HEAT SINK DESIGN AND COST STUDY
FOR
FOSSIL AND NUCLEAR
POWER PLANTS

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December 1974

Prepared for the
Office of Energy Systems Analysis,
Division of Reactor Research and Development,
United States Atomic Energy Commission
by the
Advanced Engineering Department,
United Engineers & Constructors Inc.
[Contract No. AT (11-1)-2226]

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ABSTRACT

A comprehensive design and cost study has been conducted for alternative cooling systems serving electric power generating stations. The cooling systems that were evaluated included three wet tower systems, two pond systems, two dry tower systems, and a basic once-through cooling system. The eight alternative cooling systems were designed for five reference power plants which included fossil, light water reactor, liquid metal fast breeder reactor and high temperature gas cooled reactor power plants; all in the 1000 MWe class. Each of the cooling systems, except for the basic once-through system, were optimized for each reference plant. Therefore, the system selected would have the lowest total evaluated cost with respect to certain design conditions, economic factors, ambient meteorological conditions at the reference plant site (Middletown, U.S.A.).

The total evaluated cost of a cooling system for this study is defined as the sum of the capital cost and various economic penalties which may be attributed to the system. These penalties are assigned to the system to compensate for its performance deficiencies and auxiliary energy requirements, among others. The cooling system deficiencies affect different power plants according to the plant characteristics, which necessitates the treatment of a reference power plant and a cooling system as a single entity in the optimization procedure. The optimum selection of a cooling system is achieved by assessing the proper balance between the capital cost and the total economic penalty.

For the most common wet tower systems, additional analyses have been conducted to investigate the effects on performance and costs due to both the variations in ambient temperature (for various geographic locations) and different cost escalations. These analyses were carried out by transferring the wet tower systems optimized at the Middletown Site to other locations in the country and then determining the effect of ambient temperatures and finally the effect of cost escalations.

The study concludes with a brief discussion of the environmental impact of the various cooling system alternatives investigated. The ultimate choice of a cooling system requires an understanding of its potential impact on the specific environment surrounding the individual site.

In conclusion, the results obtained from this study have been assembled to provide an engineering assessment of the total evaluated costs of alternative cooling systems at the reference site. These results can be used for cooling system comparisons, cooling system selections, and cost projections for similar power plants with similar economic and site meteorological conditions. The cost and penalty breakdowns also allow escalation of these items due to inflation or other reasons. Additionally, the study provides estimates of the costs of wet cooling tower systems best suited for various locations in the United States for a broad spectrum of capacity penalty cost, replacement energy cost, and capital cost escalation.

SUMMARY

S.1 COOLING SYSTEM OPTIMIZATION STUDY

A comprehensive design and cost study has been conducted for various cooling system alternatives interfaced with both fossil and nuclear power plants. The objective was to provide cost and design information for these cooling system alternatives as a basis for cooling system comparisons, evaluations, and cost projections of power plants.

An optimization technique, which treats a cooling system alternative and its interfacing power plant as an entity, was used to determine the design and cost of each cooling system for each reference power plant considered. The technique aids in determining the optimum design of a cooling system by assessing the proper balance between the capital expenditure and economic penalties which may be attributed to the system. These economic penalties are assigned to the cooling system to compensate for the deficiencies of cooling system performance or auxiliary energy requirements, among others.

The results obtained (Section 6.2) include cooling system size, capital cost, economic penalty, total evaluated cost and present worth cost for eight alternative cooling systems. These cooling systems are interfaced with five reference power plants located at the Middletown Site. The Middletown Site is a hypothetical site, selected by the AEC, that is used for uniform plant cost comparisons. The characteristics of the Middletown Site are described in Chapter 5.

The aforementioned results are summarized in Tables S-1 to S-5 and Figure S-1. Tables S-1 to S-5 are the summaries of the costs and economic penalties of the optimum cooling systems, and the gross plant outputs and gross heat rates

at the optimum cooling system design conditions for the five power plants. Refer to Section 6.2 for cooling system abbreviations. The bar graph (Figure S-1) gives an overall view of the costs and penalties which comprise the total evaluated cost for each of the cooling system alternatives.

The basic economic factor used to calculate the cost and penalties applicable to all reference power plant cooling system alternatives are given in Table 6-1 and are repeated below.

Year of Pricing	January 1973
Levelized Power Plant Capacity Factor	0.75
Annual Fixed Charge Rate	15%
Interest Rate	8%
Plant Life	40 years
Replacement Energy Charge Rate *	8.5 mills/kWh
Capacity Penalty Charge Rate *	\$150/kW

S.2 SENSITIVITY STUDY FOR WET TOWER SYSTEMS**

In addition to the primary optimization study for the Middletown site, the scope of work has been expanded to include analyses of the effects of changing ambient temperatures with locations, varying capital cost, varying replacement energy and capacity penalty charge rates, and the use of salt water on wet tower cooling systems. Only wet tower systems were considered for the sensitivity study, since these are the cooling systems most commonly used today. The overall objective of these analyses was to aid the potential users in applying the data obtained in the optimization study (Section 6.2) to the user's particular set of conditions and locations.

* Apply to both the losses due to ambient variations and the cooling system auxiliary power requirements.

** The optimum wet tower systems obtained in the main study for the Middletown site are referred to as "base" Middletown systems.

The first part of the sensitivity analysis is presented in Section 7.1 for the wet tower system to evaluate the effects of changing annual dry and wet bulb temperatures in different parts of this country. Eight locations, scattered across the conterminous United States representing a variety of climate conditions were evaluated. These sites are Seattle, Washington; Los Angeles, California; Phoenix, Arizona; Denver, Colorado; St. Louis, Missouri; New Orleans, Louisiana; Miami, Florida; and Boston, Massachusetts. The procedure used was as follows:

- a. For every additional site, each of the base Middletown wet tower systems was transferred to the site; the cooling system at the new site was referred to as a "transferred" system. The purpose of the transfer was to keep the cooling system size at the new site the same as that for the base Middletown system.
- b. Next, the performance and performance affected penalties for the transferred system as well as the new total evaluated cost were determined.
- c. The difference between the total evaluated cost for the site under consideration and that of the Middletown site was then calculated.
- d. Finally, the extreme locations where the cooling system have the highest or lowest total evaluated costs were determined.

For the eight sites considered, the extreme locations coincide for all wet tower cooling systems; these are Miami, Florida and Denver, Colorado. At the Florida site, the cooling systems have the highest total evaluated cost; the Colorado site the lowest. The increases or decreases in total evaluated cost with respect to Middletown for the two extreme locations are summarized in Table S-6.

For Colorado, Florida and Middletown, the sensitivity study has been extended (Section 7.2) to include the following three factors directly concerning cost: 1) capital investment cost, 2) replacement energy cost, and 3) capacity penalty charge. The basic procedure used is similar to that described in the preceding paragraph, that is, transferring the base Middletown systems to other sites including Middletown itself and then determining the cost and penalty changes resulting from the changes in the above factors. The escalation in the cost factors with respect to the base costs given in the main optimization study ranges from fifty to one hundred percent for capital investment cost, double to quadruple for replacement energy cost, and double to triple for capacity penalty cost. For each combination of the cost escalations investigated, the total evaluated cost of the wet tower systems (mechanical, natural and fan-assisted natural draft wet towers) were calculated, and the system with the lowest total evaluated cost was selected as the recommended system. The results are summarized in Table S-7, which give the recommended wet tower systems and the total evaluated costs of these systems for a number of different combinations of the escalation of these factors. It should be noted that the data for Colorado and Florida also included the effects of location change.

Figure S-2 provides a graphic representation of the recommended wet tower systems given in Table S-7, from which the following observations can be made:

- a. For the fossil plant, the dominant factor influencing the change in system selection from the base Middletown system (mechanical wet tower) is the replacement energy cost. As the replacement energy cost increases, the fan-assisted natural draft tower system becomes more and more attractive.

- b. For the LWR plant, each of the three cost factors plays an important role in affecting the change in system selection. As the capital cost and/or capacity penalty cost becomes large, the mechanical wet tower system becomes the best choice instead of the natural draft wet tower system. However, the increase in replacement energy cost negates the influence of the other two cost factors, and again makes the natural draft tower system the best choice.
- c. For both types of reference power plants, the geographic factor (ambient temperature variation with location) exerts stronger influence in system selection at low capital cost.

The sensitivity study discussed so far can also be carried out by means of optimization using the new conditions of the sensitivity factors. Optimization would, in general, result in different cooling system sizes, capital costs and penalties, as well as savings in the total evaluated costs. However, a complete analysis using this approach requires extensive effort which is beyond the scope of this work. Therefore, only a number of cases were optimized to compare the difference between the two approaches. The sample cases investigated involve two factors: location and doubling of the replacement energy charge rate. These two factors were considered either separately or jointly. The comparisons indicate the following: 1) if a single factor was considered, optimization would produce only a small savings in the effective cost of cooling systems (maximum about 3%); and 2) if the combined effect of the two factors was considered, the savings through optimization would be much greater (maximum about 10%).

In conclusion, the transfer method used in the sensitivity study provides means for extrapolating the data from the main study for system selection and cost estimation. Optimization, however, would be desirable for optimum

selection and accurate cost estimation of cooling systems for conditions deviating substantially from those assumed in the main study.

The preceding results are for fresh water cooling systems only. A discussion of the effects of salt water on the performance, size and cost of wet tower cooling systems is presented in Section 7.4. The discussion shows that for the same heat load, a salt water tower system will have:

- a. An increase in condenser size and volumetric cooling water flow rate;
- b. An increase in cooling tower size to handle the increase in cooling water flow rate;
- c. An increase in tower size to compensate for the decrease in tower efficiency as compared to that for fresh water towers.

The increase in capital cost for all salt water wet tower systems with respect to the fresh water system can be roughly estimated with the following data (include corrosion resistant material requirement).

<u>Cooling Tower System Component</u>	<u>Approximate Increase (%) in Capital Cost</u>
Cooling Tower	5
Condenser	13
Others	2

Thus, with the data of this study, together with those from the sensitivity analysis, it is possible to estimate size and cost of a cooling system, especially a wet tower system, in the planning of new power plants.

Finally, a brief discussion of the environmental impact of the various cooling system alternatives investigated in this study is presented in Chapter 8.

The ultimate choice of a cooling system requires an understanding of its potential impact on the specific environment surrounding the individual site.

TABLE S-1

SUMMARY OF COSTS AND ECONOMIC PENALTIES FOR OPTIMIZED COOLING SYSTEMS (MIDDLETOWN)
INTERFACED WITH 1000 MWe FOSSIL POWER PLANT
AND
THE PLANT OUTPUTS AND HEAT RATES AT OPTIMUM COOLING SYSTEM DESIGN CONDITIONS

Item \ Cooling System	Once-Through	Mech. Wet	Fan Wet	Nat. Wet	Pond	Spray Canal	Mech. Dry	Nat. Dry
Total Capital Investment (Equipment, Material & Labor, and Indirect Charges) (\$10 ⁶)	11.27	16.04	20.65	20.05	28.63	17.84	25.50	28.16
Total Economic Penalties Assigned to the Optimized Cooling System (\$10 ⁶)	2.74	13.03	10.94	11.82	13.56	13.94	58.49	51.79
Total Evaluated Cost (Total Capital Cost plus Total Economic Penalties) (\$10 ⁶)	14.01	29.07	31.59	31.87	42.19	31.78	83.99	79.95
Gross Plant Output at Optimum Cooling System Design Conditions, MWe	1043	1020	1026	1014	1000	1020	938	932
Gross Plant Heat Rate, Btu/kWh	7365	7531	7487	7576	7682	7531	8189	8242

TABLE S-2

SUMMARY OF COSTS AND ECONOMIC PENALTIES FOR OPTIMIZED COOLING SYSTEMS (MIDDLETOWN)
INTERFACED WITH 1000 MWe LWR POWER PLANT
AND
THE PLANT OUTPUTS AND HEAT RATES AT OPTIMUM COOLING SYSTEM DESIGN CONDITIONS

Item \ Cooling System	Once-Through	Mech. Wet	Fan Wet	Nat. Wet	Pond	Spray Canal	Mech. Dry	Nat. Dry
Total Capital Investment (Equipment, Material & Labor, and Indirect Charges) (\$10 ⁶)	16.43	21.51	25.29	23.31	39.64	19.89	36.64	44.81
Total Economic Penalties Assigned to the Optimized Cooling System (\$10 ⁶)	3.11	15.60	13.46	13.33	14.35	20.00	83.47	70.50
Total Evaluated Cost (Total Capital Cost plus Total Economic Penalties) (\$10 ⁶)	19.54	37.11	38.75	36.64	53.99	39.89	120.11	115.31
Gross Plant Output at Optimum Cooling System Design Conditions, MWe	1096	1075	1078	1069	1059	1056	933	940
Gross Plant Heat Rate, Btu/kWh	9760	9951	9923	10,007	10,101	10,130	11,465	11,380

TABLE S-3

SUMMARY OF COSTS AND ECONOMIC PENALTIES FOR OPTIMIZED COOLING SYSTEMS (MIDDLETOWN)
INTERFACED WITH 1000 MWe LMFBR POWER PLANT
AND
THE PLANT OUTPUTS AND HEAT RATES AT OPTIMUM COOLING SYSTEM DESIGN CONDITIONS

Item \ Cooling System	Once-Through	Mech. Wet	Fan Wet	Nat. Wet	Pond	Spray Canal	Mech. Dry	Nat. Dry
Total Capital Investment (Equipment, Material & Labor, and Indirect Charges) (\$10 ⁶)	12.16	17.02	20.35	19.25	29.26	17.70	25.86	34.79
Total Economic Penalties Assigned to the Optimized Cooling System (\$10 ⁶)	2.33	12.03	11.00	11.30	13.04	12.95	57.37	47.98
Total Evaluated Cost (Total Capital Cost plus Total Economic Penalties) (\$10 ⁶)	14.49	29.05	31.35	30.55	42.30	30.65	83.23	82.77
Gross Plant Output at Optimum Cooling System Design Conditions, MWe	1059	1041	1041	1031	1019	1037	935	943
Gross Plant Heat Rate, Btu/kWh	7773	7907	7907	7984	8078	7938	8804	8729

TABLE S-4

SUMMARY OF COSTS AND ECONOMIC PENALTIES FOR OPTIMIZED COOLING SYSTEMS (MIDDLETOWN)
INTERFACED WITH 1160 MWe HTGR POWER PLANT*
AND
THE PLANT OUTPUTS AND HEAT RATES AT OPTIMUM COOLING SYSTEM DESIGN CONDITIONS

Item \ Cooling System	Once-Through	Mech. Wet	Fan Wet	Nat. Wet	Pond	Spray Canal	Mech. Dry	Nat. Dry
Total Capital Investment (Equipment, Material & Labor, and Indirect Charges) (\$10 ⁶)	14.89	19.18	22.78	21.53	35.69	21.89	33.44	39.81
Total Economic Penalties Assigned to the Optimized Cooling System (\$10 ⁶)	2.85	13.71	12.09	11.79	11.96	14.33	60.27	50.81
Total Evaluated Cost (Total Capital Cost plus Total Economic Penalties) (\$10 ⁶)	17.74	32.89	34.87	33.32	47.65	36.22	93.71	90.62
Gross Plant Output at Optimum Cooling System Design Conditions, MWe	1175	1156	1158	1151	1142	1152	1048	1046
Gross Plant Heat Rate, Btu/kWh	8715	8858	8843	8897	8967	8889	9771	9790

*Twin turbine-generator units

TABLE S-5

SUMMARY OF COSTS AND ECONOMIC PENALTIES FOR OPTIMIZED COOLING SYSTEMS (MIDDLETOWN)
INTERFACED WITH 770 MWe HTGR POWER PLANT
AND
THE PLANT OUTPUTS AND HEAT RATES AT OPTIMUM COOLING SYSTEM DESIGN CONDITIONS

Item	Cooling System	Once-Through	Mech. Wet	Fan Wet	Nat. Wet	Pond	Spray Canal	Mech. Dry	Nat. Dry
Total Capital Investment (Equipment, Material & Labor, and Indirect Charges) (\$10 ⁶)		10.81	13.86	14.99	15.65	23.39	14.91	22.30	25.01
Total Economic Penalties Assigned to the Optimized Cooling System (\$10 ⁶)		1.90	8.69	8.01	7.81	8.98	8.50	41.02	34.42
Total Evaluated Cost (Total Capital Cost plus Total Economic Penalties) (\$10 ⁶)		12.71	22.55	23.00	23.46	32.37	23.41	63.32	59.43
Gross Plant Output at Optimum Cooling System Design Conditions, MWe		797	786	786	779	773	784	709	710
Gross Plant Heat Rate, Btu/kWh		8457	8575	8575	8652	8720	8597	9507	9493

Figure S-1 Cooling System Comparison

TABLE S-6

EFFECTS OF GEOGRAPHIC LOCATIONS ON TOTAL EVALUATED COST
WITH REFERENCE TO MIDDLETOWN SITE

Plant	Cooling System	C_t \$10 ⁶	$(\Delta C_t) / C_t, \%$	
			Minimum (Colorado) Transferred	Maximum (Florida) Transferred
Fossil	Mech. Wet	29.07	-7.88	16.27
	Fan Wet	31.59	-6.52	12.92
	Nat. Wet	31.87	-5.87	13.21
LWR	Mech. Wet	37.11	-5.74	11.72
	Fan Wet	38.75	-5.19	10.12
	Nat. Wet	36.64	-5.84	11.22

C_t - Total Evaluated Cost of Base Middletown System.

ΔC_t - Total Evaluated Cost Difference between the Transferred Tower System and the Base Middletown Tower System.

*
TABLE S-7 (Sheet 1 of 4)
RECOMMENDED COOLING SYSTEM -- TYPE AND TOTAL EVALUATED COST (\$10⁶)

CAPACITY PENALTY CHARGE: 1X

PLANT	Replace- ment Energy Cost Site	1X			2X			3X			4X		
	Capital	Midtn.	Col.	Fla.	Midtn.	Col.	Fla.	Midtn.	Col.	Fla.	Midtn.	Col.	Fla.
Fossil	1X	M	M	M	M	M	F	F	M	F	N	F	F
	1½X	29.07	26.34	32.95	35.71	32.89	44.53	41.79	36.71	57.47	46.33	39.45	70.41
	2X	M	M	M	M	M	M	M	M	F	N	M	F
LWR	1X	37.09	34.80	41.82	43.73	40.91	52.82	50.37	44.73	67.79	56.36	48.55	80.74
	1½X	M	M	M	M	M	M	M	M	M	M	M	F
	2X	45.11	42.82	49.84	51.75	48.93	60.84	58.39	52.75	76.57	65.03	56.57	91.07
LWR	1X	N	N	N	N	N	N	N	N	N	N	N	N
	1½X	36.64	34.30	40.44	42.84	40.37	51.36	49.04	44.10	66.07	55.24	47.83	80.79
	2X	M	M	M	N	N	N	N	N	N	N	N	N
		47.87	45.74	52.22	54.49	52.02	63.01	60.69	55.75	77.73	66.90	59.49	92.45
		M	M	M	N	N	N	N	N	N	N	N	N
		58.62	56.49	62.97	66.15	63.68	74.67	72.35	67.41	89.39	78.56	71.15	104.11

* Symbols identified on sheet 4

TABLE S-7 (Sheet 2)
RECOMMENDED COOLING SYSTEM -- TYPE AND TOTAL EVALUATED COST (\$10⁶)

CAPACITY PENALTY CHARGE: 2X

PLANT	Replacement Energy Cost	1X			2X			3X			4X		
	Site	Midtn.	Col.	Fla.	Midtn.	Col.	Fla.	Midtn.	Col.	Fla.	Midtn.	Col.	Fla.
	Capital												
Fossil	1X	M	M	M	M	M	F	F	F	F	F	F	F
	1½X	34.07	30.01	39.14	40.71	33.83	53.15	46.04	37.38	66.09	51.13	40.00	79.03
	2X	M	M	M	M	M	M	M	M	F	F	M	F
LWR	1X	42.09	38.03	47.16	48.73	41.85	62.89	55.37	45.67	76.41	61.55	49.49	89.36
	1½X	M	M	M	M	M	M	M	M	M	M	M	F
	2X	50.11	46.05	55.18	56.75	49.81	70.91	63.39	53.69	86.64	70.03	57.51	99.68
LWR	1X	M	M	N	N	N	N	N	N	N	N	N	F
	1½X	42.46	38.70	46.48	48.92	42.49	61.20	55.12	46.22	75.91	61.31	49.95	90.62
	2X	M	M	M	N	N	N	N	N	N	N	N	N
	1½X	53.22	49.45	57.86	60.57	54.08	72.85	66.77	57.88	87.57	72.97	61.60	102.30
	2X	M	M	M	M	M	N	N	N	N	N	N	N
		63.97	60.21	68.61	72.17	65.78	84.51	78.43	69.53	99.23	84.62	73.26	113.95

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TABLE S-7 (Sheet 3)
RECOMMENDED COOLING SYSTEM -- TYPE AND TOTAL EVALUATED COST (\$10⁶)

CAPACITY PENALTY CHARGE: 3X

PLANT	Replacement Energy Cost	1X			2X			3X			4X		
	Site	Midtn.	Col.	Fla.	Midtn.	Col.	Fla.	Midtn.	Col.	Fla.	Midtn.	Col.	Fla.
	Capital												
Fossil	1X	M 39.07	M 30.95	F 48.83	F 45.30	M 34.77	F 61.77	F 50.28	F 37.93	F 74.71	F 55.38	F 40.55	F 87.65
	1½X	M 47.09	M 38.97	M 57.23	M 53.73	M 42.79	F 72.10	M 60.37	M 46.61	F 85.04	M 67.00	M 50.43	F 97.98
	2X	M 55.11	M 46.99	M 65.25	M 61.75	M 50.81	M 80.98	M 68.39	M 54.63	F 95.36	M 75.02	M 58.45	F 108.35
LWR	1X	M 47.81	M 40.29	N 56.32	N 55.00	N 44.61	F 70.99	N 61.20	N 48.34	F 85.29	N 67.40	N 52.07	F 99.59
	1½X	M 58.56	M 51.04	M 67.84	N 66.66	N 52.26	N 82.70	N 72.86	N 60.00	N 97.40	N 79.06	N 63.73	N 112.14
	2X	M 63.23	M 61.80	M 78.60	M 77.52	M 67.26	N 94.35	N 84.51	N 71.65	N 109.06	N 90.71	N 75.39	N 123.80

TABLE S-7 (Sheet 4)
RECOMMENDED COOLING SYSTEM -- TYPE AND TOTAL EVALUATED COST (\$10⁶)

SYMBOLS

Cooling System:

M (Mech. Wet) = Mechanical Draft Wet Tower System

F (Fan Wet) = Fan-Assisted Natural Draft Wet Tower System

N (Nat. Wet) = Natural Draft Wet Tower System

Site: Midtn. = Middletown Reference Site

Fla. = Miami, Florida

Col. = Denver, Colorado

Definitions of 1X, 2X, 3X, etc. :

1X = Basic rate or cost

2X, 3X, etc. = Multiples of the basic rate of cost (e.g. 2X= twice the basic rate or cost)

Basic Rates and Costs:

1) Basic Capacity Penalty Charge = \$150 per kW

2) Basic Replacement Energy Cost = 8.5 mills per kWh

3) Basic Capital Costs:

Plant	Cooling System	Capital Costs (\$10 ⁶)
Fossil	Mech. Wet	16.04
	Fan Wet	20.65
	Nat. Wet	20.05
LWR	Mech. Wet	21.51
	Fan Wet	25.29
	Nat. Wet	23.31

CAPACITY ENERGY SITE CAPITAL	1X												2X												3X																							
	1X				2X				3X				4X				1X				2X				3X				4X				1X				2X				3X				4X			
	1X				2X				3X				4X				1X				2X				3X				4X				1X				2X				3X				4X			
	MI	CO	FL		MI	CO	FL		MI	CO	FL		MI	CO	FL		MI	CO	FL		MI	CO	FL		MI	CO	FL		MI	CO	FL		MI	CO	FL		MI	CO	FL									
1X																																																
1½X																																																
2X																																																

POWER PLANT: FOSSIL

CAPACITY ENERGY SITE CAPITAL	1X												2X												3X																											
	1X				2X				3X				4X				1X				2X				3X				4X																							
	1X				2X				3X				4X				1X				2X				3X				4X																							
	MI	CO	FL		MI	CO	FL		MI	CO	FL		MI	CO	FL		MI	CO	FL		MI	CO	FL		MI	CO	FL		MI	CO	FL																					
1X
1½X
2X																																																				

POWER PLANT: LWR

1X, 2X, etc.
See sheet 4 of Table S-7
for definitions.

MECHANICAL

FAN

NATURAL

LOCATION: Middletown (MI), Colorado (CO), Florida (FL.)

Figure S-2 Recommended Cooling System

CHAPTER 1

INTRODUCTION

The United States Atomic Energy Commission has sponsored a series of investment cost studies for 1000 MWe Central Station Power Plants (See WASH Reports)*, which included all major types of fossil fuel and nuclear fuel plants. These studies provided detailed cost information for power plant components, including the basic once-through cooling system. However, in many cases, once-through cooling does not meet the stringent thermal criteria being adopted by various regulatory agencies for receiving waters. As a result, various cooling system alternatives are being used for the dissipation of waste heat. The objective of this study, therefore, is to provide cost and design information of various existing cooling system alternatives for power plants consistent with the WASH studies in order to determine complete cost and design comparisons, evaluations, and projections of modern power plants.

The performances of a power plant and its associated cooling system are very much related since the plant performance is directly affected by cooling system performance. A high-performance cooling system, though very desirable, could result in excessive initial capital investment cost. Conversely, though a low-performance cooling system would require only a relatively moderate initial capital outlay, the resultant excessive loss of plant capacity would have to be supplemented by other means, thereby incurring large long-term replacement energy costs.

Therefore, the proper evaluation of alternative cooling systems is important in determining the cost and design of these alternatives. This was done by the utilization of an optimization technique which treated the power plant and the cooling system as a single entity.

*USAEC WASH-1230 Vol. I thru IV (June 1972)
USAEC WASH-1230 Vol. V (December 1973)

1.1 SCOPE OF STUDY

1.1.1 Cooling System Alternatives Investigated

Eight different cooling system alternatives were investigated, including the basic once-through cooling. Each of the cooling system alternatives differs mainly in the type of the terminal heat sink which rejects waste heat from the power plant to the atmosphere. The following cooling system alternatives were investigated:

- a. Once-through cooling
- b. Mechanical draft wet (evaporative) cooling towers
- c. Natural draft wet (evaporative) cooling towers
- d. Natural draft, fan-assisted wet (evaporative) cooling towers
- e. Cooling ponds
- f. Power spray ponds or canals
- g. Mechanical draft dry cooling towers
- h. Natural draft dry cooling towers.

1.1.2 Types of Power Plants Considered for Cooling System Optimization

The following major power plant types were considered in the cooling system optimization:

- a. 1000 MWe fossil fuel power plant
- b. 1000 MWe light water reactor nuclear power plant
- c. 1000 MWe liquid metal fast breeder reactor nuclear power plant
- d. 1160 MWe and 770 MWe high temperature gas cooled reactor nuclear power plants.

1.2 ORGANIZATION OF THIS REPORT

Presented in subsequent chapters of this report are descriptions of the following major topics: economic and performance models, cooling system alternatives, the reference site and its meteorology, results of the design and cost data for the optimized cooling system alternatives, the sensitivity analysis of wet tower systems, and the environmental impact of the cooling system alternatives. All other pertinent information needed for a complete understanding of this study is given in the appendices.

CHAPTER 2

ECONOMIC MODEL

The cooling system of a power plant determines the lowest temperature in the thermodynamic cycle of that power plant. Consequently, the performance of a power plant is affected by the performance of the cooling system, which in turn, is affected by the type and size of the cooling system, the geographic location of the plant site, the ambient weather conditions, etc. Therefore, the optimum selection of a cooling system, besides accurate cost data, requires accurate determination of cooling system performance and a method for merging the performance and cost factors into an effective cost for the cooling system. This chapter describes the economic model used for optimization.

The economic model consists of: (1) the capital cost of the cooling system, (2) various economic penalties to account for the effects of changes in ambient conditions and other variables on cooling system and power plant operations, (3) a total evaluated cost and/or present worth cost of the cooling system, and (4) an optimization procedure which models turbine-condenser heat rejection system design and searches for the proper balance between capital expenditure and economic penalties.

2.1 CAPITAL COST OF COOLING SYSTEM

The capital cost of a cooling system includes all the capital expenditure for parts and labor on the equipment comprising the system plus an indirect cost. The major equipment for a closed cooling system includes the condensers, circulating water pumps and associated equipment, piping, makeup and blowdown equipment, and the terminal heat sink, e.g., the cooling tower, the power

spray module canal, etc. The major equipment for a once-through cooling system, besides the condensers and circulating water pumps, includes the intake and discharge piping and structures. The indirect cost includes engineering and contingency charges.

2.2 ECONOMIC PENALTIES OF COOLING SYSTEM

The method for placing a dollar value on the performance of a cooling system is to assign economic penalties to this cooling system. There are several penalties which can be assigned. Two major penalties are the loss of capacity and the cooling system auxiliary power requirement. In assessing the capacity penalty, the actual capacity of a plant and the corresponding energy produced by the plant are compared to a base capacity and its corresponding energy. Deviations below the base values of both capacity and energy are charged to the cooling system as penalties, whereas, deviations above the base values are taken as credits. As for the auxiliary energy requirement, a cooling system with a large amount of energy-consuming equipment is penalized according to the cost of energy for operating this equipment.

In the present study, six penalties, in dollars per year, were assigned to the economic model for evaluating the various cooling system alternatives.

