Dry* (Low BP Turbine)	Mechanical Wet (Low BP Turbine)
118L	Circulating Water Pump Structures	(M	0.848	1.081	0.829
		(L	0.678	0.863	0.662
		(T	1.526	1.944	1.491
132.211	Circulating Water Pumps and Motors	(E	2.002	3.648	2.122
		(M	0.020	0.037	0.021
		(L	0.158	0.316	0.158
		(T	2.181	4.000	2.301
132.25	Concrete Pipelines	(M	2.269	4.538	1.931
		(L	2.084	4.168	1.711
		(T	4.353	8.706	3.642
132.3211	Cooling Tower Basin and Foundation	(M	0.342	0.817	1.297
		(L	0.614	1.472	2.334
		(T	0.956	2.290	3.630
132.3212	Cooling Towers, Installed	(E	33.831	80.942	4.914
		(M	0.342	0.818	0.050
		(L	3.940	9.427	3.206
		(T	38.112	91.196	8.170
133.1	Condensers, Installed	(E	6.857	9.472	6.577
		(M	0.034	0.048	0.033
		(L	3.934	4.937	3.833
		(T	10.825	14.457	10.444
114 & 132.1	Make-up Facilities	(E	-	-	2.034
		(M	-	-	6.828
		(L	-	-	12.949
		(T	-	-	21.810
14	Electrical Equipment	(E	1.516	3.365	0.636
		(M	1.139	2.528	0.478
		(L	2.702	6.412	0.437
		(T	5.357	12.304	1.551
	Direct Capital Cost of Cooling System	(E	44.206	97.437	16.283
		(M	4.994	9.867	11.467
		(L	14.109	27.595	25.290
		(T	63.310	134.898	53.040
	Indirect Cost		15.827	33.725	13.260
	Total Capital Cost		79.137	168.623	66.300

* This is not an optimized system because of the turbine back pressure limitation.

TABLE K-3. PENALTY BREAKDOWN AND COST SUMMARY FOR THE OPTIMIZED REFERENCE COOLING SYSTEMS ($$10^6$) AT COLSTRIP, MONTANA - 1985

Item	Mechanical Dry (High BP Turbine)	Mechanical Dry* (Low BP Turbine)	Mechanical Wet (Low BP Turbine)
Penalty Breakdown:			
Capacity Penalty	57.433	24.267	7.409
Replacement Energy Penalty	25.673	-0.126	1.750
Penalty for Circulating Water Pumping Power Requirement	2.917	4.699	3.810
Penalty for Circulating Water Pumping Energy Requirement	2.258	3.456	2.813
Penalty for Cooling Tower Fan Power Requirement	7.882	18.317	1.507
Penalty for Cooling Tower Fan Energy Requirement	5.653	11.523	1.079
Make-up Water Purchase and Treatment Penalty	0.0	0.0	4.777
Make-up Water Pumping Energy and Capacity Penalty	0.0	0.0	3.361
Cooling System Maintenance Penalty	3.793	8.091	1.946
Cost Summary:			
Total Penalty Cost	105.608	70.226	28.452
Total Capital Cost	79.137	168.623	66.300
Total Evaluated Cost	184.745	238.849	94.752

* This is not an optimized system because of the turbine back pressure limitation.

TABLE K-4. SUMMARY OF DESIGN DATA FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS AT COLSTRIP, MONTANA - MECHANICAL SERIES - S1 MODE

Variable	Percentage Make-up Requirement				
	2	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)	70.0/52.0 (21.1/11.1)	50.0/42.0 (10.0/5.6)	40.0/34.0 (4.4/1.1)	30.0/25.0 (-1.1/-3.9)	15.0/11.0 (-9.4/-11.7)
Cold Water Temperature, °F (°C)	95.0 (35.0)	90.0 (32.2)	88.0 (31.1)	83.0 (28.3)	80.0 (26.7)
Cooling Range, °F (°C)	20.0 (11.1)	22.0 (12.2)	26.0 (14.4)	28.0 (15.6)	30.0 (16.7)
Tower ITD, °F (°C)	45.0 (25.0)	62.0 (34.4)	74.0 (41.1)	81.0 (45.0)	95.0 (52.8)
Condenser Heat Load, 10^9 Btu/hr (10^{12} J/hr)	4.52 (4.77)	4.50 (4.75)	4.51 (4.76)	4.50 (4.75)	4.49 (4.74)
Design Parameters for Wet Helper Tower:					
Dry Bulb/Wet Bulb Temperatures, °F (°C)	102.0/67.0 (38.9/19.4)	102.0/67.0 (38.9/19.4)	102.0/67.0 (38.9/19.4)	102.0/67.0 (38.9/19.4)	102.0/67.0 (38.9/19.4)
Tower Approach Temperature, °F (°C)	26.0 (14.4)	26.0 (14.4)	26.0 (14.4)	20.4 (11.3)	18.4 (10.2)
Design and Maximum Operating Back Pressure P_{max}, in-HgA (mmHgA)	5.01 (127.3)	4.50 (114.3)	4.00 (101.6)	3.50 (88.9)	3.50 (88.9)
Condenser Heat Load at P_{max}, 10^9 Btu/hr (10^{12} J/hr)	4.62 (4.87)	4.59 (4.84)	4.55 (4.80)	4.52 (4.77)	4.52 (4.77)
Heat Load Distribution at P_{max} - Wet Tower/Dry Tower, %	42.3/57.7	64.3/35.7	75.6/24.4	83.7/16.3	86.1/13.9
Annual Make-up Water Requirement, 10^8 gal (10^6 m^3)	0.518 (0.196)	3.05 (1.15)	6.03 (2.28)	8.72 (3.30)	11.45 (4.33)

TABLE K-4 (continued)

Variable	Percentage Make-up Requirement				
	2	10	20	30	40
<u>Condenser</u>					
Surface Area, 10^3 ft^2 (10^3 m^2)	753 (70.0)	720 (66.9)	664 (61.7)	645 (59.9)	627 (58.3)
Number of Tubes	60,800	55,100	46,700	43,200	40,300
Tube Length, ft (m)	47.3 (14.4)	49.9 (15.2)	54.3 (16.6)	57.0 (17.4)	59.5 (18.1)
<u>Circulating Water Flow & Pump</u>					
Circulating Water Flow Rate, 10^3 gpm (m^3 /min)	452 (1711)	409 (1548)	347 (1314)	321 (1215)	299 (1132)
Number of Pumps	3	3	2	2	2
Pumping Head, ft (m) of Water	59.8 (18.2)	70.6 (21.5)	75.5 (23.0)	81.5 (24.8)	84.8 (25. 8)
Motor Rating, hp (kW) per pump	3000 (2238)	3000 (2238)	4000 (2984)	4000 (2984)	4000 (2984)
Motor Brake Horsepower, hp (kW) per pump	2554 (1905)	2731 (2037)	3718 (2774)	3717 (2773)	3600 (2686)
<u>Flow & Booster Pump for Wet Tower</u>					
Percentage of Circulating Water to Wet Helper Tower	36.2	60.7	94.4	100.0	100.0
Number of Pumps	2	2	2	2	2
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)	2000 (1492)	2500 (1865)	2500 (1865)	2000 (1492)
Motor Brake Horsepower, hp (kW) per pump	951 (709)	1446 (1079)	1906 (1422)	1868 (1394)	1742 (1300)

TABLE K-4 (continued)

Variable	Percentage Make-up Requirement				
	2	10	20	30	40
<u>Circulating Water Pipelines</u>					
Condenser Intake:					
Number of Lines	1	1	1	1	1
Diameter/Length, in/ft (cm/m)	126/1770 (320/539)	120/1770 (305/539)	108/1770 (274/539)	102/1770 (259/539)	102/1770 (259/539)
Condenser Discharge:					
Number of Lines	1	1	1	1	1
Diameter/Length, in/ft (cm/m)	126/1900 (320/579)	120/1900 (305/579)	108/1900 (274/579)	102/1900 (259/579)	102/1900 (259/579)
Connecting Pipelines:					
Number of Lines	2	2	2	2	2
Diameter/Length, in/ft (cm/m)	90/680 (229/207)	84/680 (213/207)	78/680 (198/207)	72/680 (183/207)	72/680 (183/207)
<u>Cooling Tower</u>					
Size (Number of Cells):					
Dry Tower	153	100	84	75	62
Wet Tower	7	11	13	18	20

TABLE K-5. SUMMARY OF CAPITAL INVESTMENT COST FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS ($$10^6$)
AT COLSTRIP, MONTANA - MECHANICAL SERIES - S1 MODE - 1985

Acct. No.	Equipment Item		Percentage Make-up Requirement				
			2	10	20	30	40
118L	Circulating Water Pump Structures	(M	0.888	0.856	0.806	0.783	0.762
		(L	0.710	0.685	0.643	0.625	0.609
		(T	1.598	1.540	1.450	1.408	1.371
132.211	Circulating Water Pumps and Motors	(E	3.143	3.179	3.075	3.075	2.995
		(M	0.032	0.032	0.031	0.031	0.030
		(L	0.263	0.263	0.211	0.211	0.211
		(T	3.438	3.474	3.316	3.316	3.236
132.25	Concrete Pipelines	(M	3.245	2.834	2.470	2.223	2.223
		(L	2.775	2.579	2.249	2.070	2.070
		(T	6.021	5.413	4.718	4.293	4.293
132.3211	Cooling Tower Basin and Foundation	(M	0.923	1.020	1.100	1.398	1.488
		(L	1.658	1.834	1.981	2.514	2.677
		(T	2.580	2.854	3.081	3.913	4.165
132.3212	Cooling Towers, Installed	(E	47.877	32.902	28.534	27.043	23.614
		(M	0.484	0.332	0.288	0.273	0.239
		(L	6.495	5.271	5.033	5.515	5.380
		(T	54.856	38.506	33.855	32.831	29.232
133.1	Condensers, Installed	(E	7.159	6.840	6.330	6.154	5.996
		(M	0.036	0.034	0.032	0.031	0.030
		(L	4.060	3.937	3.740	3.669	3.602
		(T	11.255	10.811	10.102	9.853	9.628
114 & 132.1	Make-up Facilities	(E	1.114	1.487	1.659	1.812	1.865
		(M	4.090	5.127	5.639	6.115	6.283
		(L	7.760	9.725	10.695	11.597	11.916
		(T	12.964	16.339	17.993	19.524	20.064
14	Electrical Equipment	(E	2.163	1.676	1.531	1.506	1.361
		(M	1.625	1.259	1.150	1.132	1.023
		(L	5.562	3.813	3.250	3.018	2.604
		(T	9.350	6.749	5.931	5.656	4.987
	Direct Capital Cost of Cooling System	(E	61.456	46.084	41.129	39.590	35.831
		(M	11.323	11.494	11.516	11.986	12.078
		(L	29.283	28.107	27.802	29.219	29.069
		(T	102.062	85.685	80.447	80.795	76.978
	Indirect Cost		25.516	21.421	20.112	20.199	19.244
	Total Capital Cost		127.578	107.106	100.559	100.994	96.222

TABLE K-6. PENALTY BREAKDOWN AND COST SUMMARY FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS ($$10^6$) AT COLSTRIP, MONTANA - MECHANICAL SERIES - S1 MODE - 1985

Item	Percentage Make-up Requirement				
	2	10	20	30	40
Penalty Breakdown:					
Capacity Penalty	23.979	19.335	14.297	9.647	9.647
Replacement Energy Penalty	3.383	7.323	8.076	6.434	6.924
Penalty for Circulating Water Pumping Power Requirement	3.843	4.455	4.519	4.489	4.293
Penalty for Circulating Water Pumping Energy Requirement	2.332	2.785	2.970	3.128	3.139
Penalty for Cooling Tower Fan Power Requirement	9.925	6.933	6.123	5.943	5.267
Penalty for Cooling Tower Fan Energy Requirement	7.401	4.961	4.287	4.005	3.515
Make-up Water Purchase and Treatment Penalty	0.086	0.508	1.006	1.453	1.908
Make-up Water Pumping Energy and Capacity Penalty	0.924	1.496	1.856	2.185	2.380
Cooling System Maintenance Penalty	5.417	4.376	3.988	3.920	3.651
Cost Summary:					
Total Penalty Cost	57.291	52.171	47.121	41.205	40.723
Total Capital Cost	127.578	107.106	100.559	100.994	96.222
Total Evaluated Cost	184.869	159.277	147.680	142.199	136.945

APPENDIX L

YOUNG, NORTH DAKOTA - REFERENCE AND MECHANICAL SERIES WET/DRY COOLING SYSTEMS

This appendix contains two different items for Young, North Dakota:

1. Design data, capital investment and penalty breakdowns for the optimized reference cooling systems
2. Design data, capital investment and penalty breakdowns for the optimized mechanical series wet/dry cooling systems, S1 mode

TABLE L-1. SUMMARY OF DESIGN DATA FOR THE OPTIMIZED REFERENCE COOLING SYSTEMS AT YOUNG, NORTH DAKOTA

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	95.0 (35.0)	104.0 (40.0)	95.0 (35.0)
Wet Bulb	66.0 (18.9)	71.0 (21.7)	66.0 (18.9)
Cold Water	134.0 (56.7)	119.0 (48.3)	87.0 (30.6)
Cooling Range	22.0 (12.2)	10.0 (5.6)	26.0 (14.4)
ITD (Dry Tower) or Approach (Wet Tower)	61.0 (33.9)	25.0 (13.9)	21.0 (11.7)
Design Turbine Back Pressure, in-HgA (mm-HgA)	9.89 (251.2)	5.00 (127.0)	3.26 (82.8)
Maximum Operating Back Pressure, in-HgA (mm-HgA)	12.59 (319.8)	5.03 (127.8)	3.43 (87.1)
Design Heat Load, 10^9 Btu/hr (10^{12} J/hr)	4.78 (5.04)	4.62 (4.87)	4.51 (4.76)
Plant Capacity at Cooling System Design Point, MWe	941.9	989.0	1023.3
Annual Make-up Water Requirement, 10^8 gal. (10^6 m^3)	0.0	0.0	26.43 (10.0)

* This is not an optimized system because of the turbine back pressure limitation.

TABLE L-1 (continued)

Variable	Mechanical Dry (High BP Turbine)	Mechanical Dry* (Low BP Turbine)	Mechanical Wet (Low BP Turbine)
<u>Condenser</u>			
Surface Area, 10^3 ft^2 (10^3 m^2)	758 (70.4)	1049 (97.5)	665 (61.8)
Number of Tubes	58,500	124,400	46,600
Tube Length, ft (m)	49.4 (15.1)	32.2 (9.8)	54.4 (16.6)
<u>Circulating Water Flow & Pump</u>			
Circulating Water Flow Rate, 10^3 gpm (m^3/min)	435 (1647)	925 (3501)	347 (1314)
Number of Pumps	3	7	2
Pumping Head, ft (m) of Water	63.8 (19.4)	51.6 (15.7)	90.2 (27.5)
Motor Rating, hp (kW) per pump	3000 (2237)	2250 (1678)	5000 (3729)
Motor Brake Horsepower, hp (kW) per pump	2626 (1958)	1933 (1441)	4436 (3308)

TABLE L-1 (continued)

Variable	Mechanical Dry (High BP Turbine)	Mechanical Dry* (Low BP Turbine)	Mechanical Wet (Low BP Turbine)
<u>Circulating Water Pipelines</u>			
Condenser Intake:			
Number of Lines	1	2	1
Diameter/Length, in/ft (cm/m)	120/1190 (305/363)	126/1190 (320/363)	108/1120 (274/341)
Condenser Discharge:			
Number of Lines	1	2	1
Diameter/Length, in/ft (cm/m)	120/540 (305/165)	126/540 (320/165)	108/940 (274/287)
Connecting Pipelines:			
Number of Lines	2	2	2
Diameter/Length, in/ft (cm/m)	84/1180 (213/360)	126/1180 (320/360)	78/710 (198/216)
<u>Cooling Tower</u>			
Size (Number of Cells):			
Dry Tower	111	269	-
Wet Tower	-	-	21

TABLE L-2. SUMMARY OF CAPITAL INVESTMENT COST FOR THE OPTIMIZED REFERENCE COOLING SYSTEMS ($$10^6$) AT YOUNG, NORTH DAKOTA - 1985

Acct. No.	Equipment Item		Mechanical Dry (High BP Turbine)	Mechanical Dry* (Low BP Turbine)	Mechanical Wet (Low BP Turbine)
118L	Circulating Water Pump Structures	(M	0.875	1.157	0.806
		(L	0.698	0.925	0.643
		(T	1.573	2.083	1.449
132.211	Circulating Water Pumps and Motors	(E	2.246	4.255	1.815
		(M	0.023	0.043	0.018
		(L	0.158	0.369	0.105
		(T	2.427	4.666	1.938
132.25	Concrete Pipelines	(M	2.032	4.483	1.641
		(L	1.821	3.568	1.472
		(T	3.853	8.051	3.113
132.3211	Cooling Tower Basin and Foundation	(M	0.338	0.821	1.362
		(L	0.609	1.477	2.450
		(T	0.947	2.298	3.812
132.3212	Cooling Towers, Installed	(E	33.529	81.254	5.160
		(M	0.339	0.821	0.052
		(L	3.903	9.461	3.366
		(T	37.771	91.536	8.578
133.1	Condensers, Installed	(E	7.148	10.420	6.336
		(M	0.036	0.052	0.032
		(L	4.044	5.301	3.742
		(T	11.228	15.773	10.110
114 & 132.1	Make-up Facilities	(E	-	-	2.010
		(M	-	-	3.543
		(L	-	-	6.686
		(T	-	-	12.239
14	Electrical Equipment	(E	1.505	3.449	0.634
		(M	1.131	2.591	0.476
		(L	2.679	6.481	0.408
		(T	5.315	12.521	1.518
	Direct Capital Cost of Cooling System	(E	44.428	99.377	15.955
		(M	4.773	9.969	7.930
		(L	13.913	27.581	18.874
		(T	63.114	136.927	42.759
	Indirect Cost		15.778	34.232	10.689
	Total Capital Cost		78.892	171.159	53.448

* This is not an optimized system because of the turbine back pressure limitation.

TABLE L-3. PENALTY BREAKDOWN AND COST SUMMARY FOR THE OPTIMIZED REFERENCE COOLING SYSTEMS ($$10^6$)
AT YOUNG, NORTH DAKOTA - 1985

Item	Mechanical Dry (High BP Turbine)	Mechanical Dry* (Low BP Turbine)	Mechanical Wet (Low BP Turbine)
Penalty Breakdown:			
Capacity Penalty	57.489	24.267	9.056
Replacement Energy Penalty	18.447	-0.349	1.322
Penalty for Circulating Water Pumping Power Requirement	3.165	5.436	3.565
Penalty for Circulating Water Pumping Energy Requirement	1.770	2.935	1.930
Penalty for Cooling Tower Fan Power Requirement	7.959	18.431	1.597
Penalty for Cooling Tower Fan Energy Requirement	4.112	7.704	0.834
Make-up Water Purchase and Treatment Penalty	0.0	0.0	4.404
Make-up Water Pumping Energy and Capacity Penalty	0.0	0.0	0.828
Cooling System Maintenance Penalty	3.890	8.444	1.809
Cost Summary:			
Total Penalty Cost	96.833	66.868	25.345
Total Capital Cost	78.892	171.159	53.448
Total Evaluated Cost	175.725	238.027	78.793

* This is not an optimized system because of the turbine back pressure limitation.

TABLE L-4. SUMMARY OF DESIGN DATA FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS AT YOUNG, NORTH DAKOTA - MECHANICAL SERIES - S1 MODE

Variable	Percentage Make-up Requirement				
	2	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)	60.0/50.0	50.0/43.0	35.0/31.0	20.0/17.0	0.0/-3.0
Cold Water Temperature, °F (°C)	89.0	93.0	82.0	83.0	80.0
Cooling Range, °F (°C)	18.0	26.0	28.0	30.0	30.0
Tower ITD, °F (°C)	47.0	69.0	75.0	93.0	110.0
Condenser Heat Load, 10^9 Btu/hr (10^{12} J/hr)	4.48	4.54	4.49	4.51	4.49
Design Parameters for Wet Helper Tower:					
Dry Bulb/Wet Bulb Temperatures, °F (°C)	104.0/70.0	104.0/70.0	104.0/70.0	104.0/70.0	104.0/70.0
Tower Approach Temperature, °F (°C)	26.0	26.0	22.0	20.1	20.0
Design and Maximum Operating Back Pressure P_{max}, in-HgA (mmHgA)	5.0	5.0	4.0	4.0	4.0
Condenser Heat Load at P_{max}, 10^9 Btu/hr (10^{12} J/hr)	4.62	4.62	4.55	4.55	4.55
Heat Load Distribution at P_{max}- Wet Tower/ Dry Tower, %	49.4/50.6	64.4/35.6	78.5/21.5	82.6/17.4	85.5/14.5
Annual Make-up Water Requirement, 10^8 gal (10^6 m^3)	0.613	2.61	5.18	7.94	10.92

TABLE L-4 (continued)

Variable	Percentage Make-up Requirement				
	2	10	20	30	40
Condenser					
Surface Area, 10^3 ft^2 (10^3 m^2)	794 (73.8)	662 (61.5)	647 (60.1)	622 (57.8)	627 (58.3)
Number of Tubes	67,000	47,000	43,200	40,400	40,300
Tube Length, ft (m)	45.3 (13.8)	53.8 (16.4)	57.2 (17.4)	58.8 (17.9)	59.5 (18.1)
Circulating Water Flow & Pump					
Circulating Water Flow Rate, 10^3 gpm (m^3 /min)	498 (1885)	349 (1321)	321 (1215)	300 (1136)	299 (1132)
Number of Pumps	3	2	2	2	2
Pumping Head, ft (m) of Water	66.1 (20.1)	73.3 (22.3)	79.2 (24.1)	84.2 (25.7)	97.3 (29.7)
Motor Rating, hp (kW) per pump	3500 (2610)	4000 (2983)	4000 (2983)	4000 (2983)	4500 (3356)
Motor Brake Horsepower, hp (kW) per pump	3109 (2318)	3634 (2710)	3605 (2688)	3587 (2675)	4131 (3080)
Flow & Booster Pump for Wet Tower					
Percentage of Circulating Water to Wet Helper Tower	39.3	73.3	100	100	100
Number of Pumps	2	2	2	2	2
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)	2000 (1491)	2500 (1864)	2000 (1491)	2000 (1491)
Motor Brake Horsepower, hp (kW) per pump	1138 (849)	1489 (1110)	1866 (1391)	1747 (1303)	1742 (1299)

TABLE L-4 (continued)

Variable	Percentage Make-up Requirement				
	2	10	20	30	40
Circulating Water Pipelines					
Condenser Intake:					
Number of Lines	1	1	1	1	1
Diameter/Length, in/ft (cm/m)	132/1980 (335/604)	108/1980 (274/604)	102/1980 (259/604)	102/1980 (259/604)	102/1980 (259/604)
Condenser Discharge:					
Number of Lines	1	1	1	1	1
Diameter/Length, in/ft (cm/m)	132/1490 (335/454)	108/1490 (274/454)	102/1490 (259/454)	102/1490 (259/454)	102/1490 (254/454)
Connecting Pipelines:					
Number of Lines	2	2	2	2	2
Diameter/Length, in/ft (cm/m)	90/760 (229/232)	78/760 (198/232)	72/760 (183/232)	72/760 (183/232)	72/760 (183/232)
Cooling Tower					
Size (Number of Cells):					
Dry Tower	133	91	82	63	50
Wet Tower	8	10	15	17	17

