OPTIMUM DRY COOLING TOWER-COOLING POND COMBINATIONS FOR POWER PLANT HEAT REJECTIONS

by

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NOMENCLATURE

Symbol	Significance	Units
A	Pond area at any point	ft^2
A_b	Outside tube surface area of air heat exchanger	ft^2
A_d	Face area of air heat exchanger	ft^2
A_p	Area of the pond	ft^2
C	Brunt's coefficient	dimensionless
C_d	Dry tower capital cost factor (w.r.t. face area)	$\$/ft^2$
C_p	Pond capital cost factor	$\$/ft^2$
C_{pa}	Specific heat of air at constant pressure	Btu/lbm-°F
C_{pf}	Fan and Pump power consumption cost factor	$/KWh
C_{pw}	Specific heat of water at constant pressure	Btu/lbm-°F
C_T	Total costs	$/day
C_w	Water cost factor	$/lbm
D_i	Inside diameter of air heat exchanger tubes	ft
D_o	Outside diameter of air heat exchanger tubes	ft
E	Pond (water surface) equilibrium temperature	°F
e_{a1}	Air vapor pressure at temperature T_{a1}	mmHg
e_s	Saturated water vapor pressure at temperature T_s	mmHg
F_s	Safety factor used in fan power calculations	dimensionless
g_c	Dimensional conversion factor	$lbm\text{-}ft/lbf\text{-}sec^2$
H_a	Longwave atmospheric radiation to the pond	$Btu/ft^2\text{-}day$
H_{ar}	H_a reflected back by the pond	$Btu/ft^2\text{-}day$

H_{br}	Long wave back radiation from pond water surface acting as a black body	Btu/ft^2-day
H_c	Heat loss or gain due to convection by pond	Btu/ft^2-day
H_e	Heat loss due to water evaporation from pond	Btu/ft^2-day
H_o	Clear sky solar radiation	Btu/ft^2-day
H_s	Shortwave radiation to the pond	Btu/ft^2-day
H_{sr}	H_s reflected back by the pond	Btu/ft^2-day
K	Heat exchange coefficient used in pond calculations	Btu/ft^2-day-°F
L	Length of air heat exchanger tubes	ft
M_e	Mass of water evaporated	lbm/day
m_a	Mass flow rate of air	lbm/day
m_w	Mass flow rate of water	lbm/day
N	Number of tubes per square foot of A_d	tubes/ft^2
P	Atmospheric ambient pressure	mmHg
P_f	Power consumption by fan	KWh/day
P_p	Power consumption by pump	KWh/day
Q	Volumetric flow rate of water	ft^3/day
Q_a	Heat dissipated by air	Btu/day
Q_r	Total heat to be dissipated	Btu/day
R	Number (depth) of tube rows in the air heat exchanger	dimensionless
R_a	Ratio of outside diameter to inside diameter of heat exchanger tubes (D_o/D_i)	dimensionless
S	Fraction of possible sunshine	dimensionless
T_A	Temperature of pond water surface at any area A	°F
T_{a1}	Ambient air dry bulb temperature	°F
T_{a2}	Temperature of (heated) air coming out of dry tower	°F

T_s	Average pond surface temperature	°F
T_1	Temperature of water coming out of the condenser	°F
T_2	Temperature of water coming out of dry tower (intermediate temperature)	°F
T_3	Temperature of water going back to the power plant (after being cooled)	°F
U	Overall heat transfer coefficient for air heat exchanger (referred to outside bare tube surface area A_b)	Btu/ft^2-day-°F
V_d	Air face velocity flowing across dry tower face area, A_d	ft/day
V_f	Air face velocity flowing across dry tower face area, A_d	ft/min
VP[T]	Notation to indicate calculation of saturated air vapor pressure at given temperature T	mmHg
V_m	Maximum air velocity at minimum cross-section in a tube row	ft/min
V_w	Velocity of water flow inside the tubes	ft/sec
W	Ambient wind velocity	mph