Specifically, these penalties are defined as follows:

P1 = Capacity penalty cost

P2 = Replacement energy cost due to turbine back pressure variation

P3 = Cost for operating the circulating water pumps

P4 = Cost of supplying makeup water to the cooling system

P5 = Cost for operating the terminal heat sink, e.g., cooling tower, spray pond, etc.

P6 = Cost of operating and maintaining the cooling system.

The equation used to evaluate the capacity penalty is given below:

$$P_1 = (K)(\Delta KW_{\max})(afcr)$$

where

K = Capacity penalty charge rate, \$/kilowatt

$\Delta KW_{\max}$ = Maximum loss of capacity at the worst ambient condition as compared to a base plant capacity, kilowatts

$afcr$ = Annual fixed charge rate, %

This penalty is treated as a capital expenditure and represents the true cost of supplementing the capacity loss as compared to the base capacity; for instance, by the addition of gas turbine generating units.

The base capacity required for evaluating the capacity penalty, P_1 , and the replacement energy penalty, P_2 , (discussed below) is arbitrarily defined. For the present study, this capacity was chosen to correspond to an exhaust pressure of 1.5 inches Hg absolute, which is the common design point for a power plant incorporating a basic once-through cooling system.

In general, the effects of turbine exhaust pressure and cooling system auxiliary loads on plant performance are penalized by calculation of plant performance and the fuel cost, based on an assumed annual loading schedule. For the central station base load power plants as assumed in this study, a simpler procedure can be used because these plants are usually run at full capacity during most of the year due to their low operating costs. Thus, in the economic evaluation, a levelized capacity factor is used, e.g., 75 percent, which assumes that the plant will run at maximum power for 75 percent of the year and otherwise at zero load. This makes the plant's fuel cost invariant with cooling system design, but the energy loss which results from the plant capacity loss or cooling system auxiliary energy requirement will have to be compensated for by an energy replacement

cost. Thus, the replacement energy penalty, P2, and the cooling system auxiliary requirement energy penalties, P3 and P5, are evaluated by the following equations:

$$P2 = \text{Cap} \int_0^{8760} (R) [\Delta KW(T)] dt$$

$$P3 = (K) (HP_w)_{\max} (afcr) + \text{Cap} \int_0^{8760} (R) [HP_w(T)] dt$$

$$P5 = (K) (HP_t)_{\max} (afcr) + \text{Cap} \int_0^{8760} (R) [HP_t(T)] dt$$

where

Cap = Levelized capacity factor, %

R = Replacement energy charge rate, \$/kilowatt hour

$\Delta KW(T)$ = Loss of capacity due to variation in ambient conditions, i.e., (plant capacity at ambient condition T) - (Base Plant capacity), kilowatts

T = A function of dry bulb and wet bulb temperatures, wind velocities, etc.; each is a function of time

$HP_w(T)$ = Power requirement for pumping cooling water at ambient condition T, kilowatts

$(HP_w)_{\max}$ = Maximum power requirement for pumping cooling water, kilowatts

$HP_t(T)$ = Power requirement for operating the terminal heat sink at ambient condition T, kilowatts

$(HP_t)_{\max}$ = Maximum power requirement for operating the terminal heat sink at the worst ambient condition, kilowatts

t = Time, hours.

It should be noted that penalties P3 and P5 both have two components, i.e., the capital expenditure of additional generating equipment and the replacement energy cost.

Penalty P4 is equal to the annual makeup water requirements for the cooling system times a charge per 1000 gallons of makeup water required. The amount of makeup water required depends on the amount of water evaporated, the allowable particle concentration in the cooling system, and the particle concentration in the makeup, thus:

$$P_4 = (G_m) (C_w)$$

where

G_m = Yearly makeup requirement, gallons/year

C_w = Cost for 1,000 gallons of makeup water

The annual operation and maintenance cost, P6, of the cooling system is based on the capital cost of the cooling system and the amount of rotating equipment in operation.

2.3 TOTAL EVALUATED COST AND PRESENT WORTH COST OF COOLING SYSTEM

The total evaluated cost is the sum of the capital cost of a cooling system and all the capitalized penalties charged against that cooling system. Thus:

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

where

C_t = Total evaluated cost, \$

P_j = Annual amount charged to penalty, j

C = Capital cost of cooling system, \$

N = Number of penalties.

This total evaluated cost represents an effective capital cost of the cooling system, and will serve as the criterion for cooling system optimization.

The present worth cost (PW) differs from the total evaluated cost only by a constant factor and is given by the following equation:

$$PW = (C_t) (afcr) (pwf_i^n)$$

where

pwf_i^n = Present worth factor of a series of equal annual payments for n years at an interest rate i.

2.4 OPTIMIZATION PROCEDURE

The basic procedures used in the optimization are as follows:

- a. Size the major components comprising the cooling system for a set of design parameters.
- b. Evaluate the performances of the terminal heat sink and the condenser for a given set of meteorological conditions.
- c. Determine the effects of cooling system performance at off-design conditions on power plant operation.
- d. Calculate the total evaluated cost and the present worth cost of the cooling system which includes the capital cost as well as penalty costs.
- e. Change the initial heat sink and condenser design parameters and repeat steps a through d until the lowest cost design, with respect to the total evaluated cost, is found.

CHAPTER 3

PERFORMANCE MODELS

3.1 PLANT PERFORMANCE

As stated previously, the performance of a cooling system and its associated power plant are related; therefore, the performance of one affects that of the other, and vice versa. Thus, a comprehensive evaluation of a cooling system requires data on plant performance for all exhaust pressures which will be encountered as the ambient condition changes.

Plant performance is mainly a function of power plant cycle and turbine design. For the purpose of this study, four major types of power plant cycles and two different turbine designs were considered. The plant performance models used were chosen on these bases.

3.1.1 Representative Power Plant Cycles

All modern steam power plants utilize improved variations of the basic Rankine cycle. The four types of power plant cycles are: (1) fossil fuel plant, (2) light water reactor nuclear plant, (3) high temperature gas cooled reactor nuclear plant, and (4) liquid metal fast breeder reactor nuclear plant. The significant features of each type of these power plants are described below.

3.1.1.1 Fossil Fuel Plants

Power plants utilizing natural gas, fuel oil, or coal are classified as fossil fuel plants. A typical plant incorporates a once-through, supercritical, single-stage, reheat type of steam generator to supply steam to the turbine. Current large fossil fuel plants are designed with steam pressures of from 2,400 to 3,500 psig, and superheat and reheat steam temperatures of approximately 1,000°F and 1,000°F, respectively.

3.1.1.2 Light Water Reactor (LWR) Plants

A light water reactor nuclear plant may be classified as either a pressurized water reactor (PWR) or a boiling water reactor (BWR) type of plant. In the PWR plant a primary coolant loop, pressurized to about 2,300 psig, transfers thermal energy from the reactor core to the secondary cooling loop in the steam generator. The BWR plant, on the other hand, has a single coolant loop in which steam is formed directly in the working fluid which passes through the reactor core. In either design, the steam at the turbine inlet is saturated or slightly superheated. Pressure levels are in the neighborhood of 1,000 psig. The light water reactor plants are usually designed with moisture separators and steam reheaters to increase turbine efficiency as well as to avoid severe erosion of turbine blades by the moisture entrained in the steam.

3.1.1.3 High Temperature Gas Cooled Reactor (HTGR) Plants

A commercial high temperature gas cooled plant utilizes helium at a pressure of about 715 psig in the primary coolant loop. The energy from the reactor core is transferred to the water in the steam generator in the same manner as in the PWR plant. The high helium temperature levels attainable in the primary coolant loop permit superheat and reheat processes similar to those of fossil fuel plants. Typical steam operating conditions are a pressure of 2,400 psig, and superheat and reheat steam temperatures of 950°F and 1,000°F, respectively.

3.1.1.4 Liquid Metal Fast Breeder Reactor (LMFBR) Plants

A liquid metal fast breeder reactor plant utilizes liquid metal, usually sodium, as the primary coolant. The major difference between this plant and the LWR

and HTGR types of nuclear plants is in the reactor core system. The reactor core of this system not only generates thermal energy for conversion to electric power but also produces excess nuclear fuel. LMFBRs are not fully developed at present but, because of its fuel generating capability, it could become the major type of the future generation of nuclear power plants. The steam operating conditions are very similar to those of fossil fuel plants; typical steam operating conditions are a pressure of 2,400 psig, and superheat and reheat steam temperatures of approximately 950°F and 980°F, respectively.

3.1.2 Steam Turbine Design

There exist two major types of turbine designs, one for high exhaust pressure operation; the other, for low exhaust pressure operation. The former turbine design is intended for use with a dry tower cooling system which, because of its inherently poor heat transfer characteristics, invariably forces the turbine to operate at high exhaust pressures, ranging from 3 to 15 inches of Hg, absolute. The other turbine design is intended for use with all other cooling systems.

Modern turbines are normally designed for a maximum back pressure of 5 to 6 inches Hg, absolute. In the last few stages of a turbine, where steam velocities increase as pressure level decreases, the design is such that high stage efficiencies are maintained while the velocities remain subsonic. When the exhaust pressure increases above the design range, the steam velocities decrease substantially with an accompanying large reduction in stage efficiencies. It is possible to decrease the annulus area of the last stage to maintain high velocities and high stage efficiencies. This modification of a

conventional turbine for high exhaust pressure operation, however, has several possible operational drawbacks as follows:

- a. High exhaust end loading
- b. Bucket heating and vibration
- c. Thermal distortion of exhaust hood and diaphragm
- d. Abnormal cycling stresses.

At least one large turbine manufacturer is prepared to provide an entirely new design, specifically for high exhaust pressure operation. Data from this manufacturer for the new design were used in this study for dry tower analyses.

3.1.3 Evaluation of Plant Performance Models

The plant performance models, in terms of base capacity, base heat rate, and heat rate correction curves, are given in Figures A-1 through A-8 (Appendix A). These models are divided into two groups, one for high exhaust pressure operation and the other for low exhaust pressure operation.

3.2 COOLING SYSTEM PERFORMANCE

After the heat rejection characteristics have been established, the size of a cooling system then becomes dependent on various design parameters and ambient conditions. A significant characteristic of alternative cooling methods is that heat is transferred directly to the atmosphere, therefore, variations in ambient conditions will inevitably affect cooling system performance. The cooling system design parameters and the effects of ambient conditions on system performance are discussed in the following subsections.

3.2.1 Design Criteria for Alternative Cooling Methods

The dry bulb and wet bulb temperatures are the most important design ambient temperatures. These design temperatures are usually selected so that they will be exceeded on no more than 5 percent of the days on an annual basis. Thus, the dry bulb and wet bulb temperatures selected for this study were 93°F and 74°F, respectively.

Other important design parameters used are the approach temperature and temperature range. For wet tower cooling systems, the approach temperature measures how closely the cold water temperature "approaches" the ambient wet bulb temperature. For dry tower cooling systems, the approach temperature represents the difference between the cold water temperature and the dry bulb temperature. The selection of the design range and approach is primarily an economic consideration, being influenced by such factors as ambient temperature variations at the site under consideration, the replacement energy cost, etc. These two variables will be further discussed in detail in Chapter 6.

3.2.2 Effects of Ambient Conditions on Cooling System Performance

The basic factors which influence cooling system performance are: (1) dry bulb temperature, (2) wet bulb temperature, (3) wind speed, (4) cloud cover and latitude, and (5) ambient stream water temperature. Not all these factors affect the performance of each of the cooling system alternatives.

In a once-through cooling system, performance is dictated by the water temperature at the cooling water intake. This temperature is a complex function of ambient wet bulb temperature, dry bulb temperature, wind speed, stream flow effect, and of solar radiation (which depends on cloud cover and latitude).

In cooling pond systems, the constructed cooling ponds or lakes are influenced by ambient conditions in essentially the same manner as for the once-through cooling system. However, cooling ponds usually operate at higher intake temperatures because the water is continuously recirculated and cannot be cooled to the natural equilibrium temperature as is done in a once-through cooling system. The performance of a spray canal is influenced primarily by the ambient wet bulb temperature and by wind direction and speed since these are the factors which most affect the heat and mass transfer of the power sprays.

In wet (or evaporative) cooling towers, the two major influencing factors are the dry bulb and wet bulb temperatures. The performances of natural draft towers is affected by both the dry bulb and wet bulb temperatures. The wet bulb temperature controls the heat and mass transfer process in the tower, whereas the dry bulb temperature controls the air flow rate. The mechanical draft cooling towers, which rely on fans to produce air flow, are sensitive mainly to wet bulb temperature variations.

In dry cooling towers of both the natural draft and mechanical draft types, tower performance is influenced mainly by the ambient dry bulb temperatures as these towers depend totally on convective heat transfer for cooling. For the natural draft tower, the dry bulb temperatures also control the air flow.

3.3 THERMAL CRITERIA FOR ONCE-THROUGH COOLING

General thermal criteria may include a 5°F temperature rise outside the mixing zone from September to June and a 1.5°F temperature rise from June to September. In addition, the mixing zone can be defined and limited to

some fraction of the free flowing cross section and/or surface area of the receiving water body. The basic criterion is that there be no significant detrimental effect on balanced indigenous populations of aquatic organisms.

CHAPTER 4

DESCRIPTION OF COOLING SYSTEM ALTERNATIVES

The cooling system alternatives studied include both the basic once-through cooling system and the closed systems of evaporative (wet) cooling towers, dry cooling towers, and cooling ponds. The evaporative cooling towers further include the mechanical draft tower, natural draft tower, and fan-assisted hyperbolic tower. The dry cooling towers include mechanical and natural draft towers. The cooling ponds include the constructed pond and cooling canal with power spray modules.

Each of these cooling system alternatives is described in the sections that follow. Refer to Appendix B for schematic diagrams and Appendix C for qualitative comparison of alternative cooling systems.

4.1 BASIC ONCE-THROUGH COOLING SYSTEM

In the basic once-through cooling system the flow of water from rivers, lakes, or the sea serves as the cooling medium. The water is then discharged back to the natural bodies of water. The major components of this system, besides the condensers and cooling water pumps, are the intake and discharge piping and structures. The intake and discharge structures require special considerations because of the potential environmental impact related to the large quantity and relatively high temperature of the cooling water discharge.

4.2 EVAPORATIVE COOLING TOWERS

In the evaporative, or wet, cooling tower systems, most of the waste heat is dissipated to the atmosphere by evaporation of a small portion of the cooling water. Hot water from the plant condensers is pumped to the top of the tower's

fill or packing material; the water then flows or splashes down through the fill to the water collecting basin, while air sweeps either up or across the fill area. As the water and air come in contact, a small portion of the water becomes vaporized thus carrying with it the latent heat of the evaporation process.

In the process, air is humidified and the remaining unvaporized water is cooled. To provide continuous flow of fresh air through the tower, three different methods may be used, resulting in the three basic types of evaporative cooling towers which are described below.

4.2.1 Mechanical Draft Wet Cooling Tower

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

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

The following descriptions state the main function of each component and the materials generally used in construction.

4.2.1.1 Tower Framework

The tower framework is a structure designed on the basis of aerodynamic, thermal, and economic considerations. It is designed to support the weight of the various components in the tower as well as the weight of the cooling water. The framework may be of wood or cement construction but must be strong enough to withstand high winds and seismic loads.

4.2.1.2 Water Distribution System

The function of the water distribution system is to provide a uniform distribution of the hot water above the fill. The distribution pipes can be made of treated redwood, cast iron, carbon steel, polyvinyl chloride (PVC), fiberglass, or asbestos cement. All spray nozzles are made of plastic.

4.2.1.3 Fill or Packing Material

The function of the fill or packing material is to break the water into many small droplets or filaments so as to increase the air-water interface area as well as the contact time. Two types of fill are in common use: film fill which breaks the water into thin filaments, and splash type fill that produces small droplets. The fill material can be made of redwood, treated fir, asbestos cement, or various types of plastics.

4.2.1.4 Drift Eliminators

Drift eliminators are located beyond the fill material. They serve as a baffle so designed to cause a sudden change in the direction of the air stream thus reducing the quantity of water droplets lost into the atmosphere. Materials used in the construction of drift eliminators are redwood, treated fir, asbestos cement, and various types of plastics.

4.2.1.5 Inlet Louvers

The inlet louvers provide a uniform air flow into the tower. Their design includes proper slope, spacing, and width to prevent water losses and to eliminate icing problems during the winter season. The materials most commonly used for construction are treated redwood, asbestos cement, and plastics.

4.2.1.6 Water Collecting Basin

The water collecting basin, located at the bottom of the tower, collects the cooled water which falls through the fill material. This water is then pumped back to the condenser system. The collecting basin is usually constructed of concrete.

4.2.1.7 Fans

In mechanical draft cooling towers, a fan provides the desired flow of air through the tower. The fan can be located at the top of the tower above the drift eliminators or at the bottom of the cooling tower. The fan in a power plant cooling tower is usually located at the top of the tower. The fan blades are made of fiberglass and either covered with a polyester resin or are aluminum/ coated with an epoxy or other synthetic resin. The materials used are selected for their corrosion- and erosion-resistant properties.

4.2.2 Natural Draft Wet Cooling Tower

The natural draft wet cooling tower performs its cooling function in much the same manner as the mechanical draft tower. The basic difference in operation is in the method by which air flow is established. Instead of depending on a constant volume of air flowing through the tower as in a mechanical draft tower, the natural draft tower has an air flow rate which is proportional to the density difference between the ambient air and the warmer humid air in the tower stack.

The basic components of the tower are essentially the same as those which comprise the mechanical draft tower with the exception of the type of construction of the tower framework and of not requiring fans to create air flow. The

tower framework of a natural draft tower is usually a hyperboloid shell made of reinforced concrete. The hyperboloid shell provides improved structural strength over the straight cylindrical shell.

4.2.3 Fan-Assisted Hyperbolic Tower

The design of the fan-assisted hyperbolic tower combines the features of the natural draft and mechanical draft towers. The hyperbolic tower has a reinforced-concrete hyperbolic shell similar to, but smaller than, the framework of a natural draft tower. In addition, large motor driven fans are located around the periphery of the base. Fans give better air-flow control than does the purely natural draft tower.

4.3 DRY COOLING TOWERS

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

Mechanical draft dry towers have been used for many years in the process industry. Dry towers, because of their relative high cost as compared to wet (evaporative) towers, have not found wide acceptance among the utilities in this country. However, a dry tower might be the best choice when fogging or water availability becomes a problem.

4.3.1 Mechanical Draft Dry Cooling Tower

In the mechanical draft dry cooling tower, ambient air is forced by fans to pass over the heat transfer coils. The coils are made of finned tubes and are

arranged in modules or cells. Each cell is complete with a fan, much like the mechanical draft wet cooling tower.

4.3.2 Natural Draft Dry Cooling Tower

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

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

4.4 COOLING POND SYSTEMS

The cooling pond system is a variation of the basic once-through cooling system. The cooling water is taken from an artificial source, a pond, instead of from natural bodies of water. Cooling ponds can be further classified as constructed ponds and power spray module ponds or canals.

4.4.1 Constructed Ponds

Constructed ponds dissipate plant waste heat in the same manner as a river or lake, that is, through convective heat and mass transfer and radiation over the free water surface and conduction through the pond bed. The major drawbacks of this system are its land requirement, at roughly $\frac{1}{2}$ to 1 acre per megawatt and the potential that after construction and filling, regulatory agencies may claim the pond as a natural resource and force the utility to meet the same stringent criteria of once-through cooling.

4.4.2 Power Spray Module Canals

In the spray module type of cooling system, the evaporative cooling from the pond or canal water surface is augmented by the spraying of water into the air. A commercially available spray module consists of 4 nozzles mounted on a 120-foot length of pipe. The entire assembly floats above the water surface along with the associated motor and pump. Modules are placed in a pond or canal with the axis of each module parallel to the stream flow.

The land requirement is reduced appreciably as compared to that of the simple pond system. Still, the land requirement is large as compared to that of cooling towers. This fact, coupled with the type of soil located at the site, will affect the already sizable cost of constructing a canal.

4.5 WET/DRY COOLING TOWER

Although not analyzed in this study, it should be mentioned here that a new wet/dry tower system is being marketed by the cooling tower manufacturers. The wet/dry tower is a wet cooling tower and a dry cooler with finned tube heat exchangers in a combined unit. The tower can be designed to eliminate fogging problems or to conserve water. There are two different basic designs the series flow and the parallel flow. In the series flow design, the heat exchangers are located either in front or behind the wet fill sections; the air flow through the dry and wet sections is in series and the water flow in parallel. In the parallel flow design, the heat exchangers are located on top of the wet sections; the air flow through the dry and wet sections is in parallel and the water flow is in series.

SECRET

CHAPTER 5

DESCRIPTION OF REFERENCE SITE AND SITE METEOROLOGY

This chapter describes the site and environmental data. These data form the basis for the cooling system design and penalty cost evaluation.

5.1 AVAILABLE LAND AND ALTITUDE

The Middletown Site is located on the east bank of the North River at a distance of 25 miles south of the city. The North River flows from north to south and is one-half mile wide at the location adjacent to the plant site. A flood plain extends from both river banks an average distance of one-half mile, ending with hilltops generally 150 to 250 feet above the river level. Beyond this area, the topography is gently rolling, with no major critical topographical features. The plant site itself extends from river level to elevations of 50 feet above river level.

Soil profiles for the site show alluvial soil and rock fill to a depth of 8 feet; Brasfield limestone to a depth of 30 feet; blue, weathered shale and fossiliferous Richmond limestone to a depth of 50 feet; and bedrock over a depth of 50 feet. Allowable soil bearing is 6,000 pounds per square foot and rock bearing characteristics are 18,000 and 15,000 pounds per square foot for Brasfield and Richmond Strata, respectively. No underground cavities exist in the limestone.

5.2 AVAILABLE COOLING WATER

The North River provides an adequate source of raw makeup and condenser cooling water.

5.2.1 Temperature of River Water

The highest temperature of the cooling water is 75°F, and the lowest, 37°F. The mean annual water temperature is approximately 57°F.

5.2.2 Salinity of River Water

The salinity of the water in the North River, expressed in parts per million of total dissolved solids is in the order of 100 to 500 ppm.

5.3 METEOROLOGY OF SITE AREA

5.3.1 Temperature Duration Curves

The winters in the Middletown area are moderately cold, with average temperatures in the low 30's. The summers are fairly humid with average temperatures in the low 70's, and with high temperatures averaging around 82°F.

The year-round temperature duration curves for the dry bulb temperatures and coincident wet bulb temperatures are shown in Figure 5-1.

5.3.2 Prevailing Wind

Winds in the site area are predominantly southwesterly 4 to 10 miles per hour during the warm months, and westerly 6 to 13 miles per hour during the cool months.

5.3.3 Severe Meteorological Phenomena

A maximum instantaneous wind velocity of 100 miles per hour has been recorded at the site. During the past 50 years, three tropical storms, all of them in the final dissipation stages, have passed to within 50 miles of the site. Some heavy precipitation and winds in excess of 40 miles per hour have been recorded, but no significant damage other than to crops has resulted.

The area near the site experiences an average of 35 thunderstorms per year, with the maximum frequency occurring in early summer. High winds near 60 miles per hour, heavy precipitation, and hail are recorded about once every four years.

In 40 years of record, there have been 20 tornadoes reported within 50 miles of the site. Maximum tornado frequency occurs in May and June.

Figure 5-1 Annual Temperature Duration Curves for the Dry Bulb and Coincident Wet Bulb Temperatures, Middletown, USA

CHAPTER 6

RESULTS OF OPTIMIZATION

Optimization was performed for each of the eight cooling systems and for each of the five power plants as stated in the introduction. Only two design parameters, i.e., approach and range temperatures, were optimized. The objective of this optimization was to select the proper range and approach temperatures at which a cooling system would have the least total evaluated cost (i.e., sum of capital investment and economic penalties).

6.1 DESIGN AND COST ASSUMPTIONS

There are several design and cost assumptions which are important in the interpretation of the results to be presented. These assumptions are summarized below:

6.1.1 Overall System Assumptions

The basic economic factors applicable to all the reference power plants are given in Table 6-1.

TABLE 6-1

ECONOMIC FACTORS

Levelized Power Plant Capacity Factor	0.75
Annual Fixed Charge Rate	15%
Interest Rate	8%
Plant Life	40 years
Replacement Energy Cost *	8.5 mills/kWh
Capacity Penalty Charge Rate *	\$150/kW
Year of Pricing	January 1973

* Apply to both the losses due to ambient variations and the cooling system auxiliary power requirements (for pumps, fans, etc.).

6.1.2 Assumption for Cooling System Alternatives

The assumptions for condenser, circulating water pumps and motors, cooling towers and spray modules are summarized in the major equipment list in Appendix D.

As indicated in Appendix D, the condenser tube material was assumed to be stainless steel SS304. The reasons for selecting SS304 tube material for fresh water service are as follows:

- a. The outer surface of the tube has excellent resistivity to steam impingement attack and erosion, and has high tensile strength;
- b. The inner surface of the tube has excellent corrosion resistance to river and lake water which has low salinity; and has resistance to sand and stone erosion;
- c. Since it has high strength and erosion resistance, thin wall tubes may be used, e.g., 20BWG;
- d. It keeps water clean and does not bring any copper into the boiler;
- e. It has excellent resistance to ammonia attack.

6.2 PRESENTATION OF OPTIMIZATION RESULTS

The design and cost results for the cooling system alternatives are presented in this section. These results were obtained, as mentioned previously, by optimizing the cooling system with respect to the range and approach temperatures of the terminal heat sink. The once-through systems were not optimized. A typical plot of the total capital cost and the total capitalized penalty as well as the total evaluated cost of a mechanical draft wet tower system, is shown in Figure 6-1. The plot shows that as the range increases the capital

cost decreases and the penalty cost increases, the approach and the condenser terminal temperature difference being assumed to remain constant. The decrease in capital cost results from the decrease in the size of the cooling system; the increase in penalty cost results from the necessity for the cooling system to operate at higher condensing temperatures. The tradeoff between the capital cost and economic penalty of the cooling system is obtained by adding the capital cost and the penalty cost and finding the minimum point of the sum, which is the total evaluated cost.

Similar observations can be made of the effect on the approach temperature of a terminal heat sink on the capital cost, penalty cost, and the tradeoff between the two. In this case, the range and the condenser terminal temperature are assumed to be constant. The overall minimum design point with respect to both the range and approach temperatures, which is called the optimum point in this study, is obtained by finding the range corresponding to the minimum total evaluated cost for each approach and then the approach which has the minimum total evaluated cost for all the approaches. This is shown in Figure 6-2 for the sample case considered.

The optimized results are given in Tables 6-2 through 6-16. These results are presented according to the reference power plants. For each of the reference power plants, the important design parameters and sizes of the cooling system alternatives are given first, followed by the data on capital cost, economic penalties, total evaluated cost and present worth cost and, finally, the capital cost breakdown.

It should be noted that the base plant outputs and heat rates, shown in the results of this chapter, and the heat rate correction curves in Appendix A, are gross plant output capacities and gross plant heat rates. Single turbine-generators were used for all the reference power plants except the 1160 MWe HTGR Plant which used twin turbine-generators. To calculate the net plant efficiency, the plant auxiliary power requirements, and the stack losses (in the case of fossil plants) should be deducted from the gross plant capacities.

In the capital cost breakdowns 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:

<u>Letter</u>	<u>Cost Item</u>
L	Labor
E	Equipment (pump, cooling tower, etc)
M	Material (pipe, cable, etc)
T	Total (L+M+E)

These capital costs are also identified with the Atomic Energy Commission (AEC) Cost Account numbers; a detailed description of these AEC account numbers is given in Appendix E. A sample computer printout of the optimization results is presented in Appendix F.

In all the tables to be presented, the names of the cooling system alternatives have been abbreviated as follows:

Mech. Wet	Mechanical draft wet tower cooling system
Fan Wet	Fan-assisted natural draft wet tower cooling system

Nat. Wet	Natural draft wet tower cooling system
Pond	Constructed pond cooling system
Spray Canal	Power spray module canal cooling system
Mech. Dry	Mechanical draft dry tower cooling system
Nat. Dry	Natural draft dry tower cooling system

6.3 AMBIENT DEPENDENT SYSTEM PERFORMANCE

In performing the cooling system optimization, the ambient dependent performance data were also calculated in which the design cooling water flow rate was assumed to remain constant at all ambient conditions. The most important of these, with regard to cost estimating, are the data concerning capacity loss at off-design ambient conditions. These data are given in Tables 6-17 through 6-21.*

* It should be noted that the river temperatures affect only the performance of the once-through open systems.