TABLE L-5. SUMMARY OF CAPITAL INVESTMENT COST FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS ($$10^6$)
AT YOUNG, NORTH DAKOTA - MECHANICAL SERIES - S1 MODE - 1985

Acct. No.	Equipment Item		Percentage Make-up Requirement				
			2	10	20	30	40
118L	Circulating Water Pump Structures	(M	0.921	0.808	0.783	0.764	0.762
		(L	0.735	0.646	0.625	0.609	0.609
		(T	1.656	1.454	1.408	1.373	1.371
132.211	Circulating Water Pumps and Motors	(E	3.262	2.833	3.075	2.995	3.075
		(M	0.033	0.029	0.031	0.030	0.031
		(L	0.263	0.211	0.211	0.211	0.211
		(T	3.558	3.073	3.317	3.236	3.317
132.25	Concrete Pipelines	(M	3.547	2.437	2.193	2.193	2.193
		(L	2.858	2.201	2.024	2.024	2.024
		(T	6.405	4.638	4.217	4.217	4.217
132.3211	Cooling Tower Basin and Foundation	(M	0.926	0.926	1.224	1.297	1.257
		(L	1.665	1.667	2.203	2.334	2.260
		(T	2.591	2.593	3.427	3.631	3.517
132.3212	Cooling Towers, Installed	(E	42.112	29.938	28.425	23.173	19.256
		(M	0.425	0.302	0.287	0.234	0.195
		(L	5.950	4.794	5.284	4.931	4.480
		(T	48.487	35.034	33.996	28.338	23.931
133.1	Condensers, Installed	(E	7.545	6.323	6.163	5.962	5.996
		(M	0.038	0.032	0.031	0.030	0.030
		(L	4.204	3.740	3.671	3.595	3.602
		(T	11.787	10.095	9.865	9.587	9.628
114 & 132.1	Make-up Facilities	(E	1.211	1.468	1.688	1.758	1.799
		(M	2.352	2.713	3.040	3.147	3.210
		(L	4.443	5.122	5.738	5.940	6.058
		(T	8.006	9.303	10.466	10.845	11.067
14	Electrical Equipment	(E	2.009	1.531	1.539	1.327	1.218
		(M	1.509	1.150	1.156	0.997	0.915
		(L	4.894	3.444	3.211	2.592	2.148
		(T	8.412	6.125	5.906	4.916	4.281
	Direct Capital Cost of Cooling System	(E	56.139	42.092	40.889	35.215	31.344
		(M	9.752	8.398	8.746	8.692	8.592
		(L	25.013	21.824	22.968	22.237	21.392
		(T	90.904	72.313	72.603	66.144	61.328
	Indirect Cost		22.726	18.078	18.150	16.536	15.332
	Total Capital Cost		113.630	90.391	90.753	82.680	76.660

TABLE L-6. PENALTY BREAKDOWN AND COST SUMMARY FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS ($\$10^6$) AT YOUNG, NORTH DAKOTA - MECHANICAL SERIES - S1 MODE - 1985

Item	Percentage Make-up Requirement				
	2	10	20	30	40
Penalty Breakdown:					
Capacity Penalty	23.900	23.859	14.297	14.297	14.297
Replacement Energy Penalty	2.484	6.570	5.092	6.637	7.529
Penalty for Circulating Water Pumping Power Requirement	4.663	4.117	4.397	4.286	4.720
Penalty for Circulating Water Pumping Energy Requirement	2.098	1.810	2.037	2.165	2.548
Penalty for Cooling Tower Fan Power Requirement	8.855	6.389	6.197	5.113	4.337
Penalty for Cooling Tower Fan Energy Requirement	4.687	3.376	3.140	2.524	2.120
Make-up Water Purchase and Treatment Penalty	0.102	0.435	0.864	1.323	1.820
Make-up Water Pumping Energy and Capacity Penalty	0.293	0.402	0.508	0.561	0.604
Cooling System Maintenance Penalty	5.084	3.955	3.990	3.587	3.340
Cost Summary:					
Total Penalty Cost	52.166	50.913	40.522	40.493	41.315
Total Capital Cost	113.630	90.391	90.753	82.680	76.660
Total Evaluated Cost	165.796	141.304	131.275	123.173	117.975

APPENDIX M

ROCK SPRINGS, WYOMING
REFERENCE AND MECHANICAL SERIES WET/DRY COOLING SYSTEMS

This appendix contains two different items for Rock Springs, Wyoming:

1. Design data, capital investment and penalty breakdowns for the optimized reference cooling systems
2. Design data, capital investment and penalty breakdowns for the optimized mechanical series wet/dry cooling systems, S1 mode

TABLE M-1. SUMMARY OF DESIGN DATA FOR THE OPTIMIZED REFERENCE COOLING SYSTEMS AT ROCK SPRINGS, WYOMING

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	88.0 (31.1)	93.0 (33.9)	88.0 (31.1)
Wet Bulb	55.0 (12.8)	56.0 (13.3)	55.0 (12.8)
Cold Water	131.0 (55.0)	108.0 (42.2)	83.0 (28.3)
Cooling Range	24.0 (13.3)	21.0 (11.7)	26.0 (14.4)
ITD (Dry Tower) or Approach (Wet Tower)	67.0 (37.2)	36.0 (20.0)	28.0 (15.6)
Design Turbine Back Pressure, in-HgA (mm-HgA)	9.65 (245.1)	5.03 (127.8)	2.91 (73.9)
Maximum Operating Back Pressure, in-HgA (mm-HgA)	11.21 (284.7)	5.03 (127.8)	2.94 (74.7)
Design Heat Load, 10^9 Btu/hr (10^{12} J/hr)	4.78 (5.04)	4.62 (4.87)	4.49 (4.74)
Plant Capacity at Cooling System Design Point, MWe	943.8	989.0	1028.8
Annual Make-up Water Requirement, 10^8 gal. (10^6 m^3)	0.0	0.0	28.03 (10.61)

* This is not an optimized system because of the turbine back pressure limitation.

TABLE M-1 (continued)

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)	723 (67.2)	750 (69.7)	670 (62.2)
Number of Tubes	53,600	59,300	46,500
Tube Length, ft (m)	51.5 (15.7)	48.3 (14.7)	55.1 (16.8)
Circulating Water Flow & Pump			
Circulating Water Flow Rate, 10^3 gpm (m^3/min)	398 (1507)	440 (1666)	345 (1306)
Number of Pumps	3	3	2
Pumping Head, ft (m) of Water	62.6 (19.1)	53.0 (16.2)	90.6 (27.6)
Motor Rating, hp (kW) per pump	3000 (2238)	2500 (1865)	5000 (3730)
Motor Brake Horsepower, hp (kW) per pump	2356 (1758)	2207 (1646)	4436 (3309)

TABLE M-1 (continued)

Variable	Mechanical Dry (High BP Turbine)	Mechanical Dry* (Low BP Turbine)	Mechanical Wet (Low BP Turbine)
<u>Circulating Water Pipelines</u>			
Condenser Intake:			
Number of Lines	1	1	1
Diameter/Length, in/ft (cm/m)	114/1190 (290/363)	120/1190 (305/363)	108/1120 (274/341)
Condenser Discharge:			
Number of Lines	1	1	1
Diameter/Length, in/ft (cm/m)	114/540 (290/165)	120/540 (305/165)	108/710 (274/216)
Connecting Pipelines:			
Number of Lines	2	2	2
Diameter/Length, in/ft (cm/m)	84/1180 (213/360)	84/1180 (213/360)	78/940 (198/287)
<u>Cooling Tower</u>			
Size (Number of Cells):			
Dry Tower	108	249	-
Wet Tower	-	-	20

TABLE M-2. SUMMARY OF CAPITAL INVESTMENT COST FOR THE OPTIMIZED REFERENCE COOLING SYSTEMS ($$10^6$) AT ROCK SPRINGS, WYOMING - 1985

Acct. No.	Equipment Item		Mechanical Dry (High BP Turbine)	Mechanical Dry* (Low BP Turbine)	Mechanical Wet (Low BP Turbine)
118L	Circulating Water Pump Structures	(M	0.848	0.881	0.804
		(L	0.678	0.703	0.641
		(T	1.526	1.584	1.445
132.211	Circulating Water Pumps and Motors	(E	2.002	2.127	1.815
		(M	0.020	0.021	0.018
		(L	0.158	0.158	0.105
		(T	2.181	2.307	1.939
132.25	Concrete Pipelines	(M	1.942	2.032	1.641
		(L	1.754	1.821	1.472
		(T	3.697	3.853	3.113
132.3211	Cooling Tower Basin and Foundation	(M	0.329	0.760	1.297
		(L	0.593	1.367	2.334
		(T	0.922	2.127	3.630
132.3212	Cooling Towers, Installed	(E	32.622	75.213	4.914
		(M	0.330	0.760	0.050
		(L	3.799	8.757	3.206
		(T	36.751	84.730	8.170
133.1	Condensers, Installed	(E	6.832	7.110	6.368
		(M	0.034	0.036	0.032
		(L	3.925	4.037	3.749
		(T	10.792	11.183	10.149
114 & 132.1	Make-up Facilities	(E	-	-	1.950
		(M	-	-	8.310
		(L	-	-	15.779
		(T	-	-	26.038
14	Electrical Equipment	(E	1.472	2.961	0.619
		(M	1.106	2.225	0.465
		(L	2.611	5.839	0.392
		(T	5.189	11.025	1.476
	Direct Capital Cost of Cooling System	(E	42.928	87.411	15.666
		(M	4.609	6.715	12.617
		(L	13.518	22.682	27.678
		(T	61.055	116.808	55.961
	Indirect Cost		15.264	29.202	13.990
	Total Capital Cost		76.319	146.010	69.951

* This is not an optimized system because of the turbine back pressure limitation.

TABLE M-3. PENALTY BREAKDOWN AND COST SUMMARY FOR THE OPTIMIZED REFERENCE COOLING SYSTEMS ($$10^6$)
AT ROCK SPRINGS, WYOMING - 1985

Item	Mechanical Dry (High BP Turbine)	Mechanical Dry* (Low BP Turbine)	Mechanical Wet (Low BP Turbine)
Penalty Breakdown:			
Capacity Penalty	52.389	24.267	5.145
Replacement Energy Penalty	27.488	0.369	1.744
Penalty for Circulating Water Pumping Power Requirement	2.841	2.660	3.565
Penalty for Circulating Water Pumping Energy Requirement	2.364	2.104	2.826
Penalty for Cooling Tower Fan Power Requirement	7.616	16.994	1.478
Penalty for Cooling Tower Fan Energy Requirement	5.853	12.194	1.149
Make-up Water Purchase and Treatment Penalty	0.0	0.0	4.983
Make-up Water Pumping Energy and Capacity Penalty	0.0	0.0	2.868
Cooling System Maintenance Penalty	3.704	6.836	1.783
Cost Summary:			
Total Penalty Cost	102.254	65.425	25.541
Total Capital Cost	76.319	146.010	69.951
Total Evaluated Cost	178.573	211.435	95.492

* This is not an optimized system because of the turbine back pressure limitation.

TABLE M-4. SUMMARY OF DESIGN DATA FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS AT ROCK SPRINGS, WYOMING - MECHANICAL SERIES - S1 MODE

Variable	Percentage Make-up Requirement				
	2	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)	55.0/41.5 (12.8/5.3)	45.0/36.0 (7.2/2.2)	30.0/25.5 (-1.1/-3.6)	15.0/13.0 (-9.4/-10.6)	0.0/-2.0 (-17.8/-16.7)
Cold Water Temperature, °F (°C)	87.0 (30.6)	86.0 (30.6)	79.0 (26.1)	72.0 (22.2)	72.0 (22.2)
Cooling Range, °F (°C)	20.0 (11.1)	22.0 (12.2)	26.0 (14.4)	32.0 (17.8)	34.0 (18.9)
Tower ITD, °F (°C)	52.0 (28.9)	63.0 (35.0)	75.0 (41.7)	89.0 (49.4)	106.0 (58.9)
Condenser Heat Load, 10^9 Btu/hr (10^{12} J/hr)	4.48 (4.73)	4.48 (4.73)	4.47 (4.72)	4.47 (4.72)	4.48 (4.73)
Design Parameters for Wet Helper Tower:					
Dry Bulb/Wet Bulb Temperatures, °F (°C)	93.0/56.0 (33.9/13.3)	93.0/56.0 (33.9/13.3)	93.0/56.0 (33.9/13.3)	93.0/56.0 (33.9/13.3)	93.0/56.0 (33.9/13.3)
Tower Approach Temperature, °F (°C)	32.0 (17.8)	32.0 (17.8)	32.0 (17.8)	26.5 (14.7)	24.1 (13.4)
Design and Maximum Operating Back Pressure P_{max}, in-HgA (mmHgA)	5.00 (127.0)	4.00 (101.6)	3.50 (88.9)	3.50 (88.9)	3.50 (88.9)
Condenser Heat Load at P_{max}, 10^9 Btu/hr (10^{12} J/hr)	4.62 (4.87)	4.55 (4.80)	4.52 (4.77)	4.52 (4.77)	4.52 (4.77)
Heat Load Distribution at P_{max}- Wet Tower/Dry Tower, %	34.6/65.4	57.5/42.5	70.7/29.3	76.2/23.8	80.2/19.8
Annual Make-up Water Requirement, 10^8 gal (10^6 m^3)	0.551 (0.209)	2.78 (1.05)	5.88 (2.23)	8.58 (3.25)	11.63 (4.40)

TABLE M-4 (continued)

Variable	Percentage Make-up Requirement				
	2	10	20	30	40
Condenser					
Surface Area, 10^3 ft^2 (10^3 m^2)	758 (70.4)	724 (67.3)	679 (63.1)	591 (54.9)	557 (51.7)
Number of Tubes	60,300	54,800	46,300	37,600	35,500
Tube Length, ft (m)	48.0 (14.6)	50.4 (15.4)	56.0 (17.1)	60.0 (18.3)	60.0 (18.3)
Circulating Water Flow & Pump					
Circulating Water Flow Rate, 10^3 gpm (m^3 /min)	448 (1696)	408 (1544)	344 (1302)	279 (1056)	263 (996)
Number of Pumps	3	3	2	2	2
Pumping Head, ft (m) of Water	64.4 (19.6)	70.4 (21.5)	76.5 (23.3)	82.3 (25.1)	85.1 (25.9)
Motor Rating, hp (kW) per pump	3000 (2238)	3000 (2238)	4000 (2984)	4000 (2984)	3500 (2611)
Motor Brake Horsepower, hp (kW) per pump	2727 (2034)	2713 (2024)	3734 (2786)	3262 (2433)	3182 (2374)
Flow & Booster Pump for Wet Tower					
Percentage of Circulating Water to Wet Helper Tower	26.1	56.1	93.6	100	100
Number of Pumps	2	2	2	2	2
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	1000 (746)	2000 (1492)	2500 (1865)	2000 (1492)	2000 (1492)
Motor Brake Horsepower, hp (kW) per pump	679 (507)	1330 (992)	1872 (1397)	1625 (1212)	1533 (1144)

TABLE M-4 (continued)

Variable	Percentage Make-up Requirement				
	2	10	20	30	40
Circulating Water Pipelines					
Condenser Intake:					
Number of Lines	1	1	1	1	1
Diameter/Length, in/ft (cm/m)	126/1980 (320/604)	120/1980 (305/604)	108/1980 (274/604)	96/1980 (244/604)	96/1980 (244/604)
Condenser Discharge:					
Number of Lines	1	1	1	1	1
Diameter/Length, in/ft (cm/m)	126/1490 (320/454)	120/1490 (305/454)	108/1490 (274/454)	96/1490 (244/454)	96/1490 (244/454)
Connecting Pipelines:					
Number of Lines	2	2	2	2	2
Diameter/Length, in/ft (cm/m)	90/760 (229/232)	84/760 (213/232)	78/760 (198/232)	66/760 (168/232)	66/760 (168/232)
Cooling Tower					
Size (Number of Cells):					
Dry Tower	129	103	85	72	58
Wet Tower	6	10	12	16	18

TABLE M-5. SUMMARY OF CAPITAL INVESTMENT COST FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS ($$10^6$)
AT ROCK SPRINGS, WYOMING - MECHANICAL SERIES - S1 MODE - 1985

Acct. No.	Equipment Item		Percentage Make-up Requirement				
			2	10	20	30	40
118L	Circulating Water Pump Structures	(M	0.884	0.856	0.802	0.743	0.728
		(L	0.708	0.682	0.641	0.593	0.582
		(T	1.592	1.538	1.443	1.336	1.309
132.211	Circulating Water Pumps and Motors	(E	3.063	3.179	3.075	2.670	2.591
		(M	0.031	0.032	0.031	0.027	0.026
		(L	0.263	0.263	0.211	0.211	0.211
		(T	3.358	3.474	3.316	2.908	2.827
132.25	Concrete Pipelines	(M	3.197	2.800	2.437	1.883	1.883
		(L	2.714	2.521	2.201	1.853	1.853
		(T	5.911	5.321	4.638	3.736	3.736
132.3211	Cooling Tower Basin and Foundation	(M	0.783	0.965	1.039	1.259	1.347
		(L	1.408	1.734	1.869	2.265	2.423
		(T	2.191	2.698	2.908	3.523	3.769
132.3212	Cooling Towers, Installed	(E	40.396	33.558	28.588	25.639	21.928
		(M	0.408	0.339	0.289	0.259	0.221
		(L	5.494	5.217	4.904	5.091	4.920
		(T	46.299	39.114	33.781	30.989	27.070
133.1	Condensers, Installed	(E	7.180	6.864	6.424	5.713	5.458
		(M	0.036	0.034	0.032	0.029	0.027
		(L	4.062	3.941	3.765	3.506	3.419
		(T	11.278	10.840	10.221	9.247	8.904
114 & 132.1	Make-up Facilities	(E	0.928	1.324	1.525	1.638	1.710
		(M	4.507	5.851	6.599	7.038	7.325
		(L	8.562	11.113	12.531	13.365	13.910
		(T	13.996	18.288	20.655	22.041	22.946
14	Electrical Equipment	(E	1.854	1.695	1.527	1.411	1.255
		(M	1.393	1.273	1.147	1.060	0.943
		(L	4.727	3.900	3.268	2.885	2.437
		(T	7.974	6.868	5.942	5.357	4.635
	Direct Capital Cost of Cooling System	(E	53.421	46.620	41.139	37.071	32.943
		(M	11.239	12.150	12.376	12.298	12.501
		(L	27.938	29.371	29.389	29.769	29.753
		(T	92.599	88.142	82.903	79.138	75.197
	Indirect Cost		23.149	22.035	20.726	19.784	18.799
	Total Capital Cost		115.748	110.177	103.629	98.922	93.996

TABLE M-6. PENALTY BREAKDOWN AND COST SUMMARY FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS ($$10^6$) AT ROCK SPRINGS, WYOMING - MECHANICAL SERIES - SI MODE - 1985

Item	Percentage Make-up Requirement				
	2	10	20	30	40
Penalty Breakdown:					
Capacity Penalty	23.859	14.297	9.638	9.638	9.638
Replacement Energy Penalty	4.478	5.345	5.683	7.198	7.728
Penalty for Circulating Water Pumping Power Requirement	3.288	4.340	4.506	3.928	3.789
Penalty for Circulating Water Pumping Energy Requirement	2.666	2.894	3.127	2.997	3.038
Penalty for Cooling Tower Fan Power Requirement	8.959	7.075	6.167	5.599	4.867
Penalty for Cooling Tower Fan Energy Requirement	6.745	5.468	4.636	4.136	3.585
Make-up Water Purchase and Treatment Penalty	0.098	0.495	1.045	1.524	2.068
Make-up Water Pumping Energy and Capacity Penalty	0.626	1.116	1.465	1.707	1.917
Cooling System Maintenance Penalty	4.836	4.414	3.986	3.604	3.309
Cost Summary:					
Total Penalty Cost	55.555	45.444	40.254	40.331	39.939
Total Capital Cost	115.748	110.177	103.629	98.922	93.996
Total Evaluated Cost	171.303	155.621	143.883	139.253	133.935

APPENDIX N

NEW HAMPTON, NEW YORK
REFERENCE AND MECHANICAL SERIES WET/DRY COOLING SYSTEMS

This appendix contains two different items for New Hampton, New York:

1. Design data, capital investment and penalty breakdowns for the optimized reference cooling systems
2. Design data, capital investment and penalty breakdowns for the optimized mechanical series wet/dry cooling systems, S1 mode

TABLE N-1. SUMMARY OF DESIGN DATA FOR THE OPTIMIZED REFERENCE COOLING SYSTEMS AT NEW HAMPTON, NEW YORK

Variable	Mechanical Dry (High BP Turbine)	Mechanical Dry* (Low BP Turbine)	Mechanical Wet (Low BP Turbine)
<u>General Design Data</u>			
Design Temperatures, ^{o}F (^{o}C):			
Dry Bulb	92.0 (33.3)	96.0 (35.6)	92.0 (33.3)
Wet Bulb	72.0 (22.2)	74.0 (23.3)	72.0 (22.2)
Cold Water	131.0 (55.0)	114.0 (45.6)	87.0 (30.6)
Cooling Range	24.0 (13.3)	12.0 (6.7)	22.0 (12.2)
ITD (Dry Tower) or Approach (Wet Tower)	63.0 (35.0)	30.0 (16.7)	15.0 (8.3)
Design Turbine Back Pressure, in-HgA (mm-HgA)	9.65 (245.1)	4.65 (118.1)	2.91 (73.9)
Maximum Operating Back Pressure, in-HgA (mm-HgA)	11.72 (297.7)	5.07 (128.8)	3.05 (77.5)
Design Heat Load, 10^9 Btu/hr (10^{12} J/hr)	4.78 (5.04)	4.60 (4.85)	4.49 (4.74)
Plant Capacity at Cooling System Design Point, MWe	943.8	996.5	1028.8
Annual Make-up Water Requirement, 10^8 gal. (10^6 m^3)	0.0	0.0	26.96 (10.21)

* This is not an optimized system because of the turbine back pressure limitation.