Greek Letters

β	Slope of saturated vapor pressure curve at that temperature	mmHg/°F
β_a	ratio of bare tube area to face area of the dry tower $\frac{A_b}{A_d}$	dimensionless
γ_w	Emmisitivity of water	dimensionless
ΔH	Net heat exchange rate between the pond and the the environment	Btu/ft^2-day

ΔP	Pressure difference	lb_f/ft^2
ρ_a	Density of air	lbm/ft^3
ρ_w	Density of water	lbm/ft^3
σ	Stephen-Boltzman Constant	$Btu/ft^2\text{-}day\text{-}°R^4$

CHAPTER 1

INTRODUCTION

In response to the energy-environment crisis, local, state and national governments have come out with strict regulations regarding the indiscriminate use of land and water by industry. As a result the once almost unlimited source of natural river water to the power industry is no longer freely available for power plant cooling. Rising costs of land and water and the strict water temperature rise standards are forcing the utility companies to look at alternate methods of power plant cooling.

The alternatives are and have been:

1. Cooling by dry tower
2. Cooling by wet tower
3. Cooling by ponds

Wet towers and ponds for heat dissipation are not new to the power industry and dry tower cooling has been used by some European power producers. However, in the U.S.A. only the chemical and refinery process industries possess experience in the application of dry cooling equipment. They have also used combinations of dry and wet cooling towers (trim cooling), for better efficiency and economy [1]*.

For a reasonable approach to ambient air dry bulb temperature with dry cooling towers, large (and expensive) heat transfer surface area is required because of the small temperature difference between the condenser cooling water and air, particularly in the last stages of the heat transfer process.

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* Number in brackets designate references in the List of References.

A system combining a dry tower and an evaporative system such as a pond or a wet tower can possibly prove to be a more economical system. It takes advantage of relatively high initial water - air dry bulb temperature difference in the dry section; and as this difference diminishes, the cooling water is transferred to the evaporative section. In the evaporative section the driving temperature difference again increases, becoming essentially the difference between the water temperature and the air wet bulb temperature.

Engineers in the power industry compared to their counterparts in the process industries are inexperienced in the area of dry cooling. Rossie and Cecil [2] state that (as of 1970) there are only two (small) power plants in the U.S.A. using dry towers for cooling purposes. Combination cooling, a possible next step to the dry or wet cooling is sparingly mentioned in the literature. For instance Kolfat [3] mentions the use of a small dry tower as a solution to dissipate a fraction of heat load so as to help in satisfying the water rise temperature requirements, when rejecting heat in a stream in otherwise a once through system.

The main objective of this study was to determine an optimum least cost dry tower - cooling pond combination for power plant heat rejection. This was accomplished by showing that for a given thermal load, ambient air condi-conditions, power plant characteristics and different capital and operational costs, an intermediate temperature T_2, within the cooling range (T_1-T_3) can be found which determines the proportions of dry and wet cooling in the least cost combination. The study includes discussion of the influence of the several variables on the results to illustrate the effects of local environmental conditions, costs and power plant economics. Comparison of the combined system to total dry and total pond systems is also provided.

The heat rejection and the subsequent dissipation is not a simple and independent process in a power plant. The temperature at which the heat is rejected in the condenser along with the cooling range, determines not only the overall thermal efficiency of the power plant but also influences its economy. For example, the size of the condenser, pumps, the boiler feed-water heaters etc. are all interrelated to the cooling process. Thus optimizing the cooling process also involves all the above mentioned variables, step by step and for the power plant as a whole. As much as the author would have wished, optimizing the entire power plant and its sections with regards to the most efficient cooling process was beyond the scope of this study. Hence a number of variables were made constant and many constraints in the plant and in the method of solving the problem had to be introduced.