TABLE 6-2 (Sheet 1 of 2)

SUMMARY OF DESIGN CONDITIONS FOR OPTIMIZED COOLING SYSTEMS FOR 1000 MWe FOSSIL POWER PLANT

Base Plant Conditions: Plant Capacity = 1043 MWe, Heat Rate=7365 Btu/kWh, Exhaust Pressure = 1.5 In-Hg

Design Ambient Conditions: Dry Bulb Temperature = 93°F, Wet Bulb Temperature = 74°F, Wind Speed = 5 mph,
Pond Equilibrium Temperature = 83°F

Variable Name	Once-Through	Mech. Wet	Fan Wet	Nat. Wet	Pond	Spray Canal	Mech. Dry	Nat. Dry
<u>General</u>								
Design Cold Water Temperature, °F	57.0	90.0	84.0	90.0	103.0	94.0	131.0	131.0
Design Approach, °F	-	16.0	10.0	16.0	29.0	20.0	38.0	38.0
Design Range, °F	15.0	21.0	24.0	24.0	16.0	17.0	25.0	28.0
Plant Capacity at Cooling System Design Point, MWe	1043	1020	1026	1014	1000	1020	938	932
Design Turbine Back Pressure, In-Hg	1.50	3.17	2.91	3.45	3.95	3.16	10.12	10.86
Maximum Turbine Back Pressure, In-Hg	2.14	3.22	2.98	3.66	4.00	3.17	11.89	12.80
Design Heat Load, 10 ⁹ Btu/hr	4.12	4.20	4.18	4.22	4.27	4.20	4.48	4.50
<u>Condenser</u>								
Surface Area, 10 ³ sq ft	396	627	595	590	715	688	608	576
Number of Tubes, 10 ³	37.0	53.8	46.9	47.3	71.8	66.5	48.2	43.3
Tube Length, ft	41.0	44.5	48.4	47.7	38.1	39.5	48.1	50.9

TABLE 6-2 (Sheet 2)

SUMMARY OF DESIGN CONDITIONS FOR OPTIMIZED COOLING SYSTEMS FOR 1000 MWe FOSSIL POWER PLANT

Variable Name	Once-Through	Mech. Wet	Fan Wet	Nat. Wet	Pond	Spray Canal	Mech. Dry	Nat. Dry
<u>Cooling Water Pump</u>								
Circulating Water Flow Rate, 10^3 gpm	549	400	348	352	533	494	358	321
Number of Pumps	4	3	2	2	3	3	2	2
Pumping Head, ft. of Water	23.7	78.1	79.2	91.6	33.3	33.2	44.2	63.8
Pumping Power Requirement, bhp/pump	924	2952	3915	4570	1679	1555	2245	2908
Rated Pump Motor Size, hp/pump motor	1250	3500	4500	5000	2000	2000	2500	3500
<u>Terminal Heat Sink</u>								
Total Power Requirement, 10^3 bhp	-	4.28	5.24	-	-	8.55	17.77	-
Terminal Heat Sink Size:	-	-	-	-	-	-	-	-
Number of Cells	-	23	-	-	-	-	94	-
Tower: Number of Towers	-	-	2	1	-	-	-	1
Base Diameter, ft	-	-	226	385	-	-	-	443
Tower Height, ft	-	-	250	500	-	-	-	446
Fan: Number of Fans/Tower	-	-	20	-	-	-	-	-
Fan Diameter, ft	-	28	28	-	-	-	28	-
Canal: Number of Modules	-	-	-	-	-	114	-	-
Canal Width, ft	-	-	-	-	-	256	-	-
Canal Length, ft	-	-	-	-	-	3340	-	-
Pond Area, Acres	-	-	-	-	432	-	-	-

TABLE 6-3

SUMMARY OF CAPITAL INVESTMENT, PENALTIES, TOTAL EVALUATED COST, AND PRESENT WORTH COST
FOR OPTIMIZED COOLING SYSTEMS (IN MILLIONS OF DOLLARS) FOR 1000 MWe FOSSIL POWER PLANT

	Once- Through	Mech. Wet	Fan Wet	Nat. Wet	Pond	Spray Canal	Mech. Dry	Nat. Dry
Total Capital Investment	11.27	16.04	20.65	20.05	28.63	17.84	25.50	28.16
Capacity Penalty (Due to Highest Turbine Back Pressure)	0.82	3.53	2.78	5.10	6.64	3.35	17.78	18.86
Energy Replacement Penalty (Due to Turbine Back Pressure Variations)	0.08	2.46	1.14	1.88	4.11	1.97	28.32	28.55
Capitalized Annual Cost for Operating Cooling Water Pumps	1.60	3.83	3.39	3.96	2.18	2.02	1.94	2.52
Capitalized Annual Cost for Operating Terminal Heat Sink	-	1.82	2.04	-	-	3.33	6.80	-
Capitalized Annual Cost for Make-Up and Water Treatment	-	0.18	0.18	0.18	0.16	0.18	-	-
Capitalized Annual Operating and Maintenance Cost	0.24	1.21	1.26	0.64	0.47	1.52	2.61	1.69
Total Evaluated Cost	14.01	29.07	31.44	31.81	42.19	31.78	83.99	79.95
Present Worth Cost	25.06	51.99	56.24	56.90	75.47	56.84	150.24	143.01

TABLE 6-4 (Sheet 1 of 2)

SUMMARY OF CAPITAL INVESTMENT FOR OPTIMIZED COOLING SYSTEMS (IN MILLIONS OF DOLLARS)FOR 1000 MWe FOSSIL POWER PLANT

AEC Acc. No.	Equipment Item		Once- Through	Mech. Wet	Fan Wet	Nat. Wet	Pond	Spray Canal	Mech. Dry	Nat. Dry
114.1	Circulating Water Structure	(M	0.582	0.424	0.411	0.409	0.414	0.445	0.330	0.320
		(L	<u>1.964</u>	<u>0.286</u>	<u>0.283</u>	<u>0.281</u>	<u>0.272</u>	<u>0.301</u>	<u>0.220</u>	<u>0.210</u>
		(T	2.546	0.710	0.694	0.690	0.686	0.746	0.550	0.530
132.21	Circulating Water Pumps & Motors	(E	0.920	0.957	0.793	0.829	0.895	0.914	0.623	0.692
		(M	0.010	0.010	0.009	0.009	0.010	0.010	0.007	0.008
		(L	<u>0.080</u>	<u>0.063</u>	<u>0.042</u>	<u>0.042</u>	<u>0.061</u>	<u>0.062</u>	<u>0.040</u>	<u>0.040</u>
		(T	1.010	1.030	0.844	0.880	0.966	0.986	0.670	0.740
132.22	Concrete Pipe	(M	0.640	0.540	0.540	0.539	0.824	0.829	0.800	0.480
		(L	<u>0.699</u>	<u>0.560</u>	<u>0.622</u>	<u>0.621</u>	<u>0.864</u>	<u>0.869</u>	<u>1.120</u>	<u>0.560</u>
		(T	1.339	1.100	1.162	1.160	1.688	1.698	1.920	1.040
132.31	Terminal Heat Sink Basins and Foundations	(M	-	0.470	0.280	0.270	-	-	0.180	0.280
		(L	-	<u>0.710</u>	<u>1.120</u>	<u>1.060</u>	-	-	<u>0.370</u>	<u>0.900</u>
		(T	-	1.180	1.400	1.330	-	-	0.550	1.180
132.32	Terminal Heat Sink	(E	-	1.891	4.128	5.346	-	2.257	9.821	8.278
		(M	-	0.019	0.042	0.054	0.650	0.023	0.049	0.042
		(L	-	<u>1.030</u>	<u>2.780</u>	<u>1.350</u>	<u>12.950</u>	<u>1.880</u>	<u>1.010</u>	<u>5.750</u>
		(T	-	2.940	6.950	6.750	13.600	4.160	10.880	14.070

TABLE 6-4 (Sheet 2)

SUMMARY OF CAPITAL INVESTMENT FOR OPTIMIZED COOLING SYSTEMS (IN MILLIONS OF DOLLARS)FOR 1000 MWe FOSSIL POWER PLANT

AEC Acc. No.	Equipment Item		Once- Through	Mech. Wet	Fan Wet	Nat. Wet	Pond	Spray Canal	Mech. Dry	Nat. Dry
133.1	Condensers, Installed	(E	2.358	3.333	3.143	3.134	3.840	3.681	3.203	3.043
		(M	0.012	0.017	0.016	0.016	0.020	0.019	0.017	0.017
		(L	<u>1.340</u>	<u>1.600</u>	<u>1.550</u>	<u>1.540</u>	<u>1.740</u>	<u>1.700</u>	<u>1.560</u>	<u>1.520</u>
		(T	3.710	4.950	4.709	4.690	5.600	5.400	4.780	4.580
14	Electrical Work	(E	0.124	0.283	0.233	0.157	0.135	0.392	0.322	0.146
		(M	0.067	0.213	0.175	0.130	0.073	0.295	0.242	0.079
		(L	<u>0.139</u>	<u>0.429</u>	<u>0.352</u>	<u>0.253</u>	<u>0.152</u>	<u>0.593</u>	<u>0.486</u>	<u>0.165</u>
		(T	0.330	0.925	0.760	0.540	0.360	1.280	1.050	0.390
	Sub-Total for the Complete Cooling System	(E	3.402	6.464	8.297	9.466	4.870	7.244	13.969	12.159
		(M	1.311	1.693	1.473	1.427	1.991	1.621	1.625	1.226
		(L	<u>4.222</u>	<u>4.678</u>	<u>6.749</u>	<u>5.147</u>	<u>16.039</u>	<u>5.405</u>	<u>4.806</u>	<u>9.145</u>
		(T	8.935	12.835	16.519	16.040	22.900	14.270	20.400	22.530
	Indirect Charges		2.334	3.209	4.130	4.010	5.725	3.568	5.100	5.633
	Total Capital Investment		11.269	16.044	20.649	20.050	28.625	17.838	25.500	28.163

TABLE 6-5 (Sheet 1 of 2)

SUMMARY OF DESIGN CONDITIONS FOR OPTIMIZED COOLING SYSTEMS FOR 1000 MWe LWR POWER PLANT

Base Plant Conditions: Plant Capacity = 1096 MWe, Heat Rate = 9760 Btu/kWh, Exhaust Pressure = 1.5 In-Hg

Design Ambient Conditions: Dry Bulb Temperature = 93°F, Wet Bulb Temperature = 74°F, Wind Speed = 5 mph,
Pond Equilibrium Temperature = 83°F

Variable Name	Once-Through	Mech. Wet	Fan Wet	Nat. Wet	Pond	Spray Canal	Mech. Dry	Nat. Dry
<u>General</u>								
Design Cold Water Temperature, °F	57.0	91.0	87.0	92.0	108.0	100.0	135.0	129.0
Design Approach	-	17.0	13.0	18.0	34.0	26.0	42.0	36.0
Design Range, °F	15.0	27.0	29.0	29.0	17.0	26.0	29.0	32.0
Plant Capacity at Cooling System Design Point, MWe	1096	1075	1078	1069	1059	1056	933	940
Design Turbine Back Pressure, In-Hg	1.50	3.85	3.64	4.17	4.65	4.77	12.20	11.38
Maximum Turbine Back Pressure, In-Hg	2.13	3.90	3.71	4.39	4.69	4.78	14.29	13.32
Design Heat Load, 10 ⁹ Btu/hr	6.96	7.03	7.02	7.05	7.09	7.10	7.52	7.49
<u>Condenser</u>								
Surface Area, 10 ³ sq ft	670	925	898	892	1157	944	944	893
Number of Tubes, 10 ³	62.4	70.1	65.2	65.5	112.0	73.5	69.8	63.0
Tube Length, ft	41.0	50.4	52.6	52.0	39.4	49.1	51.7	54.1

TABLE 6-5 (Sheet 2)

SUMMARY OF DESIGN CONDITIONS FOR OPTIMIZED COOLING SYSTEMS FOR 1000 MWe LWR POWER PLANT

Variable Name	Once-Through	Mech. Wet	Fan Wet	Nat. Wet	Pond	Spray Canal	Mech. Dry	Nat. Dry
<u>Cooling Water Pump</u>								
Circulating Water Flow Rate, 10^3 gpm	928	521	484	486	834	546	518	468
Number of Pumps	7	3	3	3	5	4	3	3
Pumping Head, ft of Water	22.2	79.0	75.6	90.3	33.7	36.7	42.4	51.0
Pumping Power Requirement, bph/pump	835	3892	3462	4153	1594	1422	2077	2259
Rated Pump Motor Size, hp/pump Motor	1000	4500	4000	4500	2000	1750	2500	3000
<u>Terminal Heat Sink</u>								
Total Power Requirement, 10^3 bhp	-	6.07	6.66	-	-	8.55	26.40	-
Terminal Heat Sink Size:	-	-	-	-	-	-	-	-
Number of Cells	-	33	-	-	-	-	141	-
Tower: Number of Towers	-	-	2	1	-	-	-	2
Base Diameter, ft	-	-	257	407	-	-	-	397
Tower Height, ft	-	-	250	527	-	-	-	416
Fan: Number of Fans/Tower	-	-	24	-	-	-	-	-
Fan Diameter, ft	-	28	28	-	-	-	28	-
Canal: Number of Modules	-	-	-	-	-	114	-	-
Canal Width, ft	-	-	-	-	-	256	-	-
Canal Length, ft	-	-	-	-	-	3340	-	-
Pond Area, Acres	-	-	-	-	565	-	-	-

TABLE 6-6

SUMMARY OF CAPITAL INVESTMENT, PENALTIES, TOTAL EVALUATED COST, AND PRESENT WORTH COST
FOR OPTIMIZED COOLING SYSTEMS (IN MILLIONS OF DOLLARS) FOR 1000 MWe LWR POWER PLANT

	Once-Through	Mech. Wet	Fan Wet	Nat. Wet	Pond	Spray Canal	Mech. Dry	Nat. Dry
Total Capital Investment	16.43	21.51	25.29	23.31	39.64	19.89	36.64	44.81
Capacity Penalty (Due to Highest Turbine Back Pressure)	0.24	3.37	2.90	4.69	5.76	6.12	27.03	25.85
Energy Replacement Penalty (Due to Turbine Back Pressure Variations)	-0.02	2.56	1.57	2.20	4.14	6.09	39.75	39.14
Capitalized Annual Cost for Operating Cooling Water Pumps	2.53	5.05	4.49	5.39	3.45	2.46	2.70	2.94
Capitalized Annual Cost for Operating Terminal Heat Sink	-	2.57	2.59	-	-	3.33	10.13	-
Capitalized Annual Cost for Make-Up and Water Treatment	-	0.32	0.31	0.31	0.27	0.32	-	-
Capitalized Annual Operating and Maintenance Cost	0.36	1.70	1.66	0.89	0.73	1.66	3.86	2.57
Total Evaluated Cost	19.54	37.08	38.81	36.79	53.99	39.89	120.11	115.31
Present Worth Cost	34.95	66.33	69.42	65.81	96.58	71.36	214.85	206.27

TABLE 6-7 (Sheet 1 of 2)

SUMMARY OF CAPITAL INVESTMENT FOR OPTIMIZED COOLING SYSTEMS (IN MILLIONS OF DOLLARS)

FOR 1000 MWe LWR POWER PLANT

AEC Acc. No.	Equipment Item		Once- Through	Mech. Wet	Fan Wet	Nat. Wet	Pond	Spray Canal	Mech. Dry	Nat. Dry
214.1	Circulating Water Structure	(M	0.833	0.504	0.514	0.514	0.509	0.496	0.380	0.360
		(L	<u>2.811</u>	<u>0.344</u>	<u>0.344</u>	<u>0.334</u>	<u>0.339</u>	<u>0.340</u>	<u>0.250</u>	<u>0.240</u>
		(T	3.644	0.848	0.848	0.848	0.848	0.836	0.630	0.600
232.21	Circulating Water Pumps & Motors	(E	1.553	1.201	1.150	1.201	1.490	1.040	0.930	0.979
		(M	0.017	0.014	0.014	0.014	0.016	0.012	0.010	0.011
		(L	<u>0.140</u>	<u>0.063</u>	<u>0.064</u>	<u>0.063</u>	<u>0.102</u>	<u>0.084</u>	<u>0.060</u>	<u>0.060</u>
		(T	1.710	1.278	1.228	1.278	1.608	1.136	1.000	1.050
232.22	Concrete Pipes	(M	1.040	0.798	0.658	0.338	1.246	0.924	1.190	0.640
		(L	<u>0.999</u>	<u>0.716</u>	<u>0.596</u>	<u>0.316</u>	<u>1.508</u>	<u>0.924</u>	<u>1.270</u>	<u>0.580</u>
		(T	2.039	1.514	1.254	0.654	2.754	1.848	2.460	1.220
232.31	Terminal Heat Sink Basins and Foundations	(M	-	0.670	0.320	0.280	-	-	0.270	0.380
		(L	-	<u>1.010</u>	<u>1.280</u>	<u>1.130</u>	-	-	<u>0.560</u>	<u>1.230</u>
		(T	-	1.680	1.600	1.410	-	-	0.830	1.610
232.32	Terminal Heat Sink	(E	-	2.713	4.782	5.930	-	2.257	14.726	14.557
		(M	-	0.027	0.048	0.060	0.850	0.023	0.074	0.073
		(L	-	<u>1.470</u>	<u>3.220</u>	<u>1.500</u>	<u>16.950</u>	<u>1.880</u>	<u>1.520</u>	<u>10.030</u>
		(T	-	4.210	8.050	7.490	17.800	4.160	16.320	24.660

TABLE 6-7 (Sheet 2)

SUMMARY OF CAPITAL INVESTMENT FOR OPTIMIZED COOLING SYSTEMS (IN MILLIONS OF DOLLARS)FOR 1000 MWe LWR POWER PLANT

AEC Acc. No.	Equipment Item		Once- Through	Mech. Wet	Fan Wet	Nat. Wet	Pond	Spray Canal	Mech. Dry	Nat. Dry
233.1	Condensers, Installed	(E	3.572	4.517	4.368	4.348	5.803	4.617	4.577	4.328
		(M	0.018	0.023	0.022	0.022	0.027	0.023	0.023	0.022
		(L	<u>1.670</u>	<u>1.910</u>	<u>1.870</u>	<u>1.860</u>	<u>2.270</u>	<u>1.940</u>	<u>1.920</u>	<u>1.850</u>
		(T	5.260	6.450	6.260	6.230	8.100	6.580	6.520	6.200
24	Electrical Work	(E	0.184	0.375	0.303	0.214	0.225	0.413	0.476	0.191
		(M	0.099	0.282	0.228	0.176	0.122	0.311	0.358	0.104
		(L	<u>0.207</u>	<u>0.568</u>	<u>0.459</u>	<u>0.345</u>	<u>0.253</u>	<u>0.626</u>	<u>0.721</u>	<u>0.215</u>
		(T	0.490	1.225	0.990	0.735	0.600	1.350	1.555	0.510
	Sub-Total for the Complete Cooling System	(E	5.309	8.806	10.603	11.693	7.518	8.327	20.709	20.055
		(M	2.007	2.318	1.804	1.404	2.770	1.789	2.305	1.590
		(L	<u>5.827</u>	<u>6.081</u>	<u>7.823</u>	<u>5.548</u>	<u>21.422</u>	<u>5.794</u>	<u>6.301</u>	<u>14.205</u>
		(T	13.143	17.205	20.230	18.645	31.710	15.910	29.315	35.850
	Indirect Charges		3.285	4.301	5.058	4.661	7.928	3.978	7.329	8.963
	Total Capital Investment		16.425	21.506	25.288	23.306	39.638	19.888	36.644	44.813

TABLE 6-8 (Sheet 1 of 2)

SUMMARY OF DESIGN CONDITIONS FOR OPTIMIZED COOLING SYSTEMS FOR 1000 MWe LMFBR POWER PLANT

Base Plant Conditions: Plant Capacity = 1059 MWe, Heat Rate = 7773 Btu/kWh, Exhaust Pressure = 1.5 In-Hg

Design Ambient Conditions: Dry Bulb Temperature = 93°F, Wet Bulb Temperature = 74°F, Wind Speed = 5 mph,
Pond Equilibrium Temperature = 83°F

Variable Name	Once Through	Mech. Wet	Fan Wet	Nat. Wet	Pond	Spray Canal	Mech. Dry	Nat. Dry
<u>General</u>								
Design Cold Water Temperature, °F	57.0	90.0	86.0	90.0	104.0	94.0	134.0	131.0
Design Approach	-	16.0	12.0	16.0	21.0	20.0	41.0	38.0
Design Range, °F	15.0	22.0	26.0	27.0	18.0	20.0	28.0	26.0
Plant Capacity at Cooling System Design Point, MWe	1059	1041	1041	1031	1019	1037	935	943
Design Turbine Back Pressure, In-Hg	1.50	3.26	3.26	3.74	4.29	3.45	11.65	10.36
Maximum Turbine Back Pressure, In-Hg	2.13	3.31	3.33	3.96	4.34	3.51	13.63	12.15
Design Heat Load, 10 ⁹ Btu/hr	4.62	4.68	4.68	4.71	4.75	4.69	5.04	5.01
<u>Condenser</u>								
Surface Area, 10 ³ sq ft	498	684	635	621	756	713	645	666
Number of Tubes, 10 ³	41.4	57.2	48.4	47.0	71.1	63.1	48.4	52.9
Tube Length, ft	41.0	45.6	50.1	50.5	40.6	43.1	50.9	49.1

TABLE 6-8 (Sheet 2)

SUMMARY OF DESIGN CONDITIONS FOR OPTIMIZED COOLING SYSTEMS FOR 1000 MWe LMFBR POWER PLANT

Variable Name	Once-Through	Mech. Wet	Fan Wet	Nat. Wet	Pond	Spray Canal	Mech. Dry	Nat. Dry
<u>Cooling Water Pump</u>								
Circulating Water Flow Rate, 10^3 gpm	615	425	360	349	528	469	360	385
Number of Pumps	4	3	2	2	3	3	2	3
Pumping Head, ft of Water	22.6	76.5	75.0	87.4	34.1	35.6	42.2	190.5
Pumping Power Requirement, bph/pump	989	3078	3827	4325	1705	1578	2155	1837
Rated Pump Motor Size, hp/pump Motor	1250	3500	4500	5000	2000	2000	2500	2250
<u>Terminal Heat Sink</u>								
Total Power Requirement, 10^3 bhp	-	4.70	4.87	-	-	8.55	18.24	-
Terminal Heat Sink Size:	-	-	-	-	-	-	-	-
Number of Cells	-	25	-	-	-	-	97	-
Tower: Number of Towers	-	-	2	1	-	-	-	2
Base Diameter, ft	-	-	219	383	-	-	-	314
Tower Height, ft	-	-	250	496	-	-	-	361
Fan: Number of Fans/Tower	-	-	20	-	-	-	-	-
Fan Diameter, ft	-	28	28	-	-	-	28	-
Canal: Number of Modules	-	-	-	-	-	114	-	-
Canal Width, ft	-	-	-	-	-	256	-	-
Canal Length, ft	-	-	-	-	-	3340	-	-
Pond Area, Acres	-	-	-	-	442	-	-	-

TABLE 6-9

SUMMARY OF CAPITAL INVESTMENT, PENALTIES, TOTAL EVALUATED COST, AND PRESENT WORTH COST
FOR OPTIMIZED COOLING SYSTEMS (IN MILLIONS OF DOLLARS) FOR 1000 MWe LMFBR POWER PLANT

	Once- Through	Mech. Wet	Fan Wet	Nat. Wet	Pond	Spray Canal	Mech. Dry	Nat. Dry
Total Capital Investment	12.16	17.02	20.35	19.25	29.26	17.70	25.86	34.79
Capacity Penalty (Due to Highest Turbine Back Pressure)	0.38	2.85	2.90	4.83	6.13	3.42	19.95	18.95
Energy Replacement Penalty (Due to Turbine Back Pressure Variations)	-0.01	1.67	1.32	1.84	4.05	2.03	25.91	24.63
Capitalized Annual Cost for Operating Cooling Water Pumps	1.71	4.00	3.31	3.74	2.21	2.05	1.87	2.39
Capitalized Annual Cost for Operating Terminal Heat Sink	-	1.99	1.90	-	-	3.33	6.98	-
Capitalized Annual Cost for Make-Up and Water Treatment	-	0.21	0.20	0.20	0.18	0.20	-	-
Capitalized Annual Operating and Maintenance Cost	0.25	1.31	1.21	0.62	0.49	1.54	2.66	2.01
Total Evaluated Cost	14.49	29.05	31.19	30.48	42.30	30.65	83.23	82.77
Present Worth Cost	25.92	51.96	55.79	54.52	75.66	54.82	148.87	148.04

TABLE 6-10 (Sheet 1 of 2)

SUMMARY OF CAPITAL INVESTMENT FOR OPTIMIZED COOLING SYSTEMS (IN MILLIONS OF DOLLARS)

FOR 1000 MWe LMFBR POWER PLANT

AEC Acc. No.	Equipment Item		Once- Through	Mech. Wet	Fan Wet	Nat. Wet	Pond	Spray Canal	Mech. Dry	Nat. Dry
214.1	Circulating Water Structure	(M	0.625	0.443	0.431	0.422	0.422	0.444	0.330	0.340
		(L	2.109	0.291	0.287	0.282	0.278	0.296	0.220	0.230
		(T	2.734	0.734	0.718	0.704	0.700	0.740	0.550	0.570
232.21	Circulating Water Pumps & Motors	(E	1.068	1.070	0.808	0.833	0.899	0.907	0.623	0.801
		(M	0.012	0.012	0.008	0.009	0.010	0.010	0.007	0.009
		(L	0.080	0.062	0.042	0.042	0.061	0.063	0.040	0.060
		(T	1.160	1.144	0.858	0.884	0.970	0.980	0.670	0.870
232.22	Concrete Pipes	(M	0.740	0.541	0.471	0.241	0.825	0.729	0.740	0.500
		(L	0.780	0.531	0.451	0.231	0.865	0.811	0.940	0.480
		(T	1.520	1.072	0.922	0.472	1.690	1.540	1.680	0.980
232.31	Terminal Heat Sink Basins and Foundations	(M	-	0.510	0.280	0.260	-	-	0.190	0.280
		(L	-	0.770	1.120	1.060	-	-	0.370	0.910
		(T	-	1.280	1.400	1.320	-	-	0.560	1.190
232.32	Terminal Heat Sink	(E	-	2.049	3.990	5.277	-	2.257	10.129	11.134
		(M	-	0.021	0.040	0.053	0.660	0.023	0.051	0.056
		(L	-	1.120	2.690	1.330	13.270	1.880	1.040	7.550
		(T	-	3.190	6.720	6.660	13.930	4.160	11.220	18.740

TABLE 6-10 (Sheet 2)

SUMMARY OF CAPITAL INVESTMENT FOR OPTIMIZED COOLING SYSTEMS (IN MILLIONS OF DOLLARS)

FOR 1000 MWe LMFBR POWER PLANT

AEC ACC. No.	Equipment Item		Once- Through	Mech. Wet	Fan Wet	Nat. Wet	Pond	Spray Canal	Mech. Dry	Nat. Dry
233.1	Condenser Installed	(E	2.567	3.562	3.303	3.234	3.970	3.731	3.333	3.443
		(M	0.013	0.018	0.017	0.016	0.020	0.019	0.017	0.017
		(L	1.400	1.660	1.580	1.570	1.770	1.710	1.590	1.620
		(T	3.980	5.240	4.900	4.820	5.760	5.460	4.940	5.080
24	Electrical Work	(E	0.124	0.292	0.233	0.157	0.135	0.392	0.328	0.149
		(M	0.067	0.220	0.175	0.130	0.073	0.295	0.247	0.081
		(L	0.139	0.443	0.352	0.253	0.152	0.593	0.495	0.168
		(T	0.330	0.955	0.760	0.540	0.360	1.280	1.070	0.398
	Sub-Total for the Complete Cooling System	(E	3.759	6.973	8.334	9.501	5.004	7.287	14.413	15.527
		(M	1.457	1.765	1.423	1.131	2.010	1.520	1.582	1.283
		(L	4.508	4.877	6.523	4.768	16.396	5.353	4.695	11.018
		(T	9.724	13.615	16.280	15.400	23.410	14.160	20.690	27.828
	Indirect Charges		2.431	3.404	4.070	3.850	5.852	3.540	5.172	6.957
	Total Capital Investment		12.155	17.019	20.350	19.250	29.262	17.700	25.862	34.785

TABLE 6-11 (Sheet 1 of 2)

SUMMARY OF DESIGN CONDITIONS FOR OPTIMIZED COOLING SYSTEMS FOR 1160 MWe HTGR POWER PLANT

Base Plant Conditions: Plant Capacity = 1175 MWe, Heat Rate = 8715 Btu/kWh, Exhaust Pressure = 1.5 In-Hg

Design Ambient Conditions: Dry Bulb Temperature = 93°F, Wet Bulb Temperature = 74°F, Wind Speed = 5 mph,
Pond Equilibrium Temperature = 83°F

Variable Name	Once-Through	Mech. Wet	Fan Wet	Nat. Wet	Pond	Spray Canal	Mech. Dry	Nat. Dry
<u>General</u>								
Design Cold Water Temperature, °F	57.0	93.0	89.0	93.0	105.0	96.0	137.0	132.0
Design Approach, °F	-	19.0	15.0	19.0	31.0	22.0	44.0	39.0
Design Range, °F	15.0	25.0	28.0	28.0	20.0	24.0	25.0	31.0
Plant Capacity at Cooling System Design Point, MWe	1175	1156	1158	1151	1142	1152	1048	1046
Design Turbine Back Pressure, In-Hg	1.50	3.85	3.74	4.17	4.65	4.00	11.65	11.92
Maximum Turbine Back Pressure, In-Hg	2.13	3.90	3.82	4.38	4.69	4.04	13.54	13.92
Design Heat Load, 10 ⁹ Btu/hr	6.23	6.30	6.29	6.31	6.34	6.31	6.66	6.67
<u>Condenser</u>								
Surface Area, 10 ³ sq ft	599	859	815	812	961	875	904	808
Number of Tubes, 10 ³	55.9	67.8	60.5	60.7	85.4	70.7	71.7	57.9
Tube Length, ft	41.0	48.4	51.5	51.1	43.0	47.3	48.1	53.3

TABLE 6-11 (Sheet 2)