TABLE N-1 (continued)

Variable	Mechanical Dry (High BP Turbine)	Mechanical Dry* (Low BP Turbine)	Mechanical Wet (Low BP Turbine)
<u>Condenser</u>			
Surface Area, 10^3 ft^2 (10^3 m^2)	723 (67.2)	969 (90.0)	723 (67.2)
Number of Tubes	53,600	103,100	54,900
Tube Length, ft (m)	51.5 (15.7)	35.9 (10.9)	50.3 (15.3)
<u>Circulating Water Flow & Pump</u>			
Circulating Water Flow Rate, 10^3 gpm (m^3/min)	398 (1507)	766 (2900)	408 (1544)
Number of Pumps	3	6	3
Pumping Head, ft (m) of Water	63.1 (19.2)	55.2 (16.8)	86.7 (26.4)
Motor Rating, hp (kW) per pump	3000 (2237)	2250 (1678)	4000 (2983)
Motor Brake Horsepower, hp (kW) per pump	2375 (1771)	2000 (1491)	3345 (2494)

TABLE N-1 (continued)

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)	114/1190 (290/363)	114/1190 (290/363)	120/1120 (305/341)
Condenser Discharge:			
Number of Lines	1	2	1
Diameter/Length, in/ft (cm/m)	114/540 (290/165)	114/540 (290/165)	120/940 (305/287)
Connecting Pipelines:			
Number of Lines	2	2	2
Diameter/Length, in/ft (cm/m)	84/1180 (213/360)	114/1180 (290/360)	84/710 (213/216)
Cooling Tower			
Size (Number of Cells):			
Dry Tower	106	217	-
Wet Tower	-	-	27

TABLE N-2. SUMMARY OF CAPITAL INVESTMENT COST FOR THE OPTIMIZED REFERENCE COOLING SYSTEMS ($10^6) AT NEW HAMPTON, NEW YORK - 1985

Acct. No.	Equipment Item		Mechanical Dry (High BP Turbine)	Mechanical Dry* (Low BP Turbine)	Mechanical Wet (Low BP Turbine)
118L	Circulating Water Pump Structures	(M	0.848	1.079	0.856
		(L	0.678	0.863	0.682
		(T	1.526	1.942	1.538
132.211	Circulating Water Pumps and Motors	(E	2.003	3.647	2.240
		(M	0.020	0.037	0.023
		(L	0.158	0.316	0.158
		(T	2.181	4.000	2.421
132.25	Concrete Pipelines	(M	1.943	3.621	1.890
		(L	1.754	3.101	1.679
		(T	3.697	6.722	3.569
132.3211	Cooling Tower Basin and Foundation	(M	0.323	0.663	1.752
		(L	0.581	1.191	3.151
		(T	0.904	1.854	4.903
132.3212	Cooling Towers, Installed	(E	32.018	65.547	6.635
		(M	0.324	0.662	0.067
		(L	3.728	7.632	4.328
		(T	36.070	73.841	11.030
133.1	Condensers, Installed	(E	6.833	9.427	6.857
		(M	0.034	0.047	0.034
		(L	3.925	4.919	3.939
		(T	10.792	14.393	10.830
114 & 132.1	Make-up Facilities	(E	-	-	2.015
		(M	-	-	5.841
		(L	-	-	11.068
		(T	-	-	18.924
14	Electrical Equipment	(E	1.450	2.808	0.786
		(M	1.090	2.110	0.591
		(L	2.565	5.244	0.545
		(T	5.105	10.162	1.922
	Direct Capital Cost of Cooling System	(E	42.303	81.429	18.534
		(M	4.582	8.220	11.054
		(L	13.390	23.265	25.550
		(T	60.275	112.914	55.138
	Indirect Cost		15.068	28.228	13.784
	Total Capital Cost		75.343	141.142	68.922

* This is not an optimized system because of the turbine back pressure limitation.

TABLE N-3. PENALTY BREAKDOWN AND COST SUMMARY FOR THE OPTIMIZED REFERENCE COOLING SYSTEMS ($$10^6$) AT NEW HAMPTON, NEW YORK - 1985

Item	Mechanical Dry (High BP Turbine)	Mechanical Dry* (Low BP Turbine)	Mechanical Wet (Low BP Turbine)
Penalty Breakdown:			
Capacity Penalty	54.290	24.715	5.990
Replacement Energy Penalty	118.089	1.030	2.359
Penalty for Circulating Water Pumping Power Requirement	2.863	4.823	4.032
Penalty for Circulating Water Pumping Energy Requirement	10.204	16.131	13.495
Penalty for Cooling Tower Fan Power Requirement	7.549	15.002	2.056
Penalty for Cooling Tower Fan Energy Requirement	24.900	44.498	6.676
Make-up Water Purchase and Treatment Penalty	-	-	0.299
Make-up Water Pumping Energy and Capacity Penalty	-	-	5.461
Cooling System Maintenance Penalty	3.661	6.980	2.205
Cost Summary:			
Total Penalty Cost	221.556	113.179	42.573
Total Capital Cost	75.343	141.142	69.922
Total Evaluated Cost	296.899	254.321	111.495

* This is not an optimized system because of the turbine back pressure limitation.

TABLE N-4. SUMMARY OF DESIGN DATA FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS AT NEW HAMPTON, NEW YORK - MECHANICAL SERIES - S1 MODE

Variable	Percentage Make-up Requirement				
	2	10	20	30	40
<u>General Design Data</u>					
Mode of Wet/Dry Tower Operation	S1	S1	S1	S1	S1
Design Parameters for Dry Towers:					
Dry Bulb/Wet Bulb Temperatures, °F (°C)	70.0/59.5 (21.1/15.3)	55.0/49.0 (12.8/9.4)	45.0/39.0 (7.2/3.9)	30.0/26.0 (-1.1/-3.3)	15.0/12.0 (-9.4/-11.1)
Cold Water Temperature, °F (°C)	100.0 (37.8)	89.0 (31.7)	86.0 (30.0)	83.0 (28.3)	82.0 (27.8)
Cooling Range, °F (°C)	18.0 (10.0)	22.0 (12.2)	24.0 (13.3)	26.0 (14.4)	26.0 (14.4)
Tower ITD, °F (°C)	48.0 (26.7)	56.0 (31.1)	65.0 (36.1)	79.0 (43.9)	93.0 (51.7)
Condenser Heat Load, 10^9 Btu/hr (10^{12} J/hr)	4.54 (4.79)	4.50 (4.75)	4.49 (4.74)	4.49 (4.74)	4.48 (4.73)
Design Parameters for Wet Helper Tower:					
Dry Bulb/Wet Bulb Temperatures, °F (°C)	99.0/75.0 (37.2/23.9)	99.0/75.0 (37.2/23.9)	99.0/75.0 (37.2/23.9)	99.0/75.0 (37.2/23.9)	99.0/75.0 (37.2/23.9)
Tower Approach Temperature, °F (°C)	20.0 (11.1)	20.0 (11.1)	16.4 (9.1)	14.4 (8.0)	14.3 (7.9)
Design and Maximum Operating Back Pressure P_{max}, in-HgA (mmHgA)	5.0 (127.0)	4.0 (101.6)	3.5 (88.9)	3.5 (88.9)	3.5 (88.9)
Condenser Heat Load at P_{max}, 10^9 Btu/hr (10^{12} J/hr)	4.62 (4.87)	4.55 (4.80)	4.52 (4.77)	4.52 (4.77)	4.52 (4.77)
Heat Load Distribution at P_{max} - Wet Tower/Dry Tower, %	39.4/60.6	62.5/37.5	74.9/25.1	79.3/20.7	82.4/17.6
Annual Make-up Water Requirement, 10^8 gal (10^6 m^3)	0.518 (0.196)	2.71 (1.03)	5.44 (2.06)	8.22 (3.11)	10.90 (4.13)

TABLE N-4 (continued)

Variable	Percentage Make-up Requirement				
	2	10	20	30	40
Condenser					
Surface Area, 10^3 ft^2, (10^3 m^2)	794 (73.8)	721 (67.0)	693 (64.4)	670 (62.2)	672 (62.4)
Number of Tubes	67,800	55,000	50,400	46,500	46,400
Tube Length, ft (m)	44.7 (13.6)	50.1 (15.3)	52.6 (16.0)	55.1 (16.8)	55.3 (16.9)
Circulating Water Flow & Pump					
Circulating Water Flow Rate, 10^3 gpm (m^3 /min)	504 (1908)	409 (1548)	374 (1416)	345 (1306)	345 (1306)
Number of Pumps	3	3	3	2	2
Pumping Head, ft (m) of Water	66.8 (20.4)	68.2 (20.8)	74.2 (22.6)	81.9 (25.0)	93.4 (28.5)
Motor Rating, hp (kW) per pump	3500 (2610)	3000 (2237)	3000 (2237)	4500 (3356)	5000 (3729)
Motor Brake Horsepower, hp (kW) per pump	3182 (2373)	2636 (1966)	2625 (1957)	4010 (2990)	4570 (3408)
Flow & Booster Pump for Wet Tower					
Percentage of Circulating Water to Wet Helper Tower, %	32.0	81.6	100.0	100.0	100.0
Number of Pumps	2	2	3	2	2
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	937 (699)	1941 (1447)	1451 (1082)	2008 (1497)	2006 (1496)

TABLE N-4 (continued)

Variable	Percentage Make-up Requirement				
	2	10	20	30	40
<u>Circulating Water Pipelines</u>					
Condenser Intake:					
Number of Lines	1	1	1	1	1
Diameter/Length, in/ft (cm/m)	132/1980 (335/604)	120/1980 (305/604)	114/1980 (290/604)	108/1980 (274/604)	108/1980 (274/604)
Condenser Discharge:					
Number of Lines	1	1	1	1	1
Diameter/Length, in/ft (cm/m)	132/1490 (335/454)	120/1490 (305/454)	114/1490 (290/454)	108/1490 (274/454)	108/1490 (274/454)
Connecting Pipelines:					
Number of Lines	2	2	2	2	2
Diameter/Length, in/ft (cm/m)	90/760 (229/232)	84/760 (213/232)	78/760 (198/232)	78/760 (198/232)	78/760 (198/232)
<u>Cooling Tower</u>					
Size (Number of Cells):					
Dry Tower	129	110	92	73	59
Wet Tower	8	13	18	21	21

TABLE N-5. SUMMARY OF CAPITAL INVESTMENT COST FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS ($$10^6$)
AT NEW HAMPTON, NEW YORK - MECHANICAL SERIES - S1 MODE - 1985

Acct. No.	Equipment Item		Percentage Make-up Requirement				
			2	10	20	30	40
118L	Circulating Water Pump Structures	(M	0.924	0.855	0.829	0.804	0.804
		(L	0.740	0.685	0.662	0.641	0.641
		(T	1.664	1.540	1.491	1.445	1.445
132.211	Circulating Water Pumps and Motors	(E	3.262	3.421	3.767	3.154	3.233
		(M	0.033	0.035	0.038	0.032	0.033
		(L	0.263	0.263	0.316	0.211	0.211
		(T	3.558	3.719	4.121	3.397	3.477
132.25	Concrete Pipelines	(M	3.547	2.800	2.580	2.437	2.437
		(L	2.858	2.521	2.336	2.201	2.201
		(T	6.405	5.321	4.916	4.638	4.638
132.3211	Cooling Tower Basin and Foundation	(M	0.913	1.180	1.450	1.587	1.545
		(L	1.644	2.123	2.608	2.856	2.778
		(T	2.557	3.303	4.058	4.443	4.323
132.3212	Cooling Towers, Installed	(E	40.918	36.390	32.173	27.176	22.947
		(M	0.413	0.368	0.325	0.274	0.232
		(L	5.816	5.951	6.112	5.929	5.436
		(T	47.147	42.709	38.610	33.379	28.615
133.1	Condensers, Installed	(E	7.564	6.845	6.585	6.368	6.382
		(M	0.038	0.034	0.033	0.032	0.032
		(L	4.213	3.937	3.836	3.749	3.753
		(T	11.815	10.816	10.454	10.149	10.167
114 & 132.1	Make-up Facilities	(E	1.034	1.423	1.634	1.715	1.759
		(M	3.383	4.287	4.817	5.028	5.145
		(L	6.415	8.124	9.127	9.527	9.750
		(T	10.832	13.834	15.578	16.270	16.654
14	Electrical Equipment	(E	1.965	1.847	1.757	1.561	1.441
		(M	1.477	1.388	1.320	1.173	1.082
		(L	4.758	4.184	3.689	2.995	2.517
		(T	8.200	7.419	6.766	5.729	5.040
	Direct Capital Cost of Cooling System	(E	54.742	49.927	45.915	39.973	35.763
		(M	10.728	10.947	11.392	11.367	11.310
		(L	26.709	27.788	28.687	28.109	27.286
		(T	92.179	88.662	85.994	79.449	74.359
	Indirect Cost		23.045	22.166	21.499	19.863	18.590
	Total Capital Cost		115.224	110.828	107.493	99.312	92.949

TABLE N-6. PENALTY BREAKDOWN AND COST SUMMARY FOR THE OPTIMIZED WET/DRY COOLING SYSTEMS ($\$10^6$) AT NEW HAMPTON, NEW YORK - MECHANICAL SERIES - S1 MODE - 1985

Item	Percentage Make-up Requirement				
	2	10	20	30	40
Penalty Breakdown:					
Capacity Penalty	23.986	14.297	9.647	9.647	9.638
Replacement Energy Penalty	21.196	23.448	22.183	28.986	32.146
Penalty for Circulating Water Pumping Power Requirement	4.590	4.737	4.914	4.836	5.285
Penalty for Circulating Water Pumping Energy Requirement	13.306	12.471	14.278	15.333	17.632
Penalty for Cooling Tower Fan Power Requirement	8.558	7.799	7.083	6.075	5.225
Penalty for Cooling Tower Fan Energy Requirement	28.993	25.199	21.725	18.126	15.472
Make-up Water Purchase and Treatment Penalty	0.006	0.030	0.060	0.091	0.121
Make-up Water Pumping Energy and Capacity Penalty	0.679	1.351	1.956	2.448	2.888
Cooling System Maintenance Penalty	4.999	4.750	4.650	4.006	3.736
Cost Summary:					
Total Penalty Cost	106.253	94.082	86.496	89.548	92.143
Total Capital Cost	115.224	110.828	107.493	99.312	92.949
Total Evaluated Cost	221.477	204.910	193.989	188.860	185.092

APPENDIX O

SITE COMPARISONS

This appendix contains the design data, and capital and penalty costs information developed for the wet/dry towers for water conservation during the alternate site evaluations.

TABLE O-1. MAJOR DESIGN DATA FOR THE OPTIMIZED COOLING TOWER SYSTEMS

SITE: SAN JUAN, NEW MEXICO BASE OUTPUT: 1039 MWe WET/DRY TYPE: MECHANICAL SERIES (S1)

Item	Mech. Dry (H)*	Mech. Dry (L)†	Percentage Make-up Requirement# Mechanical Series Wet/Dry					Mech. Wet
			2	10	20	30	40	
Number of Tower Cells, Wet Tower/Dry Tower	0/112	0/274	7/161	11/117	13/98	15/84	17/70	21/0
Maximum Operating Back Pressure P_{max}, in-HgA (mm-HgA)	12.60 (320.0)	5.03 (127.8)	5.0 (127.0)	4.5 (114.3)	4.0 (101.6)	3.5 (88.9)	3.5 (88.9)	3.12 (79.2)
Gross Plant Output at P_{max}, MWe	920.4	989.0	989.5	999.1	1009.5	1019.1	1019.1	1025.6
Heat Load at P_{max}, 10^9 Btu/hr (10^{12} J/hr)	4.86 (5.13)	4.62 (4.87)	4.62 (4.87)	4.59 (4.84)	4.55 (4.80)	4.52 (4.77)	4.52 (4.77)	4.50 (4.75)
Heat Load Distribution at P_{max}, (Wet Tower/Dry Tower), %	0.0/100.0	0.0/100.0	38.7/61.3	60.9/39.1	73.2/26.8	82.2/17.8	85.0/15.0	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)	0.625 (0.237)	2.90 (1.10)	5.97 (2.26)	8.85 (3.35)	11.90 (4.50)	29.53 (11.18)

* H-High Back Pressure Turbine

† L-Conventional Low Back Pressure Turbine

\# Percentage of annual make-up required by optimized wet tower

TABLE O-2. MAJOR CAPITAL AND PENALTY COST COMPONENTS FOR OPTIMIZED COOLING TOWER SYSTEMS ($10^6)

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

	Mech. Dry (H)*	Mech. Dry (L)†	Percentage Make-up Requirement-Mech. Ser. Wet/Dry					Mech. Wet
			2	10	20	30	40	
Capital Cost:								
Cooling Tower	39.07	95.58	60.20	47.27	41.84	38.11	34.43	12.39
Condenser	11.26	14.46	12.07	10.81	10.12	10.14	9.66	10.13
Circulating Water System	7.86	12.51	11.70	10.26	9.16	9.40	8.82	6.50
Make-up Facility	0.00	0.00	4.41	5.60	6.21	6.66	6.87	7.56
Electrical Equipment	5.36	12.45	9.81	7.60	6.62	6.01	5.29	1.52
Indirect Cost	15.88	33.75	24.55	20.38	18.48	17.58	16.26	9.53
Total Capital Cost	79.43	168.75	122.74	101.92	92.43	87.90	81.33	47.63
Penalty Cost:								
Capacity	57.54	24.27	24.01	19.37	14.30	9.64	9.64	6.48
Auxiliary Power	11.16	23.37	15.35	12.44	11.55	11.35	10.20	5.56
Replacement Energy	29.62	0.49	4.48	8.04	8.54	7.00	7.98	2.23
Auxiliary Energy	9.23	17.45	12.20	9.55	8.68	8.60	7.95	4.53
Make-up Water	0.0	0.0	0.10	0.48	0.99	1.47	1.98	4.92
Cooling System Maintenance	3.91	8.15	5.64	4.71	4.19	4.04	3.75	1.81
Total Penalty	111.46	73.73	61.78	54.59	48.25	42.10	41.50	25.53

* H-High Back Pressure Turbine

† L-Conventional Low Back Pressure Turbine

TABLE O-3. MAJOR DESIGN DATA FOR THE OPTIMIZED COOLING TOWER SYSTEMS

SITE: COLSTRIP, MONTANA BASE OUTPUT: 1039 MWe WET/DRY TYPE: MECHANICAL SERIES (S1)

Item	Mech. Dry (H)*	Mech. Dry (L)†	Percentage Make-up Requirement# Mechanical Series Wet/Dry					Mech. Wet
			2	10	20	30	40	
Number of Tower Cells, Wet Tower/Dry Tower	0/112	0/268	7/153	11/100	13/84	18/75	20/62	20/0
Maximum Operating Back Pressure P_{max}, in-HgA (mm-HgA)	12.58 (319.6)	5.03 (127.8)	5.01 (127.3)	4.50 (114.3)	4.00 (101.6)	3.50 (88.9)	3.50 (88.9)	3.23 (82.0)
Gross Plant Output at P_{max}, MWe	920.6	988.9	989.6	999.1	1009.5	1019.1	1019.1	1023.7
Heat Load at P_{max}, 10^9 Btu/hr (10^{12} J/hr)	4.62 (4.87)	4.86 (5.13)	4.52 (4.77)	4.50 (4.75)	4.51 (4.76)	4.50 (4.75)	4.49 (4.74)	4.50 (4.75)
Heat Load Distribution at P_{max}, (Wet Tower/Dry Tower), %	0.0/ 100.0	0.0/ 100.0	42.7/ 57.7	64.3/ 35.7	75.6/ 24.4	83.7/ 16.3	86.1/ 13.9	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)	0.518 (0.196)	3.05 (1.15)	6.03 (2.28)	8.72 (3.30)	11.45 (4.33)	28.66 (10.85)

* H-High Back Pressure Turbine

† L-Conventional Low Back Pressure Turbine

Percentage of annual make-up required by optimized wet tower

TABLE O-4. MAJOR CAPITAL AND PENALTY COST COMPONENTS FOR OPTIMIZED COOLING TOWER SYSTEMS ($$10^6$)

SITE: COLSTRIP, MONTANA YEAR: 1985 WET/DRY TYPE: MECHANICAL SERIES (S1)

	Mech. Dry (H)*	Mech. Dry (L)†	Percentage Make-up Requirement-Mech. Ser. Wet/Dry					Mech. Wet
			2	10	20	30	40	
Capital Cost:								
Cooling Tower	39.07	93.49	57.44	41.36	36.94	36.74	33.40	11.80
Condenser	10.82	14.46	11.26	10.81	10.10	9.85	9.63	10.44
Circulating Water System	8.06	14.65	11.06	10.43	9.48	9.02	8.90	7.43
Make-up Facility	0.00	0.00	12.96	16.34	17.99	19.52	20.06	21.81
Electrical Equipment	5.36	12.30	9.35	6.75	5.93	5.66	4.99	1.55
Indirect Cost	15.83	33.72	25.52	21.42	20.11	20.20	19.24	13.26
Total Capital Cost	79.14	168.62	127.58	107.11	100.56	100.99	96.22	66.30
Penalty Cost:								
Capacity	57.43	24.27	23.98	19.34	14.30	9.65	9.65	7.41
Auxiliary Power	10.80	23.02	14.67	12.75	12.23	12.24	11.44	7.47
Replacement Energy	25.67	-0.13	3.38	7.32	8.08	6.43	6.92	1.75
Auxiliary Energy	7.91	14.98	9.76	7.88	7.52	7.51	7.15	5.12
Make-up Water	0.00	0.00	0.09	0.51	1.01	1.45	1.91	4.78
Cooling System Maintenance	3.79	8.09	5.42	4.38	3.99	3.92	3.65	1.95
Total Penalty	105.61	70.23	57.29	52.17	47.12	41.20	40.72	28.45

* H-High Back Pressure Turbine

† L-Conventional Low Back Pressure Turbine

TABLE O-5. MAJOR DESIGN DATA FOR THE OPTIMIZED COOLING TOWER SYSTEMS

SITE: YOUNG, NORTH DAKOTA BASE OUTPUT: 1039 MWe WET/DRY TYPE: MECHANICAL SERIES (S1)

Item	Mech. Dry (H)*	Mech. Dry (L)†	Percentage Make-up Requirement# Mechanical Series Wet/Dry					Mech. Wet
			2	10	20	30	40	
Number of Tower Cells, Wet Tower/Dry Tower	0/111	0/269	8/133	10/91	15/82	17/63	17/50	21/0
Maximum Operating Back Pressure P_{max}, in-HgA (mm-HgA)	12.59 (319.8)	5.03 (127.8)	5.0 (127.0)	5.0 (127.0)	4.0 (101.6)	4.0 (101.6)	4.0 (101.6)	3.43 (87.1)
Gross Plant Output at P_{max}, MWe	920.5	989.0	989.7	989.8	1009.5	1009.5	1009.5	1020.3
Heat Load at P_{max}, 10^9 Btu/hr (10^{12} J/hr)	4.86 (5.13)	4.62 (4.87)	4.62 (4.87)	4.62 (4.87)	4.55 (4.80)	4.55 (4.80)	4.55 (4.80)	4.52 (4.77)
Heat Load Distribution at P_{max}, (Wet Tower/Dry Tower), %	0.0/ 100.0	0.0/ 100.0	49.4/ 50.6	64.4/ 35.6	78.5/ 21.5	82.6/ 17.4	85.5/ 14.5	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)	0.613 (0.232)	2.61 (0.99)	5.18 (1.96)	7.94 (3.01)	10.92 (4.13)	26.43 (10.00)

* H-High Back Pressure Turbine

† L-Conventional Low Back Pressure Turbine

\# Percentage of annual make-up required by optimized wet tower

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

SITE: YOUNG, NORTH DAKOTA YEAR: 1985 WET/DRY TYPE: MECHANICAL SERIES (S1)

	Mech. Dry (H)*	Mech. Dry (L)†	Percentage Make-up Requirement-Mech. Ser. Wet/Dry					Mech. Wet
			2	10	20	30	40	
Capital Cost:								
Cooling Tower	38.72	93.83	51.08	37.63	37.42	31.97	27.45	12.39
Condenser	11.23	15.77	11.79	10.09	9.87	9.59	9.63	10.11
Circulating Water System	7.85	14.80	11.62	9.16	8.94	8.83	8.91	6.50
Make-up Facility	0.0	0.0	8.01	9.30	10.46	10.84	11.06	12.24
Electrical Equipment	5.32	12.52	8.41	6.13	5.91	4.92	4.28	1.52
Indirect Cost	15.77	34.24	22.73	18.08	18.15	16.53	15.33	10.69
Total Capital Cost	78.89	171.16	113.63	90.39	90.75	82.68	76.66	53.45
Penalty Cost:								
Capacity	57.49	24.27	23.90	23.86	14.30	14.30	14.30	9.06
Auxiliary Power	11.12	23.87	13.81	10.88	11.06	9.89	9.56	5.75
Replacement Energy	18.45	-0.35	2.48	6.57	5.09	6.64	7.53	1.32
Auxiliary Energy	5.88	10.64	6.79	5.21	5.22	4.76	4.77	3.00
Make-up Water	0.0	0.0	0.10	0.44	0.86	1.32	1.82	4.40
Cooling System Maintenance	3.89	8.44	5.08	3.96	3.99	3.59	3.34	1.81
Total Penalty	96.83	66.87	52.16	50.92	40.52	40.50	41.32	25.34