The conditions in the entire power plant from the boiler to the steam condenser were assumed to be fixed, i.e. everything about the plant was known and the heat rejection load kept constant. From this system a known amount of heated water at a given temperature T_1 comes out to be cooled by a cooling process and then returns back to the plant at a given temperature T_3. With these assumptions, the heat load was considered to be dissipated by three different cooling processes:

1. By a dry tower alone
2. By a cooling pond alone
3. By a combination of the above two.

The three systems are indicated in Figures 1a, b and c. Modeling equations for these systems were written and were used to determine total costs resulting from specification of different sets of environmental conditions, capital and operational costs. Additionally, for the combined system, T_2 was varied to determine its influence on total cost.

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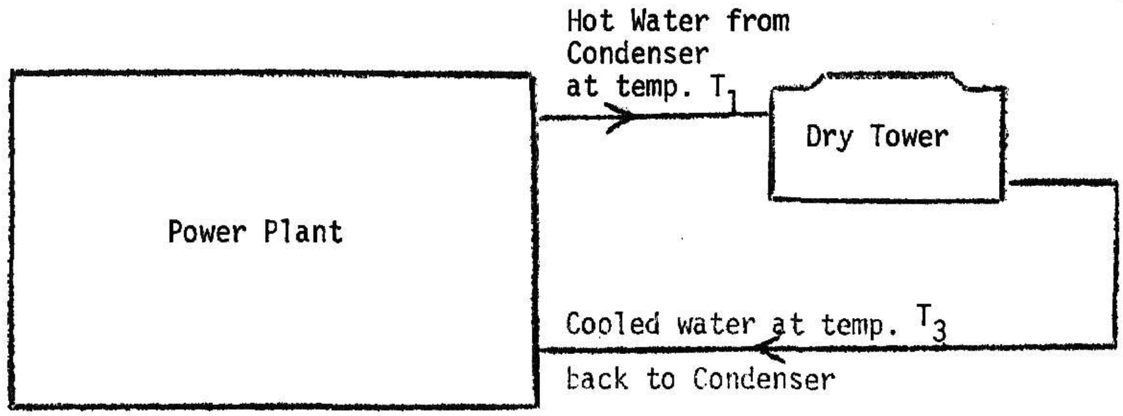
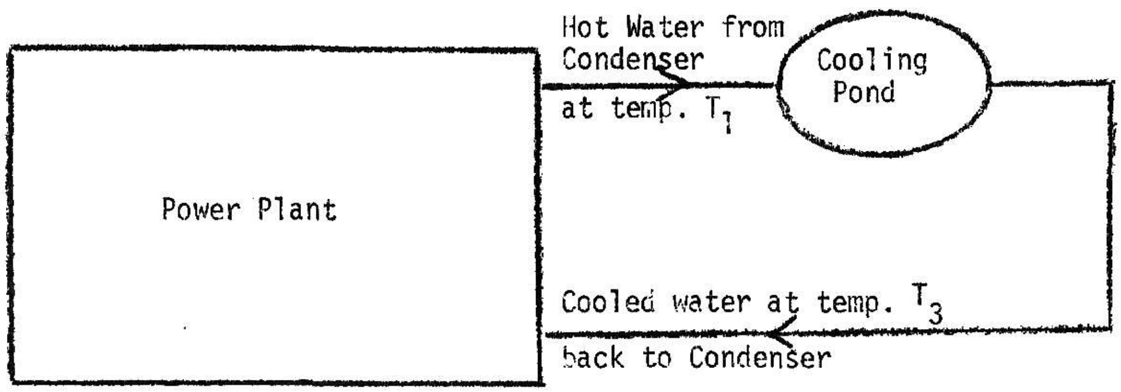
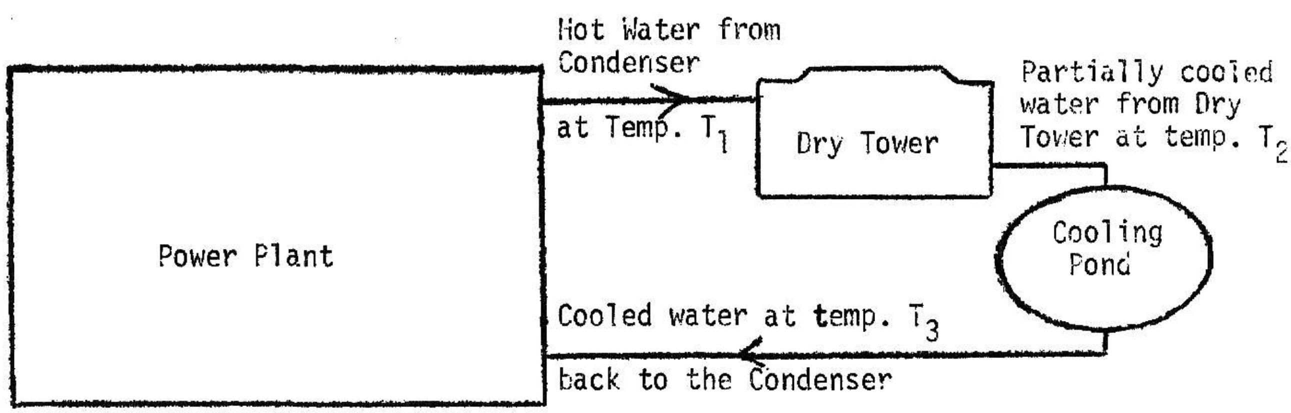