SUMMARY OF DESIGN CONDITIONS FOR OPTIMIZED COOLING SYSTEMS FOR 1160 MWe HTGR POWER PLANT

Variable Name	Once-Through	Mech. Wet	Fan Wet	Nat. Wet	Pond	Spray Canal	Mech. Dry	Nat. Dry
<u>Cooling Water Pump</u>								
Circulating Water Flow Rate, 10^3 gpm	831	504	449	451	634	526	533	430
Number of Pumps	6	3	3	3	4	3	3	3
Pumping Head, ft. of Water	23.0	77.0	74.6	87.1	34.5	37.1	40.0	51.3
Pumping Power Requirement, bph/pump	897	3670	3169	3716	1551	1843	2016	2087
Rated Pump Motor Size, hp/pump Motor	1000	4000	3500	4000	2000	2250	2250	2500
<u>Terminal Heat Sink</u>								
Total Power Requirement, 10^3 bhp	-	5.00	5.24	-	-	9.90	23.40	-
Terminal Heat Sink Size:								
Number of Cells	-	27	-	-	-	-	125	-
Tower: Number of Towers	-	-	2	1	-	-	-	2
Base Diameter, ft	-	-	226	385	-	-	-	358
Tower Height, ft	-	-	250	499	-	-	-	377
Fan: Number of Fans/Tower	-	-	20	-	-	-	-	-
Fan Diameter, ft	-	-	28	-	-	-	-	-
Canal: Number of Modules	-	-	-	-	-	132	-	-
Canal Width, ft	-	-	-	-	-	256	-	-
Canal Length, ft	-	-	-	-	-	382	-	-
Pond Area, Acres	-	-	-	-	545	-	-	-

TABLE 6-12

SUMMARY OF CAPITAL INVESTMENT, PENALTIES, TOTAL EVALUATED COST, AND PRESENT WORTH COST
FOR OPTIMIZED COOLING SYSTEMS (IN MILLIONS OF DOLLARS) FOR 1160 MWe HTGR POWER PLANT

	Once- Through	Mech. Wet	Fan Wet	Nat. Wet	Pond	Spray Canal	Mech. Dry	Nat. Dry
Total Capital Investment	14.89	19.18	22.78	21.53	35.69	21.89	33.44	39.81
Capacity Penalty (Due to Highest Turbine Back Pressure)	0.14	2.99	2.79	4.21	5.08	3.34	20.57	20.80
Energy Replacement Penalty (Due to Turbine Back Pressure Variations)	0.05	2.15	1.46	1.78	3.35	2.20	24.69	25.02
Capitalized Annual Cost for Operating Cooling Water Pumps	2.33	4.76	4.11	4.82	2.68	2.39	2.61	2.70
Capitalized Annual Cost for Operating Terminal Heat Sink	-	2.11	2.04	-	-	3.86	8.98	-
Capitalized Annual Cost for Make-Up and Water Treatment	-	0.28	0.28	0.28	0.24	0.28	-	-
Capitalized Annual Operating and Maintenance Cost	0.33	1.48	1.41	0.80	0.61	1.82	3.45	2.29
Total Evaluated Cost	17.74	32.95	34.87	33.42	47.65	36.22	93.71	90.62
Present Worth Cost	31.73	58.94	62.38	59.78	85.24	64.79	167.64	162.11

TABLE 6-13 (Sheet 1 of 2)

SUMMARY OF CAPITAL INVESTMENT FOR OPTIMIZED COOLING SYSTEMS (IN MILLIONS OF DOLLARS)

FOR 1160 MWe HTGR POWER PLANT

AEC Acc. No.	Equipment Item		Once- Through	Mech. Wet	Fan Wet	Nat. Wet	Pond	Spray Canal	Mech. Dry	Nat. Dry
214.1	Circulating Water Structure	(M	0.771	0.495	0.486	0.486	0.469	0.903	0.380	0.350
		(L	<u>2.603</u>	<u>0.335</u>	<u>0.324</u>	<u>0.324</u>	<u>0.309</u>	<u>0.947</u>	<u>0.250</u>	<u>0.230</u>
		(T	3.374	0.830	0.810	0.810	0.778	1.850	0.630	0.580
232.21	Circulating Water Pumps & Motors	(E	1.325	1.144	1.085	1.144	1.193	1.215	0.900	0.930
		(N	0.015	0.013	0.012	0.013	0.013	0.014	0.010	0.010
		(L	<u>0.120</u>	<u>0.063</u>	<u>0.063</u>	<u>0.063</u>	<u>0.082</u>	<u>0.081</u>	<u>0.060</u>	<u>0.060</u>
		(T	1.460	1.220	1.160	1.220	1.288	1.310	0.970	1.000
232.22	Concrete Pipes	(M	0.900	0.666	0.636	0.326	1.007	0.903	1.000	0.540
		(L	<u>0.900</u>	<u>0.604</u>	<u>0.574</u>	<u>0.294</u>	<u>0.977</u>	<u>0.947</u>	<u>1.170</u>	<u>0.510</u>
		(T	1.800	1.270	1.210	0.620	1.984	1.850	2.170	1.050
232.31	Terminal Heat Sink Basins and Foundations	(M	-	0.550	0.280	0.270	-	-	0.210	0.350
		(L	-	<u>0.830</u>	<u>1.120</u>	<u>1.060</u>	-	-	<u>0.520</u>	<u>1.120</u>
		(T	-	1.380	1.400	1.330	-	-	0.730	1.470
232.32	Terminal Heat Sink	(E	-	2.218	4.128	5.346	-	2.614	13.064	12.806
		(M	-	0.022	0.042	0.054	0.820	0.026	0.066	0.064
		(L	-	<u>1.210</u>	<u>2.780</u>	<u>1.350</u>	<u>16.360</u>	<u>2.160</u>	<u>1.340</u>	<u>8.710</u>
		(T	-	3.450	6.950	6.750	17.180	4.800	14.470	21.580

TABLE 6-13 (Sheet 2)

SUMMARY OF CAPITAL INVESTMENT FOR OPTIMIZED COOLING SYSTEMS (IN MILLIONS OF DOLLARS)

FOR 1160 MWe HTGR POWER PLANT

AEC Acc. No.	Equipment Item		Once- Through	Mech. Wet	Fan Wet	Nat. Wet	Pond	Spray Canal	Mech. Dry	Nat. Dry
233.1	Condensers, Installed	(E	3.264	4.269	4.040	4.030	4.816	4.358	4.468	3.940
		(M	0.016	0.021	0.020	0.020	0.024	0.022	0.022	0.020
		(L	1.580	1.840	1.780	1.780	2.000	1.870	1.900	1.770
		(T	4.860	6.150	5.840	5.830	6.840	6.250	6.390	5.780
24	Electrical Work	(E	0.157	0.325	0.262	0.193	0.180	0.445	0.427	0.163
		(M	0.085	0.244	0.197	0.158	0.097	0.335	0.320	0.088
		(L	0.178	0.491	0.396	0.309	0.203	0.673	0.646	0.184
		(T	0.420	1.060	0.855	0.660	0.480	1.453	1.393	0.435
	Sub-Total for the Complete Cooling System	(E	4.746	7.956	9.515	10.713	6.189	8.632	18.859	17.839
		(M	1.787	2.011	1.673	1.327	2.430	2.203	2.008	1.422
		(L	5.381	5.373	7.037	5.180	19.931	6.678	5.886	12.584
		(T	11.914	15.340	18.225	17.220	28.550	17.513	26.753	31.845
	Indirect Charges		2.978	3.835	4.556	4.305	7.137	4.378	6.688	7.961
	Total Capital Investment		14.892	19.175	22.781	21.525	35.687	21.891	33.441	39.806

TABLE 6-14 (Sheet 1 of 2)

SUMMARY OF DESIGN CONDITIONS FOR OPTIMIZED COOLING SYSTEMS FOR 770 MWe HTGR POWER PLANT

Base Plant Conditions: Plant Capacity = 797 MWe, Heat Rate = 8457 Btu/kWh, Exhaust Pressure = 1.5 In-Hg

Design Ambient Conditions: Dry Bulb Temperature = 93°F, Wet Bulb Temperature = 74°F, Wind Speed = 5 mph,
Pond Equilibrium Temperature = 83°F

Variable Name	Once-Through	Mech. Wet	Fan Wet	Nat. Wet	Pond	Spray Canal	Mech. Dry	Nat. Dry
<u>General</u>								
Design Cold Water Temperature, °F	57.0	93.0	92.0	92.0	109.0	98.0	137.0	132.0
Design Approach	-	19.0	18.0	18.0	26.0	24.0	44.0	39.0
Design Range, °F	15.0	23.0	24.0	30.0	17.0	20.0	27.0	31.0
Plant Capacity at Cooling System Design Point, MWe	797	786	786	779	773	784	709	710
Design Turbine Back Pressure, In-Hg	1.50	3.64	3.64	4.29	4.77	3.75	12.20	11.92
Maximum Turbine Back Pressure, In-Hg	2.13	3.69	3.71	4.50	4.82	3.78	14.13	13.91
Design Heat Load, 10 ⁹ Btu/hr	4.02	4.06	4.06	4.08	4.11	4.06	4.32	4.32
<u>Condenser</u>								
Surface Area, 10 ³ sq ft	387	577	566	507	670	616	564	523
Number of Tubes, 10 ³	36.1	47.5	45.5	37.0	65.0	54.7	43.1	37.5
Tube Length, ft	41.0	46.4	47.5	52.9	39.4	43.0	50.0	53.3

TABLE 6-14 (Sheet 2)

SUMMARY OF DESIGN CONDITIONS FOR OPTIMIZED COOLING SYSTEMS FOR 770 MWe HTGR POWER PLANT

Variable Name	Once-Through	Mech. Wet	Fan Wet	Nat. Wet	Pond	Spray Canal	Mech. Dry	Nat. Dry
<u>Cooling Water Pump</u>								
Circulating Water Flow Rate, 10^3 gpm	536	353	338	272	483	406	320	279
Number of Pumps	3	2	2	2	3	3	2	2
Pumping Head, ft. of Water	23.5	77.3	73.4	82.9	33.9	35.2	44.8	55.0
Pumping Power Requirement, bph/pump	1192	3871	3519	3202	1550	1353	2033	2175
Rated Pump Motor Size, hp/pump Motor	1500	4500	4000	3500	2000	1750	2500	2500
<u>Terminal Heat Sink</u>								
Total Power Requirement, 10^3 bhp	-	3.30	3.34	-	-	6.30	15.0	-
Terminal Heat Sink Size:								
Number of Cells	-	18	-	-	-	-	80	-
Tower: Number of Towers	-	-	1	1	-	-	-	1
Base Diameter, ft	-	-	257	328	-	-	-	416
Tower Height, ft	-	-	250	425	-	-	-	424
Fan: Number of Fans/Tower	-	-	24	-	-	-	-	-
Fan Diameter, ft	-	28	28	-	-	-	28	-
Canal: Number of Modules	-	-	-	-	-	84	-	-
Canal Width, ft	-	-	-	-	-	256	-	-
Canal Length, ft	-	-	-	-	-	2540	-	-
Pond Area, Acres	-	-	-	-	314	-	-	-

TABLE 6-15

SUMMARY OF CAPITAL INVESTMENT, PENALTIES, TOTAL EVALUATED COST, AND PRESENT WORTH COST

FOR OPTIMIZED COOLING SYSTEMS (IN MILLIONS OF DOLLARS) FOR 770 MWe HTGR POWER PLANT

	Once- Through	Mech. Wet	Fan Wet	Nat. Wet	Pond	Spray Canal	Mech. Dry	Nat. Dry
Total Capital Investment	10.81	13.86	14.99	15.65	23.39	14.91	22.30	25.01
Capacity Penalty (Due to Highest Turbine Back Pressure)	0.09	1.69	1.72	3.08	3.70	1.83	14.18	14.10
Energy Replacement Penalty (Due to Turbine Back Pressure Variations)	0.03	1.08	0.91	1.37	2.68	1.09	17.12	16.95
Capitalized Annual Cost for Operating Cooling Water Pumps	1.55	3.35	3.05	2.77	2.01	1.76	1.76	1.91
Capitalized Annual Cost for Operating Terminal Heat Sink	-	1.41	1.30	-	-	2.45	5.74	-
Capitalized Annual Cost for Make-Up and Water Treatment	-	0.18	0.18	0.18	0.16	0.18	-	-
Capitalized Annual Operating and Maintenance Cost	0.23	0.92	0.95	0.49	0.43	1.19	2.22	1.46
Total Evaluated Cost	12.71	22.53	23.15	23.36	32.37	23.41	63.32	59.43
Present Worth Cost	22.73	40.29	41.40	41.79	57.89	41.87	113.25	106.29

TABLE 6-16 (Sheet 1 of 2)

SUMMARY OF CAPITAL INVESTMENT FOR OPTIMIZED COOLING SYSTEMS (IN MILLIONS OF DOLLARS)

FOR 770 MWe HTGR POWER PLANT

AEC Acc. No.	Equipment Item		Once- Through	Mech. Wet	Fan Wet	Nat. Wet	Pond	Spray Canal	Mech. Dry	Nat. Dry
214.1	Circulating Water Structure	(M	0.565	0.414	0.405	0.384	0.404	0.407	0.310	0.300
		(L	1.907	0.276	0.265	0.256	0.262	0.275	0.210	0.200
		(T	2.472	0.690	0.670	0.640	0.666	0.682	0.520	0.500
232.21	Circulating Water Pumps & Motors	(E	0.821	0.800	0.760	0.651	0.886	0.772	0.623	0.554
		(M	0.009	0.008	0.008	0.007	0.009	0.008	0.007	0.006
		(L	0.060	0.042	0.042	0.042	0.061	0.062	0.040	0.040
		(T	0.890	0.850	0.810	0.700	0.956	0.842	0.670	0.600
232.22	Concrete Pipes	(M	0.640	0.470	0.240	0.190	0.724	0.627	0.630	0.180
		(L	0.699	0.470	0.240	0.200	0.808	0.759	0.840	0.190
		(T	1.339	0.940	0.480	0.390	1.532	1.386	1.470	0.370
232.31	Terminal Heat Sink Basins and Foundations	(M	-	0.370	0.160	0.230	-	-	0.160	0.230
		(L	-	0.550	0.640	0.910	-	-	0.300	0.730
		(T	-	0.920	0.800	1.140	-	-	0.460	0.960
232.32	Terminal Heat Sink	(E	-	1.475	2.396	4.019	-	1.668	8.358	7.671
		(M	-	0.015	0.024	0.041	0.470	0.012	0.042	0.039
		(L	-	0.800	1.610	1.010	9.420	1.430	0.860	5.300
		(T	-	2.290	4.030	5.070	9.890	3.110	9.260	13.010

TABLE 6-16 (Sheet 2)

SUMMARY OF CAPITAL INVESTMENT FOR OPTIMIZED COOLING SYSTEMS (IN MILLIONS OF DOLLARS)

FOR 770 MWe HTGR POWER PLANT

AEC Acc. No.	Equipment Item		Once- Through	Mech. Wet	Fan Wet	Nat. Wet	Pond	Spray Canal	Mech. Dry	Nat. Dry
233.1	Condensers, Installed	(E)	2.318	3.094	3.035	2.746	3.612	3.303	3.005	2.816
		(M)	0.012	0.016	0.015	0.014	0.018	0.017	0.015	0.014
		(L)	1.330	1.530	1.520	1.430	1.680	1.590	1.510	1.450
		(T)	3.660	4.640	4.570	4.190	5.310	4.910	4.530	4.280
24	Electrical Work	(E)	0.107	0.233	0.193	0.114	0.135	0.306	0.285	0.109
		(M)	0.058	0.175	0.145	0.094	0.073	0.230	0.214	0.059
		(L)	0.120	0.352	0.292	0.182	0.152	0.462	0.431	0.122
		(T)	0.285	0.760	0.630	0.390	0.360	0.998	0.930	0.290
	Sub-Total for the	(E)	3.246	5.602	6.384	7.530	4.633	6.049	12.271	11.150
	Complete Cooling	(M)	1.284	1.468	0.997	0.960	1.698	1.301	1.378	0.828
	System	(L)	4.116	4.020	4.609	4.030	12.383	4.578	4.191	8.032
		(T)	8.646	11.090	11.990	12.520	18.714	11.928	17.840	20.010
	Indirect Charges		2.162	2.773	2.998	3.130	4.679	2.982	4.460	5.003
	Total Capital Investment		10.808	13.863	14.988	15.650	23.393	14.910	22.300	25.013

TABLE 6-17

LOSS OF CAPACITY vs AMBIENT TEMPERATURES FOR OPTIMIZED COOLING SYSTEMSFOR 1000 MWe FOSSIL POWER PLANT

Base Plant Conditions: Capacity = 1043 MWe, Heat Rate = 7365 Btu/kWh, Exhaust Pressure = 1.5 In-Hg

Wet Bulb Temp. °F	Dry Bulb Temp. °F	River Temp. °F	Capacity Loss, kW							
			Once- Through	Mech. Wet	Fan Wet	Nat. Wet	Pond	Spray Canal	Mech. Dry	Nat. Dry
75.0	99.0	71.5	5,440	23,500	18,560	34,050	44,240	22,380	118,560	125,750
74.0	94.0	68.0	3,479	22,440	17,380	29,330	42,780	21,280	107,350	113,200
69.0	89.0	65.8	2,500	17,860	12,910	22,580	34,460	16,480	97,410	102,300
67.0	84.0	65.0	2,200	16,280	11,330	18,950	31,120	14,850	89,920	93,400
62.0	77.0	63.3	1,600	12,900	8,190	13,660	25,530	11,370	82,970	85,120
58.0	67.0	60.2	700	10,660	6,120	9,200	20,140	9,130	76,940	78,000
51.0	57.0	57.5	0	7,600	3,560	5,210	12,780	6,100	74,010	74,450
41.0	47.0	52.5	- 720	4,540	1,260	2,100	5,700	3,200	72,890	73,000
33.0	37.0	48.4	-1,180	2,860	90	420	2,730	1,670	73,000	72,900
24.0	27.0	42.5	-1,600	1,480	- 790	- 710	- 9	470	73,890	73,700
13.0	17.0	36.9	-1,830	310	-1,480	-1,510	- 890	- 520	75,110	74,800

TABLE 6-18

LOSS OF CAPACITY vs AMBIENT TEMPERATURES FOR OPTIMIZED COOLING SYSTEMSFOR 1000 MWe LWR POWER PLANT

Base Plant Conditions: Capacity = 1097 MWe, Heat Rate = 9760 Btu/kWh, Exhaust Pressure = 1.5 In-Hg

Wet Bulb Temp. °F	Dry Bulb Temp. °F	River Temp. °F	Capacity Loss, kW							
			Once- Through	Mech. Wet	Fan Wet	Nat. Wet	Pond	Spray Canal	Mech. Dry	Nat. Dry
75.0	99.0	71.5	1,590	22,460	19,300	31,290	38,370	40,830	180,210	172,300
74.0	94.0	68.0	930	21,550	18,180	27,720	37,200	39,140	166,090	159,000
69.0	89.0	65.8	640	17,400	13,900	22,260	30,810	32,350	153,490	147,000
67.0	84.0	65.0	550	15,930	12,300	19,090	28,320	30,210	141,290	135,000
62.0	77.0	63.3	390	12,730	9,110	14,140	24,080	25,820	126,110	121,000
58.0	67.0	60.2	160	10,590	7,000	9,780	19,570	22,880	110,990	108,300
51.0	57.0	57.5	0	7,660	4,490	5,850	12,850	18,470	103,660	102,440
41.0	47.0	52.5	-170	4,850	2,400	2,960	6,150	13,520	100,250	99,580
33.0	37.0	48.4	-290	3,380	1,420	1,570	3,470	10,520	98,460	98,180
24.0	27.0	42.5	-400	2,270	760	730	1,500	7,930	97,790	97,750
13.0	17.0	36.9	-470	1,390	300	220	780	5,650	97,820	97,870

TABLE 6-19

LOSS OF CAPACITY vs AMBIENT TEMPERATURES FOR OPTIMIZED COOLING SYSTEMSFOR 1000 MWe LMFBR POWER PLANT

Base Plant Conditions: Capacity = 1059 MWe, Heat Rate = 7773 Btu/kWh, Exhaust Pressure = 1.5 In-Hg

Wet Bulb Temp. °F	Dry Bulb Temp. °F	River Temp. °F	Capacity Loss, kW							
			Once- Through	Mech. Wet	Fan Wet	Nat. Wet	Pond	Spray Canal	Mech. Dry	Nat. Dry
75.0	99.0	71.5	2,520	19,000	19,370	32,200	40,870	22,830	133,000	126,340
74.0	94.0	68.0	1,290	18,070	18,130	28,200	39,760	21,720	125,440	117,400
69.0	89.0	65.8	800	14,010	13,410	21,950	33,140	16,890	116,640	109,050
67.0	84.0	65.0	660	12,620	11,720	18,430	30,280	15,220	108,280	99,860
62.0	77.0	63.3	430	9,630	8,340	13,190	25,190	11,650	95,160	86,850
58.0	67.0	60.2	160	7,680	6,100	8,720	19,950	9,310	78,760	73,500
51.0	57.0	57.5	20	5,030	3,390	4,670	12,570	6,140	68,340	64,930
41.0	47.0	52.5	- 160	2,560	1,260	1,740	5,320	3,130	61,770	59,530
33.0	37.0	48.4	- 270	1,380	470	560	2,400	1,690	57,700	56,280
24.0	27.0	42.5	- 380	630	90	80	420	770	55,310	54,490
13.0	17.0	36.9	- 450	180	- 140	- 180	60	230	54,000	53,520

TABLE 6-20

LOSS OF CAPACITY vs AMBIENT TEMPERATURES FOR OPTIMIZED COOLING SYSTEMSFOR 1160 MWe HTGR POWER PLANT

Base Plant Conditions: Capacity = 1175 MWe, Heat Rate = 8715 Btu/kWh, Exhaust Pressure = 1.5 In-Hg

Wet Bulb Temp. F	Dry Bulb Temp. F	River Temp. F	Capacity Loss, kW							
			Once- Through	Mech. Wet	Fan Wet	Nat. Wet	Pond	Spray Canal	Mech. Dry	Nat. Dry
75.0	99.0	71.5	930	19,950	18,600	28,090	33,850	22,280	137,160	138,640
74.0	94.0	68.0	470	19,120	17,510	24,950	32,900	21,300	128,560	130,680
69.0	89.0	65.8	280	15,330	13,390	19,820	27,540	16,880	118,820	120,630
67.0	84.0	65.0	220	13,990	11,840	16,820	25,250	15,310	109,560	111,360
62.0	77.0	63.3	130	11,060	8,720	12,160	21,130	11,890	94,920	96,900
58.0	67.0	60.2	27	9,100	6,600	8,090	16,740	9,610	76,610	78,000
51.0	57.0	57.5	0	6,430	4,110	4,510	10,310	6,520	64,930	65,850
41.0	47.0	52.5	50	3,910	2,080	2,040	4,010	3,710	57,530	58,100
33.0	37.0	48.4	150	2,620	1,170	950	1,770	2,360	52,960	53,330
24.0	27.0	42.5	320	1,680	590	360	610	1,410	50,280	50,600
13.0	17.0	36.9	430	970	200	60	320	740	48,820	49,000

TABLE 6-21

LOSS OF CAPACITY vs AMBIENT TEMPERATURES FOR OPTIMIZED COOLING SYSTEMSFOR 770 MWe HTGR POWER PLANT

Base Plant Conditions: Capacity = 797 MWe, Heat Rate = 8457 Btu/kWh. Exhaust Pressure = 1.5 In-Hg

Wet Bulb Temp. °F	Dry Bulb Temp. °F	River Temp. °F	Capacity Loss, kW							
			Once- Through	Mech. Wet	Fan Wet	Nat. Wet	Pond	Spray Canal	Mech. Dry	Nat. Dry
75.0	99.0	71.5	630	11,290	11,500	20,550	24,650	12,190	94,590	94,000
74.0	94.0	68.0	320	10,760	10,800	18,270	24,020	11,600	89,410	88,600
69.0	89.0	65.8	190	8,400	8,260	14,620	20,300	8,970	82,750	81,830
67.0	84.0	65.0	150	7,580	7,300	12,500	18,720	8,050	76,400	75,520
62.0	77.0	63.3	90	5,810	5,400	9,150	15,920	6,090	66,750	65,670
58.0	67.0	60.2	20	4,680	4,080	6,190	12,940	4,820	53,570	52,860
51.0	57.0	57.5	0	3,190	2,570	3,510	8,460	3,190	45,050	44,540
41.0	47.0	52.5	40	1,840	1,320	1,630	3,790	1,750	39,690	39,360
33.0	37.0	48.4	100	1,190	750	770	1,860	1,080	36,340	36,140
24.0	27.0	42.5	220	720	380	310	710	630	34,360	34,280
13.0	17.0	36.9	290	380	130	60	400	310	33,280	33,270

Figure 6-1 Optimization of Mechanical Draft Wet Tower Cooling System with respect to Range for One Design Approach Temperature (Design Approach = 19°F, Wet Bulb = 74°F, Power Plant = 1160 MWe HTGR Plant)

Figure 6-2 Optimization of Mechanical Draft Wet Tower Cooling System with respect to Both Range and Approach Temperatures (Wet Bulb = 74 $^{\circ}\text{F}$, Power Plant = 1160 MWe HTGR Plant)

CHAPTER 7

SENSITIVITY ANALYSIS

Since the ambient meteorological conditions and the economic situation at a plant site exert significant influence upon the performance and cost of a cooling system, any attempt to extrapolate the data presented in this report to other areas of the country should be performed with care. As an aid to this extrapolation, sensitivity analyses were performed with respect to geographic location, replacement energy and capacity charge rates, capital cost, and the use of salt water. The results are described in this chapter.

Only the wet tower cooling systems were evaluated since they are the most commonly used today. The fossil and light water reactor (LWR) plants were discussed as representative power plants. The results for the 1000 MWe fossil plant can be used to approximate the 1000 MWe LMFBR and 770 MWe HTGR plants and those for the 1000 MWe LWR plant can be used to approximate the 1160 MWe twin turbine-generator HTGR plant. (See Section 6.2 for heat rejection requirements of these units)

To simplify the discussion in this chapter, the optimum wet tower systems at Middletown, as described in Section 6.2, are defined as "base" Middletown systems.

7.1 SENSITIVITY ANALYSIS FOR VARIOUS GEOGRAPHIC LOCATIONS

The optimization results given in Section 6.2 are for the reference site (Middletown). To determine effects of variation in annual ambient dry bulb and wet bulb temperatures in different parts of the United States, the cooling systems were evaluated for eight sites in addition to Middletown. These locations represent a variety of meteorological conditions (cool snow forest climate, desert climate, steppe climate, tropical rainy climate, and a warm

temperature rainy climate) and are scattered across the conterminous United States. The eight sites are: Seattle, Washington; Los Angeles, California; Phoenix, Arizona; Denver, Colorado; St. Louis, Missouri; New Orleans, Louisiana; Miami, Florida; and Boston, Massachusetts. The procedure used was as follows:

- a. For every additional site, each of the base Middletown wet tower systems was transferred to the site; the cooling system at the new site was referred to as a "transferred" system. The purpose of the transfer was to keep the cooling system size at the new site the same as that for the base Middletown system.
- b. Next, the performance and performance affected penalties for the transferred system as well as the new total evaluated cost were determined.
- c. The difference between the total evaluated cost for the site under consideration and that of the Middletown site was then calculated.
- d. Finally, the extreme locations where the cooling system have the highest or lowest total evaluated costs were determined.

For the eight sites considered, the extreme locations coincide for all wet tower cooling systems and these are Miami, Florida and Denver, Colorado. At the Florida site, the cooling systems have the highest total evaluated cost; the Colorado site the lowest. The annual variations in ambient dry bulb and wet bulb temperatures for these two locations are given in Appendix G.

The results for the two extreme locations (expressed as a percentage increases or decreases in total evaluated cost with respect to the base costs at the Middletown site) indicate that for both fossil and LWR plants, the mechanical draft wet tower system is most affected by ambient

temperature variations. For the mechanical wet tower system of a fossil plant, the range is from -7.88 percent for Colorado to +16.27 percent for Florida. Similarly, for a LWR plant, the range is from -5.74 percent for Colorado to +11.72 percent for Florida. The detailed data of these percentages and also the penalties and costs for the transferred systems at Colorado and Florida are given in Section 7.3.

7.2 EFFECTS OF VARYING REPLACEMENT ENERGY COST, CAPACITY PENALTY CHARGE AND CAPITAL COST IN WET COOLING TOWER SYSTEMS

In the preceding section, the effects of ambient temperature variation on the performance and cost of wet cooling tower systems have been discussed. To aid the potential users in extrapolating the results of this study to other areas coupled with different economic conditions, the sensitivity analysis has been extended to include the following three factors:

1) escalation in replacement energy charge; 2) escalation in capacity penalty charge; and 3) escalation in capital investment cost. The causes for the increases in these factors may be inflation, site economic conditions, and others such as the recent oil crisis. Three sites have been considered; the Middletown reference site, and the two extreme locations found in Section 7.1 (i.e., Miami, Florida and Denver, Colorado).

The basic procedure used is similar to that described in Section 7.1, that is, transferring the base Middletown optimum systems to the new locations, and then determining the changes in total evaluated cost due to these factors. For the Middletown site, of course, transferring of the cooling systems is not required, but to simplify the discussion in this section, the cooling systems are also referred to as "transferred" systems when determining the changes in penalties and costs.

The effects on cooling system costs and penalties due to the escalation of replacement energy cost, capacity penalty charge, and capital investment cost can be illustrated by the following: doubling the energy cost to 17 mills per kWh, the capacity penalty charge to \$300 per kW, and by escalating the capital cost 100 percent. The changes in total evaluated cost caused by doubling of energy cost or capacity penalty charge were evaluated by doubling the penalties of the base transferred systems which are dependent on either of these two factors. The increases in total evaluated cost due to the escalation of capital cost were calculated by doubling the capital costs of the base transferred systems. The results are given in Table 7-1, expressed as percentage increases in total evaluated cost with respect to the base Middletown systems. The detailed data given in Tables 7-2 and 7-3 are the costs and penalties for the transferred systems with doubled replacement energy cost or with doubled capacity penalty charge.