* H-High Back Pressure Turbine

† L-Conventional Low Back Pressure Turbine

TABLE O-7. MAJOR DESIGN DATA FOR THE OPTIMIZED COOLING TOWER SYSTEMS

SITE: ROCK SPRINGS, WYOMING   BASE OUTPUT: 1039 MWe   WET/DRY TYPE: MECHANICAL SERIES (S1)

Item	Mech. Dry (H)*	Mech. Dry (L)†	Percentage Make-up Requirement# Mechanical Series Wet/Dry					Mech. Wet
			2	10	20	30	40	
Number of Tower Cells, Wet Tower/Dry Tower	0/108	0/249	6/129	10/103	12/85	16/72	18/58	20/0
Maximum Operating Back Pressure P_{max}, in-HgA (mm-HgA)	11.21 (284.7)	5.03 (127.8)	5.00 (127.0)	4.00 (101.6)	3.50 (88.9)	3.50 (88.9)	3.50 (88.9)	2.94 (74.7)
Gross Plant Output at P_{max}, MWe	931.0	989.0	989.8	1009.5	1019.1	1019.1	1019.1	1028.4
Heat Load at P_{max}, 10^9 Btu/hr (10^{12} J/hr)	4.82 (5.08)	4.62 (4.87)	4.62 (4.87)	4.55 (4.80)	4.52 (4.77)	4.52 (4.77)	4.52 (4.77)	4.49 (4.74)
Heat Load Distribution at P_{max}, (Wet Tower/Dry Tower), %	0.0/ 100.0	0.0/ 100.0	34.6/ 65.4	57.5/ 42.5	70.7/ 29.3	76.2/ 23.8	80.2/ 19.8	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)	0.551 (0.209)	2.78 (1.05)	5.88 (2.23)	8.58 (3.25)	11.63 (4.40)	28.03 (10.61)

* H-High Back Pressure Turbine

† L-Conventional Low Back Pressure Turbine

\# Percentage of annual make-up required by optimized wet tower

TABLE O-8. MAJOR CAPITAL AND PENALTY COST COMPONENTS FOR OPTIMIZED COOLING TOWER SYSTEMS ($$10^6$)

SITE: ROCK SPRINGS, WYOMING YEAR: 1985 WET/DRY TYPE: MECHANICAL SERIES (S1)

	Mech. Dry (H)*	Mech. Dry (L)†	Percentage Make-up Requirement-Mech. Ser. Wet/Dry					Mech. Wet
			2	10	20	30	40	
Capital Cost:								
Cooling Tower	37.67	86.86	48.49	41.81	36.69	33.51	30.84	11.80
Condenser	10.79	11.18	11.28	10.84	10.22	9.25	8.90	10.15
Circulating Water System	7.40	7.74	10.86	10.33	9.40	7.98	7.87	6.50
Make-up Facility	0.00	0.00	14.00	18.29	20.66	22.04	22.95	26.04
Electrical Equipment	5.19	11.02	7.97	6.87	5.94	5.36	4.64	1.48
Indirect Cost	15.26	29.20	23.15	22.04	20.73	19.78	18.80	13.99
Total Capital Cost	76.32	146.01	115.75	110.18	103.63	98.92	94.00	69.95
Penalty Cost:								
Capacity	52.39	24.27	23.86	14.30	9.64	9.64	9.64	5.14
Auxiliary Power	10.46	19.66	12.85	12.42	11.90	10.88	10.10	6.79
Replacement Energy	27.49	0.37	4.48	5.34	5.68	7.20	7.73	1.74
Auxiliary Energy	8.22	14.30	9.43	8.48	8.00	7.48	7.10	5.10
Make-up Water	0.0	0.0	0.10	0.50	1.04	1.52	2.07	4.98
Cooling System Maintenance	3.70	6.84	4.84	4.41	3.99	3.60	3.31	1.78
Total Penalty	102.25	65.42	55.56	45.44	40.25	40.33	39.94	25.54

* H-High Back Pressure Turbine

† L-Conventioanl Low Back Pressure Turbine

TABLE O-9. MAJOR DESIGN DATA FOR THE OPTIMIZED COOLING TOWER SYSTEMS

SITE: NEW HAMPTON, NEW YORK BASE OUTPUT: 1039 MWe WET/DRY TYPE: MECHANICAL SERIES (S1)

Item	Mech. Dry (H)*	Mech. Dry (L)†	Percentage Make-up Requirement# Mechanical Series Wet/Dry					Mech. Wet
			2	10	20	30	40	
Number of Tower Cells, Wet Tower/Dry Tower	0/106	0/217	8/129	13/110	18/92	21/73	21/59	27/0
Maximum Operating Back Pressure P_{max}, in-HgA (mm-HgA)	11.72 (297.7)	5.07 (128.8)	5.0 (127.0)	4.0 (101.6)	3.5 (88.9)	3.5 (88.9)	3.5 (88.9)	3.05 (77.5)
Gross Plant Output at P_{max}, MWe	927.1	988.0	989.5	1009.5	1019.1	1019.1	1019.1	1026.6
Heat Load at P_{max}, 10^9 Btu/hr (10^{12} J/hr)	4.83 (5.10)	4.63 (4.88)	4.62 (4.87)	4.55 (4.80)	4.52 (4.77)	4.52 (4.77)	4.52 (4.77)	4.49 (4.74)
Heat Load Distribution at P_{max}, (Wet Tower/Dry Tower), %	0.0/ 100.0	0.0/ 100.0	39.4/ 60.6	62.5/ 37.5	74.9/ 25.1	79.3/ 20.7	82.4/ 17.6	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)	0.518 (0.196)	2.71 (1.03)	5.44 (2.06)	8.22 (3.11)	10.90 (4.13)	26.96 (10.21)

* H-High Back Pressure Turbine

† L-Conventional Low Back Pressure Turbine

\# Percentage of annual make-up required by optimized wet tower

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

SITE: NEW HAMPTON, NEW YORK YEAR: 1985 WET/DRY TYPE: MECHANICAL SERIES (S1)

	Mech. Dry (H)*	Mech. Dry (L)†	Percentage Make-up Requirement-Mech. Ser. Wet/Dry					Mech. Wet
			2	10	20	30	40	
Capital Cost:								
Cooling Tower	36.97	75.69	49.70	46.01	42.67	37.82	32.94	15.94
Condenser	10.79	14.39	11.82	10.82	10.45	10.15	10.17	10.83
Circulating Water System	7.40	12.67	11.62	10.58	10.52	9.48	9.56	7.53
Make-up Facility	-	-	10.83	13.83	15.58	16.27	16.65	18.92
Electrical Equipment	5.11	10.16	8.20	7.42	5.77	5.73	5.04	1.92
Indirect Cost	15.07	28.23	23.05	22.17	21.50	19.86	18.59	13.78
Total Capital Cost	75.34	141.14	115.22	110.83	107.49	99.31	92.95	68.92
Penalty Cost:								
Capacity	54.29	24.72	23.99	14.30	9.65	9.65	9.64	5.99
Auxiliary Power	10.42	19.82	13.75	13.48	13.16	12.14	11.80	7.64
Replacement Energy	118.09	1.03	21.20	23.45	22.18	28.99	32.15	2.36
Auxiliary Energy	35.10	60.63	42.30	38.07	36.80	34.67	34.69	24.07
Make-up Water	-	-	0.01	0.03	0.06	0.09	0.12	0.30
Cooling System Maintenance	3.66	6.98	5.00	4.75	4.65	4.01	3.74	2.21
Total Penalty	221.56	113.18	106.25	94.08	86.50	89.55	92.14	42.57

* H-High Back Pressure Turbine

† L-Conventional Low Back Pressure Turbine

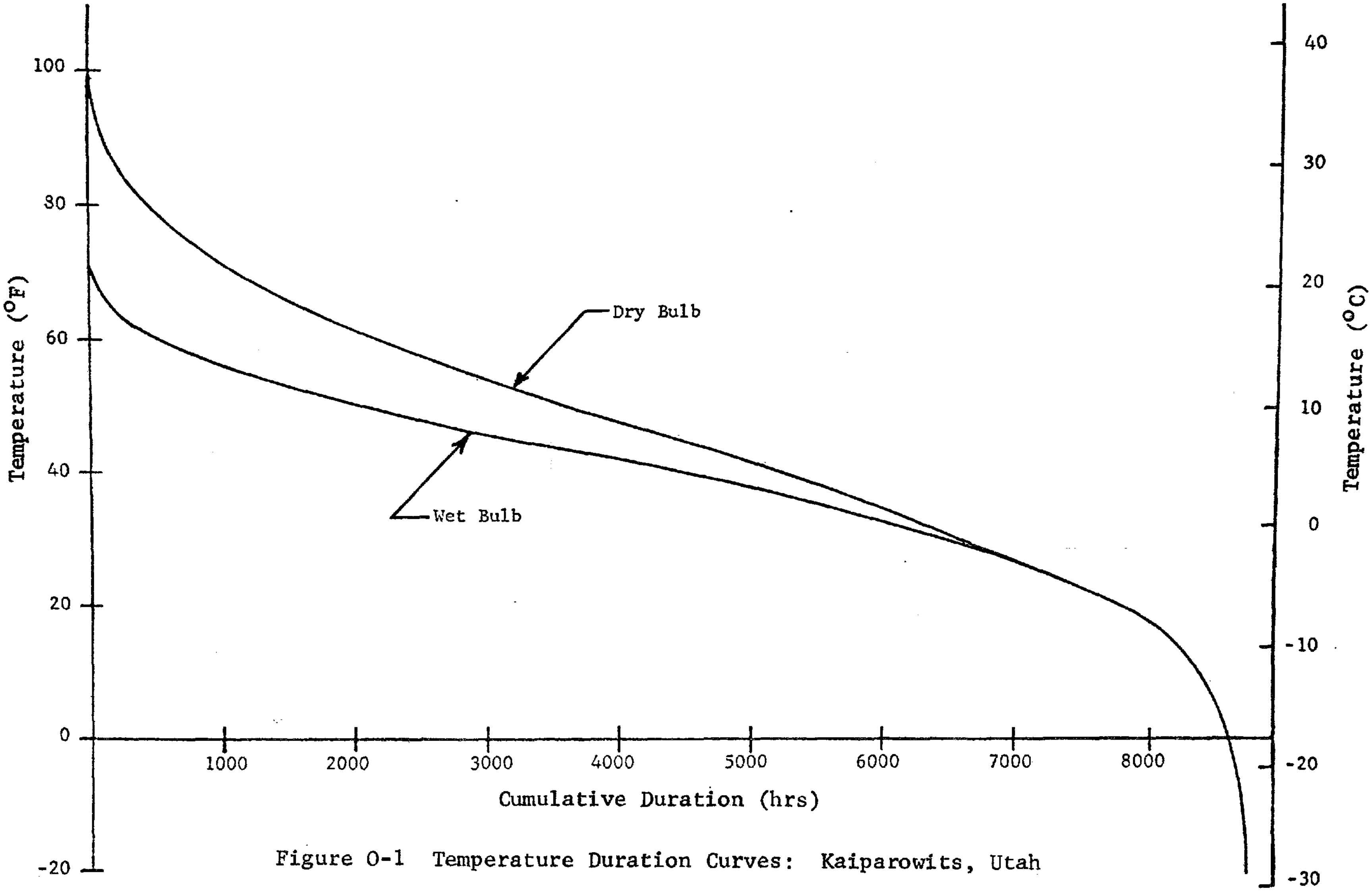


Figure O-1 Temperature Duration Curves: Kaiparowits, Utah

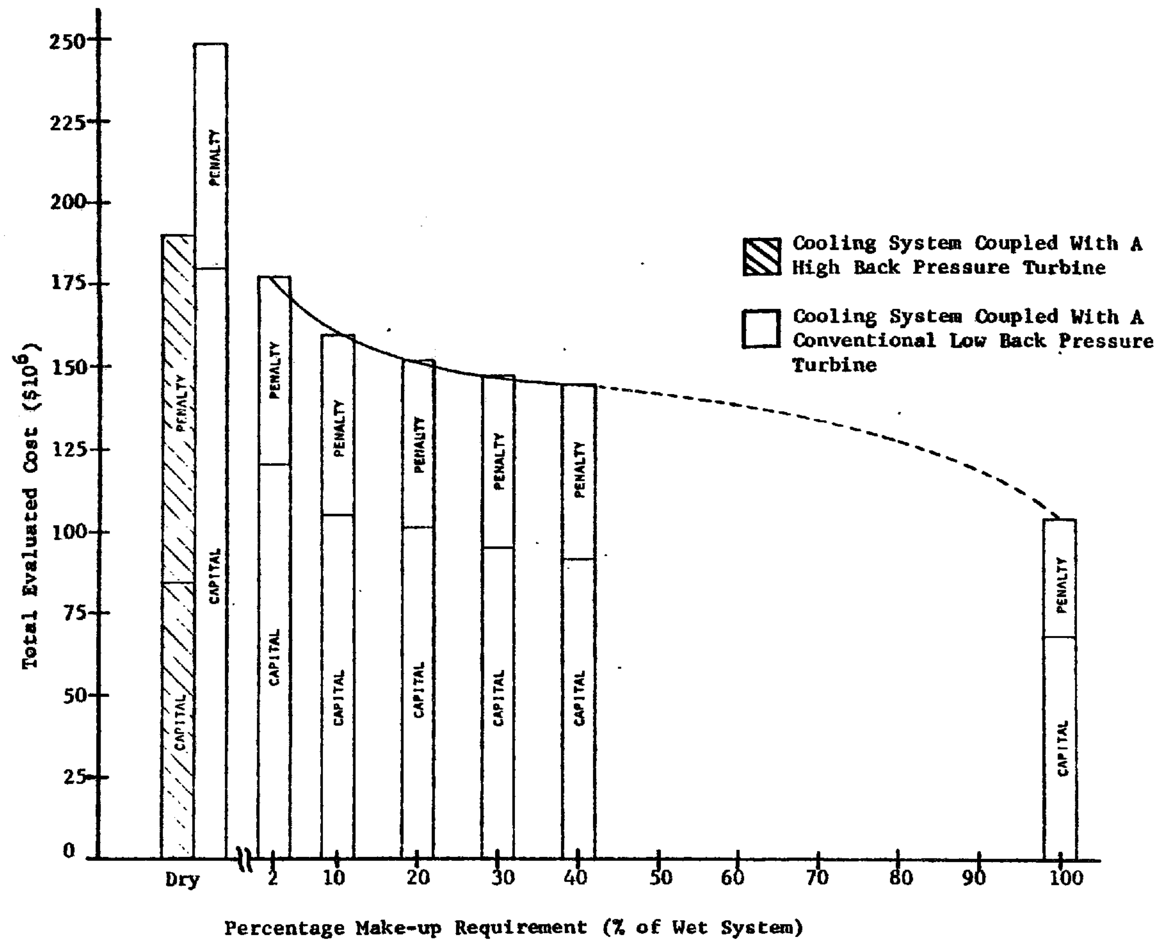


Figure O-2 Total Evaluated Cost and the Penalty and Capital Components for the Optimized Systems (Kaiparowits, Mechanical Series, S1 Mode, 1985)

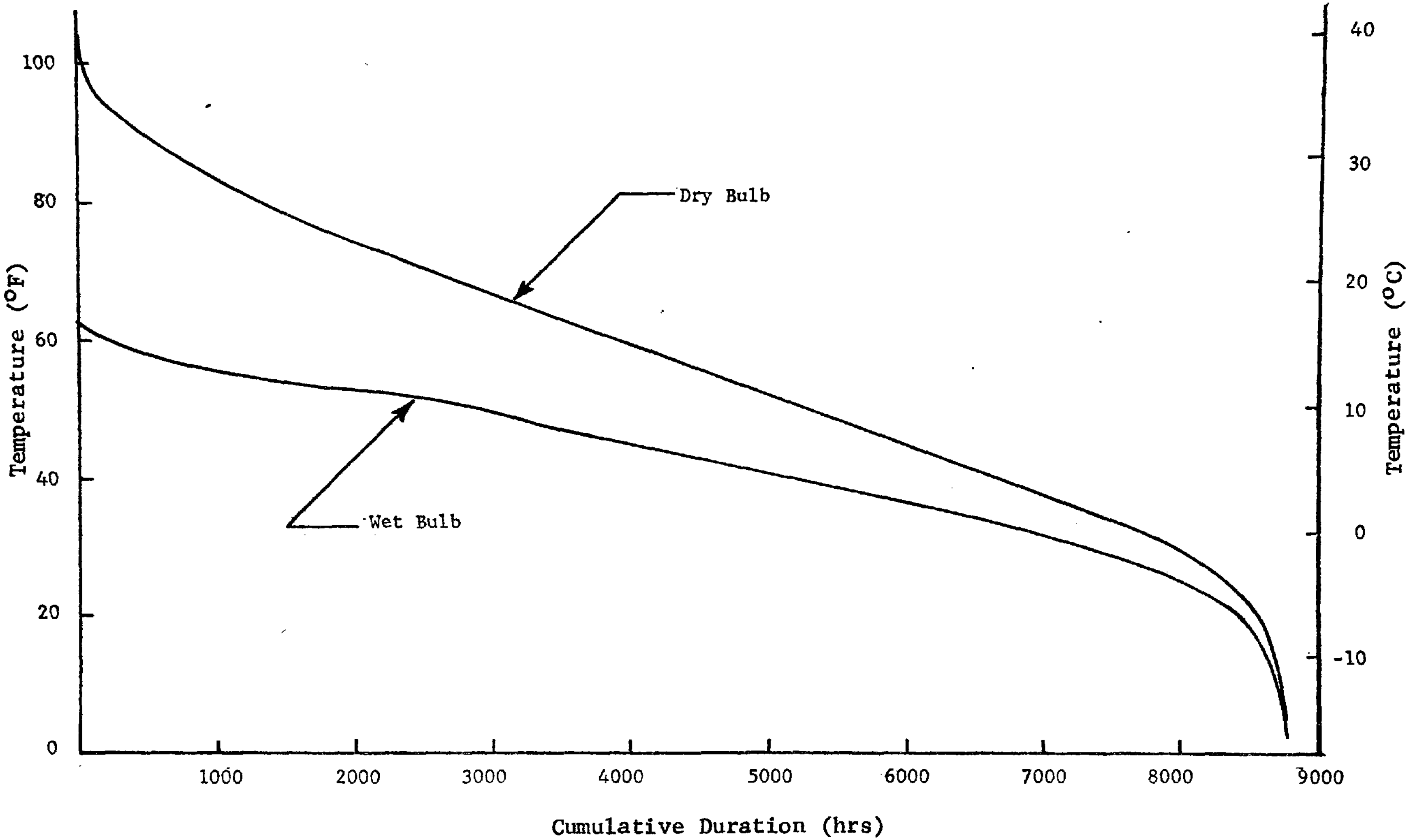


Figure O-3 Temperature Duration Curves: San Juan, New Mexico

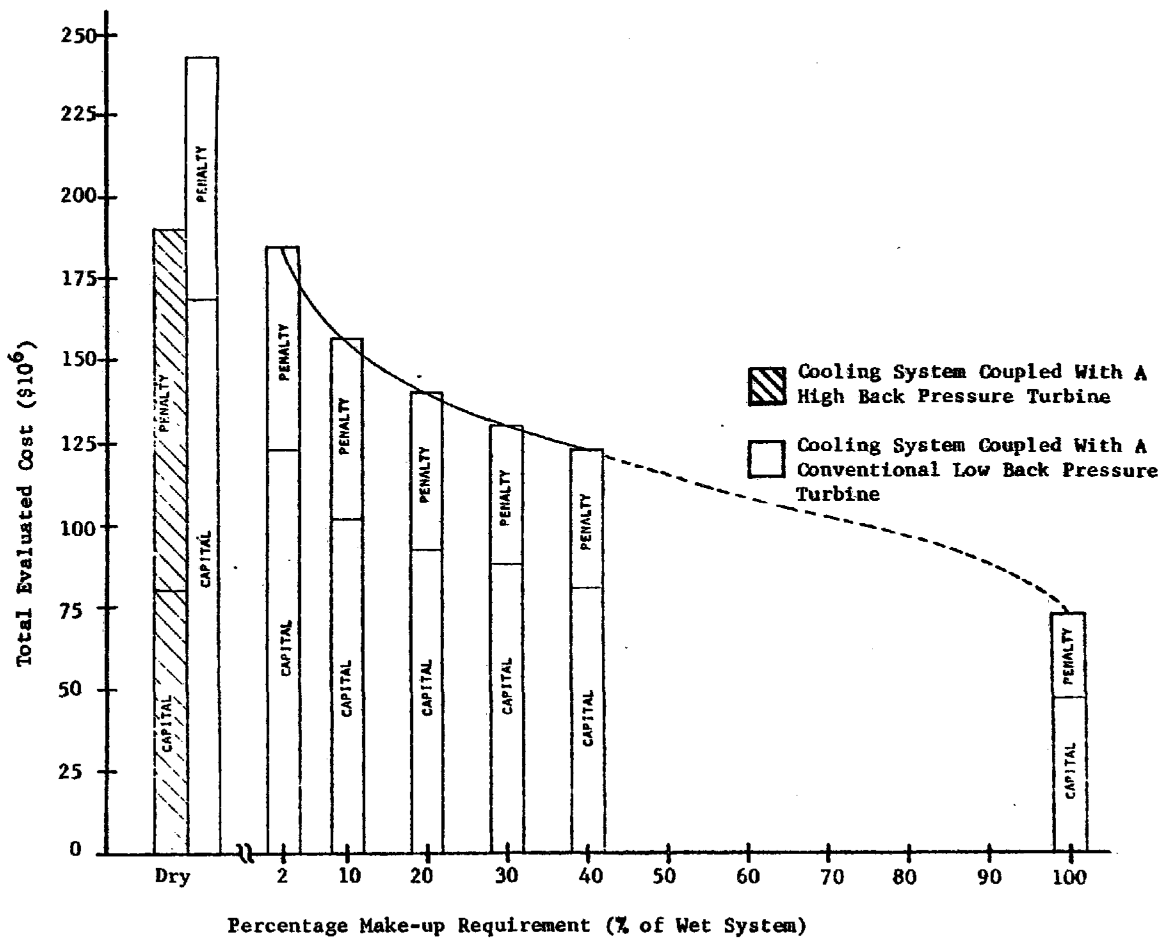


Figure O-4 Total Evaluated Cost and the Penalty and Capital Components for the Optimized Systems (San Juan, Mechanical Series, S1 Mode, 1985)