a) Cooling by a Dry Tower



b) Cooling by a Pond



c) Cooling by a Combination of a Dry Tower and a Pond

Figure 1. Schematic Diagrams of Three Different Cooling Processes.

CHAPTER 2

SPECIFICATION OF STANDARD PLANT SIZE AND OPERATING CONDITIONS

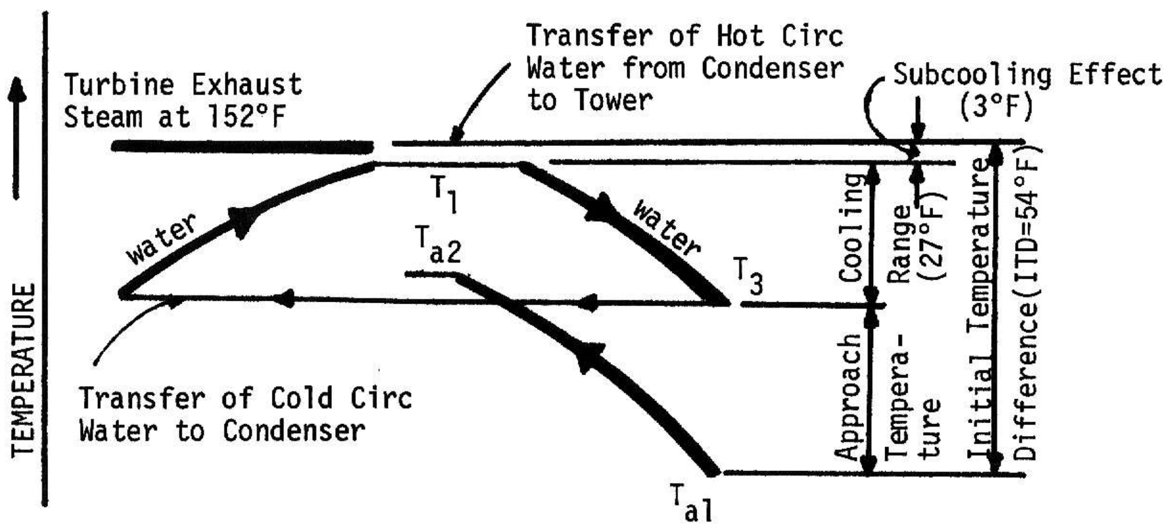
Specification of Plant Size

Out of 292 fossil fueled power plants in the 500 MW to 4000 MW range tentatively planned for the year 1990, Rossie and Cecil [2] estimate that 244 will be in 500-2000 MW range. Most of them seem to be around 1000 MW. Hence, a 1000 MW plant output was chosen for this study. Based on the figures given by Cootner and Löf [4] an overall plant efficiency of 40.0 percent, a heat loss of 10.0 percent in the boiler furnace and a generator efficiency of 97.5 percent was assumed. A cooling range of 27°F was selected, the rationale for this selection will be developed later.

Specification of Environmental Conditions

For reference temperatures, 98°F air dry bulb and 50°F dew point temperatures were picked. These temperatures were obtained after averaging one percent summer design temperatures given in the ASHRAE Handbook of Fundamentals [5] for parts of the states of Wyoming, Utah, South Dakota, Arizona, New Mexico and Texas. Because of water shortages, these areas are representative of areas where dry cooling may be planned. Also, being some of the hottest parts of the country, dry cooling may not be very attractive (thus hopefully giving equal disadvantages to both dry and wet cooling). Sunny day conditions (0.1 cloud cover) and a wind velocity of ten miles per hour were specified.

Because of high condenser cooling water temperatures resulting from dry cooling tower use in hot environments, a high back pressure turbine is required. An eight inch back pressure turbine was selected as reasonable. Conventional turbines can be operated at this back pressure if modified [2]. For this back pressure the exhaust steam temperature is 152°F; consequently, the difference between the exhaust steam temperature and the air dry bulb (initial temperature difference ITD) is 54°F. Graphs plotted in reference [2] suggest a cooling range of 27°F for these conditions. A 3°F subcooling effect was assumed in the condenser. Thus water at 149°F was cooled to 122°F (see Figure 2).