From Table 7-1, the effect on the total evaluated costs of cooling systems for different combinations of varying degree of escalation of the three cost factors can be obtained by superimposing the changes in these factors. The ranges of cost escalation are from fifty to one hundred percent for capital investment cost, from double to quadruple for replacement energy cost, and from double to triple for capacity penalty cost. For each combination of the cost escalations investigated, the total evaluated cost of the wet tower systems (mechanical, natural and fan-assisted natural draft wet towers) were calculated, and the system with the lowest total evaluated cost was selected as the recommended system. The results are summarized in Table 7-4 where the recommended system and its total evaluated cost are given for each combination. The generation of

Table 7-4 from Table 7-1 is best illustrated by an example. The cost of a natural wet tower system at the Florida site for a 1000-MWe LWR plant with

n_1 times the capital cost,

n_2 times the replacement energy charge rate, and

n_3 times the capacity penalty charge rate

of the base Middletown optimum system is evaluated as follows:

$$C_t = [1 + (n_1 - 1) (0.6362) + (n_2 - 1) (0.4017) + (n_3 - 1) (0.2686)] \quad (36.64)$$

where

C_t is in $\$10^6$.

7.3 COMPARISON BETWEEN THE TRANSFERRED SYSTEMS AND THE RE-OPTIMIZED SYSTEMS

The cooling systems at each of the conditions shown in Table 7-4 can be re-optimized, which would, in general, result in different cooling systems, sizes, costs and penalties as well as savings in the total evaluated costs compared to the transferred systems. It may also result in different types of recommended systems than those given in Table 7-4. However, complete optimization and comparison of all cases would require extensive effort which is beyond the scope of this work. Therefore, only a few cases have been examined which will be described below.

First, optimization was performed for the wet tower systems at the two extreme locations (i.e., Colorado and Florida) without escalating the cost factors. The results obtained were then compared to those for the transferred systems described in Section 7.1. The comparisons are given in Tables 7-5 through 7-7; and the design data for the optimized systems are given in Tables 7-8 and 7-9.

In Table 7-5 the data are expressed in the form of percentage increase or decrease in total evaluated cost for the systems under consideration compared to the base Middletown systems. Table 7-5 shows that only a slight advantage has been gained by optimizing the cooling systems at the "transferred" locations, with a maximum saving in total evaluated cost of approximately 3 percent. It should be noted, however, that optimization has produced a different size cooling system and a redistribution of the capital cost and economic penalties as can be seen in Tables 7-6 through 7-9.

Optimization was also performed for the wet tower systems with doubled replacement energy charge (17 mills per kWh) at the Middletown, Colorado, and Florida sites. The results obtained were compared to the corresponding transferred systems discussed in Section 7.2. These comparisons are given in Tables 7-10 through 7-12 while the design data of the optimized systems are given in Tables 7-13 and 7-14.

Table 7-10 gives the percentage increase in total evaluated cost compared to the base Middletown optimum system cost at the three locations mentioned above. The data for the Middletown site contains the influence of doubling replacement energy charge only, while those for Colorado and Florida are affected by both the location change and the doubling of replacement energy charge. The comparison shows that, for doubling of energy charge alone, optimization provides only a small saving in total evaluated cost for each of the cooling systems (maximum saving about 3 percent). When the combined effect of location change and the doubling of energy charge are considered, however, optimization has resulted in much higher savings (maximum about 10 percent).

From the sample comparisons presented in this section, it appears that if a single sensitivity factor (location, energy charge, capacity penalty charge or escalation in capital investment cost), is considered, optimization provides no substantial savings in cooling system cost. Thus, the results for the transferred systems provide a very good estimate. When several factors are considered together, the savings may be much greater. Therefore, while the data provided in Section 7.2 can be used for an initial estimate, detailed optimization would be desirable if a more accurate estimate is required.

7.4 EFFECTS OF SALT WATER ON WET TOWER COOLING SYSTEMS

The present study has been concerned with fresh water cooling systems. The decreasing availability of fresh water sources for cooling purposes and the location of new plants in coastal areas point to the need for a discussion about the salt water effects on cooling tower size, performance, and capital cost. Therefore, the data presented in this Section may be used to estimate salt water wet tower system sizes and capital costs. In order to show the effects of salt water on a cooling system, a comparison between the use of fresh water and salt water with 70,000 ppm total dissolved solids will be made (i.e., two times the concentration of sea water). The properties of fresh water and salt water are listed below for a typical average cooling water temperature of 100^o F in a cooling tower for summertime conditions.

<u>Property</u>	<u>Fresh Water</u>	<u>Salt Water (70,000 ppm)</u>
Density, d , lb/ft ³	62.05	65.26
Specific Heat, c , Btu/lb- °F	0.998	0.922
Thermal Conductivity, k , Btu/h-ft- °F	0.36	0.35
Viscosity, z , Centipoise	0.68	0.78
Vapor Pressure, P , psi	0.9492	0.9105
Enthalpy of Saturated Air at 100°F, $H(100)$, Btu/lb	71.52	69.46
Enthalpy of Saturated Air at 87°F, $H(87)$, Btu/lb	51.81	50.32

As indicated in these data, an increase in salinity has the following effects:

- a. Increase in density and viscosity;
- b. Decrease in specific heat and thermal conductivity;
- c. Reduction in vapor pressure which, in turn, causes a reduction in enthalpy of saturated air.

The results of the above changes in physical and transport properties of water on cooling system size and on performance for an equal amount of heat rejection from both systems are as follows:

- a. Increase in condenser size and volumetric cooling water flow rate;
- b. Increase in cooling tower size to handle the increased cooling water flow rate;
- c. Increase in tower size to compensate for the decrease in tower efficiency due to the use of salt water.

The increase in flow rate results from changes in the density and specific heat of the salt water. Since, for the condenser:

$$Q = V_f d_f c_f \Delta T = V_s d_s c_s \Delta T$$

where

Q = Heat load, Btu/hour

ΔT = Temperature rise in condenser, °F

V = Volumetric flow of cooling water, ft³/hour

Subscripts:

f = fresh water

s = salt water

hence:

$$\frac{V_s}{V_f} = \frac{d_f c_f}{d_s c_s} = \frac{62.05 \times 0.998}{65.26 \times 0.922}$$

= 1.03, or a 3 percent increase in volumetric flow rate

The increase in condenser area results from the decrease of heat transfer coefficient in the condenser:

for

$$Q = U_f \left[(\Delta T)_{lm} \right] A_f = U_s \left[(\Delta T)_{lm} \right] A_s$$

where

U = Overall condenser heat transfer coefficient,

Btu/h-ft²-°F

$(\Delta T)_{lm}$ = Log mean temperature difference, °F

A = Condenser surface area, ft²

hence

$$\frac{A_s}{A_f} = \frac{U_f}{U_s}$$

The overall heat transfer coefficients, U_f and U_s , are approximately 505 Btu/h-ft²-°F and 461 Btu/h-ft²-°F for the typical conditions assumed.

Hence

$$\frac{A_s}{A_f} = \frac{505}{461} = 1.09, \text{ that is, an increase of 9 percent in condenser surface}$$

For a tower, the driving force for rejecting heat to the atmosphere is proportional to the enthalpy difference between the bulk of air flow through the tower and the saturated air at the water temperature. An average water temperature of 100°F has already been assumed. The average air temperature as the air passes through the tower will be assumed to be 87°F.

The decrease in efficiency of the salt water tower is:

$$\begin{aligned}\Delta \text{ Eff} &= \frac{[H(100)_f - H(87)_f] - [H(100)_s - H(87)_s]}{H(100)_f - H(87)_f} \\ &= \frac{(71.52 - 51.81) - (68.46 - 50.32)}{71.52 - 51.81} \\ &= 2.9 \text{ percent}\end{aligned}$$

This decreased tower efficiency, coupled with the increased flow, would require the use of larger cooling towers or more cells.

As far as capital cost is concerned, the following data can be used to estimate the increase in capital cost of a salt water cooling system as compared to that of a fresh water system of equal heat rejection capacity:

	<u>Approximate Increase in Capital Cost for Salt Water System (Including corrosion resistant materials, %)</u>
Cooling tower	5
Condenser	13
Pumps, piping, etc.	2

The most commonly used tube material for salt water service is 90-10 Cu-Ni. The difference in materials for circulating water pumps used in fresh and salt water services assumed in this study are given as follows:

Pump Parts	Material	
	Fresh Water	Salt Water
Bowls	Carbon Steel	SS316 or Ni-Resist 12% chrome cast iron
Impeller	Bronze	SS316
Column	Carbon Steel	SS316
Nozzle	Carbon Steel	SS316
Shaft	SS410	SS410

7.5 ABBREVIATIONS

The abbreviations of nomenclature used in Tables 7-1 thru 7-14 are defined as follows:

<u>Abbreviations</u>	<u>Definitions</u>
Col.	Colorado Site
C_t	Total evaluated cost of base Middletown system
ΔC_t	Difference in total evaluated cost compared to base Middletown system
DC Trans.	Transferred system with doubled capacity penalty charge rate
DE Opt.	Optimum system with doubled replacement energy cost
DE Trans.	Transferred system with doubled replacement energy cost
Fan Wet (or F)	Fan-assisted natural draft wet tower cooling system
Fla.	Florida Site
Mech. Wet (or M)	Mechanical draft wet tower cooling system
Midtn.	Middletown Site
Nat. Wet (or N)	Natural draft wet tower cooling system
Opt.	Optimum system
Trans.	Base transferred system i.e., the transferred system without cost escalation.

TABLE 7-1

INCREASE IN TOTAL EVALUATED COST DUE TO THE DOUBLING OF REPLACEMENT ENERGY COST ,
CAPACITY PENALTY CHARGE AND CAPITAL COST

Plant	Cooling System	C _t , \$10 ⁶ Base Middletown System	(Capital Cost)/ C _t , %	$\Delta C_t/C_t$, %					
				Middletown		Minimum (Colorado)		Maximum (Florida)	
				DE Trans.	DC Trans.	DE Trans.	DC Trans.	DE Trans.	DC Trans.
Fossil	Mech. Wet	29.07	55.18	22.84	17.20	13.14	3.23	54.11	34.64
	Fan Wet	31.59	65.37	16.14	13.45	8.29	1.74	40.96	27.29
	Nat. Wet	31.87	62.91	15.12	19.20	9.16	7.56	42.96	30.91
LWR	Mech. Wet	37.11	57.96	22.10	14.42	15.01	4.28	44.68	26.92
	Fan Wet	38.75	65.26	17.42	12.39	11.17	3.05	36.90	23.15
	Nat. Wet	36.64	63.62	16.92	16.59	10.18	5.79	40.17	26.86

Note: Abbreviations explained in Section 7.5

TABLE 7-2 (Sheet 1 of 3)

SUMMARY OF CAPITAL INVESTMENT, PENALTIES AND TOTAL EVALUATED COST FOR TRANSFERRED WET TOWER

SYSTEMS (\$10⁶) INTERFACED WITH 1000 MWe FOSSIL POWER PLANTS

A. Mechanical Wet Tower

Costs and Penalties	Base Middle- town System	Middletown		Colorado			Florida		
		DE Trans.	DC Trans.	Trans.	DE Trans.	DC Trans.	Trans.	DE Trans.	DC Trans.
Total Capital Investment	16.04	16.04	16.04	16.04	16.04	16.04	16.04	16.04	16.04
Capacity Penalty (Due to Highest Turbine Back Pressure)	3.53	3.53	7.06	1.76	1.76	3.52	3.87	3.87	7.74
Energy Replacement Penalty (Due to Turbine Back Pressure Variations)	2.46	4.92	2.46	1.92	3.84	1.92	6.87	13.74	6.87
Capitalized Annual Cost for Operating Cooling Water Pumps	3.83	6.67	4.82	3.83	6.67	4.82	3.83	6.67	4.82
Capitalized Annual Cost for Operating Terminal Heat Sink	1.82	3.16	2.30	1.83	3.18	2.31	1.77	3.06	2.25
Capitalized Annual Cost for Make-Up and Water Treatment	0.18	0.18	0.18	0.19	0.19	0.19	0.21	0.21	0.21
Capitalized Annual Operating and Maintenance Cost	1.21	1.21	1.21	1.21	1.21	1.21	1.21	1.21	1.21
Total Evaluated Cost	29.07	35.71	34.07	26.78	32.89	30.01	33.80	44.80	39.14

Note: Abbreviations explained in Section 7.5

TABLE 7-2 (Sheet 2)

SUMMARY OF CAPITAL INVESTMENT, PENALTIES AND TOTAL EVALUATED COST FOR TRANSFERRED WET TOWER

SYSTEMS (\$10⁶) INTERFACED WITH 1000 MWe FOSSIL POWER PLANTS

B. Fan-Assisted Wet Tower

Costs and Penalties	Base Middle- town System	Middletown		Colorado			Florida		
		DE Trans.	DC Trans.	Trans.	DE Trans.	DC Trans.	Trans.	DE Trans.	DC Trans.
Total Capital Investment	20.65	20.65	20.65	20.65	20.65	20.65	20.65	20.65	20.65
Capacity Penalty (Due to Highest Turbine Back Pressure)	2.78	2.78	5.56	1.14	1.14	2.28	3.07	3.07	6.14
Energy Replacement Penalty (Due to Turbine Back Pressure Variations)	1.14	2.28	1.14	0.72	1.44	0.72	4.90	9.80	4.90
Capitalized Annual Cost for Operating Cooling Water Pumps	3.39	5.90	4.27	3.39	5.90	4.27	3.39	5.90	4.27
Capitalized Annual Cost for Operating Terminal Heat Sink	2.04	3.49	2.63	2.04	3.49	2.63	2.04	3.49	2.63
Capitalized Annual Cost for Make-Up and Water Treatment	0.18	0.18	0.12	0.18	0.18	0.18	0.21	0.21	0.21
Capitalized Annual Operating and Maintenance Cost	1.41	1.41	1.41	1.41	1.41	1.41	1.41	1.41	1.41
Total Evaluated Cost	31.59	36.69	35.84	29.53	34.21	32.14	35.67	44.53	40.21

TABLE 7-2 (Sheet 3)

SUMMARY OF CAPITAL INVESTMENT, PENALTIES AND TOTAL EVALUATED COST FOR TRANSFERRED WET TOWER

SYSTEMS (\$10⁶) INTERFACED WITH 1000 MWe FOSSIL POWER PLANTSC. Natural Wet Tower

Costs and Penalties	Base Middle- town System	Middletown		Colorado			Florida		
		DE Trans.	DC Trans.	Trans.	DE Trans.	DC Trans.	Trans.	DE Trans.	DC Trans.
Total Capital Investment	20.05	20.05	20.05	20.05	20.05	20.05	20.05	20.05	20.05
Capacity Penalty (Due to Highest Turbine Back Pressure)	5.10	5.10	10.20	3.26	3.26	6.52	4.62	4.62	9.24
Energy Replacement Penalty (Due to Turbine Back Pressure Variations)	1.88	3.76	1.88	1.85	3.70	1.85	6.54	13.08	6.54
Capitalized Annual Cost for Operating Cooling Water Pumps	3.96	6.90	4.98	3.96	6.90	4.98	3.96	6.90	4.98
Capitalized Annual Cost for Operating Terminal Heat Sink	0	0	0	0	0	0	0	0	0
Capitalized Annual Cost for Make-Up and Water Treatment	0.18	0.18	0.18	0.18	0.18	0.18	0.21	0.21	0.21
Capitalized Annual Operating and Maintenance Cost	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70
Total Evaluated Cost	31.87	36.69	37.99	30.00	34.79	34.28	36.08	45.56	41.72

TABLE 7-3 (Sheet 1 of 3)

SUMMARY OF CAPITAL INVESTMENT, PENALTIES, AND TOTAL EVALUATED COST FOR TRANSFERRED WET TOWERSYSTEMS (\$10⁶) INTERFACED WITH 1000 MWe LWR POWER PLANTSA. Mechanical Wet Tower

Costs and Penalties	Base Middle- town System	Middletown		Colorado			Florida		
		DE Trans.	DC Trans.	Trans.	DE Trans.	DC Trans.	Trans.	DE Trans.	DC Trans.
Total Capital Investment	21.51	21.51	21.51	21.51	21.51	21.51	21.51	21.51	21.51
Capacity Penalty (Due to Highest Turbine Back Pressure)	3.37	3.37	6.74	1.74	1.74	3.48	3.66	3.66	7.32
Energy Replacement Penalty (Due to Turbine Back Pressure Variations)	2.56	5.12	2.56	2.05	4.10	2.05	6.66	13.32	6.66
Capitalized Annual Cost for Operating Cooling Water Pumps	5.05	8.80	6.35	5.05	8.80	6.35	5.05	8.80	6.35
Capitalized Annual Cost for Operating Terminal Heat Sink	2.57	4.46	3.25	2.58	4.48	3.26	2.50	4.32	3.18
Capitalized Annual Cost for Make-up and Water Treatment	0.32	0.32	0.32	0.32	0.32	0.32	0.35	0.35	0.35
Capitalized Annual Operating and Maintenance Cost	1.73	1.73	1.73	1.73	1.73	1.73	1.73	1.73	1.73
Total Evaluated Cost	37.11	45.31	42.46	34.98	42.68	38.70	41.46	53.69	47.10

Note: Abbreviations explained in Section 7.5

TABLE 7-3 (Sheet 2)

SUMMARY OF CAPITAL INVESTMENT, PENALTIES, AND TOTAL EVALUATED COST FOR TRANSFERRED WET TOWERSYSTEMS (\$10⁶) INTERFACED WITH 1000 MWe LWR POWER PLANTSB. Fan-Assisted Wet Tower

Costs and Penalties	Base Middle- town System	Middletown		Colorado			Florida		
		DE Trans.	DC Trans.	Trans.	DE Trans.	DC Trans.	Trans.	DE Trans.	DC Trans.
Total Capital Investment	25.29	25.29	25.29	25.29	25.29	25.29	25.29	25.29	25.29
Capacity Penalty (Due to Highest Turbine Back Pressure	2.90	2.90	5.80	1.29	1.29	2.58	3.15	3.15	6.30
Energy Replacement Penalty (Due to Turbine Back Pressure Variations)	1.57	3.14	1.57	1.16	2.32	1.16	5.20	10.40	5.20
Capitalized Annual Cost for Operating Cooling Water Pumps	4.49	7.82	5.65	4.49	7.82	5.65	4.49	7.82	5.65
Capitalized Annual Cost for Operating Terminal Heat Sink	2.59	4.44	3.33	2.59	4.44	3.33	2.59	4.44	3.33
Capitalized Annual Cost for Make-Up and Water Treatment	0.31	0.31	0.31	0.32	0.32	0.32	0.35	0.35	0.35
Capitalized Annual Operating and Maintenance Cost	1.60	1.60	1.60	1.60	1.60	1.60	1.60	1.60	1.60
Total Evaluated Cost	38.75	45.50	43.55	36.74	43.08	39.93	42.67	53.05	47.72

TABLE 7-3 (Sheet 3)

SUMMARY OF CAPITAL INVESTMENT, PENALTIES, AND TOTAL EVALUATED COST FOR TRANSFERRED WET TOWERSYSTEMS (\$10⁶) INTERFACED WITH 1000 MWe LWR POWER PLANTSC. Natural Wet Tower

Costs and Penalties	Base Middle- town System	Middletown		Colorado			Florida		
		DE Trans.	DC Trans.	Trans.	DE Trans.	DC Trans.	Trans.	DE Trans.	DC Trans.
Total Capital Investment	23.31	23.31	23.31	23.31	23.31	23.31	23.31	23.31	23.31
Capacity Penalty (Due to Highest Turbine Back Pressure)	4.69	4.69	9.38	2.87	2.87	5.74	4.34	4.34	8.68
Energy Replacement Penalty (Due to Turbine Back Pressure Variations)	2.20	4.40	2.20	1.85	3.70	1.85	6.59	13.18	6.59
Capitalized Annual Cost for Operating Cooling Water Pumps	5.39	9.39	6.78	5.41	9.43	6.80	5.41	9.43	6.80
Capitalized Annual Cost for Operating Terminal Heat Sink	0	0	0	0	0	0	0	0	0
Capitalized Annual Cost for Make-Up and Water Treatment	0.31	0.31	0.31	0.32	0.32	0.32	0.36	0.36	0.36
Capitalized Annual Operating and Maintenance Cost	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74
Total Evaluated Cost	36.64	42.84	42.72	34.50	40.37	38.76	40.75	51.36	46.48

TABLE 7-4 * (Sheet 1 of 4)
RECOMMENDED COOLING SYSTEM--TYPE AND TOTAL EVALUATED COST (\$10⁶)

CAPACITY PENALTY CHARGE: 1X

PLANT	Replace- ment Energy Cost Site	1X			2X			3X			4X		
	Capital	Midtn.	Col.	Fla.	Midtn.	Col.	Fla.	Midtn.	Col.	Fla.	Midtn.	Col.	Fla.
Fossil	1X	M	M	M	M	M	F	F	M	F	N	F	F
	1½X	29.07	26.34	32.95	35.71	32.89	44.53	41.79	36.71	57.47	46.33	39.45	70.41
	2X	M	M	M	M	M	M	M	M	F	N	M	F
LWR	1X	37.09	34.80	41.82	43.73	40.91	52.82	50.37	44.73	67.79	56.36	48.55	80.74
	1½X	M	M	M	M	M	M	M	M	M	M	M	F
	2X	45.11	42.82	49.84	51.75	48.93	60.84	58.39	52.75	76.57	65.03	56.57	91.07
LWR	1X	N	N	N	N	N	N	N	N	N	N	N	N
	1½X	36.64	34.30	40.44	42.84	40.37	51.36	49.04	44.10	66.07	55.24	47.83	80.79
	2X	M	M	M	N	N	N	N	N	N	N	N	N
		47.87	45.74	52.22	54.49	52.02	63.01	60.69	55.75	77.73	66.90	59.49	92.45
		M	M	M	N	N	N	N	N	N	N	N	N
		58.62	56.49	62.97	66.15	63.68	74.67	72.35	67.41	89.39	78.56	71.15	104.11

* Symbols identified on sheet 4

TABLE 7-4 (Sheet 2)
RECOMMENDED COOLING SYSTEM--TYPE AND TOTAL EVALUATED COST (\$10⁶)

CAPACITY PENALTY CHARGE: 2X

PLANT	Replacement Energy Cost	1X			2X			3X			4X		
	Site												
	Capital	Midtn.	Col.	Fla.	Midtn.	Col.	Fla.	Midtn.	Col.	Fla.	Midtn.	Col.	Fla.
Fossil	1X	M 34.07	M 30.01	M 39.14	M 40.71	M 33.83	F 53.15	F 46.04	F 37.38	F 66.09	F 51.13	F 40.00	F 79.03
	1½X	M 42.09	M 38.03	M 47.16	M 48.73	M 41.85	M 62.89	M 55.37	M 45.67	F 76.41	F 61.55	M 49.49	F 89.36
	2X	M 50.11	M 46.05	M 55.18	M 56.75	M 49.81	M 70.91	M 63.39	M 53.69	M 86.64	M 70.03	M 57.51	F 99.68
LWR	1X	M 42.46	M 38.70	N 46.48	N 48.92	N 42.49	N 61.20	N 55.12	N 46.22	N 75.91	N 61.31	N 49.95	F 90.62
	1½X	M 53.22	M 49.45	M 57.86	N 60.57	N 54.08	N 72.85	N 66.77	N 57.88	N 87.57	N 72.97	N 61.60	N 102.30
	2X	M 63.97	M 60.21	M 68.61	M 72.17	M 65.78	N 84.51	N 78.43	N 69.53	N 99.23	N 84.62	N 73.26	N 113.95

TABLE 7-4 (Sheet 3)
RECOMMENDED COOLING SYSTEM--TYPE AND TOTAL EVALUATED COST (\$10⁶)

CAPACITY PENALTY CHARGE: 3X

PLANT	Replacement Energy Cost	1X			2X			3X			4X		
	Site	Midtn.	Col.	Fla.	Midtn.	Col.	Fla.	Midtn.	Col.	Fla.	Midtn.	Col.	Fla.
	Capital												
Fossil	1X	M	M	F	F	M	F	F	F	F	F	F	F
	1½X	39.07	30.95	48.83	45.30	34.77	61.77	50.28	37.93	74.71	55.38	40.55	87.65
	2X	M	M	M	M	M	F	M	M	F	M	M	F
LWR	1X	47.81	40.29	56.32	55.00	44.61	70.99	61.20	48.34	85.29	67.40	52.07	99.59
	1½X	M	M	M	N	N	N	N	N	N	N	N	N
	2X	58.56	51.04	67.84	66.66	52.26	82.70	72.86	60.00	97.40	79.06	63.73	112.14
LWR	1X	M	M	M	M	M	N	N	N	N	N	N	N
	1½X	63.23	61.80	78.60	77.52	67.26	94.35	84.51	71.65	109.06	90.71	75.39	121.80
	2X	M	M	M	M	M	N	N	N	N	N	N	N

TABLE 7-4 (Sheet 4)
RECOMMENDED COOLING SYSTEM -- TYPE AND TOTAL EVALUATED COST (\$10⁶)

SYMBOLS

Cooling System:

M (Mech. Wet) = Mechanical Draft Wet Tower System

F (Fan Wet) = Fan-Assisted Natural Draft Wet Tower System

N (Nat. Wet) = Natural Draft Wet Tower System

Site: Midtn. = Middletown Reference Site

Fla. = Miami, Florida

Col. = Denver, Colorado

Definitions of 1X, 2X, 3X, etc. :

1X = Basic rate or cost

2X, 3X, etc. = Multiples of the basic rate of cost (e.g. 2X= twice the basic rate or cost)

Basic Rates and Costs:

1) Basic Capacity Penalty Charge = \$150 per kW

2) Basic Replacement Energy Cost = 8.5 mills per kWh

3) Basic Capital Costs:

Plant	Cooling System	Capital Costs (\$10 ⁶)
Fossil	Mech. Wet	16.04
	Fan Wet	20.65
	Nat. Wet	20.05
LWR	Mech. Wet	21.51
	Fan Wet	25.29
	Nat. Wet	23.31

TABLE 7-5
OVERALL COMPARISON OF THE TRANSFERRED
AND OPTIMUM WET TOWER SYSTEMS AS
AFFECTED BY GEOGRAPHIC LOCATION

Plant	Cooling System	Ct, \$10 ⁶	$(\Delta C_t) / C_t, \%$			
			Colorado (Minimum)		Florida (Maximum)	
			Trans.	Opt.	Trans.	Opt.
Fossil	Mech. Wet	29.07	-7.88	-9.39	16.27	13.34
	Fan Wet	31.59	-6.52	-7.69	12.92	12.25
	Nat. Wet	31.87	-5.87	-7.00	13.21	12.83
LWR	Mech. Wet	37.11	-5.74	-6.87	11.72	11.29
	Fan Wet	38.75	-5.19	-6.30	10.12	8.65
	Nat. Wet	36.64	-5.84	-6.39	11.22	10.37

Note: Abbreviations explained in Section 7.5

TABLE 7-6 (Sheet 1 of 3)

DETAILED COMPARISON OF COSTS AND PENALTIES (IN \$10⁶) BETWEEN THE
TRANSFERRED AND OPTIMUM WET TOWER SYSTEMS AS AFFECTED BY
GEOGRAPHIC LOCATION ONLY--1000 MWe FOSSIL POWER PLANT

A. Mechanical Wet

Costs and Penalties	Base Middletown System	Colorado		Florida	
		Trans.	Opt.	Trans.	Opt.
Total Capital Investment	16.04	16.04	15.74	16.04	17.99
Capacity Penalty (Due to Highest Turbine Back Pressure)	3.53	1.76	1.78	3.87	2.60
Energy Replacement Penalty (Due to Turbine Back Pressure Variations)	2.46	1.92	1.86	6.87	4.32
Capitalized Annual Cost for Operating Cooling Water Pumps	3.83	3.83	3.47	3.83	4.30
Capitalized Annual Cost for Operating Terminal Heat Sink	1.82	1.83	1.99	1.77	2.11
Capitalized Annual Cost for Make-Up and Water Treatment	0.18	0.19	0.19	0.21	0.21
Capitalized Annual Operating and Maintenance Cost	1.21	1.21	1.31	1.21	1.42
Total Evaluated Cost, C _t	29.07	26.78	26.34	33.80	32.95

Note: Abbreviations explained in Section 7.5.