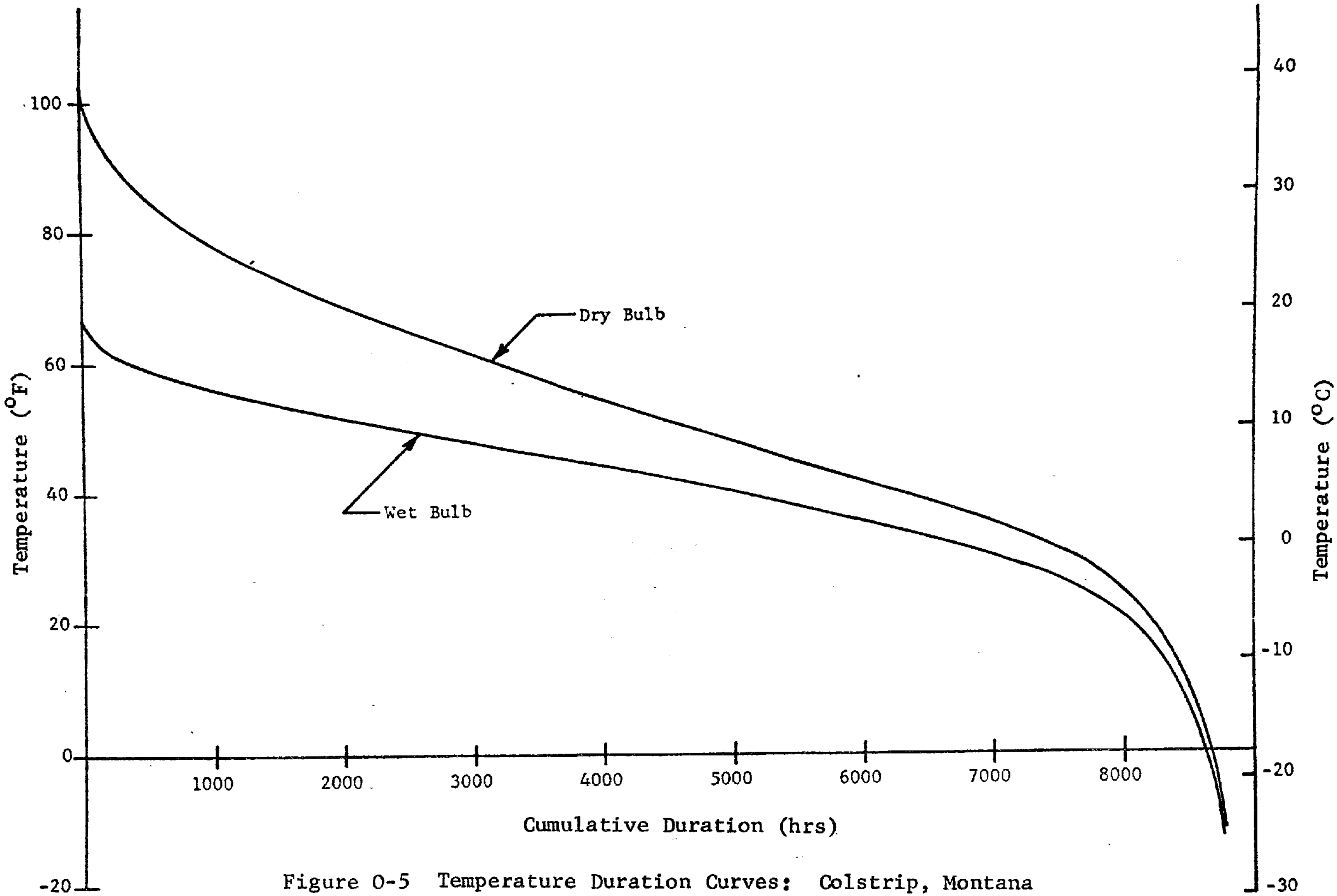


Figure 0-5 Temperature Duration Curves: Colstrip, Montana

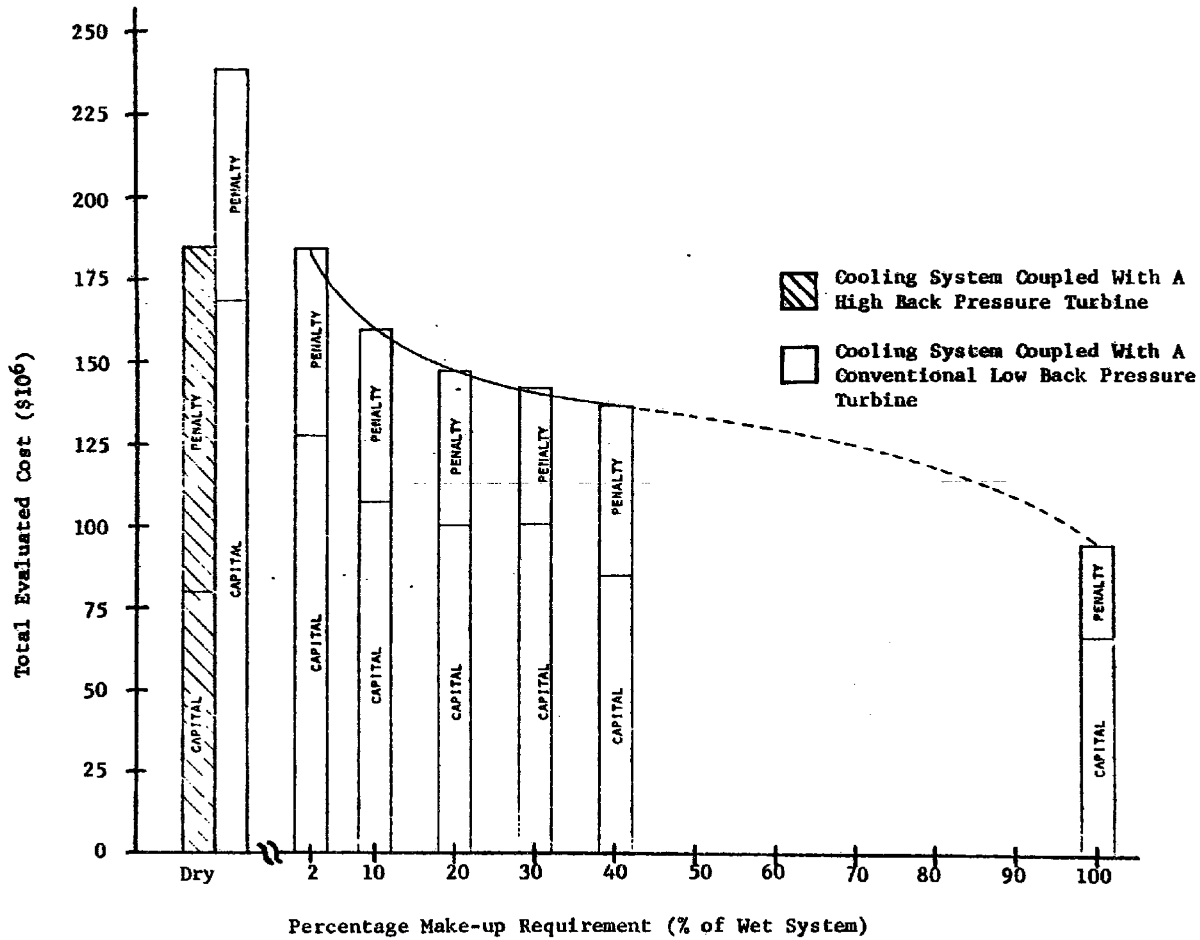


Figure O-6 Total Evaluated Cost and the Penalty and Capital Components for the Optimized Systems (Colstrip, Mechanical Series, S1 Mode, 1985)

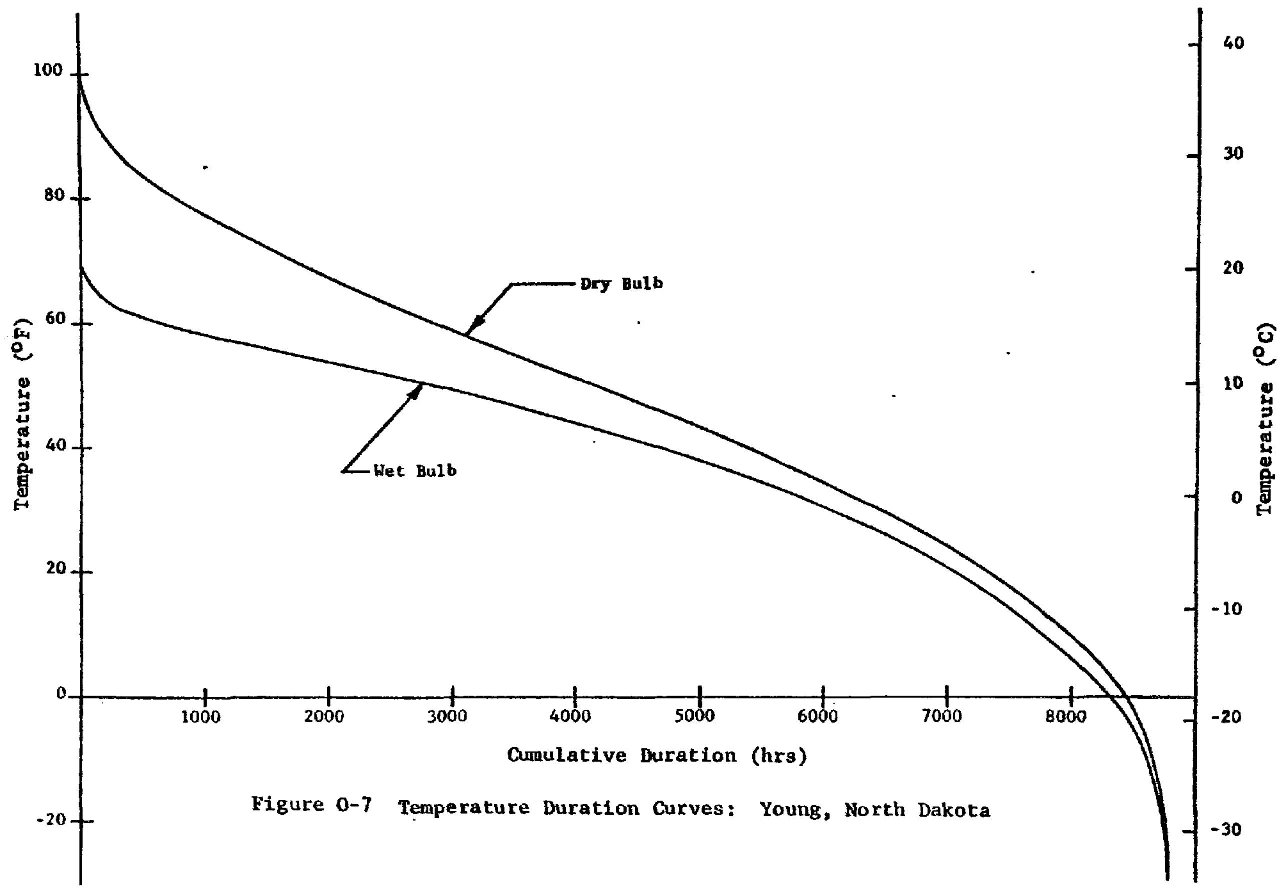


Figure O-7 Temperature Duration Curves: Young, North Dakota

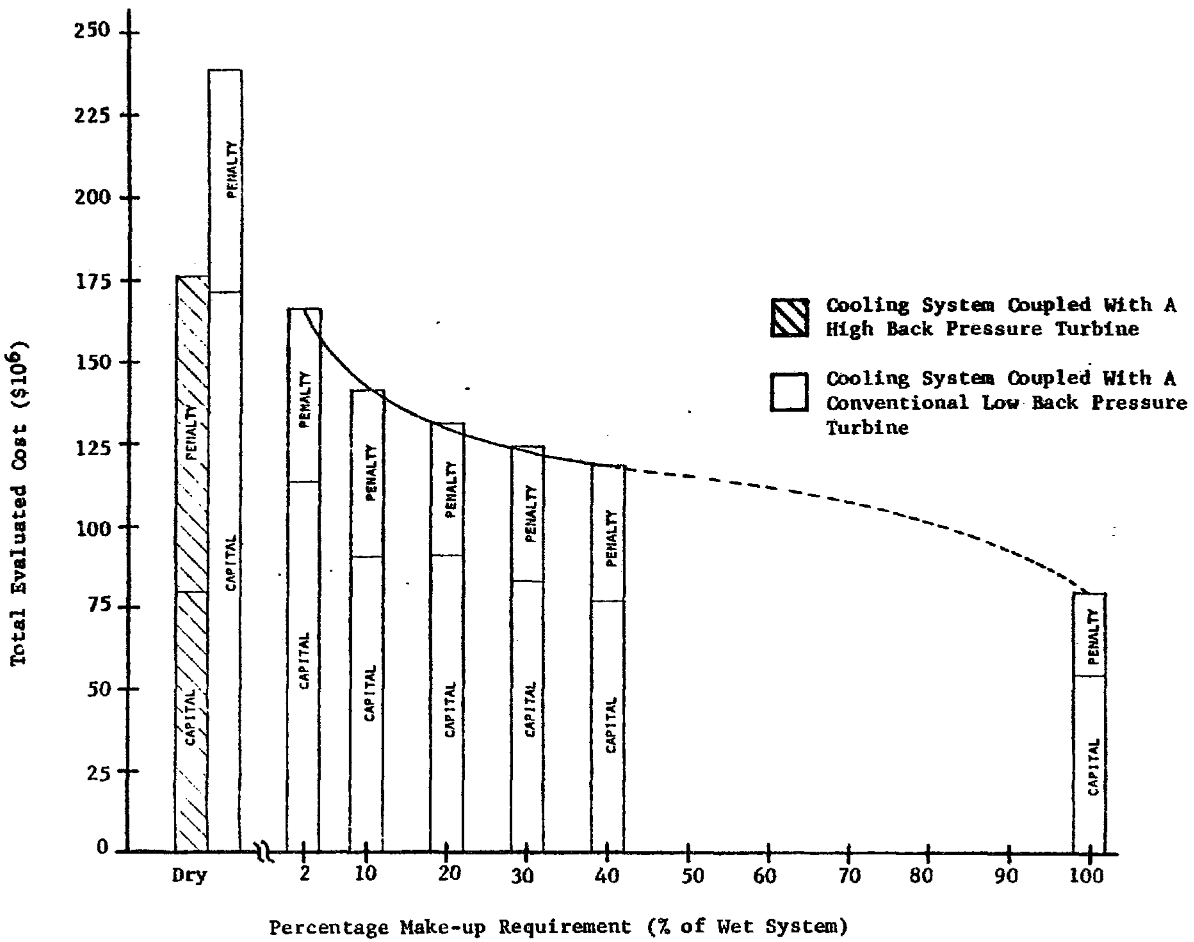


Figure O-8 Total Evaluated Cost and the Penalty and Capital Components for the Optimized Systems (Young, Mechanical Series, S1 Mode, 1985)

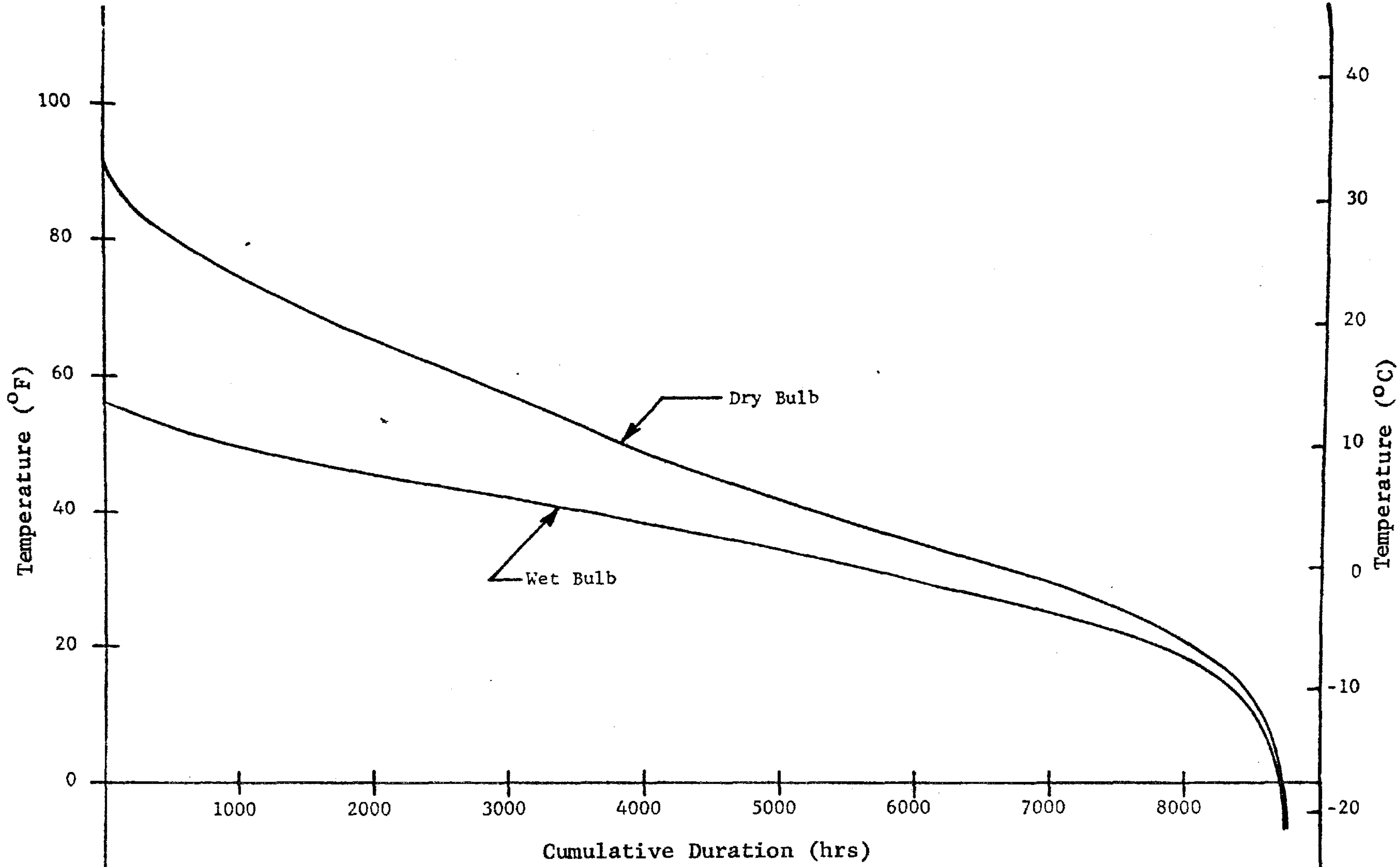


Figure O-9 Temperature Duration Curves: Rock Springs, Wyoming

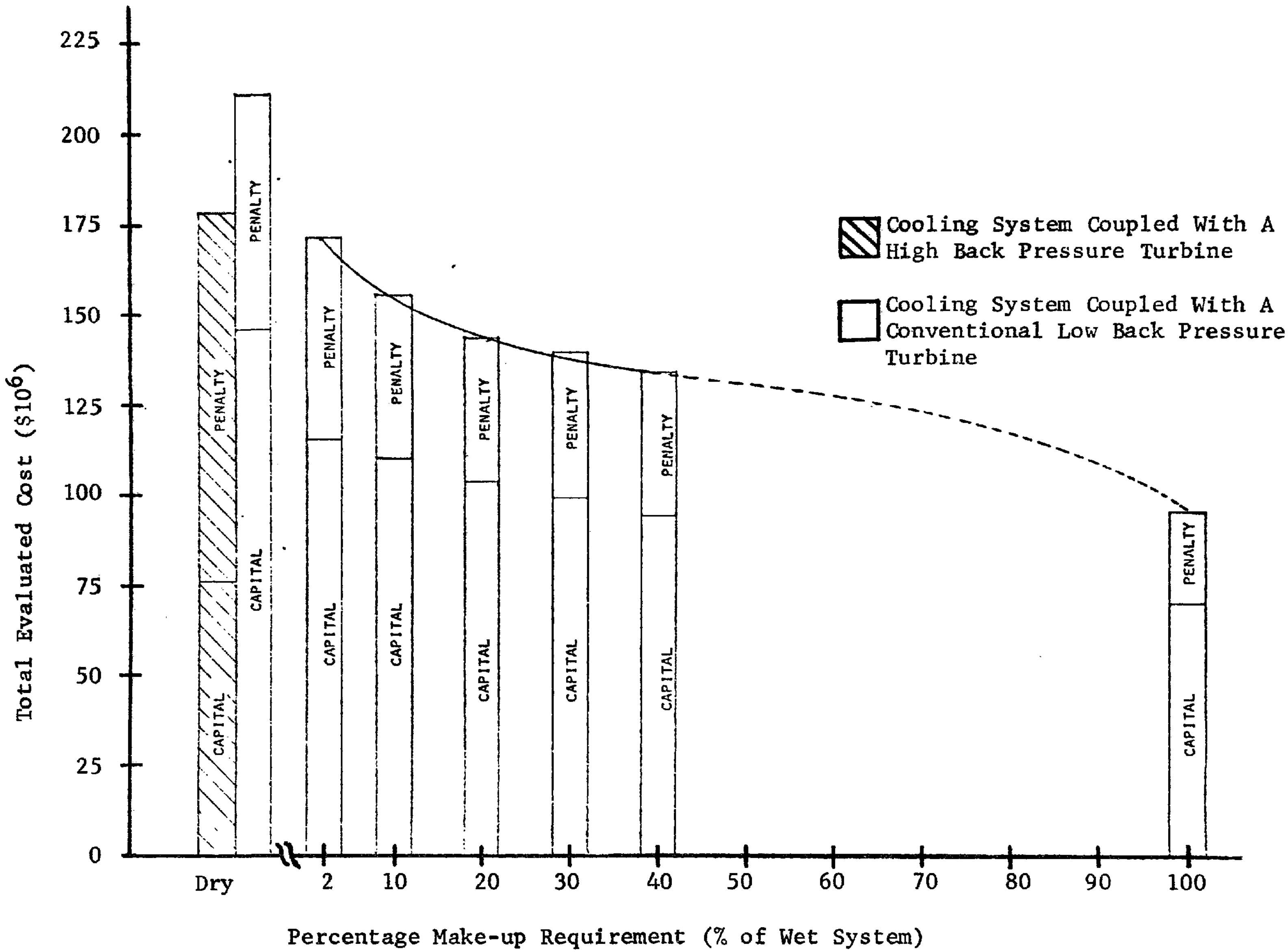


Figure O-10 Total Evaluated Cost and the Penalty and Capital Components for the Optimized Systems (Rock Springs, Mechanical Series, S1 Mode, 1985)