Note: The above sketch does not imply flow relationships.

Figure 2. Temperature Diagram of Indirect Dry Cooling Tower Heat Transfer System.

The intital temperature difference of 54°F fits within the optimum ITD range suggested by Rossie and Cecil [2]. These conditions also give an approach of 24°F to the air dry bulb temperature.

Specifications of Dry Tower and Pond Types

Dry tower specifications were taken from a brochure published by the Hudson Products Corporation [6]. The values were assumed to be typical of dry tower specifications. An air heat exchanger having an overall heat transfer coefficient U (referred to the bare tube outside surface) of 2880 Btu/day-ft^2-°F, tube size of one inch O.D. and 0.782 inside diameter (0.762 sq. ft./lineal ft.) was chosen. Fins are 5/8" high, spaced 8 per inch with a surface ratio of 16.9. Ratio of bare tube area to face area of 5.04 and air face velocity V_f of 595 ft./min. was assumed. The depth of the tube rows, R, was four. On the water side of the exchanger, the water velocity V_w inside the tubes was fixed as 10 ft./sec.

A flow-through pond with an average depth of five feet was chosen. Edinger and Geyer [7] point out that a shallow pond dissipates much more heat than a deep pond. They also show that a flow-through pond requires less area than a completely mixed pond for the same amount of heat dissipation.

CHAPTER 3

THEORY AND MODELING EQUATIONS

Heat Balance and Transfer Equations

The heat transfer and balance equations for the combined cooling process were written as:

$$Q_r = m_w C_{pw} (T_1 - T_3) \tag{1}$$

$$m_w C_{pw} (T_1 - T_3) = m_a C_{pa} (T_{a1} - T_{a2}) + KA_p (T_s - E) \tag{2}$$

$$m_a C_{pa} (T_{a1} - T_{a2}) = \frac{UA_b}{2} [(T_1 - T_{a2}) + (T_2 - T_{a1})] \tag{3}$$

$$m_a = \frac{\rho_a V_d A_b}{\beta_a} \tag{4}$$

$$KA_p (T_s - E) = m_w C_{pw} (T_2 - T_3) \tag{5}$$

Equations for dry tower cooling only can be obtained by substituting A_p=0 and T_2=T_3 in the above equations. Similarly if A_b=0 and T_2=T_1 are substituted, equations for pond cooling only can be obtained.