TABLE 7-6 (Sheet 2)
DETAILED COMPARISON OF COSTS AND PENALTIES (IN \$10⁶) BETWEEN THE
TRANSFERRED AND OPTIMUM WET TOWER SYSTEMS AS AFFECTED BY
GEOGRAPHIC LOCATION ONLY--1000 MWe FOSSIL POWER PLANT

B. Fan-Assisted Wet

Costs and Penalties	Base Middletown System	Colorado		Florida	
		Trans.	Opt.	Trans.	Opt.
Total Capital Investment	20.65	20.65	19.72	20.65	20.97
Capacity Penalty (Due to Highest Turbine Back Pressure)	2.78	1.14	1.60	3.07	2.84
Energy Replacement Penalty (Due to Turbine Back Pressure Variations)	1.14	0.72	1.34	4.90	4.49
Capitalized Annual Cost for Operating Cooling Water Pumps	3.39	3.39	3.18	3.39	3.45
Capitalized Annual Cost for Operating Terminal Heat Sink	2.04	2.04	1.80	2.04	2.08
Capitalized Annual Cost for Make-Up and Water Treatment	0.18	0.18	0.19	0.21	0.21
Capitalized Annual Operating and Maintenance Cost	1.41	1.41	1.33	1.41	1.42
Total Evaluated Cost, C_t	31.59	29.53	29.16	35.67	35.46

TABLE 7-6 (Sheet 3)
DETAILED COMPARISON OF COSTS AND PENALTIES (IN \$10⁶) BETWEEN THE
TRANSFERRED AND OPTIMUM WET TOWER SYSTEMS AS AFFECTED BY
GEOGRAPHIC LOCATION ONLY--1000 MWe FOSSIL POWER PLANT

C. Natural Wet

Costs and Penalties	Base Middletown System	Colorado		Florida	
		Trans.	Opt.	Trans.	Opt.
Total Capital Investment	20.05	20.05	19.64	20.05	21.57
Capacity Penalty (Due to Highest Turbine Back Pressure)	5.10	3.26	3.37	4.62	3.96
Energy Replacement Penalty (Due to Turbine Back Pressure Variations)	1.88	1.85	2.05	6.54	5.42
Capitalized Annual Cost for Operating Cooling Water Pumps	3.96	3.96	3.72	3.96	4.06
Capitalized Annual Cost for Operating Terminal Heat Sink	0	0	0	0	0
Capitalized Annual Cost for Make-Up and Water Treatment	0.18	0.18	0.19	0.21	0.21
Capitalized Annual Operating and Maintenance Cost	0.70	0.70	0.67	0.70	0.74
Total Evaluated Cost, C_t	31.87	30.00	29.64	36.08	35.96

TABLE 7-7 (Sheet 1 of 3)

DETAILED COMPARISON OF COSTS AND PENALTIES (IN \$10⁶) BETWEEN THE
TRANSFERRED AND OPTIMUM WET TOWER SYSTEMS AS AFFECTED BY
GEOGRAPHIC LOCATION ONLY--1000 MWe LWR POWER PLANT

A. Mechanical Wet

Costs and Penalties	Base Middletown System	Colorado		Florida	
		Trans.	Opt.	Trans.	Opt.
Total Capital Investment	21.51	21.51	21.09	21.51	23.87
Capacity Penalty (Due to Highest Turbine Back Pressure)	3.37	1.74	1.83	3.66	2.48
Energy Replacement Penalty (Due to Turbine Back Pressure Variations)	2.56	2.05	2.18	6.66	4.15
Capitalized Annual Cost for Operating Cooling Water Pumps	5.05	5.05	5.06	5.05	5.52
Capitalized Annual Cost for Operating Terminal Heat Sink	2.57	2.58	2.45	2.50	2.94
Capitalized Annual Cost for Make-Up and Water Treatment	0.32	0.32	0.32	0.35	0.35
Capitalized Annual Operating and Maintenance Cost	1.73	1.73	1.63	1.73	1.99
Total Evaluated Cost, C _t	37.11	34.98	34.56	41.46	41.30

Note: Abbreviations explained in Section 7.5.

TABLE 7-7 (Sheet 2)
DETAILED COMPARISON OF COSTS AND PENALTIES (IN \$10⁶) BETWEEN THE
TRANSFERRED AND OPTIMUM WET TOWER SYSTEMS AS AFFECTED BY
GEOGRAPHIC LOCATION ONLY--1000 MWe LWR POWER PLANT

B. Fan-Assisted Wet

Costs and Penalties	Base Middletown System	Colorado		Florida	
		Trans.	Opt.	Trans.	Opt.
Total Capital Investment	25.29	25.29	23.78	25.29	24.98
Capacity Penalty (Due to Highest Turbine Back Pressure)	2.90	1.29	2.03	3.15	2.97
Energy Replacement Penalty (Due to Turbine Back Pressure Variations)	1.57	1.16	2.00	5.20	4.87
Capitalized Annual Cost for Operating Cooling Water Pumps	4.49	4.49	4.00	4.49	4.74
Capitalized Annual Cost for Operating Terminal Heat Sink	2.59	2.59	2.58	2.59	2.59
Capitalized Annual Cost for Make-Up and Water Treatment	0.31	0.32	0.32	0.35	0.35
Capitalized Annual Operating and Maintenance Cost	1.60	1.60	1.60	1.60	1.60
Total Evaluated Cost, C_t	38.75	36.74	36.31	42.67	42.10

TABLE 7-7 (Sheet 3)

DETAILED COMPARISON OF COSTS AND PENALTIES (IN \$10⁶) BETWEEN THE
TRANSFERRED AND OPTIMUM WET TOWER SYSTEMS AS AFFECTED BY
GEOGRAPHIC LOCATION ONLY--1000 MWe LWR POWER PLANT

C. Natural Wet

Costs and Penalties	Base Middletown System	Colorado		Florida	
		Trans.	Opt.	Trans.	Opt.
Total Capital Investment	23.31	23.31	22.39	23.31	24.52
Capacity Penalty (Due to Highest Turbine Back Pressure)	4.69	2.87	3.51	4.34	3.79
Energy Replacement Penalty (Due to Turbine Back Pressure Variations)	2.20	1.85	2.54	6.59	5.48
Capitalized Annual Cost for Operating Cooling Water Pumps	5.39	5.41	4.81	5.41	5.53
Capitalized Annual Cost for Operating Terminal Heat Sink	0	0	0	0	0
Capitalized Annual Cost for Make-Up and Water Treatment	0.31	0.32	0.32	0.36	0.34
Capitalized Annual Operating and Maintenance Cost	0.74	0.74	0.73	0.74	0.78
Total Evaluated Cost, C_t	36.64	34.50	34.30	40.75	40.44

TABLE 7-8 (Sheet 1 of 2)

SUMMARY OF DESIGN CONDITIONS FOR OPTIMIZED COOLING SYSTEMS FOR 1000 MWe FOSSIL POWER PLANT

Base Plant Conditions: Plant Capacity = 1043 MWe; Heat Rate=7365 Btu/kWh, Exhaust Pressure = 1.5 In-Hg

Item	Mech. Wet			Fan Wet			Nat. Wet		
	Midtn.	Col.	Fla.	Midtn.	Col.	Fla.	Midtn.	Col.	Fla.
<u>General</u>									
Dry Bulb Temperature, °F	93.0	92.0	92.0	93.0	92.0	92.0	93.0	92.0	92.0
Wet Bulb Temperature, °F	74.0	60.0	77.0	74.0	60.0	77.0	74.0	60.0	77.0
Design Cold Water Temperature, °F	90.0	80.0	90.0	84.0	78.0	86.0	90.0	86.0	89.0
Design Approach, °F	16.0	20.0	13.0	10.0	18.0	9.0	16.0	26.0	12.0
Design Range, °F	21.0	24.0	18.0	24.0	25.0	23.0	24.0	25.0	24.0
Plant Capacity at Cooling System Design Point, MWe	1020	1031	1025	1026	1032	1024	1014	1020	1017
Design Turbine Back Pressure, In-Hg	3.17	2.60	2.91	2.91	2.52	2.99	3.45	3.17	3.35
Maximum Turbine Back Pressure, In-Hg	3.22	2.60	2.91	2.98	2.52	3.00	3.66	3.17	3.35
Design Heat Load, 10 ⁹ Btu/hr	4.20	4.16	4.18	4.18	4.16	4.19	4.22	4.20	4.21
<u>Condenser</u>									
Surface Area, 10 ³ sq ft	627	601	672	595	594	604	590	581	591
Number of Tubes, 10 ³	53.8	46.7	62.5	46.9	44.8	49.0	47.3	45.2	47.2
Tube Length, ft	44.5	49.2	41.1	48.4	50.6	47.1	47.7	49.1	47.8

Note: Abbreviations explained in Section 7.5

TABLE 7-8 (Sheet 2)

SUMMARY OF DESIGN CONDITIONS FOR OPTIMIZED COOLING SYSTEMS FOR 1000 MWe FOSSIL POWER PLANT

Item	Mech. Wet			Fan Wet			Nat. Wet		
	Midtn.	Col.	Fla.	Midtn.	Col.	Fla.	Midtn.	Col.	Fla.
<u>Cooling Water Pump</u>									
Circulating Water Flow Rate, 10^3 gpm	400	347	464	348	333	364	352	336	351
Number of Pumps	3	2	3	2	2	3	2	2	2
Pumping Head, ft. of Water	78.1	81.5	75.4	79.2	77.8	77.2	91.6	90.2	94.3
Pumping Power Requirement, bhp/pump	2952	4009	3313	3915	3671	2659	4570	4300	4696
Rated Pump Motor Size, hp/pump motor	3500	4500	4000	4500	4000	3000	5000	5000	5000
<u>Terminal Heat Sink</u>									
Total Power Requirement, 10^3 bhp	4.28	4.76	5.09	5.24	41.63	5.33	--	--	--
Terminal Heat Sink Size: Number of Cells	23	25	27	--	--	--	--	--	--
Tower: Number of Towers	--	--	--	2	2	2	1	1	1
Base Diameter, ft	--	--	--	221	212	228	385	371	411
Tower Height, ft	--	--	--	250	250	250	500	481	532
Fan: Number of Fans/Tower	--	--	--	20	20	20	--	--	--
Fan Diameter, ft	28	28	28	28	26	28	--	--	--

TABLE 7-9 (Sheet 1 of 2)

SUMMARY OF DESIGN CONDITIONS FOR OPTIMIZED COOLING SYSTEMS FOR 1000 MWe LWR POWER PLANT

Base Plant Conditions: Plant Capacity = 1096 MWe; Heat Rate=9760 Btu/kWh, Exhaust Pressure = 1.5 In-Hg

Item	Mech. Wet			Fan Wet			Nat. Wet		
	Midtn.	Col.	Fla.	Midtn.	Col.	Fla.	Midtn.	Col.	Fla.
<u>General</u>									
Dry Bulb Temperature, °F	93.0	92.0	92.0	93.0	96.0	92.0	93.0	92.0	92.0
Wet Bulb Temperature, °F	74.0	60.0	77.0	74.0	60.0	77.0	74.0	60.0	77.0
Design Cold Water Temperature, °F	91.0	85.0	91.0	87.0	78.0	89.0	92.0	86.0	91.0
Design Approach, °F	17.0	25.0	14.0	13.0	18.0	12.0	18.0	26.0	14.0
Design Range, °F	27.0	27.0	24.0	29.0	35.0	28.0	29.0	33.0	29.0
Plant Capacity at Cooling System Design Point, MWe	1075	1084	1080	1078	1083	1077	1069	1073	1071
Design Turbine Back Pressure, In-Hg	3.85	3.26	3.54	3.64	3.35	3.74	4.17	3.95	4.06
Maximum Turbine Back Pressure, In-Hg	3.90	3.26	3.54	3.71	3.35	3.74	4.39	3.95	4.06
Design Heat Load, 10 ⁹ Btu/hr	7.03	7.00	7.02	7.02	7.01	7.03	7.05	7.04	7.06
<u>Condenser</u>									
Surface Area, 10 ³ sq ft	925	935	980	898	836	911	892	842	893
Number of Tubes, 10 ³	70.1	69.8	78.7	65.2	53.9	67.6	65.5	57.0	65.4
Tube Length, ft	50.4	51.1	47.6	52.6	59.3	51.5	52.0	56.0	51.1

Note: Abbreviations explained in Section 7.5

TABLE 7-9 (Sheet 2)

SUMMARY OF DESIGN CONDITIONS FOR OPTIMIZED COOLING SYSTEMS FOR 1000 MWe LWR POWER PLANT

Item	Mech. Wet			Fan Wet			Nat. Wet		
	Midtn.	Col.	Fla.	Midtn.	Col.	Fla.	Midtn.	Col.	Fla.
<u>Cooling Water Pump</u>									
Circulating Water Flow Rate, 10^3 gpm	521	519	585	484	400	502	486	427	486
Number of Pumps	3	3	4	3	3	3	3	3	3
Pumping Head, ft. of Water	79	79.5	76.9	75.6	81.4	77.0	90.4	91.8	92.7
Pumping Power Requirement, bhp/pump	3892	3901	3188	3462	3081	3657	4153	3703	4258
Rated Pump Motor Size, hp/pump motor	4500	4500	3500	4000	3500	4000	4500	4000	5000
<u>Terminal Heat Sink</u>									
Total Power Requirement, 10^3 bhp	6.07	5.86	7.09	6.66	6.62	6.66	--	--	--
Terminal Heat Sink Size:									
Number of Cells	33	31	38	--	--	--	--	--	--
Tower: Number of Towers	--	--	--	2	2	2	1	1	1
Base Diameter, ft	--	--	--	257	257	257	407	403	429
Tower Height, ft	--	--	--	250	250	250	527	522	556
Fan: Number of Fans/Tower	--	--	--	24	24	24	--	--	--
Fan Diameter, ft	28	28	28	28	28	28	--	--	--

TABLE 7-10

OVERALL COMPARISON BETWEEN TRANSFERRED AND OPTIMUM SYSTEMS WITH DOUBLED REPLACEMENT ENERGY COST

Plant	Cooling System	$C_t, \$10^6$ Base Middletown System	$\Delta C_t / C_t, \%$					
			Middletown		Colorado		Florida	
			DE Trans.	DE Opt.	DE Trans.	DE Opt.	DE Trans.	DE Opt.
Fossil	Mech. Wet	29.07	22.84	20.40	13.14	10.11	54.11	43.82
	Fan Wet	31.59	16.14	15.42	8.29	7.66	40.96	38.18
	Nat. Wet	31.87	15.12	14.68	9.16	6.24	42.96	36.81
LWR	Mech. Wet	37.11	22.10	21.93	15.01	13.15	44.68	38.70
	Fan Wet	38.75	17.42	16.83	11.17	8.67	36.90	34.30
	Nat. Wet	36.64	16.92	15.67	10.18	8.49	40.17	32.86

Note: Abbreviations explained in Section 7.5

TABLE 7-11 (Sheet 1 of 3)

DETAILED COMPARISON OF COSTS AND PENALTIES (IN \$10⁶) BETWEEN THE
TRANSFERRED AND OPTIMUM WET TOWER SYSTEMS AS AFFECTED BY DOUBLED
REPLACEMENT ENERGY COST AND GEOGRAPHIC LOCATION
1000 MWe FOSSIL POWER PLANT

A. Mechanical Wet

Costs and Penalties	Base Middletown System	Middletown		Colorado		Florida	
		DE Trans.	DE Opt.	DE Trans.	DE Opt.	DE Trans.	DE Opt.
Total Capital Investment	16.04	16.04	17.22	16.04	16.50	16.04	18.66
Capacity Penalty (Due to Highest Turbine Back Pressure)	3.53	3.53	2.74	1.76	1.43	3.87	2.38
Energy Replacement Penalty (Due to Turbine Back Pressure Variations)	2.46	4.92	2.99	3.84	2.63	13.74	7.56
Capitalized Annual Cost for Operating Cooling Water Pumps	3.83	6.67	6.83	6.67	5.95	6.67	8.83
Capitalized Annual Cost for Operating Terminal Heat Sink	1.82	3.16	3.62	3.18	3.84	3.06	4.44
Capitalized Annual Cost for Make-Up and Water Treatment	0.18	0.18	0.18	0.19	0.19	0.21	0.21
Capitalized Annual Operating and Maintenance Cost	1.21	1.21	1.42	1.21	1.47	1.21	1.73
Total Evaluated Cost, C_t	29.07	35.71	35.00	32.89	32.01	44.80	41.81

Note: Abbreviations explained in Section 7.5

TABLE 7-11 (Sheet 2)
DETAILED COMPARISON OF COSTS AND PENALTIES (IN \$10⁶) BETWEEN THE
TRANSFERRED AND OPTIMUM WET TOWER SYSTEMS AS AFFECTED BY DOUBLED
REPLACEMENT ENERGY COST AND GEOGRAPHIC LOCATION
1000 MWe FOSSIL POWER PLANT

B. Fan Assisted Wet

Costs and Penalties	Base Middletown System	Middletown		Colorado		Florida	
		DE Trans.	DE Opt.	DE Trans.	DE Opt.	DE Trans.	DE Opt.
Total Capital Investment	20.65	20.65	20.50	20.65	19.96	20.65	21.29
Capacity Penalty (Due to Highest Turbine Back Pressure)	2.78	2.78	2.78	1.14	1.43	3.07	2.60
Energy Replacement Penalty (Due to Turbine Back Pressure Variations)	1.14	2.28	2.30	1.44	2.18	9.80	8.16
Capitalized Annual Cost for Operating Cooling Water Pumps	3.39	5.90	5.80	5.90	5.52	5.90	6.48
Capitalized Annual Cost for Operating Terminal Heat Sink	2.04	3.49	3.49	3.49	3.35	3.49	3.50
Capitalized Annual Cost for Make-up and Water Treatment	0.18	0.18	0.18	0.18	0.19	0.21	0.21
Capitalized Annual Operating and Maintenance Cost	1.41	1.41	1.41	1.41	1.38	1.41	1.41
Total Evaluated Cost, C_t	31.59	36.69	36.46	34.21	34.01	44.53	43.65

TABLE 7-11 (Sheet 3)

DETAILED COMPARISON OF COSTS AND PENALTIES (IN \$10⁶) BETWEEN THE
TRANSFERRED AND OPTIMUM WET TOWER SYSTEMS AS AFFECTED BY DOUBLED
REPLACEMENT ENERGY COST AND GEOGRAPHIC LOCATION
1000 MWe FOSSIL POWER PLANT

C. Natural Wet

Costs and Penalties	Base Middletown System	Middletown		Colorado		Florida	
		DE Trans.	DE Opt.	DE Trans.	DE Opt.	DE Trans.	DE Opt.
Total Capital Investment	20.05	20.05	21.66	20.05	20.30	20.05	23.60
Capacity Penalty (Due to Highest Turbine Back Pressure)	5.10	5.10	4.39	3.26	3.10	4.62	3.10
Energy Replacement Penalty (Due to Turbine Back Pressure Variations)	1.88	3.76	2.61	3.70	3.37	13.08	7.92
Capitalized Annual Cost for Operating Cooling Water Pumps	3.96	6.90	6.97	6.40	6.20	6.90	7.99
Capitalized Annual Cost for Operating Terminal Heat Sink	0	0	0	0	0	0	0
Capitalized Annual Cost for Make-Up and Water Treatment	0.18	0.18	0.18	0.18	0.18	0.21	0.21
Capitalized Annual Operating and Maintenance Cost	0.70	0.70	0.74	0.70	0.71	0.70	0.78
Total Evaluated Cost, C_t	31.87	36.69	36.55	34.79	33.86	45.56	43.60

TABLE 7-12 (Sheet 1 of 3)

DETAILED COMPARISON OF COSTS AND PENALTIES (IN \$10⁶) BETWEEN THE
TRANSFERRED AND OPTIMUM WET TOWER SYSTEMS AS AFFECTED BY DOUBLED
REPLACEMENT ENERGY COST AND GEOGRAPHIC LOCATION
1000 MWe LWR POWER PLANT

A. Mechanical Wet

Costs and Penalties	Base Middletown System	Middletown		Colorado		Florida	
		DE Trans	DE Opt.	DE Trans	DE Opt.	DE Trans	DE Opt.
Total Capital Investment	21.51	21.51	22.68	21.51	21.80	21.51	23.87
Capacity Penalty (Due to Highest Turbine Back Pressure)	3.37	3.37	2.84	1.74	1.46	3.66	2.48
Energy Replacement Penalty (Due to Turbine Back Pressure Variations)	2.56	5.12	3.82	4.10	3.27	13.32	8.30
Capitalized Annual Cost for Operating Cooling Water Pumps	5.05	8.80	8.95	8.80	8.97	8.80	9.45
Capitalized Annual Cost for Operating Terminal Heat Sink	2.57	4.46	4.76	4.48	4.47	4.32	5.03
Capitalized Annual Cost for Make-Up and Water Treatment	0.32	0.32	0.31	0.32	0.32	0.35	0.35
Capitalized Annual Operating and Maintenance Cost	1.73	1.73	1.89	1.73	1.73	1.73	1.99
Total Evaluated Cost, C_t	37.11	45.31	45.25	42.68	41.99	53.69	51.47

Note: Abbreviations explained in Section 7.5

TABLE 7-12 (Sheet 2)

DETAILED COMPARISON OF COSTS AND PENALTIES (IN \$10⁶) BETWEEN THE
TRANSFERRED AND OPTIMUM WET TOWER SYSTEMS AS AFFECTED BY DOUBLED
REPLACEMENT ENERGY COST AND GEOGRAPHIC LOCATION
1000 MWe LWR POWER PLANT

B. Fan-Assisted Wet

Costs and Penalties	Base Middletown System	Middletown		Colorado		Florida	
		DE Trans.	DE Opt.	DE Trans.	DE Opt.	DE Trans.	DE Opt.
Total Capital Investment	25.29	25.29	24.25	25.29	24.34	25.29	24.95
Capacity Penalty (Due to Highest Turbine Back Pressure)	2.90	2.90	3.43	1.29	1.64	3.15	2.97
Energy Replacement Penalty (Due to Turbine Back Pressure Variations)	1.57	3.14	4.01	2.32	3.08	10.40	9.73
Capitalized Annual Cost for Operating Cooling Water Pumps	4.49	7.82	7.24	7.82	7.30	7.82	8.00
Capitalized Annual Cost for Operating Terminal Heat Sink	2.59	4.44	4.43	4.44	4.43	4.44	4.44
Capitalized Annual Cost for Make-up and Water Treatment	0.31	0.31	0.31	0.32	0.32	0.35	0.35
Capitalized Annual Operating and Maintenance Cost	1.60	1.60	1.60	1.60	1.60	1.60	1.60
Total Evaluated Cost, C_t	38.75	45.50	45.27	43.08	42.11	53.05	52.04

TABLE 7-12 (Sheet 3)

DETAILED COMPARISON OF COSTS AND PENALTIES (IN \$10⁶) BETWEEN THE
 TRANSFERRED AND OPTIMUM WET TOWER SYSTEMS AS AFFECTED BY DOUBLED
REPLACEMENT ENERGY COST AND GEOGRAPHIC LOCATION
1000 MWe LWR POWER PLANT

C. Natural Wet

Costs and Penalties	Base Middletown System	Middletown		Colorado		Florida	
		DE Trans.	DE Opt.	DE Trans.	DE Opt.	DE Trans.	DE Opt.
Total Capital Investment	23.31	23.31	24.04	23.31	23.72	23.31	26.60
Capacity Penalty (Due to Highest Turbine Back Pressure)	4.69	4.69	4.37	2.87	2.97	4.34	2.97
Energy Replacement Penalty (Due to Turbine Back Pressure Variations)	2.20	4.40	3.75	3.70	3.73	13.18	7.82
Capitalized Annual Cost for Operating Cooling Water Pumps	5.39	9.39	9.14	9.43	8.18	9.43	10.10
Capitalized Annual Cost for Operating Terminal Heat Sink	0	0	0	0	0	0	0
Capitalized Annual Cost for Make-Up and Water Treatment	0.31	0.31	0.31	0.32	0.31	0.32	0.35
Capitalized Annual Operating and Maintenance Cost	0.74	0.74	0.77	0.74	0.84	0.74	0.84
Total Evaluated Cost, C _t	36.64	42.84	42.38	40.37	39.75	51.36	48.68

TABLE 7-13 (Sheet 1 of 2)

SUMMARY OF DESIGN CONDITIONS FOR OPTIMUM COOLING SYSTEMS WITH DOUBLE ENERGY REPLACEMENT COST
1000 MWe FOSSIL POWER PLANT

Base Plant Conditions: Plant Capacity = 1043 MWe; Heat Rate=7365 Btu/kWh, Exhaust Pressure = 1.5 In-Hg

Item	Mech. Wet			Fan Wet			Nat. Wet		
	Midtn.	Col.	Fla.	Midtn.	Col.	Fla.	Midtn.	Col.	Fla.
<u>General</u>									
Dry Bulb Temperature, °F	93.0	92.0	92.0	93.0	92.0	92.0	93.0	92.0	92.0
Wet Bulb Temperature, °F	74.0	60.0	77.0	74.0	60.0	77.0	74.0	60.0	77.0
Design Cold Water Temperature, °F	88.0	78.0	87.0	84.0	76.0	87.0	88.0	83.0	89.0
Design Approach, °F	14.0	18.0	10.0	10.0	16.0	10.0	14.0	23.0	12.0
Design Range, °F	20.0	24.0	20.0	24.0	26.0	21.0	24.0	27.0	21.0
Plant Capacity at Cooling System Design Point, MWe	1025	1033	1027	1025	1033	1025	1018	1022	1022
Design Turbine Back Pressure, In-Hg	2.91	2.45	2.83	2.91	2.45	2.91	3.26	3.08	3.08
Maximum Turbine Back Pressure, In-Hg	2.96	2.45	2.83	2.98	2.45	2.91	3.47	3.08	3.08
Design Heat Load, 10 ⁹ Btu/hr	4.18	4.15	4.18	4.18	4.15	4.18	4.20	4.19	4.19
<u>Condenser</u>									
Surface Area, 10 ³ sq ft	643	605	644	595	587	629	591	563	628
Number of Tubes, 10 ³	56.3	46.6	56.2	46.9	43.0	53.6	47.2	41.8	53.7
Tube Length, ft	43.6	49.6	43.7	48.4	52.1	44.9	47.9	51.5	44.6

Note: Abbreviations explained in Section 7.5

TABLE 7-13 (Sheet 2)

SUMMARY OF DESIGN CONDITIONS FOR OPTIMUM COOLING SYSTEMS WITH DOUBLE ENERGY REPLACEMENT COST
1000 MWe FOSSIL POWER PLANT

Item	Mech. Wet			Fan Wet			Nat. Wet		
	Midtn.	Col.	Fla.	Midtn.	Col.	Fla.	Midtn.	Col.	Fla.
<u>Cooling Water Pump</u>									
Circulating Water Flow Rate, 10^3 gpm	418	346	418	348	320	398	350	310	399
Number of Pumps	3	2	3	2	2	3	2	2	2
Pumping Head, ft. of Water	71.7	81.8	77.7	79.2	82.2	77.4	94.6	94.9	95.2
Pumping Power Requirement, bhp/pump	3070	4015	3070	3920	3726	2916	4700	4180	3595
Rated Pump Motor Size, hp/pump motor	3500	4500	3500	4500	4000	3500	5000	4500	4000
<u>Terminal Heat Sink</u>									
Total Power Requirement, 10^3 bhp	4.98	5.36	6.25	5.24	5.02	5.24	--	--	--
Terminal Heat Sink Size:									
Number of Cells	27	28	33	--	--	--	--	--	--
Tower: Number of Towers	--	--	--	2	2	2	1	1	1
Base Diameter, ft	--	--	--	226	222	226	412	394	433
Tower Height, ft	--	--	--	250	250	250	534	511	561
Fan: Number of Fans/Tower	--	--	--	20	20	20	--	--	--
Fan Diameter, ft	28	28	28	28	28	28	--	--	--

TABLE 7-14 (Sheet 1 of 2)
SUMMARY OF DESIGN CONDITIONS FOR OPTIMUM COOLING SYSTEMS WITH DOUBLE REPLACEMENT ENERGY COST
1000 MWe LWR POWER PLANT

Base Plant Conditions: Plant Capacity = 1096 MWe; Heat Rate=9760 Btu/kWh, Exhaust Pressure = 1.5 In-Hg

Item	Mech. Wet			Fan Wet			Nat. Wet		
	Midtn.	Col.	Fla.	Midtn.	Col.	Fla.	Midtn.	Col.	Fla.
<u>General</u>									
Dry Bulb Temperature, °F	93.0	92.0	92.0	93.0	92.0	92.0	93.0	92.0	92.0
Wet Bulb Temperature, °F	74.0	60.0	77.0	74.0	60.0	77.0	74.0	60.0	77.0
Design Cold Water Temperature, °F	90.0	84.0	91.0	86.0	79.0	89.0	90.0	82.0	89.0
Design Approach, °F	16.0	24.0	14.0	12.0	19.0	12.0	16.0	22.0	12.0
Design Range, °F	26.0	26.0	24.0	32.0	32.0	28.0	30.0	35.0	28.0
Plant Capacity at Cooling System Design Point, MWe	1078	1087	1080	1075	1086	1077	1071	1077	1077
Design Turbine Back Pressure, In-Hg	3.64	3.08	3.54	3.85	3.17	3.74	4.06	3.74	3.74
Maximum Turbine Back Pressure, In-Hg	3.70	3.08	3.54	3.92	3.17	3.74	4.28	3.74	3.74
Design Heat Load, 10 ⁹ Btu/hr	7.02	6.99	7.02	7.03	7.00	7.03	7.05	7.03	7.03
<u>Condenser</u>									
Surface Area, 10 ³ sq ft	944	955	980	855	873	911	878	824	911
Number of Tubes, 10 ³	72.7	72.4	78.7	59.2	58.9	67.6	63.2	54.0	67.6
Tube Length, ft	49.6	50.4	47.6	55.2	56.7	51.5	53.1	53.3	51.5

Note: Abbreviations explained in Section 7.5

TABLE 7-14 (Sheet 2)

SUMMARY OF DESIGN CONDITIONS FOR OPTIMUM COOLING SYSTEMS WITH DOUBLE REPLACEMENT ENERGY COST
1000 MWe LWR POWER PLANT

Item	Mech. Wet			Fan Wet			Nat. Wet		
	Midtn.	Col.	Fla.	Midtn.	Col.	Fla.	Midtn.	Col.	Fla.
<u>Cooling Water Pump</u>									
Circulating Water Flow Rate, 10^3 gpm	540	538	585	440	437	502	470	402	502
Number of Pumps	4	3	4	3	3	3	3	3	3
Pumping Head, ft. of Water	78.7	79.3	76.9	78.4	79.3	75.8	92.5	96.9	95.7
Pumping Power Requirement, bhp/pump	3016	4035	3188	3258	3281	3599	4109	3679	4542
Rated Pump Motor Size, hp/pump motor	3500	4500	3500	4000	4000	4000	4500	4000	5000
<u>Terminal Heat Sink</u>									
Total Power Requirement, 10^3 bhp	6.56	6.25	7.09	6.64	6.64	6.66	--	--	--
Terminal Heat Sink Size; Number of Cells	36	33	38	--	--	--	--	--	--
Tower: Number of Towers	--	--	--	2	2	2	1	1	1
Base Diameter, ft	--	--	--	257	257	257	425	463	463
Tower Height, ft	--	--	--	250	250	250	560	565	600
Fan: Number of Fans/Tower	--	--	--	24	24	24	--	--	--
Fan Diameter, ft	28	28	28	28	28	28	--	--	--

CHAPTER 8

ENVIRONMENTAL IMPACT

In Chapter 6, the cooling system design and cost data were presented to aid the potential user in system selection. However, the ultimate choice of a cooling system for a power plant installation requires one to consider not only the traditional "dollar" cost but also the impact of the cooling system on the surrounding environment. A qualitative description of the environmental impact of the various cooling system alternatives is described below.