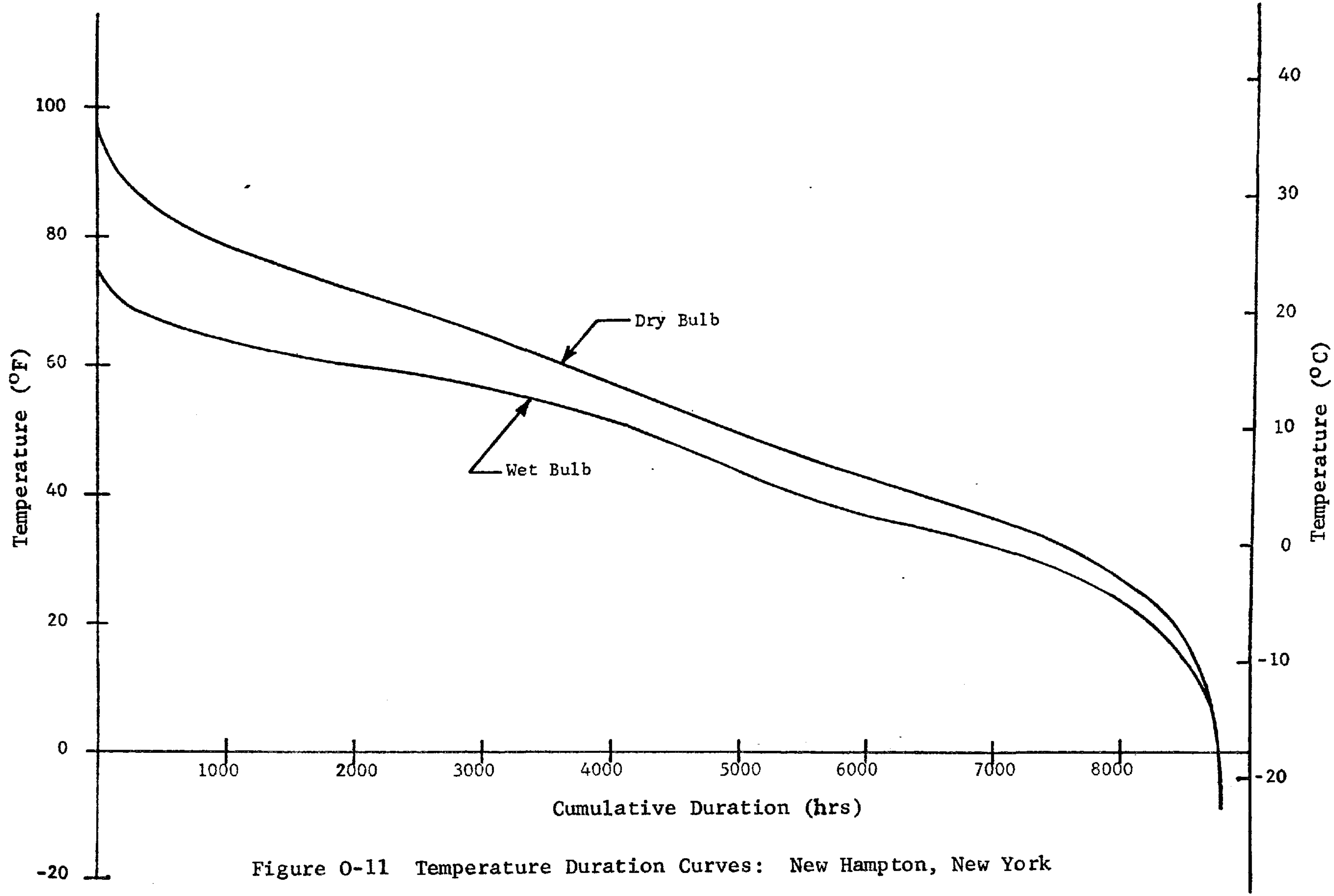


Figure O-11 Temperature Duration Curves: New Hampton, New York

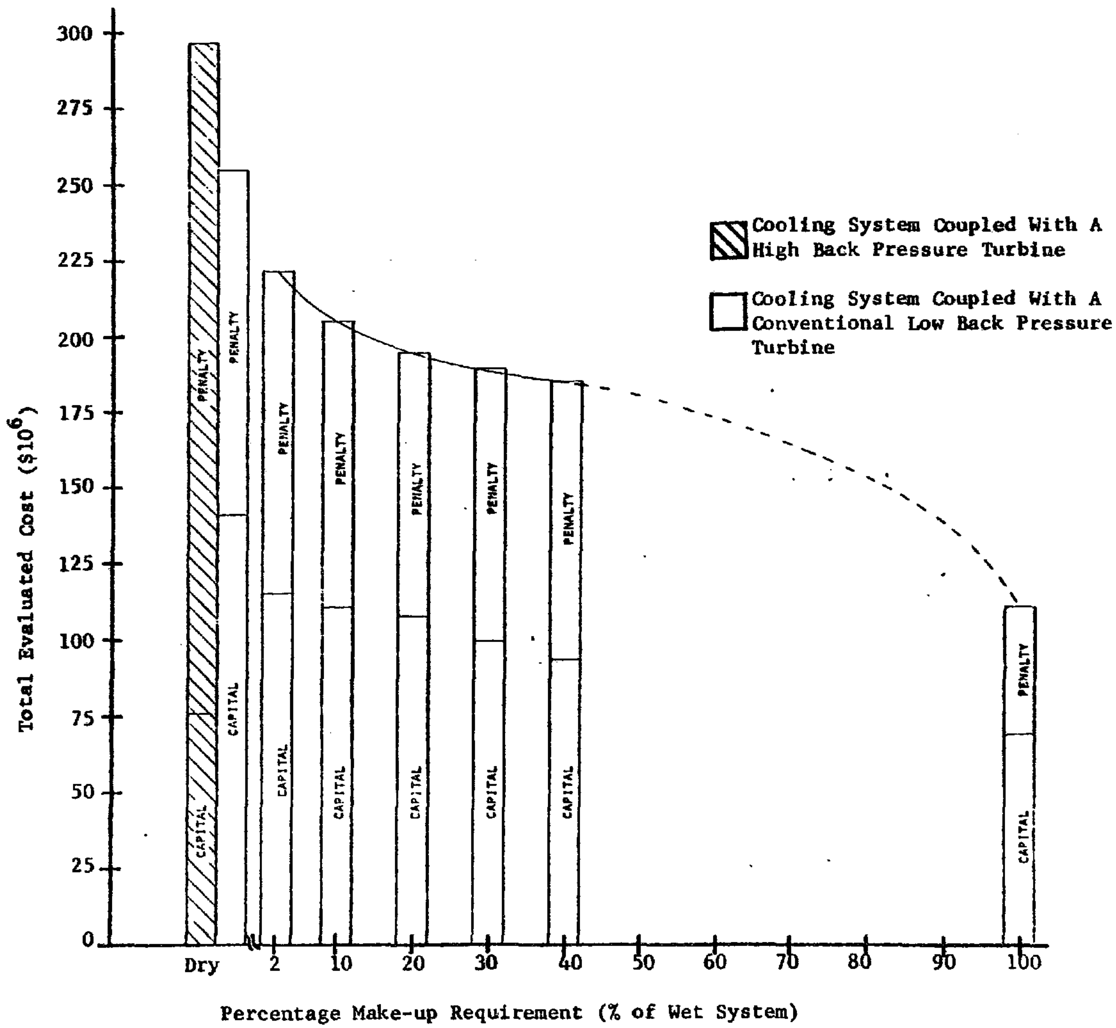


Figure O-12 Total Evaluated Cost and the Penalty and Capital Components for the Optimized Systems (New Hampton, Mechanical Series, S1 Mode, 1985)

APPENDIX P

MECHANICAL WET AND HYBRID WET/DRY COOLING SYSTEMS FOR PLUME ABATEMENT

This appendix contains design data, capital investment and penalty breakdowns for the optimized mechanical wet and hybrid wet/dry cooling systems operating at Seattle, Washington; Cleveland, Ohio; Newark, New Jersey; and Charlotte, North Carolina.

TABLE P-1. SUMMARY OF DESIGN DATA FOR THE OPTIMIZED MECHANICAL WET COOLING SYSTEMS

SITE: SEATTLE, WASHINGTON

Variable	MECHANICAL WET TOWER - GROUND FOGGING				
	5 Hours	10 Hours	20 Hours	30 Hours	60 Hours
General Design Data					
Design Temperatures, °F (°C):					
Dry Bulb	80.0 (26.7)	80.0 (26.7)	80.0 (26.7)	80.0 (26.7)	80.0 (26.7)
Wet Bulb	64.0 (17.8)	64.0 (17.8)	64.0 (17.8)	64.0 (17.8)	64.0 (17.8)
Cold Water	74.0 (23.3)	75.0 (23.9)	76.0 (24.4)	78.0 (25.6)	82.0 (27.8)
Cooling Range	30.0 (16.7)	28.0 (15.6)	30.0 (16.7)	26.0 (14.4)	26.0 (14.4)
Approach	10.0 (5.6)	11.0 (6.1)	12.0 (6.7)	14.0 (7.8)	18.0 (10.0)
Design Turbine Back Pressure, in-HgA (mm-HgA)	2.54 (64.5)	2.45 (62.2)	2.68 (68.1)	2.52 (64.0)	2.83 (71.9)
Maximum Operating Back Pressure, in-HgA (mm-HgA)	2.78 (70.6)	2.69 (68.3)	2.91 (73.9)	2.75 (69.9)	3.04 (77.2)
Design Heat Load, 10^9 Btu/hr (10^{12} J/hr)	4.47 (4.72)	4.47 (4.71)	4.48 (4.72)	4.47 (4.72)	4.48 (4.73)
Plant Capacity at Cooling System Design Point, MWe	1033.9	1034.9	1032.1	1034.1	1030.0
Ground Fogging (hrs/year)	5	9	19	32	60

TABLE P-1 (continued)

Variable	MECHANICAL WET TOWER - GROUND FOGGING				
	5 Hours	10 Hours	20 Hours	30 Hours	60 Hours
<u>Condenser</u>					
Surface Area, 10^3 ft^2 (10^3 m^2)	630 (58.5)	664 (61.7)	631 (58.6)	682 (63.3)	672 (62.4)
Number of Tubes	40,100	42,900	40,200	46,300	46,400
Tube Length, ft (m)	60.0 (18.3)	59.1 (18.0)	60.0 (18.3)	56.3 (17.2)	55.3 (16.9)
<u>Circulating Water Flow & Pump</u>					
Circulating Water Flow Rate, 10^3 gpm (m^3/min)	298 (1128)	319 (1208)	298 (1128)	344 (1302)	345 (1306)
Number of Pumps	2	2	2	2	2
Pumping Head, ft (m) of Water	87.4 (26.6)	88.4 (26.9)	87.6 (26.7)	86.0 (26.2)	85.4 (26.0)
Motor Rating, hp (kW) per pump	4000 (2984)	4500 (3357)	4000 (2984)	4500 (3357)	4500 (3357)
Motor Brake Horsepower, hp (kW) per pump	3695 (2756)	3999 (2983)	3709 (2767)	4194 (3129)	4178 (3117)

TABLE P-1 (continued)

Variable	MECHANICAL WET TOWER - GROUND FOGGING				
	5 Hours	10 Hours	20 Hours	30 Hours	60 Hours
<u>Circulating Water Pipelines</u>					
Condenser Intake:					
Number of Lines	1	1	1	1	1
Diameter/Length, in/ft (cm/m)	102/1120 (259/341)	102/1120 (259/341)	102/1120 (259/341)	108/1120 (259/341)	108/1120 (259/341)
Condenser Discharge:					
Number of Lines	1	1	1	1	1
Diameter/Length, in/ft (cm/m)	102/940 (259/287)	102/940 (259/287)	102/940 (259/287)	108/940 (259/287)	108/940 (259/287)
Connecting Pipelines:					
Number of Lines	2	2	2	2	2
Diameter/Length, in/ft (cm/m)	72/710 (183/216)	72/710 (183/216)	72/710 (183/216)	78/710 (198/216)	78/710 (198/216)
<u>Cooling Tower</u>					
Number of Cells	43	41	37	33	26
Heat Exchanger Tube Length, ft (m)	-	-	-	-	-

TABLE P-2. PENALTY BREAKDOWN AND COST SUMMARY FOR THE OPTIMIZED MECHANICAL WET COOLING SYSTEMS ($$10^6$)

SITE: SEATTLE, WASHINGTON YEAR: 1985

Item	GROUND FOGGING HOURS - MECHANICAL WET TOWERS				
	5	10	20	30	Reference 60
Penalty Breakdown:					
Capacity Penalty	4.004	3.392	4.949	3.816	5.893
Replacement Energy Penalty	-.220	-.657	.760	.008	2.357
Circulating Water Pumping Power Penalty	2.969	3.214	2.981	3.371	3.358
Circulating Water Pumping Energy Penalty	5.985	6.475	6.014	6.796	6.784
Cooling Tower Fan Power Penalty	2.782	2.645	2.372	2.099	1.627
Cooling Tower Fan Energy Penalty	5.376	5.115	4.603	4.083	3.187
Make-up Water Purchase and Treatment Penalty	0.393	0.393	0.393	0.394	0.399
Make-up Water Pumping Energy and Capacity Penalty	.215	.213	.211	.209	.207
Cooling System Maintenance Penalty	2.267	2.266	2.114	2.073	1.891
Cost Summary:					
Total Penalty Cost	23.771	23.056	24.397	27.849	25.703
Total Capital Cost	56.406	55.589	51.840	50.246	44.815
Total Evaluated Cost	80.177	78.645	76.237	73.095	70.518

TABLE P-3. SUMMARY OF CAPITAL INVESTMENT COST FOR THE OPTIMIZED MECHANICAL WET COOLING SYSTEMS ($$10^6$)

SITE: SEATTLE, WASHINGTON PRICING YEAR: 1985

Acct. No.	Equipment Item		GROUND FOGGING HOURS - MECHANICAL WET TOWERS 5	10	20	30	Reference 60
118L	Circulating Water Pump Structures	(M	0.762	0.781	0.762	0.802	0.804
		(L	0.609	0.623	0.609	0.641	0.641
		(T	1.371	1.404	1.371	1.443	1.445
132.211	Circulating Water Pumps and Motors	(E	1.656	1.736	1.656	1.736	1.736
		(M	0.017	0.018	0.017	0.018	0.018
		(L	0.105	0.105	0.105	0.105	0.105
		(T	1.778	1.859	1.778	1.859	1.859
132.25	Concrete Pipelines	(M	1.660	1.660	1.660	1.853	1.853
		(L	1.351	1.351	1.351	1.472	1.472
		(T	3.011	3.011	3.011	3.325	3.325
132.3211	Cooling Tower Basin and Foundation	(M	2.791	2.661	2.401	2.141	1.687
		(L	5.020	4.786	4.319	3.852	3.034
		(T	7.810	7.447	6.720	5.993	4.721
132.3212	Cooling Towers, Installed	(E	8.917	8.501	7.673	6.843	5.391
		(M	0.090	0.086	0.078	0.069	0.054
		(L	7.234	6.897	6.224	5.551	4.374
		(T	16.242	15.484	13.975	12.463	9.819
133.1	Condensers, Installed	(E	6.653	6.956	6.661	7.142	7.077
		(M	0.033	0.035	0.033	0.036	0.036
		(L	3.604	3.701	3.607	3.769	3.753
		(T	10.291	10.692	10.301	10.947	10.866
114 & 132.1	Make-up Facilities	(E	0.561	0.555	0.545	0.534	0.517
		(M	0.652	0.646	0.635	0.623	0.605
		(L	1.110	1.100	1.081	1.061	1.031
		(T	2.323	2.301	2.261	2.218	2.153
14	Electrical Equipment	(E	0.891	0.893	0.802	0.777	0.674
		(M	0.669	0.671	0.602	0.583	0.506
		(L	0.740	0.710	0.650	0.589	0.483
		(T	2.299	2.274	2.054	1.949	1.663
	Direct Capital Cost of Cooling System	(E	18.678	18.641	17.337	17.032	15.395
		(M	6.674	6.558	6.188	6.125	5.563
		(L	19.773	19.273	17.496	17.040	14.893
		(T	45.125	44.472	41.471	40.197	35.851
	Indirect Cost		11.281	11.117	10.369	10.049	8.962
	Total Capital Cost		56.406	55.589	51.840	50.246	44.815

TABLE P-4. SUMMARY OF DESIGN DATA FOR THE OPTIMIZED WET/DRY AND REFERENCE COOLING SYSTEMS

5 HOURS PER YEAR GROUND FOG

SITE: SEATTLE, WASHINGTON

Variable	DRY HEAT EXCHANGER TUBE LENGTH 15 ft	10 ft	5 ft	Wet Tower System
General Design Data				
Design Temperatures, °F (°C):				
Dry Bulb	80.0 (26.7)	80.0 (26.7)	80.0 (26.7)	80.0 (26.7)
Wet Bulb	64.0 (17.8)	64.0 (17.8)	64.0 (17.8)	64.0 (17.8)
Cold Water	80.0 (26.7)	79.0 (26.1)	77.0 (25.0)	74.0 (23.3)
Cooling Range	26.0 (14.4)	26.0 (14.4)	28.0 (15.6)	30.0 (16.7)
Approach	16.1 (8.9)	15.0 (8.3)	13.0 (7.2)	10.0 (5.6)
Design Turbine Back Pressure, in-HgA (mm-HgA)	2.67 (67.9)	2.60 (65.9)	2.60 (65.9)	2.54 (64.5)
Maximum Operating Back Pressure, in-HgA (mm-HgA)	2.90 (73.7)	2.82 (71.6)	2.83 (71.9)	2.78 (70.6)
Design Heat Load, 10^9 Btu/hr (10^{12} J/hr)	4.48 (4.73)	4.47 (4.72)	4.47 (4.72)	4.47 (4.72)
Plant Capacity at Cooling System Design Point, MWe	1032.2	1033.2	1033.2	1033.9
Ground Fogging (hrs/year)	4	4	4	5

TABLE P-4 (continued)

Variable	DRY HEAT EXCHANGER TUBE LENGTH			Wet Tower System
	15 ft	10 ft	5 ft	
Condenser				
Surface Area, 10^3 ft^2 (10^3 m^2)	676 62.8	679 (63.1)	658 (61.1)	630 (58.5)
Number of Tubes	46,300	46,300	42,900	40,100
Tube Length, ft (m)	55.8 (17.0)	56.0 (17.1)	58.4 (17.8)	60.0 (18.3)
Circulating Water Flow & Pump				
Circulating Water Flow Rate, 10^3 gpm (m^3/min)	344 (1302)	344 (1302)	319 (1207)	298 (1128)
Number of Pumps	2	2	2	2
Pumping Head, ft (m) of Water	93.5 (28.5)	91.1 (27.8)	90.8 (27.7)	87.4 (26.6)
Motor Rating, hp (kW) per pump	5000 (3730)	5000 (3730)	4500 (3356)	4000 (2984)
Motor Brake Horsepower, hp (kW) per pump	4560 (3405)	4444 (3314)	4109 (3064)	3695 (2756)

TABLE P-4 (continued)

Variable	DRY HEAT EXCHANGER TUBE LENGTH			Wet Tower System
	15 ft	10 ft	5 ft	
<u>Circulating Water Pipelines</u>				
Condenser Intake:				
Number of Lines	1	1	1	1
Diameter/Length, in/ft (cm/m)	108/1120(274/341)	108/1120(274/341)	102/1120(259/341)	102/1120(259/341)
Condenser Discharge:				
Number of Lines	1	1	1	1
Diameter/Length, in/ft (cm/m)	108/940(274/287)	108/940(274/287)	102/940(259/287)	102/940(259/287)
Connecting Pipelines:				
Number of Lines	2	2	2	2
Diameter/Length, in/ft (cm/m)	78/710(198/216)	78/710(198/216)	72/710(183/216)	72/710(183/216)
<u>Cooling Tower</u>				
Number of Cells	29	31	35	43
Heat Exchanger Tube Length, ft (m)	15	10	5	-

TABLE P-5. PENALTY BREAKDOWN AND COST SUMMARY FOR THE OPTIMIZED WET/DRY AND REFERENCE COOLING SYSTEMS ($$10^6$)

5 HOURS PER YEAR GROUND FOG

SITE: SEATTLE, WASHINGTON YEAR: 1985

Item	DRY HEAT EXCHANGER TUBE LENGTH			Wet Tower System
	15 ft	10 ft	5 ft	
Penalty Breakdown:				
Capacity Penalty	4.818	4.289	4.347	4.004
Replacement Energy Penalty	1.095	.512	.330	-.220
Circulating Water Pumping Power Penalty	3.670	3.570	3.307	2.969
Circulating Water Pumping Energy Penalty	7.405	7.203	6.669	5.985
Cooling Tower Fan Power Penalty	1.829	1.964	2.235	2.782
Cooling Tower Fan Energy Penalty	3.570	3.826	4.342	5.376
Make-up Water Purchase and Treatment Penalty	0.396	0.395	0.393	0.393
Make-up Water Pumping Energy and Capacity Penalty	.207	.208	.210	0.215
Cooling System Maintenance Penalty	2.360	2.336	2.316	2.267
Cost Summary:				
Total Penalty Cost	25.350	24.303	24.149	23.771
Total Capital Cost	53.919	54.077	54.742	56.406
Total Evaluated Cost	79.269	78.380	78.891	80.177

TABLE P-6. SUMMARY OF CAPITAL INVESTMENT COST FOR THE OPTIMIZED WET/DRY AND REFERENCE COOLING SYSTEMS ($$10^6$)

SITE: SEATTLE, WASHINGTON PRICING YEAR: 1985

Acct. No.	Equipment Item		HEAT EXCHANGER TUBE LENGTH 15 ft.	10 ft.	5 ft.	Wet Tower System
118L	Circulating Water Pump Structures	(M	0.804	0.802	0.781	0.762
		(L	0.641	0.641	0.625	0.609
		(T	1.445	1.443	1.406	1.371
132.211	Circulating Water Pumps and Motors	(E	1.815	1.815	1.736	1.656
		(M	0.018	0.018	0.018	0.017
		(L	0.105	0.105	0.105	0.105
		(T	1.938	1.938	1.859	1.778
132.25	Concrete Pipelines	(M	1.853	1.853	1.660	1.660
		(L	1.472	1.472	1.351	1.351
		(T	3.325	3.325	3.011	3.011
132.3211	Cooling Tower Basin and Foundation	(M	1.881	2.011	2.271	2.791
		(L	3.385	3.618	4.085	5.020
		(T	5.266	5.629	6.356	7.811
132.3212	Cooling Towers, Installed	(E	8.912	8.717	8.925	8.917
		(M	0.090	0.088	0.090	0.090
		(L	7.232	7.072	7.241	7.234
		(T	16.234	15.877	16.256	16.241
133.1	Condensers, Installed	(E	7.108	7.125	6.912	6.653
		(M	0.036	0.036	0.035	0.033
		(L	3.760	3.765	3.689	3.604
		(T	10.904	10.926	10.636	10.290
114 & 132.1	Make-up Facilities	(E	0.524	0.529	0.539	0.561
		(M	0.612	0.618	0.629	0.652
		(L	1.043	1.052	1.071	1.110
		(T	2.179	2.199	2.239	2.323
14	Electrical Equipment	(E	0.750	0.780	0.806	0.890
		(M	0.564	0.586	0.606	0.669
		(L	0.529	0.559	0.618	0.740
		(T	1.843	1.925	2.030	2.299
	Direct Capital Cost of Cooling System	(E	19.109	18.966	18.918	18.677
		(M	5.858	6.012	6.090	6.674
		(L	18.167	18.284	18.785	19.773
		(T	43.134	43.262	43.793	45.124
	Indirect Cost		10.785	10.815	10.949	11.282
	Total Capital Cost		53.919	54.077	54.742	56.406

TABLE P-7. SUMMARY OF DESIGN DATA FOR THE OPTIMIZED MECHANICAL WET COOLING SYSTEMS

SITE: CLEVELAND, OHIO

Variable	MECHANICAL WET TOWER - GROUND FOGGING				
	5 Hours	10 Hours	20 Hours	30 Hours	38 Hours
General Design Data					
Design Temperatures, °F (°C):					
Dry Bulb	90.0 (32.2)	90.0 (32.2)	90.0 (32.2)	90.0 (32.2)	90.0 (32.2)
Wet Bulb	71.0 (21.7)	71.0 (21.7)	71.0 (21.7)	71.0 (21.7)	71.0 (21.7)
Cold Water	80.0 (26.7)	82.0 (27.8)	84.0 (28.9)	86.0 (30.0)	86.0 (30.0)
Cooling Range	28.0 (15.6)	26.0 (14.4)	26.0 (14.4)	24.0 (13.3)	26.0 (14.4)
Approach	9.0 (5.0)	11.0 (6.1)	13.0 (7.2)	15.0 (8.3)	15.0 (8.3)
Design Turbine Back Pressure, in-HgA (mm-HgA)	2.83 (71.9)	2.83 (71.9)	2.99 (76.1)	2.99 (76.1)	3.17 (80.5)
Maximum Operating Back Pressure, in-HgA (mm-HgA)	2.87 (72.9)	2.86 (72.6)	3.02 (76.7)	3.01 (76.5)	3.19 (81.0)
Design Heat Load, 10^9 Btu/hr (10^{12} J/hr)	4.48 (4.73)	4.48 (4.73)	4.49 (4.74)	4.49 (4.74)	4.50 (4.75)
Plant Capacity at Cooling System Design, Point, MWe	1030.0	1030.0	1027.6	1027.6	1024.8
Ground Fogging (hrs/year)	4	11	21	31	38