The theory presented for the heat exchange between the pond and the environment is that developed by Edinger and Geyer [7]. In equation (2), the equilibrium temperature E is the same as that given by Edinger and Geyer [7]. They define it as the water surface temperature T_s=E, for which there is no net heat exchange between the water and the environment. E (calculated for no heat load from the power plant to the pond), is dependent on the meterological conditions including radiation, dry and wet bulb temperatures and the wind velocity. Details of determination of E are given in Appendix A.

In equation (3), it would be more exact to use a log mean temperature difference. However, for the conditions being considered, the change in water temperature in the dry tower is relatively small, making it acceptable to use the arithmetic mean temperature. The approximation allowed for algebraic simplicity in determination of T_{a2} from equations 2, 3 and 4.

The Cost Equation

To determine the cooling system costs the following equation was used:

$$C_T = C_d A_d + C_p A_p + C_w M_e + C_{pf}(P_f + P_p) \tag{6}$$

The areas A_d and A_p, the evaporated water mass M_e and the fan and pump power requirements P_f and P_p were determined in terms of T_2 so that T_2 could be varied to study its influence on total cost. Detailed derivations of A_d, A_p, M_e, P_f and P_p in terms of T_2 are shown in Appendix A. In the final form the derived relationships are as follows:

By the use of equations (1, 2, 3 and 4), A_d can be expressed as

$$A_d = \frac{m_w C_{pw}(T_1 - T_2)\left(1 + \frac{\beta_a U}{2\rho_a V_d C_{pa}}\right)}{0.5\ \beta_a U(T_1 + T_2 - 2Ta_1)} \tag{7}$$

A_p was obtained by Edinger and Geyer [7] theory.

$$A_p = \frac{\rho_w C_{pw} Q}{K} \times \log_e\left(\frac{T_2 - E}{T_3 - E}\right) \tag{8}$$

M_e was determined as a function of A_p and T_2

$$M_e = \frac{A_p(73 + 7.3W)}{971.0} \{VP[(T_2 - T_3)/\log_e(\frac{T_2 - E}{T_3 - E}) + E] - VP(T_{dp})\} \tag{9}$$

P_f was determined from the expression given by Cook [8]

$$P_f = \frac{A_d F_s R V_f (1.945 V_f)^{1.725} \times 3.24 \times 60 \times 24 \times 5.20218 \times 3.766 \times 10^{-7}}{10^8 \rho_a} \tag{10}$$

Using friction factors and formula outlined in Kreith's heat transfer text [9]

$$P_p = \frac{0.184 R_e^{-0.2}}{2 \times 4 \times R_a g_c} \rho_w V_w^3 \beta_a A_d \times 3600 \times 24 \times 3.766 \times 10^{-7} \tag{11}$$

It may be noted that for the sake of calculational simplicity and uniformity, all the dry tower bare tube surface areas A_b were converted to equivalent face areas, A_d.

Estimation of Cost Factors

Referring back to equation (6), the cost factors to be estimated were C_d, C_p, C_w and C_{pf}. Since the costs vary from location to location, a range had to be estimated in which these factors could vary. Most of the values were taken directly as quoted in the various literature sources. Different authors have given different costs which were of great help in determining the range of variation.

Determination of C_{pf}. Leung and Moore [10] and Larinoff [11] quote unit power costs of 1.7 cents per KWh to the consumer. Reistad et.al. [12] give a range of 0.75 cents to 1.75 cents per KWh. From these values a range from 1 cent to 2 cents per KWh was established as reasonable for this study.