8.1 ONCE-THROUGH OPEN SYSTEM

As described previously for the once-through system, the flow of water from a river or other water source is passed through condensers to absorb the waste heat from a power plant and then is discharged back to the natural bodies of water. Because the amount of heat rejected from a modern 1000 MWe power plant can range from 3.95×10^6 to 6.35×10^6 Btu/MWh, the major environmental influences of the once-through system are the impact of heated water on the environment and the impingement and entrainment of organisms at the intake to the cooling system.

The environmental impact of a once-through cooling system is difficult to quantify, without recourse to the courts, the water quality law of 1972, and EPA's proposed rules and regulations (March 1974). The EPA's proposal mandates implementation of plans by the utility industry for cooling alternates other than once-through, except for stations on the open ocean coast. A utility wishing to use once-through cooling may seek judicial relief if a case can be made that once-through cooling will not cause biological harm.

The environmental effect of the once-through cooling alternate is a complex combination of time-temperature-flow rate parameters. For this study, it was assumed that the station would be located reasonably close to the discharge structure, thus limiting the time that entrained organisms are held at elevated temperatures. The temperature rise was assumed to be 15°F. In order to minimize the potential for impingement, the intake structure was designed with an approach velocity to the traveling screens of 0.5 ft/sec.

8.2 CLOSED COOLING SYSTEM

The closed cooling system can be a wet system or a dry system; the former includes all the evaporative tower systems and the pond systems while the latter includes all the dry tower systems. A dry tower system causes very little known environmental impact but there may be some potential harmful meteorological impact due to large quantities of hot air leaving a dry tower. Any environmental impact from a wet system would come mainly from three sources: entrainment of biota through the intake structure into the system, blowdown water from the tower, and the wet plume. A wet air plume is defined as that air, emanating from a tower or pond, which contains water vapor. These environmental impacts are described below.

8.2.1 ENTRAINMENT

Although the amount of water used for a cooling tower application is significantly lower than that required for once-through cooling, all of the biota entrained in the system must be assumed to die because of the time, temperature and chemical stress in the tower. In other words, aquatic organisms in the water used will be unable to survive the long exposures to the relatively high temperatures that are characteristically imposed during multiple recycling through the plant

condensers and cooling towers. In addition, cooling tower systems generally require the addition of sulfuric acid to alter the water chemistry to prevent the deposition of scale and the addition of biocides to control slime growth on heat exchanger surface. The entrained organisms are exposed to these for long periods. Similarly, harmless ambient levels of naturally occurring chemical species (or those resulting from erosion/corrosion within the system) may be concentrated by the evaporative action within the towers, eventually reaching toxic quantities.

On the other hand, large percentages of entrained organisms can survive passage through a properly designed once-through cooling system. Impact on organisms pumped through a once-through system can be minimized by designing for a short period exposure to a relatively low temperature. These criteria can be met by reducing to a minimum discharge length from plant condensers to receiving waters, and by designing condensers for high flow, low temperature rise operation. Once-through cooling may allow reduction of time periods over which biocides are used. If biofouling problems are mainly in relation to heat exchanger capability (rather than growths on intake piping), then biocides may be injected at the intake end of the condensers (rather than at the plant intake). Thus, entrained organisms will be exposed for as short a time period as possible before the biocides are diluted in the receiving waters or by flow from parallel condensers that are treated at different time periods.

8.2.2 Blowdown from Wet Cooling System

Although the blowdown temperatures from a closed system are usually higher than those from a once-through open system, the problem of thermal impact may be much less severe because of the smaller quantity of heat in the blowdown water.

However, a major concern in the operation of this type of system is the potential harmful effect of the high concentration of total dissolved solids, corrosion/erosion products, biocides, and the other chemicals (especially if brackish water or salt water is used for makeup).

8.2.3 Environmental Effects from Wet Plume

The air plume from a wet tower system or a pond system is saturated with water vapor. As the ambient temperature changes the plume may become supersaturated causing condensation of part of the water vapor which then is formed into small liquid droplets thereby causing ground level fogging or icing conditions. These conditions are hazardous to ground transportation and, in the case of salt water towers, there is the additional problem of salt drift (and other chemicals) which can be detrimental to the surrounding environment.

8.2.3.1 Cooling Tower Plumes and Fog

The severity of the environmental impact caused by the cooling tower plume depends on the type of wet tower system used as well as on the meteorological and topographic conditions existing at the power plant site.

The plume emanating from the cooling tower is cooled, and also diluted, by the outside atmosphere. The release of latent heat during the cooling process imparts further convective motion to the plume. The dispersion of the plume into the atmosphere is a phenomenon of simultaneous heat and mass transfer in a turbulent atmosphere. Hence, the meteorological conditions existing at the plant site play an important role in determining the behavior of the plume.

In the analytic model developed at UE&C, the rise of the plume is assumed to be proportional to the sensible heat content of the plume and inversely proportional

to the wind velocity at the site of the cooling tower. For the same wind velocity, the height of the plume will increase with an increase in the heat rejected from the system. The length of the plume, once it has started moving with the wind velocity, is determined by the water-absorbing capacity of the atmosphere. If the atmosphere is highly unsaturated, the plume from the cooling tower is dispersed without any accompanying environmental impact. If the atmosphere has a tendency towards fogging, or if the atmospheric relative humidity is very high, the plume will persist for a much longer time, thereby increasing its propensity to touch the ground. Ground level fogging therefore, can occur in the vicinity of the power plant since the high atmospheric relative humidity reduces the water absorbing capacity of the ambient air. If the plume impacts a structure or transmission line, and the atmospheric temperature is below the freezing point of water, the suspended water droplets in the plume are deposited as ice on the structure or on the ground.

The influence of a tower type on this environmental impact of a plume is mainly due to tower height which contributes to the tower's ability to disperse the plume. The mechanical draft wet cooling tower, being the lowest in height, has the least ability to disperse the plume. Therefore, ground level fogging and icing are more likely to occur when this type of tower is used.

The natural draft wet cooling tower, on the other hand being the tallest of wet tower types, discharges its plume at a much higher elevation than does the mechanical draft tower; hence, the probability of a plume touching the ground, when emanated from a natural draft tower, is considerably curtailed. Since the height of a fan-assisted natural draft tower is between the mechanical and natural draft towers, it is clear that the ground fogging potential of the plume from a fan-assisted tower will lie between the other two types of wet towers.

8.2.3.2 Impact of Cooling Pond Fog

The environmental impact due to operation of a constructed cooling pond or a power spray module canal is dependent upon the prevailing meteorological conditions at the power plant site. The discharge of hot water into a constructed cooling pond leads to the evaporation of water. The entire area of a constructed cooling pond can be fogged under low ambient temperature conditions. This type of fog is called steam fog. This fog is extensively shallow and does not impair the area's visibility to a large extent. Steam fogs are ascribed to a difference in vapor pressure between the water surface of the pond and the air above it; this pressure difference can be on the order of 5 millibars.

The fogging and icing due to operation of a spray module canal is caused mainly by the evaporation and drift of water droplets from the pond site. The effective source strength of the plume is very small, due to the very large area of the spray module canal, as compared to a mechanical draft wet cooling tower which is considered as a point source. The comparative height of the plume from a spray module canal is very small; however, the water droplets can be carried over long distances due to prevailing wind velocity. These droplets can freeze at low ambient temperatures, thereby causing icing conditions on nearby structures, transmission lines, and roadways. Unlike the mobile droplets, the icing effects are localized. The fogging caused by a spray module canal is steam fog and remains restricted to the banks of the canal.

APPENDIX A

HEAT RATE CORRECTION CURVES FOR THE REFERENCE POWER PLANTS

The heat rate correction curves used for cooling system optimization are shown in Figures A-1 through A-8. The heat rate correction curves are expressed as a percentage change of heat rate with respect to the base heat rate at 1.5 inches Hg absolute back pressure. Figures A-1 through A-4 present data for low exhaust pressure turbines and were used for all cooling system optimization except dry tower systems. Figures A-5 through A-8 present data for high exhaust pressure turbines and were used for optimization of dry tower cooling systems only.

Figure A-1 Estimated Heat Rate Corrections for Fossil Power Plant with Low Exhaust Pressures

Figure A-2 Estimated Heat Rate Corrections for LWR Power Plant with Low Exhaust Pressures

Figure A-3 Estimated Heat Rate Corrections for LMFBR Power Plant with Low Exhaust Pressures

Figure A-4 Estimated Heat Rate Corrections for HTGR Power Plants with Low Exhaust Pressures

Figure A-5 Estimated Heat Rate Corrections for Fossil Power Plant with High Exhaust Pressures

*Basic conventional unit

Figure A-6 Estimated Heat Rate Corrections for LWR Power Plant with High Exhaust Pressures

*Basic conventional unit

Figure A-7 Estimated Heat Rate Corrections for LMFBR Power Plant with High Exhaust Pressures.

*Basic conventional unit

Figure A-8 Estimated Heat Corrections for HTGR Power Plants with High Exhaust Pressures
*Basic conventional unit

APPENDIX B

SCHEMATIC DIAGRAMS OF TYPICAL COOLING TOWERS AND POWER SPRAY MODULE CANALS

This appendix presents the typical schematic diagrams for all the types of wet cooling towers, dry cooling towers, and power spray module canals investigated in this study. These examples are representative only.

Figure B-1 shows a typical crossflow mechanical draft wet cooling tower and Figure B-2 shows a counterflow type. In the former, the air flows through the fills or packings horizontally and at right angle to the flow of water; in the latter the air flows through the packings vertically upward and parallel to the flow of water which is downward. The arrangement of the packings in both types of tower are clearly shown. Some typical packings or fills are shown in Figure B-3; typical drift eliminators for use in wet towers are shown in Figure B-4.

Figures B-5 and B-6 show typical crossflow and counterflow types of natural draft wet towers. The hyperbolic concrete shell is supported at the bottom by reinforced concrete columns so as to allow the free flow of air. The water distribution system, the packing material, and the drift eliminators are located near the bottom of the tower behind the air inlet louvers.

Figure B-7 shows a fan-assisted natural draft wet tower with fans located about the periphery of the tower base.

A typical mechanical draft dry tower is shown in Figure B-8 with the modules or cells arranged back-to-back. The finned tubes in each cell are arranged

in a diagonal position so as to save space and yet allow for the free flow of air. The internal detail of a dry tower cell is shown in Figure B-9.

Figure B-10 shows a typical natural draft dry cooling tower with a hyperbolic shell with horizontally arranged heat exchanger elements. Figure B-11 shows the detail of a heat exchanger element. Figure B-12 shows a natural draft dry cooling tower with hyperbolic shell and vertically-oriented heat exchanger elements.

A power spray module canal showing details of a spray module is shown in Figure B-13. The spray from each nozzle of a module covers a diameter of about 40 feet.

Series and parallel path wet-dry towers are shown in Figures B-14 and B-15, respectively.

Figure B-1 Typical Crossflow type Mechanical Draft Wet Cooling Tower

Figure B-2 Typical Counterflow Type Mechanical Draft Wet Cooling Tower

Figure B-3 Typical packing configurations for Wet Cooling Towers

Figure B-4 Typical Drift Eliminators for Wet Cooling Towers

Figure B-5 Typical Crossflow Type Natural Draft Wet Cooling Tower

Figure B-6 Typical Counterflow Type Natural Draft Wet Cooling Towers

Figure B-7 Typical Fan-Assisted Natural Draft Wet Cooling Tower

Figure B-8 Typical Mechanical Draft Dry Tower Showing a Typical Cells Arrangement

Figure B-9 Side View of a Typical Mechanical Draft Dry Tower Cell shown in Figure B-8

Figure B-10 Typical Natural Draft Dry Tower with Horizontal Heat Exchangers Elements

Figure B-11 Details of a Horizontal Heat Exchanger Element for Natural Draft Dry Tower

Figure B-12 Typical Natural Draft Dry Tower with Vertical Heat Exchanger Elements

Figure B-13 Typical Power Spray Canal System with Power Spray Module Details

Figure B-14 Series Path Wet-Dry Tower

Figure B-15 Parallel Path Wet-Dry Tower

APPENDIX C

QUALITATIVE DESCRIPTION OF THE ADVANTAGES AND DISADVANTAGES OF COOLING SYSTEM ALTERNATIVES

The advantages and disadvantages of the eight cooling systems alternatives investigated in this study are described and tabulated in Table C-1.

TABLE C-1 (Sheet 1 of 2)

QUALITATIVE ADVANTAGES AND DISADVANTAGES OF COOLING SYSTEM ALTERNATIVES

<u>Cooling System</u>	<u>Advantages</u>	<u>Disadvantages</u>
Once-Through System	1. Normally simplest, most economical.	1. Cooling water supply problem for large power plants 2. Possibility of significant ecological problems with receiving waters
Cooling Pond	1. Serves as settling basin for suspended solids 2. Relatively simple operation 3. May be beneficial for other purposes e.g., recreation.	1. Large land area required 2. Large capital cost 3. Blowdown disposal problem.
Spray Module Canal	1. Requires less land area as compared to cooling pond 2. Economical, compared to cooling pond.	1. Performance dependent upon wind conditions 2. Low altitude fogging and icing 3. Increased water loss due to drift 4. Blowdown disposal problem.
Mechanical Draft Wet Tower	1. Positive control over air supply 2. Relatively close control over cold water temperature 3. Generally low pumping head 4. Ambient relative humidity has minimal effect on tower performance 5. More packing per unit volume of tower 6. Usually lower capital cost than natural draft wet tower.	1. Operating and maintenance costs higher than natural draft tower 2. Subject to recirculation of the humid exhaust air 3. More severe localized fogging and icing problem than natural or fan-assisted wet tower 4. Blowdown disposal problem 5. Greater concentrations of salt deposition near site boundary than non-mechanical draft systems.
Natural Draft Wet Tower	1. Fewer mechanical and electrical components than mechanical draft wet tower 2. Lower operating and maintenance costs than mechanical draft wet tower 3. Better plume dispersion because of high elevation discharge.	1. Internal resistance to air flow must be kept minimal 2. Requires greater tower height to produce draft 3. Substantially larger capital cost than mechanical draft wet tower 4. Performance dependent on both wet bulb and dry bulb temperatures 5. Normal fogging and icing 6. Soil and wind loading problems caused by large size and weight of structure 7. Blowdown disposal problem.

TABLE C-1 (Sheet 2)

QUALITATIVE ADVANTAGES AND DISADVANTAGES OF COOLING SYSTEM ALTERNATIVES

<u>Cooling System</u>	<u>Advantages</u>	<u>Disadvantages</u>
Fan-Assisted Natural Draft Wet Tower	<ol style="list-style-type: none"> 1. Better control of air flow than natural draft tower 2. Smaller structure and lighter weight than natural draft tower 3. Consumes less power than mechanical draft wet tower if fans are turned off when not needed. 4. Less serious fog-ice problems than mechanical draft towers. 	<ol style="list-style-type: none"> 1. Higher capital cost than mechanical draft tower. 2. More serious fog-ice problems than natural draft towers.
Mechanical Draft Dry Tower	<ol style="list-style-type: none"> 1. Avoids problems of fogging and icing 2. Eliminates such water problems as: availability, evaporative losses, and blowdown. 	<ol style="list-style-type: none"> 1. Substantially higher capital and operating costs than other systems 2. High maintenance costs 3. Larger volumes of air must be circulated 4. Decreased plant output and efficiency at high dry bulb temperatures 5. Larger land area required than wet towers. 6. Dry towers may have greater freeze-protection problems than wet towers.
Natural Draft Dry Tower	<ol style="list-style-type: none"> 1. Same as mechanical draft dry tower, items 1 and 2 2. Fewer mechanical and electrical components than mechanical draft dry tower 3. Lower operating and maintenance costs than mechanical draft dry tower. 	<ol style="list-style-type: none"> 1. Higher capital cost than all other cooling systems, including mechanical draft dry tower 2. Soil and wind loading problems caused by large size and weight of structure. 3. Dry towers may have greater freeze-protection problems than wet towers.

APPENDIX D

MAJOR EQUIPMENT LIST

TABLE D-1 (Sheet 1 of 2)

LIST OF MAJOR EQUIPMENT

AEC Acc. No.	Item	Description
133.1/233.1	Condensers	Each cooling system has three field tubed main surface condensers with fabricated steel water boxes and steel shell. Each condenser has 1-inch o.d., 20 BWG guage, 304 stainless steel tubes and a design water velocity of 7.0 ft/sec. The condenser has one tube pass for the once-through cooling system and two tube passes for the closed cooling systems. Condenser design data for each cooling system can be found in Tables 6-2, 6-5, 6-8, 6-11, and 6-14.
132.2/232.2	Circulating Water Pumps and Motors	The circulating water pumps are each of the vertical, wet pit, motor driven type with 4160 volts, 3 phase, 60 cycle motors. The pumps have carbon steel casings with chrome steel shaft and bronze impeller. Pump design data for each system can be found in Tables 6-2, 6-5, 6-8, 6-11 and 6-14.
132.32/232.32	Terminal Heat Sink	The following are the descriptions of alternative terminal heat sinks. The design data for each alternative can be found in Tables 6-2, 6-5, 6-8, 6-11 and 6-14.
	A) Mechanical Draft Wet Cooling Tower	The mechanical draft wet tower cells or modules are the induced draft, cross-flow type of concrete construction with 41 feet fill height. Each cell has a fan; the fan has a diameter of 28 feet and is driven by a 200 horsepower motor. The cell dimensions are 71 feet wide, 36 feet long, and 54 feet high.
	B) Natural Draft Wet Cooling Tower	The natural draft wet towers are the counter flow type with a maximum base diameter of 500 feet. The hyperbolic shell is made of reinforced concrete with a minimum thickness of six inches.

TABLE D-1 (Sheet 2)

LIST OF MAJOR EQUIPMENT

AEC Acc. No.	Item	Description
132.32/232.32	Terminal Heat Sink (Cont'd)	
	C) Fan-assisted Natural Draft Wet Tower	The fan-assisted natural draft wet towers are the counterflow type with a minimum height of 250 feet. The hyperbolic shell is made of reinforced concrete with a minimum thickness of six inches. The maximum number of fans is 24, with a maximum fan diameter of 28 feet. The fans are driven by 150 horsepower motors.
	D) Power Spray Modules	Each spray module has 4 nozzles mounted on a 120-foot length, 10-inch diameter carbon steel pipe. Each is complete with floats and a pump at the center of the pipe. The pump can deliver 10,000 gpm and is driven by a 75 horsepower motor.
	E) Mechanical Draft Dry Tower	The mechanical draft dry tower cells are the induced flow type. The cells are arranged back-to-back to form towers. Each cell has 776 tubes arranged in two passes and equipped with a 150 horsepower motor and 28-foot diameter fan. The cell dimensions are 41 feet wide, 61 feet long and 65 feet high. The tubes are of 1-inch outside diameter admiralty tubes with aluminum fins.
	F) Natural Draft Dry Tower	The natural draft tower has hyperbolic concrete shell with a maximum base diameter of 500 feet and a minimum thickness of six inches. The finned tube heat exchanger modules are arranged vertically around the tower base. Each module has 176 tubes in two passes. The tubes are of 1-inch outside diameter admiralty tubes with aluminum fins.

APPENDIX E

DESCRIPTION OF THE UNITED STATES ATOMIC ENERGY COMMISSION ACCOUNT NUMBERS FOR COOLING SYSTEM COST BREAKDOWNS

There are two systems of cost account numbers in the AEC codes. The numbering system listed in Table E-1 is applied to those cooling systems interfaced with fossil power plants. The numbering system listed in Table E-2 is applied to the systems in nuclear power plants.

Not all the account numbers are applicable in the present study, for instance, the highway and railway access was not included in the cooling system costs given in Chapter 6.

TABLE E-1 (Sheet 1 of 2)

COMPARISON OF COSTS, ALTERNATE HEAT SINK SYSTEMS VERSUS
BASIC ONCE-THROUGH COOLING FOR FOSSIL-FIRED PLANTS

Account Number	Description
111.3	<u>Highway and Railway Access</u> This includes the bridge over the discharge canal.
114.1	<u>Intake and Discharge Structures</u> This includes screen and pump well excavation work, concrete work, miscellaneous iron, coffer dam, and bulkhead.
132.1	<u>Water Intake Facilities</u> This includes traveling screens, trash racks, trash rake, fine screens, water chlorination equipment and piping, sluice gates, and stop logs.
132.2	<u>Circulating Water Systems</u> This includes: <ol style="list-style-type: none"> 1. Circulating water pumps and drives, de-icing pumps and drives, make-up pumps and drives, and recirculating pumps and drives. 2. Circulating water piping intake, discharge, and warming line. Excavation, backfill, supports, etc. 3. Discharge tunnel excavation, backfill dewatering, concrete work, granite wear slabs, stop logs, and adjustable weir. 4. Discharge canal outside of building excavation and backfill temporary sheeting, stop logs, pumping, rip-rap, concrete work, permanent sheet piling, discharge structure, miscellaneous iron, shut-off gates, and concrete pipe.
132.3	<u>Cooling Towers</u> This includes: <ol style="list-style-type: none"> 1. Cooling tower basins and foundations excavation and backfill, forms, reinforcing steel, concrete, concrete finish, anchor bolts, miscellaneous iron, and dewatering.

TABLE E-1 (Sheet 2)

COMPARISON OF COSTS, ALTERNATE HEAT SINK SYSTEMS VERSUS
BASIC ONCE-THROUGH COOLING FOR FOSSIL-FIRED PLANTS

Account Number	Description
132.3 (Cont'd)	<p>2. Recirculating pump wells excavation and backfill, de-watering forms, reinforcing steel, concrete, concrete finish, miscellaneous iron, trash racks, screens, and screen wash pumps.</p> <p>3. Cooling towers (induced draft or natural draft).</p>
133.1	<u>Condensers</u>
141.2	<p><u>Station Service</u> This includes switchgear and controls for traveling screens, trash rake, circulating water pumps, de-icing pumps, make-up pumps, recirculating pumps, screen wash pumps, and induced draft tower fans.</p>
142.1	<p><u>Transformers</u> This includes the incremental transformer capacities involved.</p>
145.2	<u>Cable Trays and Supports</u>
145.3	<u>Conduit</u>
146.2	<p><u>Station Service Power Wiring</u> This includes cable and wire.</p>

TABLE E-2 (Sheet 1 of 2)

COMPARISON OF COSTS, ALTERNATE HEAT SINK SYSTEMS VERSUS
BASIC ONCE-THROUGH COOLING FOR NUCLEAR PLANTS

Account Number	Description
211.3	<u>Highway and Railway Access</u> This includes the bridge over the discharge canal.
214.1	<u>Intake Structure</u> This includes screen and pump well excavation work, concrete work, miscellaneous iron, coffer dam, and bulkhead.
232.1	<u>Water Intake Common Facilities</u> This includes traveling screens, trash racks, trash rake, fine screens, water chlorination equipment and piping, sluice gates, and stop logs.
232.2	<u>Circulating Water Systems</u> This includes: <ol style="list-style-type: none"> 1. Circulating water pumps and driver, de-icing pumps and drives, make-up pumps and drives, and recirculating pumps and drives. 2. Circulating water piping intake, discharge, and warming line. Excavation, backfill, supports, etc. 3. Discharge tunnel excavation, back-fill dewatering, concrete work, granite wear slabs, stop logs, and adjustable weir. 4. Discharge canal outside of building excavation and back-fill, temporary sheeting, stop logs, pumping, rip-rap, concrete work, permanent sheet piling, discharge structure, miscellaneous iron, shut-off gates, and concrete pipe.
232.3	<u>Cooling Towers</u> This includes: <ol style="list-style-type: none"> 1. Cooling tower basins and foundations, excavation and back-fill, forms, reinforcing steel, concrete, concrete finish, miscellaneous iron, trash racks, screens, and screen wash pumps. 2. Cooling towers (induced draft or natural draft).
233.1	<u>Condensers</u>

TABLE E-2 (Sheet 2)

COMPARISON OF COSTS, ALTERNATE HEAT SINK SYSTEMS VERSUS
BASIC ONCE-THROUGH COOLING FOR NUCLEAR PLANTS

Account Number	Description
241.2	<u>Station Service</u> This includes switchgear and controls for traveling screens, trash rake, circulating water pumps, de-icing pumps, make-up pumps, recirculating pumps, screen wash pumps, and induced draft tower fans.
242.1	<u>Station Service and Startup Transformers</u> This includes the incremental transformer capacities involved.
245.2	<u>Cable Trays and Supports</u>
245.3	<u>Conduit</u>
246.2	<u>Station Service Power Wiring</u> This includes cable and wire.

APPENDIX F

SAMPLE COMPUTER PRINTOUT OF OPTIMIZATION RESULTS

In this Appendix, a sample set of computer printout sheets of the optimization results is presented. The meanings of the variables are printed on the top of each page. On the printout sheets, variable "DT1" should read "Terminal Temperature Difference."

This sample set shows the results for a mechanical draft wet tower system at a particular design approach. The data include the summary of cost, penalties, etc., cost breakdown of the cooling system, capitalized economic penalties, condenser design data, condenser cost breakdown, piping data, data for circulating water pumps and motors, and the data for the terminal heat sink.

AEC STUDY - JOB NO. 9765-001 - MECH. WET - MIDDLETOWN-HTGR
MECHANICAL DRAFT TOWER

14.46.58.

*****SUMMARY OF COST AND PLANT PERFORMANCE*****

TC=SATURATED STEAM TEMP.	DTI=INITIAL TEMP. DIFFERENCE
RA=TEMP. RISE	PENIL=TOTAL EVALUATED PENALTIES(\$)
LAROR=TOTAL LAROR COST(\$)	MAT=TOTAL MATERIAL COST(\$)
CAP=TOTAL CAPITAL COST(\$)	INDIR=INDIRECT AND OVERHEAD COSTS(\$)
TOTEV=TOTAL EVALUATED COST(\$)	PWC=PRESENT WORTH COST(\$)
PMAX=MAXIMUM BACK PRESSURE	NEPY=NET ENERGY PRODUCTION PER YEAR
SIZE=ACTUAL PLANT OUTPUT AT DESIGN CONDITIONS	HEATR=HEAT RATE AT DESIGN CONDITIONS

NOTE*****

THE COST GIVEN TAKE INTO ACCOUNT THE NUMBER OF UNITS-- SIZE AND HEATR ARE PER UNIT VALUES.
THE VALUES OF TC ARE THE MINIMUM VALUES FOR WHICH IT IS POSSIBLE TO DESIGN

F-2 THE DESIGN TERMINAL TEMP. DIFFERENCE IS 6.00
THE DESIGN COLD WATER TEMPERATURE IS 93.00
THE DESIGN APPROACH IS 19.00

TC	DTI	RA	PENIL	MAT	LAROR	CAP	INDIR	TOTEV	PWC	SIZE	HEATR	PMAX	NEPY
120.0	6.0	21.0	1.2675E+07	1.0995E+07	5.5336E+06	1.6528E+07	4.1320E+06	3.3335E+07	5.9628E+07	1162.10	8811.73	3.49	.76022746E+10
121.0	6.0	22.0	1.2903E+07	1.0794E+07	5.4528E+06	1.6247E+07	4.0617E+06	3.3212E+07	5.9408E+07	1160.66	8822.69	3.59	.76011362E+10
122.0	6.0	23.0	1.3058E+07	1.0427E+07	5.3395E+06	1.5767E+07	3.9417E+06	3.2767E+07	5.8611E+07	1159.14	8834.27	3.69	.76002998E+10
123.0	6.0	24.0	1.3360E+07	1.0176E+07	5.2452E+06	1.5421E+07	3.8553E+06	3.2637E+07	5.8379E+07	1157.54	8846.42	3.79	.75982410E+10
124.0	6.0	25.0	1.3674E+07	9.8564E+06	5.1156E+06	1.4972E+07	3.7430E+06	3.2389E+07	5.7936E+07	1155.88	8859.14	3.90	.75953695E+10
125.0	6.0	26.0	1.4086E+07	9.7204E+06	5.0656E+06	1.4786E+07	3.6965E+06	3.2569E+07	5.8258E+07	1154.16	8872.40	4.01	.75918644E+10
126.0	6.0	27.0	1.4515E+07	9.6355E+06	5.0401E+06	1.4677E+07	3.6692E+06	3.2861E+07	5.8781E+07	1152.37	8886.18	4.12	.75881093E+10
127.0	6.0	28.0	1.4952E+07	9.4443E+06	4.9359E+06	1.4380E+07	3.5950E+06	3.2927E+07	5.8899E+07	1150.51	8900.54	4.23	.75836049E+10
128.0	6.0	29.0	1.5577E+07	9.3013E+06	4.8711E+06	1.4172E+07	3.5431E+06	3.3293E+07	5.9553E+07	1148.56	8915.63	4.35	.75773859E+10
129.0	6.0	30.0	1.6178E+07	9.1486E+06	4.8496E+06	1.3998E+07	3.4996E+06	3.3676E+07	6.0238E+07	1146.51	8931.58	4.46	.75715206E+10
130.0	6.0	31.0	1.6791E+07	8.8610E+06	4.7492E+06	1.3610E+07	3.4025E+06	3.3803E+07	6.0466E+07	1144.34	8948.52	4.58	.75649499E+10

AEC STUDY - JOB NO. 9765-001 - MECH. WET - MIDDLETOWN-HTGR

14.46.58.