TABLE P-7 (continued)

Variable	MECHANICAL WET TOWER - GROUND FOGGING				
	5 Hours	10 Hours	20 Hours	30 Hours	38 Hours
Condenser					
Surface Area, 10^3 ft^2 (10^3 m^2)	651(605)	672(624)	669(621)	694(64.5)	666(61.9)
Number of Tubes	43,100	46,400	46,500	50,400	46,600
Tube Length, ft (m)	57.7(17.6)	55.3(16.9)	54.9(16.7)	52.6(16.0)	54.6(16.6)
Circulating Water Flow & Pump					
Circulating Water Flow Rate, 10^3 gpm (m^3/min)	320(1211)	345(1306)	345(1306)	374(1416)	346(1310)
Number of Pumps	2	2	2	3	2
Pumping Head, ft (m) of Water	87.6(26.7)	85.4(26.0)	85.7(26.0)	83.9(25.6)	84.9(25.9)
Motor Rating, hp (kW) per pump	4500(3357)	4500(3357)	4500(3357)	3500(2611)	4500(3357)
Motor Brake Horsepower, hp (kW) per pump	3978(2967)	4178(3117)	4174(3114)	2969(2215)	4172(3112)

TABLE P-7 (continued)

Variable	MECHANICAL WET TOWER - GROUND FOGGING				
	5 Hours	10 Hours	20 Hours	30 Hours	38 Hours
Circulating Water Pipelines					
Condenser Intake:					
Number of Lines	1	1	1	1	1
Diameter/Length, in/ft (cm/m)	102/1120 (259/341)	108/1120 (274/341)	108/1120 (274/341)	114/1120 (296/341)	105/1120 (267/341)
Condenser Discharge:					
Number of Lines	1	1	1	1	1
Diameter/Length, in/ft (cm/m)	102/940 (259/287)	108/940 (274/287)	108/940 (274/287)	114/940 (290/287)	108/940 (274/287)
Connecting Pipelines:					
Number of Lines	2	2	2	2	2
Diameter/Length, in/ft (cm/m)	72/710 (183/216)	78/710 (198/216)	78/710 (198/216)	78/710 (198/216)	78/710 (198/216)
Cooling Tower					
Number of Cells	40	35	30	27	26
Heat Exchanger Tube Length, ft (m)	-	-	-	-	-

TABLE P-8. PENALTY BREAKDOWN AND COST SUMMARY FOR THE OPTIMIZED MECHANICAL WET COOLING SYSTEMS ($\$10^6$)

SITE: CLEVELAND, OHIO YEAR: 1985

Item	GROUND FOGGING HOURS - MECHANICAL WET TOWERS				
	5	10	20	30	Reference 38
Penalty Breakdown:					
Capacity Penalty	4.637	4.564	5.726	5.663	7.041
Replacement Energy Penalty	0.392	0.553	1.820	1.992	3.377
Circulating Water Pumping Power Penalty	3.197	3.358	3.354	3.579	3.353
Circulating Water Pumping Energy Penalty	6.447	6.773	6.774	7.229	6.779
Cooling Tower Fan Power Penalty	2.583	2.238	1.895	1.691	1.623
Cooling Tower Fan Energy Penalty	4.924	4.285	3.652	3.271	3.147
Make-up Water Purchase and Treatment Penalty	0.399	0.398	0.400	0.401	0.403
Make-up Water Pumping Energy and Capacity Penalty	0.218	0.214	0.212	0.210	0.210
Cooling System Maintenance Penalty	2.236	2.120	1.991	2.114	1.888
Cost Summary:					
Total Penalty Cost	25.033	24.503	25.824	26.150	27.821
Total Capital Cost	54.747	51.730	47.880	47.016	44.799
Total Evaluated Cost	79.780	76.230	73.704	73.166	72.620

TABLE P-9. SUMMARY OF CAPITAL INVESTMENT COST FOR THE OPTIMIZED MECHANICAL WET COOLING SYSTEMS ($$10^6$)

SITE: CLEVELAND, OHIO PRICING YEAR: 1985

Acct. No.	Equipment Item		GROUND FOGGING HOURS - MECHANICAL WET TOWERS				
			5	10	20	30	Reference 38
118L	Circulating Water Pump Structures	(M	0.781	0.804	0.804	0.829	0.804
		(L	0.625	0.541	0.643	0.662	0.643
		(T	1.406	1.445	1.447	1.491	1.447
132.211	Circulating Water Pumps and Motors	(E	1.736	1.736	1.736	2.122	1.736
		(M	0.018	0.018	0.018	0.021	0.018
		(L	0.105	0.105	0.105	0.158	0.105
		(T	1.859	1.859	1.859	2.301	1.859
132.25	Concrete Pipelines	(M	1.660	1.853	1.853	1.940	1.853
		(L	1.351	1.472	1.472	1.550	1.472
		(T	3.011	3.325	3.325	3.500	3.325
132.3211	Cooling Tower Basin and Foundation	(M	2.596	2.271	1.945	1.751	1.687
		(L	4.669	4.085	3.503	3.152	3.034
		(T	7.265	6.356	5.448	4.903	4.721
132.3212	Cooling Towers, Installed	(E	8.295	7.257	6.221	5.599	5.391
		(M	0.084	0.073	0.063	0.057	0.054
		(L	6.730	5.888	5.047	4.543	4.374
		(T	15.109	13.218	11.331	10.199	9.819
114 & 132.1	Condensers, Installed	(E	6.861	7.077	7.055	7.311	7.035
		(M	0.034	0.036	0.035	0.037	0.035
		(L	3.678	3.753	3.746	3.836	3.742
		(T	10.573	10.866	10.836	11.084	10.812
14	Make-up Facilities	(E	0.565	0.551	0.537	0.529	0.527
		(M	0.657	0.641	0.627	0.618	0.616
		(L	1.119	1.092	1.067	1.052	1.049
		(T	2.341	2.284	2.231	2.199	2.192
	Electrical Equipment	(E	0.879	0.806	0.733	0.737	0.674
		(M	0.660	0.606	0.551	0.554	0.506
		(L	0.694	0.618	0.543	0.545	0.484
		(T	2.233	2.030	1.827	1.836	1.664
	Direct Capital Cost of Cooling System	(E	18.336	17.427	16.282	16.298	15.363
		(M	6.490	6.301	5.896	5.817	5.573
		(L	18.971	17.656	16.126	15.498	14.903
		(T	43.797	41.384	38.304	37.613	35.839
	Indirect Cost		10.950	10.346	9.576	9.403	8.960
	Total Capital Cost		54.747	51.730	47.880	47.016	44.799

TABLE P-10. SUMMARY OF DESIGN DATA FOR THE OPTIMIZED WET/DRY AND REFERENCE COOLING SYSTEMS

5 HOURS PER YEAR GROUND FOG

SITE: CLEVELAND, OHIO

Variable	DRY HEAT EXCHANGER TUBE LENGTH			Wet Tower System
	15 ft	10 ft	5 ft	
General Design Data				
Design Temperatures, °F (°C):				
Dry Bulb	90.0 (32.2)	90.0 (32.2)	90.0 (32.2)	90.0 (32.2)
Wet Bulb	71.0 (21.7)	71.0 (21.7)	71.0 (21.7)	71.0 (21.7)
Cold Water	86.0 (30.0)	84.0 (28.9)	83.0 (28.3)	80.0 (26.7)
Cooling Range	25.0 (13.9)	25.0 (13.9)	26.0 (14.4)	28.0 (15.6)
Approach	15.0 (8.3)	13.0 (7.2)	12.0 (6.7)	9.0 (5.0)
Design Turbine Back Pressure, in-HgA (mm-HgA)	3.08 (78.2)	2.91 (73.9)	2.91 (73.9)	2.83 (71.9)
Maximum Operating Back Pressure, in-HgA (mm-HgA)	3.08 (78.2)	2.95 (74.9)	2.94 (74.7)	2.87 (72.9)
Design Heat Load, 10^9 Btu/hr (10^{12} J/hr)	4.50 (4.75)	4.49 (4.74)	4.49 (4.74)	4.48 (4.73)
Plant Capacity at Cooling System Design Point, MWe	1026.2	1028.8	1028.8	1030.0
Ground Fogging (hrs/year)	4	4	4	4

TABLE P-10 (continued)

Variable	DRY HEAT EXCHANGER TUBE LENGTH			Wet Tower System
	15 ft	10 ft	5 ft	
Condenser				
Surface Area, 10^3 ft^2 (10^3 m^2)	679 (63.1)	682 (63.4)	670 (62.2)	651 (60.5)
Number of Tubes	48,400	48,300	46,500	43,100
Tube Length, ft (m)	53.6 (16.3)	53.9 (16.4)	55.1 (16.8)	57.7 (17.6)
Circulating Water Flow & Pump				
Circulating Water Flow Rate, 10^3 gpm (m^3/min)	360 (1363)	359 (1359)	345 (1306)	320 (1211)
Number of Pumps	2	2	2	2
Pumping Head, ft (m) of Water	92.8 (28.3)	90.5 (27.6)	87.9 (26.8)	87.6 (26.7)
Motor Rating, hp (kW) per pump	5000 (3730)	5000 (3730)	5000 (3730)	4500 (3357)
Motor Brake Horsepower, hp (kW) per pump	4737 (3532)	4609 (3437)	4302 (3209)	3978 (2968)

TABLE P-10 (continued)

Variable	DRY HEAT EXCHANGER TUBE LENGTH			Wet Tower System
	15 ft	10 ft	5 ft	
<u>Circulating Water Pipelines</u>				
Condenser Intake:				
Number of Lines	1	1	1	1
Diameter/Length, in/ft (cm/m)	108/1120(274/341)	108/1120(274/341)	108/1120(274/341)	102/1120(259/341)
Condenser Discharge:				
Number of Lines	1	1	1	1
Diameter/Length, in/ft (cm/m)	108/940(274/287)	108/940(274/287)	108/940(274/287)	102/940(259/287)
Connecting Pipelines:				
Number of Lines	2	2	2	2
Diameter/Length, in/ft (cm/m)	78/710(198/216)	78/710(198/216)	78/710(198/216)	72/710(183/216)
<u>Cooling Tower</u>				
Number of Cells	27	30	32	40
Heat Exchanger Tube Length, ft (m)	15 (4.6)	10 (3.0)	5 (1.5)	-

TABLE P-11. PENALTY BREAKDOWN AND COST SUMMARY FOR THE OPTIMIZED WET/DRY AND REFERENCE COOLING SYSTEMS ($\$10^6$)

5 HOURS PER YEAR GROUND FOG

SITE: CLEVELAND, OHIO YEAR: 1985

Item	DRY HEAT EXCHANGER TUBE LENGTH			Mechanical Wet System
	15 ft	10 ft	5 ft	
Penalty Breakdown:				
Capacity Penalty	6.198	5.168	5.166	4.637
Replacement Energy Penalty	2.537	1.321	1.198	0.392
Circulating Water Pumping Power Penalty	3.807	3.703	3.457	3.197
Circulating Water Pumping Energy Penalty	7.693	7.476	6.977	6.447
Cooling Tower Fan Power Penalty	1.692	1.895	2.032	2.583
Cooling Tower Fan Energy Penalty	3.272	2.651	3.905	4.924
Make-up Water Purchase and Treatment Penalty	0.402	0.400	0.399	0.399
Make-up Water Pumping Energy and Capacity Penalty	0.210	0.211	0.213	0.218
Cooling System Maintenance Penalty	2.230	2.308	2.264	2.236
Cost Summary:				
Total Penalty Cost	28.041	25.133	25.611	25.033
Total Capital Cost	52.144	53.355	53.060	54.747
Total Evaluated Cost	80.185	78.488	78.671	79.780

TABLE P-12. SUMMARY OF CAPITAL INVESTMENT COST FOR THE OPTIMIZED WET/DRY AND REFERENCE COOLING SYSTEMS ($$10^6$)

SITE: CLEVELAND, OHIO PRICING YEAR: 1985

Acct. No.	Equipment Item		HEAT EXCHANGER TUBE LENGTH			Mechanical Wet System
			15 ft.	10 ft.	5 ft.	
118L	Circulating Water Pump Structures	(M	0.817	0.817	0.804	0.781
		(L	0.653	0.653	0.641	0.625
		(T	1.470	1.470	1.445	1.406
132.211	Circulating Water Pumps and Motors	(E	1.815	1.815	1.815	1.736
		(M	0.019	0.019	0.019	0.018
		(L	0.105	0.105	0.105	0.105
		(T	1.939	1.939	1.939	1.859
132.25	Concrete Pipelines	(M	1.853	1.853	1.853	1.660
		(L	1.472	1.472	1.472	1.351
		(T	3.325	3.325	3.325	3.011
132.3211	Cooling Tower Basin and Foundation	(M	1.753	1.948	2.076	2.596
		(L	3.153	3.504	3.735	4.669
		(T	4.906	5.452	5.811	7.265
132.3212	Cooling Towers, Installed	(E	8.299	8.436	8.159	8.295
		(M	0.084	0.086	0.082	0.084
		(L	6.735	6.845	6.621	6.730
		(T	15.118	15.367	14.862	15.109
133.1	Condensers, Installed	(E	7.170	7.187	7.064	6.861
		(M	0.036	0.036	0.035	0.034
		(L	3.788	3.792	3.749	3.678
		(T	10.994	11.015	10.848	10.573
114 & 132.1	Make-up Facilities	(E	0.529	0.537	0.543	0.565
		(M	0.618	0.626	0.632	0.657
		(L	1.053	1.067	1.077	1.119
		(T	2.200	2.230	2.252	2.341
14	Electrical Equipment	(E	0.722	0.766	0.794	0.879
		(M	0.542	0.575	0.597	0.660
		(L	0.499	0.545	0.575	0.694
		(T	1.763	1.886	1.966	2.233
	Direct Capital Cost of Cooling System	(E	18.535	18.741	18.375	18.336
		(M	5.722	5.960	6.098	6.490
		(L	17.458	17.983	17.975	18.971
		(T	41.715	42.684	42.448	43.797
	Indirect Cost		10.429	10.671	10.612	10.950
	Total Capital Cost		52.144	53.355	53.060	54.747

TABLE P-13. SUMMARY OF DESIGN DATA FOR THE OPTIMIZED WET/DRY AND MECHANICAL WET COOLING SYSTEMS

SITE: NEWARK, NEW JERSEY

Variable	Mechanical Wet/Dry Towers (5' Exchanger) 5 Hours	MECHANICAL WET TOWER - GROUND FOGGING		
		5 Hours	10 Hours	Reference 16 Hours
General Design Data				
Design Temperatures, ^{o}F (^{o}C):				
Dry Bulb	92.0 (33.3)	92.0 (33.3)	92.0 (33.3)	92.0 (33.3)
Wet Bulb	75.0 (23.9)	75.0 (23.9)	75.0 (23.9)	75.0 (23.9)
Cold Water	88.0 (31.1)	86.0 (30.0)	88.0 (31.1)	90.0 (32.2)
Cooling Range	22.0 (12.2)	26.0 (14.4)	22.0 (12.2)	22.0 (12.2)
Approach	13.0 (7.2)	11.0 (6.1)	13.0 (7.2)	15.0 (8.3)
Design Turbine Back Pressure, in-HgA (mm-HgA)	2.99 (76.1)	3.17 (80.5)	2.99 (76.1)	3.17 (80.5)
Maximum Operating Back Pressure, in-HgA (mm-HgA)	3.26 (82.8)	3.46 (87.9)	3.26 (82.8)	3.41 (86.6)
Design Heat Load, 10^9 Btu/hr (10^{12} J/hr)	4.49 (4.74)	4.50 (4.75)	4.49 (4.74)	4.50 (4.75)
Plant Capacity at Cooling System Design Point, MWe	1027.6	1024.8	1027.6	1024.8
Ground Fogging (hrs/year)	3	3	10	16

TABLE P-13 (continued)

Variable	Mechanical Wet/Dry Towers (5' Exchanger) 5 Hours	MECHANICAL WET TOWER - GROUND FOGGING 5 Hours	10 Hours	Reference 16 Hours
Condenser				
Surface Area, 10^3 ft^2 (10^3 m^2)	722 (67.1)	666 (61.9)	722 (67.1)	720 (66.9)
Number of Tubes	55000	46600	55000	55100
Tube Length, ft (m)	50.2 (15.3)	54.6 (16.6)	50.2 (15.3)	49.9 (15.2)
Circulating Water Flow & Pump				
Circulating Water Flow Rate, 10^3 gpm (m^3/min)	408 (1544)	346 (1310)	408 (1544)	409 (1548)
Number of Pumps	3	2	3	3
Pumping Head, ft (m) of Water	84.3 (25.7)	84.9 (25.9)	81.8 (24.9)	81.6 (21.9)
Motor Rating, hp (kW) per pump	4000 (2954)	4500 (3337)	3500 (2611)	3500 (2611)
Motor Brake Horsepower, hp (kW) per pump	3257 (2430)	4172 (3112)	3159 (2357)	3159 (2357)

TABLE P-13 (continued)

Variable	Mechanical Wet/Dry Towers (5' Exchanger) 5 Hours	MECHANICAL WET TOWER - GROUND FOGGING		
		5 Hours	10 Hours	Reference 16 Hours
<u>Circulating Water Pipelines</u>				
Condenser Intake:				
Number of Lines	1	1	1	1
Diameter/Length, in/ft (cm/m)	120/1120(305/341)	108/1120(274/341)	120/1120(305/341)	120/1120(305/341)
Condenser Discharge:				
Number of Lines	1	1	1	1
Diameter/Length, in/ft (cm/m)	120/940(305/287)	108/940(274/287)	120/940(305/287)	120/940(305/287)
Connecting Pipelines:				
Number of Lines	2	2	2	2
Diameter/Length, in/ft (cm/m)	84/710(213/216)	78/710(198/216)	84/710(213/216)	84/710(213/216)
<u>Cooling Tower</u>				
Number of Cells	28	31	28	25
Heat Exchanger Tube Length, ft (m)	5	-	-	-

TABLE P-14. PENALTY BREAKDOWN AND COST SUMMARY FOR THE OPTIMIZED WET/DRY AND MECHANICAL WET COOLING SYSTEMS ($$10^6$)

SITE: NEWARK, NEW JERSEY YEAR: 1985

Item	Mechanical Wet/Dry Towers (5' Exchanger) 5 Hours	MECHANICAL WET TOWER - GROUND FOGGING		
		5 Hours	10 Hours	Reference 16 Hours
Penalty Breakdown:				
Capacity Penalty	7.633	9.254	7.633	8.892
Replacement Energy Penalty	1.321	2.176	1.321	2.616
Circulating Water Pumping Power Penalty	3.926	3.353	3.808	3.808
Circulating Water Pumping Energy Penalty	7.925	6.772	7.685	7.695
Cooling Tower Fan Power Penalty	1.813	2.024	1.813	1.604
Cooling Tower Fan Energy Penalty	3.498	3.893	3.498	3.109
Make-up Water Purchase and Treatment Penalty	0.398	0.397	0.398	0.400
Make-up Water Pumping Energy and Capacity Penalty	0.210	0.212	0.210	0.209
Cooling System Maintenance Penalty	2.370	2.016	2.156	2.079
Cost Summary:				
Total Penalty Cost	29.094	30.097	28.522	30.412
Total Capital Cost	52.034	48.624	48.736	46.439
Total Evaluated Cost	81.128	78.721	77.258	76.851

TABLE P-15. SUMMARY OF CAPITAL INVESTMENT COST FOR THE OPTIMIZED WET/DRY AND MECHANICAL WET COOLING SYSTEMS ($$10^6$)

SITE: NEWARK, NEW JERSEY

PRICING YEAR: 1985

Acct. No.	Equipment Item		Mechanical Wet/Dry Towers (5' Exchanger) 5 hours	MECHANICAL WET TOWER - GROUND FOGGING		
				5 Hours	10 Hours	Reference 16 Hours
118L	Circulating Water Pump Structures	(M	0.856	0.804	0.856	0.856
		(L	0.682	0.643	0.682	0.685
		(T	1.538	1.447	1.538	1.541
132.211	Circulating Water Pumps and Motors	(E	2.241	1.736	2.122	2.122
		(M	0.023	0.018	0.021	0.021
		(L	0.158	0.105	0.158	0.158
		(T	2.422	1.859	2.301	2.301
132.25	Concrete Pipelines	(M	2.133	1.853	2.133	2.133
		(L	1.679	1.472	1.679	1.679
		(T	3.812	3.325	3.812	3.812
132.3211	Cooling Tower Basin and Foundation	(M	1.816	2.011	1.816	1.622
		(L	3.268	3.618	3.268	2.917
		(T	5.084	5.629	5.084	4.539
132.3212	Cooling Towers, Installed	(E	7.140	6.429	5.805	5.183
		(M	0.072	0.065	0.059	0.052
		(L	5.794	5.217	4.711	4.207
		(T	13.006	11.711	10.575	9.442
133.1	Condensers, Installed	(E	7.611	7.035	7.611	7.600
		(M	0.038	0.035	0.038	0.038
		(L	3.939	3.743	3.939	3.937
		(T	11.588	10.813	11.588	11.575
114 & 132.1	Make-up Facilities	(E	0.533	0.542	0.533	0.526
		(M	0.622	0.631	0.622	0.615
		(L	1.059	1.075	1.059	1.046
		(T	2.214	2.248	2.214	2.187
14	Electrical Equipment	(E	0.802	0.747	0.753	0.708
		(M	0.602	0.561	0.565	0.533
		(L	0.559	0.559	0.559	0.513
		(T	1.963	1.867	1.877	1.754
	Direct Capital Cost of Cooling System	(E	18.327	16.489	16.824	16.139
		(M	6.162	5.978	6.110	5.870
		(L	17.138	16.432	16.055	15.142
		(T	41.627	38.899	38.989	37.151
	Indirect Cost		10.407	9.725	9.747	9.288
	Total Capital Cost		52.034	48.624	48.736	46.439

TABLE P-16. SUMMARY OF DESIGN DATA FOR THE OPTIMIZED MECHANICAL WET COOLING SYSTEMS

SITE: CHARLOTTE, NORTH CAROLINA

Variable	MECHANICAL WET TOWER - GROUND FOGGING			
	10	20	30	Reference 61
<u>General Design Data</u>				
Design Temperatures, °F (°C):				
Dry Bulb	97.0 (36.1)	97.0 (36.1)	97.0 (36.1)	97.0 (36.1)
Wet Bulb	73.0 (22.8)	73.0 (22.8)	73.0 (22.8)	73.0 (22.8)
Cold Water	83.0 (28.3)	85.0 (29.4)	85.0 (29.4)	89.0 (31.7)
Cooling Range	26.0 (14.4)	24.0 (13.3)	26.0 (14.4)	22.0 (12.2)
Approach	10.0 (5.6)	12.0 (6.7)	12.0 (6.7)	16.0 (8.9)
Design Turbine Back Pressure, in-HgA (mm-HgA)	2.91 (73.9)	2.91 (73.9)	3.08 (78.2)	3.08 (78.2)
Maximum Operating Back Pressure, in-HgA (mm-HgA)	3.01 (76.5)	3.00 (76.2)	3.17 (80.5)	3.13 (79.5)
Design Heat Load, 10^9 Btu/hr (10^{12} J/hr)	4.49 (4.74)	4.49 (4.74)	4.50 (4.75)	4.50 (4.75)
Plant Capacity at Cooling System Design Point, MWe	1028.8	1028.8	1026.2	1026.2
Ground Fogging (hrs/year)	11	20	32	61