MECHANICAL DRAFT TOWER

THE DESIGN TERMINAL TEMP. DIFFERENCE IS 6.00

THE DESIGN COLD WATER TEMPERATURE IS 93.00

THE DESIGN APPROACH IS 19.00

*****TOTAL MATERIAL AND LABOR COST COMPONENTS*****

TC=SATURATED STEAM TEMP.

DT1=INITIAL TEMP. DIFFERENCE

RA=TEMP. RISE

MAT(1)=CONDENSER (MATERIAL)

LAB(1)=CONDENSER (LABOR)

MAT(2)=PIPELINE (MATERIAL)

LAB(2)=PIPELINE (LABOR)

MAT(3)=PUMPS, MOTORS (MATERIAL)

LAB(3)=PUMPS, MOTORS (LABOR)

MAT(4)=INTAKE AND DISCHARGE STRUCTURE INCLUDING SCREENS AND OTHER FACILITIES (MATERIAL)

LAB(4)=INTAKE AND DISCHARGE STRUCTURE INCLUDING SCREENS AND OTHER FACILITIES (LABOR)

	TC	DT1	RA	MAT(1)	LAB(1)	MAT(2)	LAB(2)	MAT(3)	LAB(3)	MAT(4)	LAB(4)
F-3	120.0	6.0	21.0	4.687E+06	1.957E+06	8.023E+05	6.747E+05	1.390E+06	8.000E+04	3.969E+05	2.646E+05
	121.0	6.0	22.0	4.576E+06	1.926E+06	7.196E+05	6.293E+05	1.390E+06	8.000E+04	3.903E+05	2.602E+05
	122.0	6.0	23.0	4.473E+06	1.897E+06	7.196E+05	6.293E+05	1.246E+06	8.000E+04	3.841E+05	2.560E+05
	123.0	6.0	24.0	4.377E+06	1.870E+06	6.788E+05	6.059E+05	1.147E+06	6.000E+04	3.782E+05	2.521E+05
	124.0	6.0	25.0	4.287E+06	1.845E+06	6.503E+05	5.853E+05	1.095E+06	6.000E+04	3.727E+05	2.484E+05
	125.0	6.0	26.0	4.203E+06	1.822E+06	6.037E+05	5.625E+05	1.095E+06	6.000E+04	3.674E+05	2.450E+05
	126.0	6.0	27.0	4.125E+06	1.800E+06	6.037E+05	5.625E+05	1.095E+06	6.000E+04	3.625E+05	2.417E+05
	127.0	6.0	28.0	4.050E+06	1.779E+06	6.037E+05	5.625E+05	1.095E+06	6.000E+04	3.578E+05	2.385E+05
	128.0	6.0	29.0	3.981E+06	1.759E+06	5.351E+05	5.204E+05	1.095E+06	6.000E+04	3.533E+05	2.355E+05
	129.0	6.0	30.0	3.915E+06	1.740E+06	5.351E+05	5.204E+05	1.042E+06	6.000E+04	3.491E+05	2.327E+05
	130.0	6.0	31.0	3.852E+06	1.723E+06	5.351E+05	5.204E+05	9.345E+05	6.000E+04	3.450E+05	2.300E+05

AEC STUDY - JOB NO. 9765-001 - MECH. WET - MIDDLETOWN-HTGR
 MECHANICAL DRAFT TOWER
 THE DESIGN TERMINAL TEMP. DIFFERENCE IS 6.00
 THE DESIGN COLD WATER TEMPERATURE IS 93.00
 THE DESIGN APPROACH IS 19.00

14.46.58.

*****TOTAL MATERIAL AND LABOR COST COMPONENTS CONTINUED*****

MAT(5)=CAPITAL COST OF TOWERS (MATERIAL) LAB(5)=CAPITAL COST OF TOWERS (LABOR)
 MAT(6)=CAPITAL COST OF MAKE-UP FACILITIES (MATERIAL) LAB(6)=CAPITAL COST OF MAKE-UP FACILITIES (LABOR)
 MAT(7)=COST OF BASIN AND FOUNDATION FOR MECHANICAL DRAFT TOWER (MATERIAL)
 LAB(7)=COST OF BASIN AND FOUNDATION FOR MECHANICAL DRAFT TOWER (LABOR)
 MAT(8)=COST OF ELECTRICAL COMPONENTS (MATERIALS) LAB(8)=COST OF ELECTRICAL COMPONENTS (LABOR)

	TC	DT1	RA	MAT(5)	LAB(5)	MAT(6)	LAB(6)	MAT(7)	LAB(7)	MAT(8)	LAB(8)
F-4	120.0	6.0	21.0	2.403E+06	1.294E+06	1.507E+05	1.507E+05	5.928E+05	8.892E+05	5.714E+05	2.235E+05
	121.0	6.0	22.0	2.403E+06	1.294E+06	1.505E+05	1.505E+05	5.928E+05	8.892E+05	5.714E+05	2.235E+05
	122.0	6.0	23.0	2.320E+06	1.249E+06	1.503E+05	1.503E+05	5.724E+05	8.586E+05	5.614E+05	2.186E+05
	123.0	6.0	24.0	2.320E+06	1.249E+06	1.502E+05	1.502E+05	5.724E+05	8.586E+05	5.514E+05	1.986E+05
	124.0	6.0	25.0	2.238E+06	1.205E+06	1.501E+05	1.501E+05	5.520E+05	8.280E+05	5.113E+05	1.936E+05
	125.0	6.0	26.0	2.238E+06	1.205E+06	1.500E+05	1.500E+05	5.520E+05	8.280E+05	5.113E+05	1.936E+05
	126.0	6.0	27.0	2.238E+06	1.205E+06	1.499E+05	1.499E+05	5.520E+05	8.280E+05	5.113E+05	1.936E+05
	127.0	6.0	28.0	2.155E+06	1.160E+06	1.498E+05	1.498E+05	5.316E+05	7.974E+05	5.013E+05	1.887E+05
	128.0	6.0	29.0	2.155E+06	1.160E+06	1.497E+05	1.497E+05	5.316E+05	7.974E+05	5.013E+05	1.887E+05
	129.0	6.0	30.0	2.155E+06	1.160E+06	1.497E+05	1.497E+05	5.316E+05	7.974E+05	4.713E+05	1.887E+05
	130.0	6.0	31.0	2.072E+06	1.116E+06	1.496E+05	1.496E+05	5.112E+05	7.668E+05	4.612E+05	1.837E+05

AEC STUDY - JOB NO. 9765-001 - MECH. WET - MIDDLETOWN-HTGR

14.46.58.

MECHANICAL DRAFT TOWER

THE DESIGN TERMINAL TEMP. DIFFERENCE IS 6.00

THE DESIGN COLD WATER TEMPERATURE IS 93.00

THE DESIGN APPROACH IS 19.00

*****TOTAL EVALUATION PENALTIES*****

TC=SATURATED STEAM TEMP.

DTI=INITIAL TEMP. DIFFERENCE

RA=TEMP. RISE

PENIL(1)=CAPACITY PENALTY(\$)

PENIL(2)=DIFFERENTIAL FUEL COST PENALTY

PENIL(3)=COST OF PUMP ENERGY

PENIL(4)=COST OF MAKE-UP

PENIL(5)=COST OF FAN ENERGY

PENIL(6)=COST OF OPERATION AND MAINTENANCE OF COOLING SYSTEM

	TC	DTI	RA	PENIL(1)	PENIL(2)	PENIL(3)	PENIL(4)	PENIL(5)	PENIL(6)
F-S	120.0	6.0	21.0	2.04207E+06	1.15923E+06	5.46209E+06	2.81487E+05	2.25066E+06	1.47900E+06
	121.0	6.0	22.0	2.26289E+06	1.36492E+06	5.30166E+06	2.81988E+05	2.21302E+06	1.47900E+06
	122.0	6.0	23.0	2.49540E+06	1.59795E+06	5.07784E+06	2.82529E+05	2.17641E+06	1.42800E+06
	123.0	6.0	24.0	2.73859E+06	1.85934E+06	4.91014E+06	2.83082E+05	2.14108E+06	1.42800E+06
	124.0	6.0	25.0	2.99190E+06	2.15052E+06	4.76402E+06	2.83655E+05	2.10697E+06	1.37700E+06
	125.0	6.0	26.0	3.25481E+06	2.47257E+06	4.62383E+06	2.84138E+05	2.07402E+06	1.37700E+06
	126.0	6.0	27.0	3.52741E+06	2.82642E+06	4.45778E+06	2.84711E+05	2.04217E+06	1.37700E+06
	127.0	6.0	28.0	3.81187E+06	3.21243E+06	4.30512E+06	2.85297E+05	2.01138E+06	1.32600E+06
	128.0	6.0	29.0	4.11069E+06	3.63082E+06	4.24231E+06	2.85896E+05	1.98164E+06	1.32600E+06
	129.0	6.0	30.0	4.42650E+06	4.08149E+06	4.10506E+06	2.86506E+05	1.95291E+06	1.32600E+06
	130.0	6.0	31.0	4.76122E+06	4.56409E+06	3.97806E+06	2.87127E+05	1.92523E+06	1.27500E+06

AEC STUDY - JOB NO. 9765-001 - MECH. WET - MIDDLETOWN-HTGR

14.46.58.

MECHANICAL DRAFT TOWER

THE DESIGN TERMINAL TEMP. DIFFERENCE IS 6.00

THE DESIGN COLD WATER TEMPERATURE IS 93.00

THE DESIGN APPROACH IS 19.00

*****CONDENSER*****

TC=SATURATED STEAM TEMP. DT1=INITIAL TEMP.DIFFERENCE

RA=TEMP. RISE QREJ=HEAT REJECTED

GPM=FLOW RATE UALL=HEAT TRANSFER COEFFICIENT

ACOND=SURFACE AREA TL=TUBE LENGTH (FI.)

NP=NUMBER OF PASSES DPT=PRESSURE DROP IN TUBES

DPE=PRESSURE DROP IN ENDS DPN=PRESSURE DROP IN NOZZLES

TDPC=TOTAL PRESSURE DROP NT=NUMBER OF TUBES

VEL=WATER VELOCITY IN TUBES

F-6	TC	DT1	RA	QREJ	GPM	VEL	UALL	ACOND	TL	NP	NT	DPT	DPE	DPN	TDPC
	120.0	6.0	21.0	6.2739E+09	5.9751E+05	7.00	481.62	9.33003E+05	44.3	2	80421	18.23	1.83	1.14	21.20
	121.0	6.0	22.0	6.2788E+09	5.7080E+05	7.00	481.62	9.12844E+05	45.4	2	76825	18.67	1.83	1.14	21.64
	122.0	6.0	23.0	6.2840E+09	5.4643E+05	7.00	481.62	8.93783E+05	46.4	2	73546	19.09	1.83	1.14	22.06
	123.0	6.0	24.0	6.2894E+09	5.2412E+05	7.00	481.62	8.75730E+05	47.4	2	70542	19.50	1.83	1.14	22.48
	124.0	6.0	25.0	6.2951E+09	5.0361E+05	7.00	481.62	8.58602E+05	48.4	2	67782	19.90	1.83	1.14	22.87
	125.0	6.0	26.0	6.3010E+09	4.8469E+05	7.00	481.62	8.42322E+05	49.3	2	65236	20.29	1.83	1.14	23.26
	126.0	6.0	27.0	6.3071E+09	4.6719E+05	7.00	481.62	8.26842E+05	50.2	2	62881	20.66	1.83	1.14	23.63
	127.0	6.0	28.0	6.3134E+09	4.5096E+05	7.00	481.62	8.12091E+05	51.1	2	60696	21.02	1.83	1.14	23.99
	128.0	6.0	29.0	6.3201E+09	4.3587E+05	7.00	481.62	7.98030E+05	52.0	2	58665	21.37	1.83	1.14	24.34
	129.0	6.0	30.0	6.3271E+09	4.2181E+05	7.00	481.62	7.84619E+05	52.8	2	56772	21.71	1.83	1.14	24.68
	130.0	6.0	31.0	6.3345E+09	4.0868E+05	7.00	481.62	7.71823E+05	53.6	2	55005	22.05	1.83	1.14	25.02

AEC STUDY - JOB NO. 9765-001 - MECH. WET - MIDDLETOWN-HTGR

14.46.58.

MECHANICAL DRAFT TOWER

THE DESIGN TERMINAL TEMP. DIFFERENCE IS 6.00

THE DESIGN COLD WATER TEMPERATURE IS 93.00

THE DESIGN APPROACH IS 19.00

*****CONDENSER COST BREAKDOWN*****

TC=SATURATED STEAM TEMP.

DTI=INITIAL TEMP. DIFFERENCE

RA=TEMP. RISE

SC=BASE COST OF SHELL

CT=COST OF TUBES

EC=LABOR COST PER SHELL

CONCST=COST OF SHELL

CI=LABOR COST FOR INSTALLING CONDENSER

TECST=LABOR COST TUBING CONDENSERS

NCND=NUMBER OF CONDENSERS PER UNIT

NOTE*****

THE COST GIVEN HERE ARE FOR ONE UNIT

F-7	TC	DTI	RA	SC	CT	EC	CONCST	CI	TECST	NCND
	120.0	6.0	21.0	1.11707E+06	2.32476E+06	9.98462E+05	2.36228E+06	6.36601E+05	3.21684E+05	3
	121.0	6.0	22.0	1.08012E+06	2.27451E+06	9.85963E+05	2.30149E+06	6.32569E+05	3.07300E+05	3
	122.0	6.0	23.0	1.04643E+06	2.22703E+06	9.74146E+05	2.24594E+06	6.28757E+05	2.94184E+05	3
	123.0	6.0	24.0	1.01557E+06	2.18203E+06	9.62953E+05	2.19493E+06	6.25146E+05	2.82168E+05	3
	124.0	6.0	25.0	9.87218E+05	2.13937E+06	9.52334E+05	2.14795E+06	6.21720E+05	2.71128E+05	3
	125.0	6.0	26.0	9.61050E+05	2.09882E+06	9.42243E+05	2.10450E+06	6.18466E+05	2.60944E+05	3
	126.0	6.0	27.0	9.36855E+05	2.06024E+06	9.32642E+05	2.06426E+06	6.15368E+05	2.51524E+05	3
	127.0	6.0	28.0	9.14416E+05	2.02348E+06	9.23496E+05	2.02688E+06	6.12418E+05	2.42784E+05	3
	128.0	6.0	29.0	8.93550E+05	1.98845E+06	9.14779E+05	1.99208E+06	6.09606E+05	2.34660E+05	3
	129.0	6.0	30.0	8.74101E+05	1.95503E+06	9.06464E+05	1.95960E+06	6.06924E+05	2.27088E+05	3
	130.0	6.0	31.0	8.55947E+05	1.92314E+06	8.98530E+05	1.92927E+06	6.04365E+05	2.20020E+05	3

AEC STUDY - JOB NO. 9765-001 - MECH. WET - MIDDLETOWN-HTGR
 MECHANICAL DRAFT TOWER
 THE DESIGN TERMINAL TEMP. DIFFERENCE IS 6.00
 THE DESIGN COLO WATER TEMPERATURE IS 93.00
 THE DESIGN APPROACH IS 19.00

14.46.58.

*****CONNECTING PIPELINE AND INTAKE AND EXIT STRUCTURES*****

TC=SATURATED STEAM TEMP. DTI=INITIAL TEMP. DIFFERENCE
 RA=TEMP. RISE DP=DIAMETER OF PIPELINE (INCHES)
 NL=NUMBER OF LINES VP=WATER VELOCITY
 DPL=PRESSURE DROP (FT.) PCSI=PIPE COST PER UNIT
 ESCST=TOTAL EXCAVATION COST TPIPE=TOTAL COST OF EXCAVATING AND PIPE COST FOR ALL UNITS
 PICST=PIPE PLACEMENT COST CSTITS=COST OF INTAKE STRUCTURE
 NOTE*****

EACH UNIT WILL HAVE ITS OWN PIPELINES WITH PUMPS AND MOTORS. THE INTAKE STRUCTURE AND EXCAVATION ARE SHARED BY ALL UNITS...

	TC	DTI	RA	DP	NL	VP	DPL	PCST	PICST	ESCST	TPIPE	CSTITS	
F-8	120.0	6.0	21.0	144.0	1	11.77	.42	1.19533E+05	2.16000E+04	5.13000E+04	1.47691E+06	6.61549E+05	4.25
				102.0	2	11.73	1.55	2.27901E+05	7.48000E+04	1.44925E+05			
				102.0	2	11.73	.35	9.38250E+04	1.70000E+04	3.29375E+04			
				144.0	1	11.77	1.93	3.60992E+05	9.84000E+04	2.33700E+05			
	121.0	6.0	22.0	138.0	1	12.24	.48	1.09594E+05	2.07000E+04	4.78687E+04	1.34896E+06	6.50478E+05	5.00
				96.0	2	12.65	1.91	1.97729E+05	7.04000E+04	1.32000E+05			
				96.0	2	12.65	.43	8.25814E+04	1.60000E+04	3.00000E+04			
				138.0	1	12.24	2.18	3.29721E+05	9.43000E+04	2.18069E+05			
	122.0	6.0	23.0	138.0	1	11.72	.44	1.09594E+05	2.07000E+04	4.78687E+04	1.34896E+06	6.40090E+05	4.62
				96.0	2	12.11	1.77	1.97729E+05	7.04000E+04	1.32000E+05			
				96.0	2	12.11	.40	8.25814E+04	1.60000E+04	3.00000E+04			
				138.0	1	11.72	2.01	3.29721E+05	9.43000E+04	2.18069E+05			
F-8	123.0	6.0	24.0	132.0	1	12.29	.51	9.98257E+04	1.98000E+04	4.45500E+04	1.28471E+06	6.30318E+05	4.82
				96.0	2	11.62	1.64	1.97729E+05	7.04000E+04	1.32000E+05			
				96.0	2	11.62	.37	8.25814E+04	1.60000E+04	3.00000E+04			
				132.0	1	12.29	2.31	2.98673E+05	9.02000E+04	2.02950E+05			
	124.0	6.0	25.0	132.0	1	11.81	.47	9.98257E+04	1.98000E+04	4.45500E+04	1.23564E+06	6.21101E+05	5.17
				96.0	2	12.70	2.08	1.77903E+05	6.60000E+04	1.19625E+05			
				96.0	2	12.70	.47	7.39284E+04	1.50000E+04	2.71875E+04			
				132.0	1	11.81	2.14	2.98673E+05	9.02000E+04	2.02950E+05			
	125.0	6.0	26.0	126.0	1	12.47	.55	8.91025E+04	1.89000E+04	4.13437E+04	1.16616E+06	6.12388E+05	5.44
				96.0	2	12.22	1.94	1.77903E+05	6.60000E+04	1.19625E+05			
				96.0	2	12.22	.44	7.39284E+04	1.50000E+04	2.71875E+04			
				126.0	1	12.47	2.51	2.62723E+05	8.61000E+04	1.88344E+05			
F-8	126.0	6.0	27.0	126.0	1	12.02	.51	8.91025E+04	1.89000E+04	4.13437E+04	1.16616E+06	6.04135E+05	5.08
				96.0	2	11.78	1.81	1.77903E+05	6.60000E+04	1.19625E+05			
				96.0	2	11.78	.41	7.39284E+04	1.50000E+04	2.71875E+04			
				126.0	1	12.02	2.34	2.62723E+05	8.61000E+04	1.88344E+05			
	127.0	6.0	28.0	126.0	1	11.60	.48	8.91025E+04	1.89000E+04	4.13437E+04	1.16616E+06	5.96303E+05	4.76
				96.0	2	11.37	1.70	1.77903E+05	6.60000E+04	1.19625E+05			
				96.0	2	11.37	.39	7.39284E+04	1.50000E+04	2.71875E+04			
				126.0	1	11.60	2.19	2.62723E+05	8.61000E+04	1.88344E+05			
	128.0	6.0	29.0	120.0	1	12.36	.57	7.85496E+04	1.80000E+04	3.82500E+04	1.05548E+06	5.88860E+05	5.92
				84.0	2	12.62	2.23	1.62923E+05	6.16000E+04	1.07800E+05			
				84.0	2	12.62	.51	6.66159E+04	1.40000E+04	2.45000E+04			
				120.0	1	12.36	2.61	2.26996E+05	8.20000E+04	1.74250E+05			
F-8	129.0	6.0	30.0	120.0	1	11.97	.54	7.85496E+04	1.80000E+04	3.82500E+04	1.05548E+06	5.81777E+05	5.57
				84.0	2	12.21	2.10	1.62923E+05	6.16000E+04	1.07800E+05			
				84.0	2	12.21	.48	6.66159E+04	1.40000E+04	2.45000E+04			
				120.0	1	11.97	2.46	2.26996E+05	8.20000E+04	1.74250E+05			

AEC STUDY - JOB NO. 9765-001 - MECH. WET - MIDDLETOWN-HTGR
 MECHANICAL DRAFT TOWER
 THE DESIGN TERMINAL TEMP. DIFFERENCE IS 6.00
 THE DESIGN COLD WATER TEMPERATURE IS 93.00
 THE DESIGN APPROACH IS 19.00

14.46.58.

*****CONNECTING PIPELINE AND INTAKE AND EXIT STRUCTURES*****

TC=SATURATED STEAM TEMP. DT1=INITIAL TEMP. DIFFERENCE
 RA=TEMP. RISE DP=DIAMETER OF PIPELINE (INCHES)
 NL=NUMBER OF LINES VP=WATER VELOCITY
 DPL=PRESSURE DROP (FT.) PCST=PIPE COST PER UNIT
 ESCST=TOTAL EXCAVATION COST TPIPE=TOTAL COST OF EXCAVATING AND PIPE COST FOR ALL UNITS
 PICST=PIPE PLACEMENT COST CSTITS=COST OF INTAKE STRUCTURE

NOTE*****

EACH UNIT WILL HAVE ITS OWN PIPELINES WITH PUMPS AND MOTORS. THE INTAKE STRUCTURE AND EXCAVATION ARE SHARED BY ALL UNITS..

F-9	TC	DT1	RA	DP	NL	VP	DPL	PCST	PICST	ESCST	TPIPE	CSTITS	
	130.0	6.0	31.0	120.0	1	11.59	.51	7.85496E+04	1.80000E+04	3.82500E+04	1.05548E+06	5.75029E+05	5.26
				84.0	2	11.83	1.98	1.62923E+05	6.16000E+04	1.07800E+05			
				84.0	2	11.83	.45	6.66159E+04	1.40000E+04	2.45000E+04			
				120.0	1	11.59	2.32	2.26996E+05	8.20000E+04	1.74250E+05			

AEC STUDY - JOB NO. 9765-001 - MECH. WET - MIDDLETOWN-HTGR
 MECHANICAL DRAFT TOWER
 THE DESIGN TERMINAL TEMP. DIFFERENCE IS 6.00
 THE DESIGN COLD WATER TEMPERATURE IS 93.00
 THE DESIGN APPROACH IS 19.00

14.46.58.

*****PUMPS, MOTORS AND ASSOCIATED ELECTRICAL COMPONENTS*****

TC=SATURATED STEAM TEMP. DTI=INITIAL TEMP. DIFFERENCE
 RA=TEMP. RISE IPMP=TYPE NUMBER OF PUMP
 NPMP=NUMBER OF PUMPS AND MOTORS MHP=RATED MOTOR HORSEPOWER
 PHPP=RAKE HORSEPOWER OF PUMPS THD=TOTAL HEAD IN FT.
 CPMP=TOTAL COST OF PUMPS(\$) MCT=TOTAL COST OF MOTORS(\$)
 ECT=COST OF INSTALLATION OF ELECTRICAL COMPONENTS RLCT=TOTAL LABOR COST
 TCMPT=TOTAL COST OF PUMPS, MOTORS, AND ASSOCIATED ELECTRICAL COMPONENTS

NOTE*****

THE COSTS GIVEN ARE THE COSTS PER UNIT

F-10

TC	DTI	RA	IPMP	NPMP	MHP	PHPP	THD	CPMP	MCT	ECT	RLCT	TCMPT
120.0	6.0	21.0	3	4	3500	3155.4	74.45	9.00000E+05	4.90000E+05	2.80000E+05	1.60000E+05	1.83000E+06
121.0	6.0	22.0	3	4	3500	3062.7	75.64	9.00000E+05	4.90000E+05	2.80000E+05	1.60000E+05	1.83000E+06
122.0	6.0	23.0	2	4	3500	2933.4	75.68	7.56000E+05	4.90000E+05	2.80000E+05	1.60000E+05	1.68600E+06
123.0	6.0	24.0	3	3	4500	3782.1	76.30	6.75000E+05	4.72500E+05	2.70000E+05	1.20000E+05	1.53750E+06
124.0	6.0	25.0	3	3	4000	3669.5	77.04	6.75000E+05	4.20000E+05	2.40000E+05	1.20000E+05	1.45500E+06
125.0	6.0	26.0	3	3	4000	3561.5	77.69	6.75000E+05	4.20000E+05	2.40000E+05	1.20000E+05	1.45500E+06
126.0	6.0	27.0	3	3	4000	3433.6	77.71	6.75000E+05	4.20000E+05	2.40000E+05	1.20000E+05	1.45500E+06
127.0	6.0	28.0	3	3	4000	3316.1	77.75	6.75000E+05	4.20000E+05	2.40000E+05	1.20000E+05	1.45500E+06
128.0	6.0	29.0	3	3	4000	3267.7	79.27	6.75000E+05	4.20000E+05	2.40000E+05	1.20000E+05	1.45500E+06
129.0	6.0	30.0	3	3	3500	3162.0	79.26	6.75000E+05	3.67500E+05	2.10000E+05	1.20000E+05	1.37250E+06
130.0	6.0	31.0	2	3	3500	3064.1	79.27	5.67000E+05	3.67500E+05	2.10000E+05	1.20000E+05	1.26450E+06

AEC STUDY - JOB NO. 9765-001 - MECH. WET - MIDDLETOWN-HTGR

14.46.59.

MECHANICAL DRAFT TOWER

THE DESIGN TERMINAL TEMP. DIFFERENCE IS 6.00

THE DESIGN COLD WATER TEMPERATURE IS 93.00

THE DESIGN APPROACH IS 19.00

*****MECHANICAL DRAFT COOLING TOWER*****

RA=TEMP. RISE

PHDM=TOWER PUMPING HEAD

HP=FAN HORSEPOWER

NTOW=NUMBER OF TOWERS

NCELLS=TOTAL NUMBER OF CELLS

WATERF=WATER FLOW RATE PER CELL

COST=COST PER CELL

GPM MAX=MAXIMUM MAKE-UP FLOW RATE

GPY=YEARLY MAKE-UP REQUIRED

CHAR77=DESIGN CHARACTERISTIC

RLG77=DESIGN WATER TO AIR RATIO

	RA	PHDM	HP	NTOW	NCELLS	WATERF	COST	GPM MAX	GPY	CHAR77	RLG77
F-11	21.0	41.00	183.59	3	29	2.0604E+04	1.2750E+05	1.3828E+04	4.2223E+09	.9912	1.9090
	22.0	41.00	180.55	3	29	1.9683E+04	1.2750E+05	1.3809E+04	4.2298E+09	1.0076	1.8557
	23.0	41.00	183.93	3	28	1.9515E+04	1.2750E+05	1.3792E+04	4.2379E+09	1.0231	1.8074
	24.0	41.00	180.98	3	28	1.8719E+04	1.2750E+05	1.3784E+04	4.2462E+09	1.0379	1.7633
	25.0	41.00	184.72	3	27	1.8652E+04	1.2750E+05	1.3772E+04	4.2548E+09	1.0520	1.7228
	26.0	41.00	181.85	3	27	1.7952E+04	1.2750E+05	1.3761E+04	4.2621E+09	1.0654	1.6855
	27.0	41.00	179.08	3	27	1.7303E+04	1.2750E+05	1.3752E+04	4.2707E+09	1.0782	1.6511
	28.0	41.00	183.19	3	26	1.7345E+04	1.2750E+05	1.3744E+04	4.2795E+09	1.0905	1.6193
	29.0	41.00	180.50	3	26	1.6764E+04	1.2750E+05	1.3737E+04	4.2884E+09	1.1022	1.5897
	30.0	41.00	177.90	3	26	1.6223E+04	1.2750E+05	1.3732E+04	4.2976E+09	1.1134	1.5622
	31.0	41.00	182.40	3	25	1.6347E+04	1.2750E+05	1.3729E+04	4.3069E+09	1.1242	1.5365

APPENDIX G

ANNUAL TEMPERATURE DURATION CURVES

This appendix presents the annual temperature duration curves for the dry bulb and coincident wet bulb temperatures of Denver, Colorado (Figure G-1) and Miami, Florida (Figure G-2) that were used in the sensitivity analysis.

FIGURE G-1

Annual Temperature Duration Curves for the Dry Bulb and Coincident Wet Bulb Temperatures used in the Sensitivity Analysis, Denver, Colorado

FIGURE G-2

Annual Temperature Duration Curves for the Dry Bulb and Coincident Wet Bulb Temperatures used in the Sensitivity Analysis, Miami, Florida