TABLE P-16 (continued)

Variable	MECHANICAL WET TOWER - GROUND FOGGING			
	10	20	30	Reference 61
Condenser				
Surface Area, 10^3 ft^2 (10^3 m^2)	670 (62.2)	695 (64.6)	667 (62.0)	721 (67.0)
Number of Tubes	46,500	50,300	46,500	55,000
Tube Length, ft (m)	55.1 (16.8)	52.7 (16.1)	54.7 (16.8)	50.1 (15.3)
<u>Circulating Water Flow & Pump</u>				
Circulating Water Flow Rate, 10^3 gpm (m^3/min)	345 (1306)	374 (1416)	346 (1310)	409 (1548)
Number of Pumps	2	3	2	3
Pumping Head, ft (m) of Water	85.3 (26.0)	84.0 (25.6)	85.1 (25.9)	81.7 (24.9)
Motor Rating, hp (kW) per pump	4500 (3357)	3500 (2611)	4500 (3357)	3500 (2611)
Motor Brake Horsepower, hp (kW) per pump	4176 (3115)	2970 (2216)	4173 (3113)	3159 (2357)

TABLE P-16 (continued)

Variable	MECHANICAL WET TOWER - GROUND FOGGING			
	10	20	30	Reference 61
Circulating Water Pipelines				
Condenser Intake:				
Number of Lines	1	1	1	1
Diameter/Length, in/ft (cm/m)	108/1120 (274/341)	114/1120 (290/341)	108/1120 (274/341)	120/1120 (305/341)
Condenser Discharge:				
Number of Lines	1	1	1	1
Diameter/Length, in/ft (cm/m)	108/940 (214/287)	114/940 (290/287)	108/940 (274/287)	120/940 (305/287)
Connecting Pipelines:				
Number of Lines	2	2	2	2
Diameter/Length, in/ft (cm/m)	78/710 (198/216)	78/710 (198/216)	78/710 (198/216)	84/710 (213/216)
Cooling Tower				
Number of Cells	35	31	30	25
Heat Exchanger Tube Length, ft (m)	-	-	-	-

TABLE P-17. PENALTY BREAKDOWN AND COST SUMMARY FOR THE OPTIMIZED MECHANICAL WET COOLING SYSTEMS ($\$10^6$)

SITE: CHARLOTTE, NORTH CAROLINA YEAR: 1985

Item	MECHANICAL WET TOWER - GROUND FOGGING			
	10	20	30	Reference 61
Penalty Breakdown:				
Capacity Penalty	5.667	5.559	6.909	6.560
Replacement Energy Penalty	1.819	2.006	3.338	3.526
Circulating Water Pumping Power Penalty	3.356	3.580	3.353	3.808
Circulating Water Pumping Energy Penalty	6.777	7.231	6.781	7.700
Cooling Tower Fan Power Penalty	2.214	1.945	1.878	1.544
Cooling Tower Fan Energy Penalty	4.266	3.760	3.638	3.007
Make-up Water Purchase and Treatment Penalty	0.429	0.427	0.427	0.427
Make-up Water Pumping Energy and Capacity Penalty	0.225	0.222	0.221	0.218
Cooling System Maintenance Penalty	2.119	2.216	1.991	2.080
Cost Summary:				
Total Penalty Cost	26.872	26.946	28.536	28.870
Total Capital Cost	51.728	50.103	47.883	46.454
Total Evaluated Cost	78.600	77.049	76.419	75.324

TABLE P-18. SUMMARY OF CAPITAL INVESTMENT COST FOR THE OPTIMIZED WET/DRY AND MECHANICAL WET COOLING SYSTEMS ($$10^6$)

SITE: CHARLOTTE, NORTH CAROLINA PRICING YEAR: 1985

Acct. No.	Equipment Item		MECHANICAL WET TOWER - GROUND FOGGING			
			10	20	30	Reference 61
118L	Circulating Water Pump Structures	(M	0.804	0.829	0.804	0.856
		(L	0.641	0.662	0.643	0.685
		(T	1.445	1.491	1.447	1.541
132.211	Circulating Water Pumps and Motors	(E	1.736	2.122	1.736	2.122
		(M	0.018	0.021	0.018	0.021
		(L	0.105	0.158	0.105	0.158
		(T	1.859	2.301	1.859	2.301
132.25	Concrete Pipelines	(M	1.853	1.950	1.853	2.133
		(L	1.472	1.550	1.472	1.679
		(T	3.325	3.500	3.325	3.812
132.3211	Cooling Tower Basin and Foundation	(M	2.271	2.011	1.946	1.622
		(L	4.085	3.618	3.501	2.917
		(T	6.356	5.629	5.447	4.539
132.3212	Cooling Towers, Installed	(E	7.257	6.429	6.221	5.183
		(M	0.073	0.065	0.063	0.052
		(L	5.888	5.217	5.047	4.207
		(T	13.218	11.711	11.331	9.442
133.1	Condensers, Installed	(E	7.064	7.321	7.043	7.606
		(M	0.035	0.037	0.035	0.038
		(L	3.749	3.838	3.744	3.937
		(T	10.848	11.796	10.822	11.581
114 & 132.1	Make-up Facilities	(E	0.555	0.544	0.542	0.528
		(M	0.646	0.634	0.631	0.616
		(L	1.100	1.079	1.075	1.050
		(T	2.301	2.257	2.248	2.194
14	Electrical Equipment	(E	0.806	0.796	0.733	0.709
		(M	0.606	0.598	0.551	0.533
		(L	0.618	0.605	0.543	0.513
		(T	2.030	1.999	1.827	1.755
	Direct Capital Cost of Cooling System	(E	17.418	17.212	15.275	16.148
		(M	6.306	6.145	5.901	5.171
		(L	17.659	16.727	16.130	15.146
		(T	41.383	40.084	38.306	37.165
	Indirect Cost		10.345	10.020	9.576	9.291
	Total Capital Cost		51.728	50.103	47.883	46.454

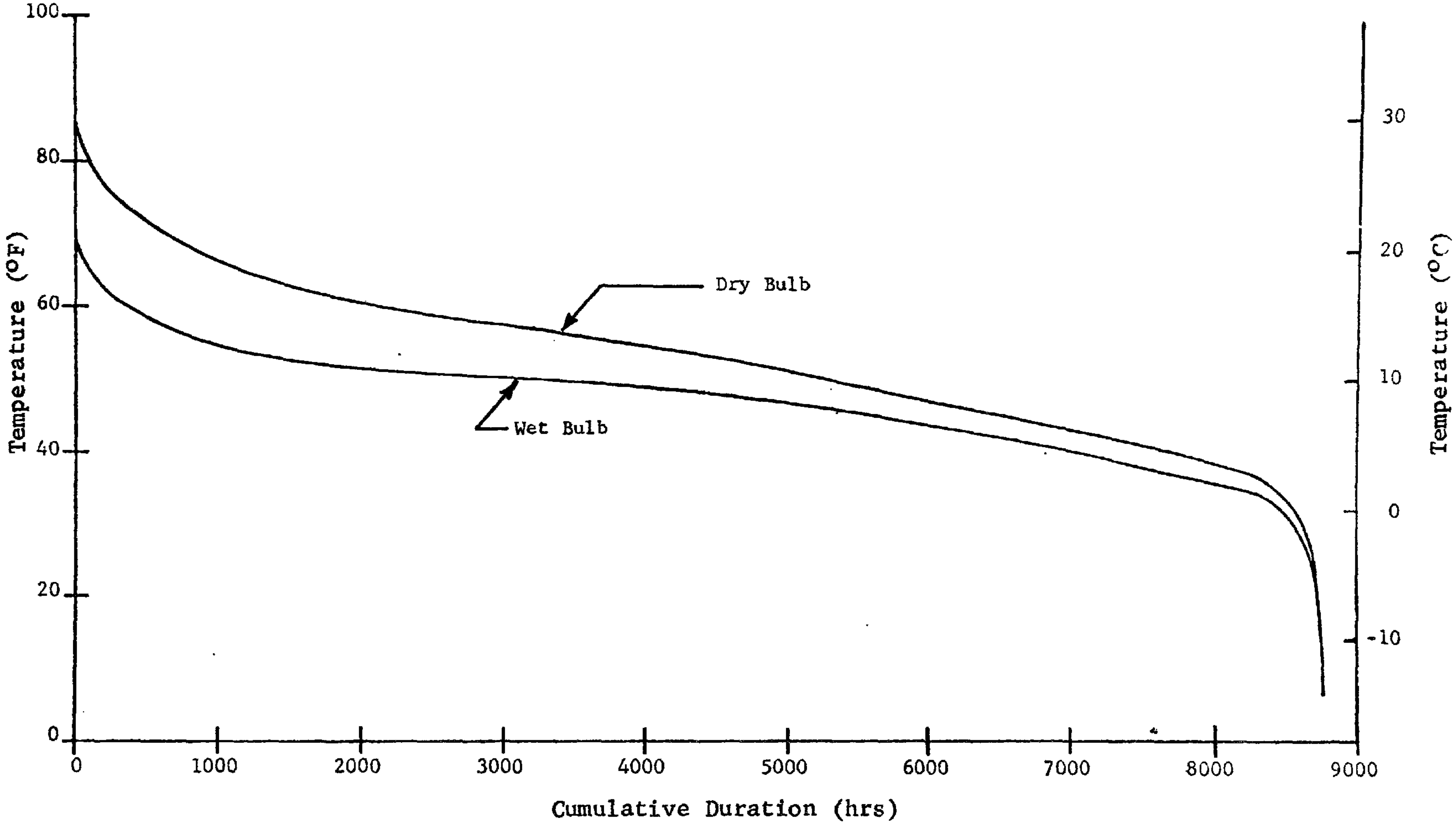


Figure P-1 Temperature Duration Curves: Seattle, Washington

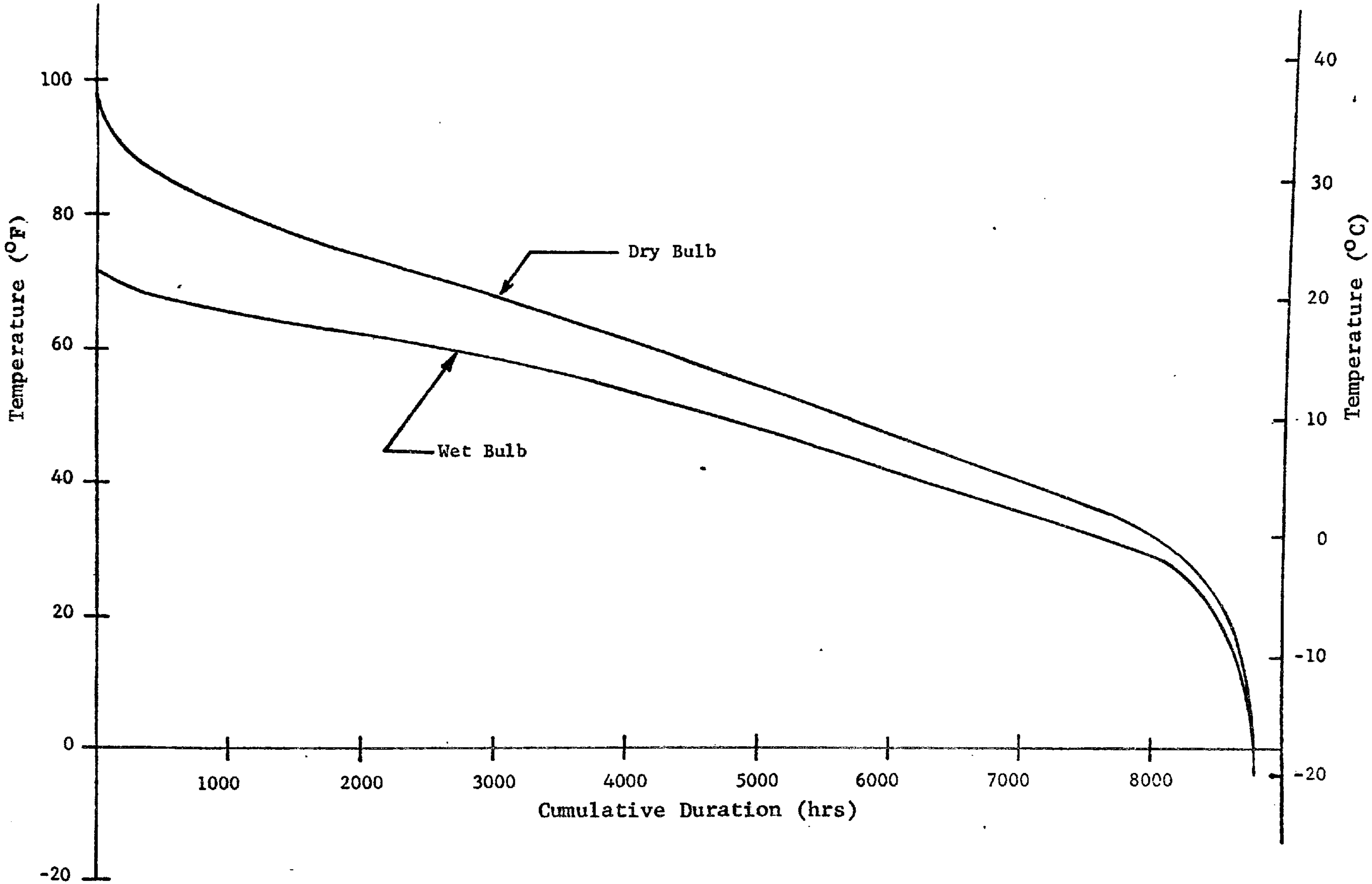


Figure P-2 Temperature Duration Curves: Cleveland, Ohio

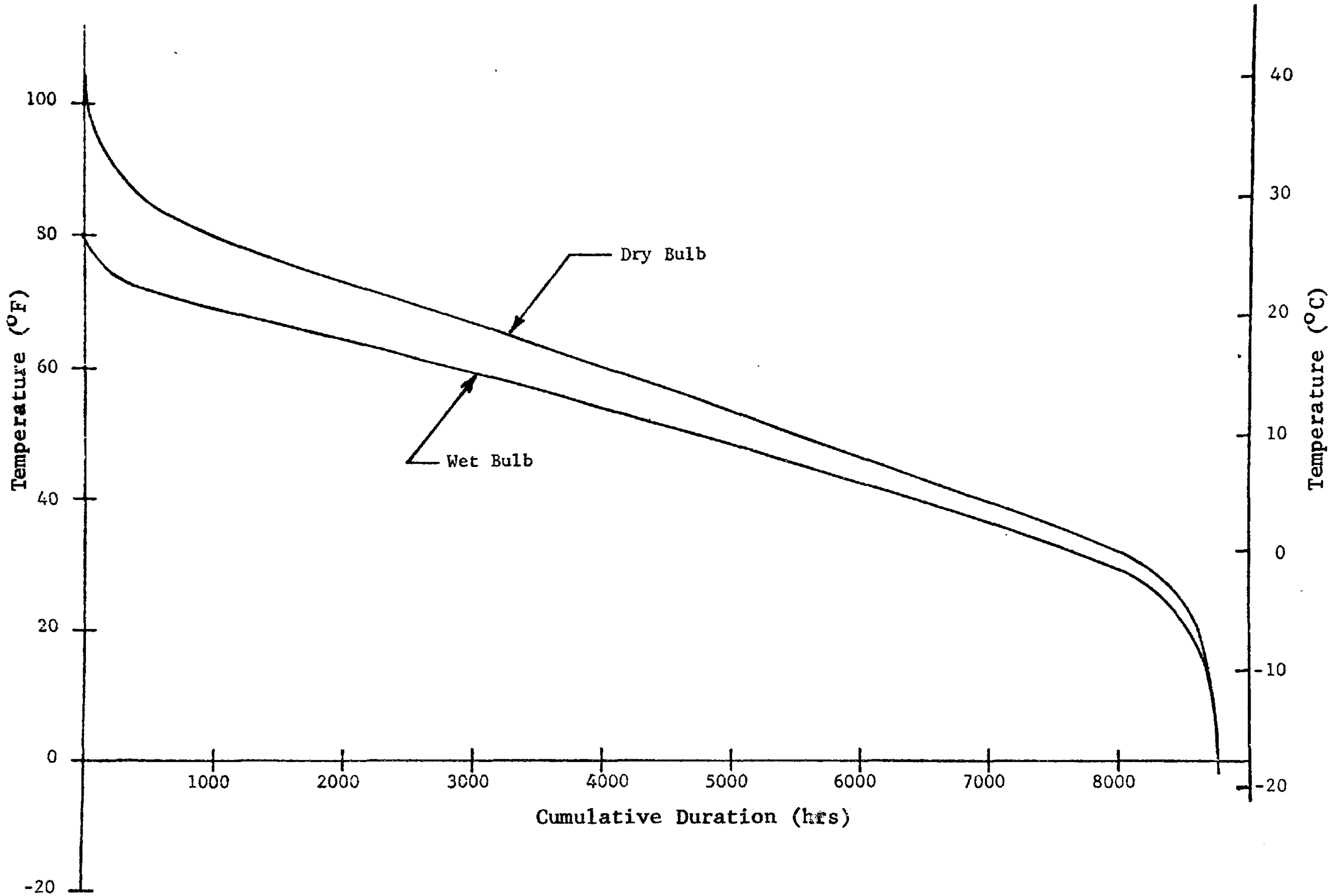


Figure P-3 Temperature Duration Curves: Newark, New Jersey

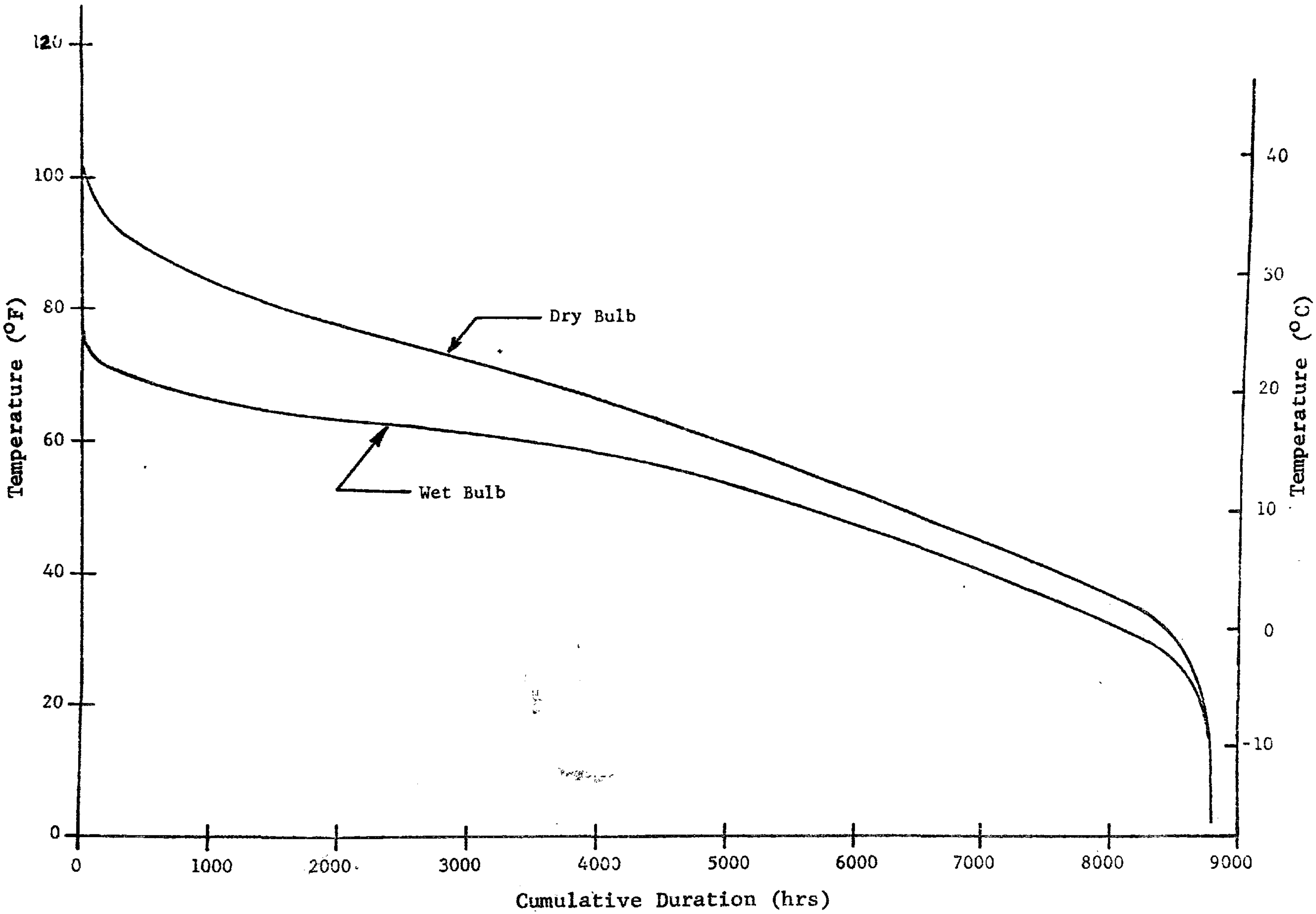


Figure P-4 Temperature Duration Curves: Charlotte, North Carolina

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/7-77-137	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE Wet/Dry Cooling Systems for Fossil-Fueled Power Plants: Water Conservation and Plume Abatement		5. REPORT DATE November 1977 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) M.C. Hu and G.A. Englesson		8. PERFORMING ORGANIZATION REPORT NO. UEandC-EPA-771130
9. PERFORMING ORGANIZATION NAME AND ADDRESS United Engineers and Constructors, Inc. 30 South 17th Street Philadelphia, Pennsylvania 19101		10. PROGRAM ELEMENT NO. EHE624 11. CONTRACT/GRANT NO. 68-03-2202
12. SPONSORING AGENCY NAME AND ADDRESS EPA, Office of Research and Development Industrial Environmental Research Laboratory Research Triangle Park, NC 27711		13. TYPE OF REPORT AND PERIOD COVERED Final; 6/75-9/77 14. SPONSORING AGENCY CODE EPA/600/13

15. SUPPLEMENTARY NOTES IERL-RTP project officer for this report is Theodore G. Brna, Mail Drop 61, 919/541-2683.

16. ABSTRACT The report gives results of a study of technical and economic feasibilities of wet/dry cooling towers for water conservation and vapor plume abatement. Results of cost optimizations of wet/dry cooling for 1000-MWe fossil-fueled power plants are presented. Five sites in the western coal region and one in New York are evaluated for water conservation; four urban sites (Seattle, Cleveland, Newark, and Charlotte) are used in the plume abatement analyses. Results are given as the total evaluated cost of the cooling system. Separate cost components include initial capital cost, operating expenses, and penalties for the cooling system operation capitalized over a plant life of 40 years. The year of pricing is 1985. For the water conservation analyses, optimized all-wet and all-dry cooling towers are reference systems. The wet/dry system has separate wet and dry mechanical draft towers. Costs are related to the make-up water requirement expressed as a percentage of the water required by an all-wet system. Parametric and sensitivity analyses show the effect of changing the system design and economic factors. A parallel air-flow hybrid wet/dry tower is used in the plume abatement studies. Costs are presented for an allowable number of hours of fogging. An all-wet system, optimized solely for cost, is the reference.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Pollution	Plumes	Pollution Control	13B	21B
Cooling Towers		Stationary Sources	13A,07A	
Fossil Fuel		Wet/Dry Cooling	21D	
Electric Power Plants			10B	
Water Conservation			02C	
Vapors			07D	

18. DISTRIBUTION STATEMENT Unlimited	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES 300
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

EPA Form 2220-1 (9-73)