Determination of C_w. Smith and Larinoff [13] quote present day water costs of 30 cents per 1000 gallons which may go up to 50 cents per 1000 gallons in the future. Several other sources agree with the above figures. Hence the range was taken to be 30 cents to 50 cents per 1000 gallons.

Determination of C_p. Estimation of pond capital costs involved mainly three individual costs, namely: the cost of the land, the cost of excavation, and the cost of land improvement and initial water fill up. Eicher [14] indicates land costs between $500 to $2000 per acre which is again confirmed by other sources. Excavation costs were estimated from some examples given by Peurifoy [15] to be from 60 cents to 90 cents per cubic yard. Land improvement and water fill up costs were taken between $500 to $2000 per acre. A similar range is given by Szego [16]. Adding all these costs, the range of C_p for a five foot deep pond was from 38 cents to 60 cents per square foot.

Determination of C_d. Price estimates in reference [6] suggest a range of $7 to $10 per square foot of bare tube surface area. In terms of face area, after lowering the lower end of the range and adding approximately $5 as costs for transportation, steel structures etc., the estimated range selected was $30 to $54 per square foot of face area.

Calculational Scheme

A computer program (shown in Appendix B) was written which, for specified values of T_2, determined values for the terms of equation (6). After calculating the heat load from the power plant, the program calculates E and K for specified T_{a1} and T_{dp}. With E and K known, the program then through a set of do-loops, determines A_d, A_p, M_e, P_f and P_p and then computes various subcosts and total costs. 720 data sets were generated by varying environmental and cost parameters, T_{a1}, T_{dp}, C_p, C_w and C_{pf}, over the ranges specified above.

Several things must be noted at this point. To keep the generated data to a managable amount, C_p was not varied. Instead an average value of 50 cents per square foot was assumed. All the costs were determined on daily basis and included daily capital costs and operational costs, which consisted of the cost of water evaporated and power costs to run the fan and the pumps. In the dry tower and pond capital costs a capital recovery factor of 0.0937 was used (based on a life period of 25 years and an interest rate of eight percent).

The program was arranged to determine minimum total costs and the corresponding T_2 by a search routine. Since this study was concerned with illustrating the relative effect of each of the variables, complete information for each value of T_2 was computed and the minimum cost was easily selected.

If only the minimum cost conditions are desired, a preferred method would be to determine T_2 from solution of the equation obtained by differentiating equation (6) the cost equation, with respect to T_2 and setting it equal to zero. This development is presented in Appendix A. The solution by this method is not simple. The problem arises in getting an exact derivative of the evaporation term in the equation.

CHAPTER 4

RESULTS AND DISCUSSION

As mentioned in the introduction, a reference set of environmental conditions and costs was assumed. Results for the reference case were established for comparison to results obtained when the various parameters were varied over their allowable ranges. The reference case used was:

$$T_{a1} = 98°F, \quad T_{dp} = 50°F$$

with cost factors C_d = \$38.0/sq.ft., C_p = \$0.5/sq.ft., C_w = \$0.000044/lbm and C_{pf} = \$0.015/KWh.

For this reference case the results are shown in Figure 3. The top curve in the figure is a plot of equation (6) giving the total costs as a function of T_2, the temperature at which water is taken from the dry tower and introduced into the pond. A distinct minimum is obtained at 135°F. The water coming out of the condenser at 149°F is first cooled in the dry tower to 135°F, then transferred to the pond for cooling to 122°F. From Table 1, it can be seen that this combination results in a net saving of 9.5 percent compared to all-dry cooling costs and a net daily saving of 8.2 percent compared to total-pond cooling system costs. In Figure 3, the breakdown of various costs shows that the pond and dry tower capital costs are small compared to evaporation and power costs on a daily basis. These proportions will change, of course, with capital costs, depreciation schedule, power and water costs.

The effects of various parameters on the reference case are shown in Figures 4, 5, 6 and 7. Figure 4 shows the effect of variation of the dry bulb

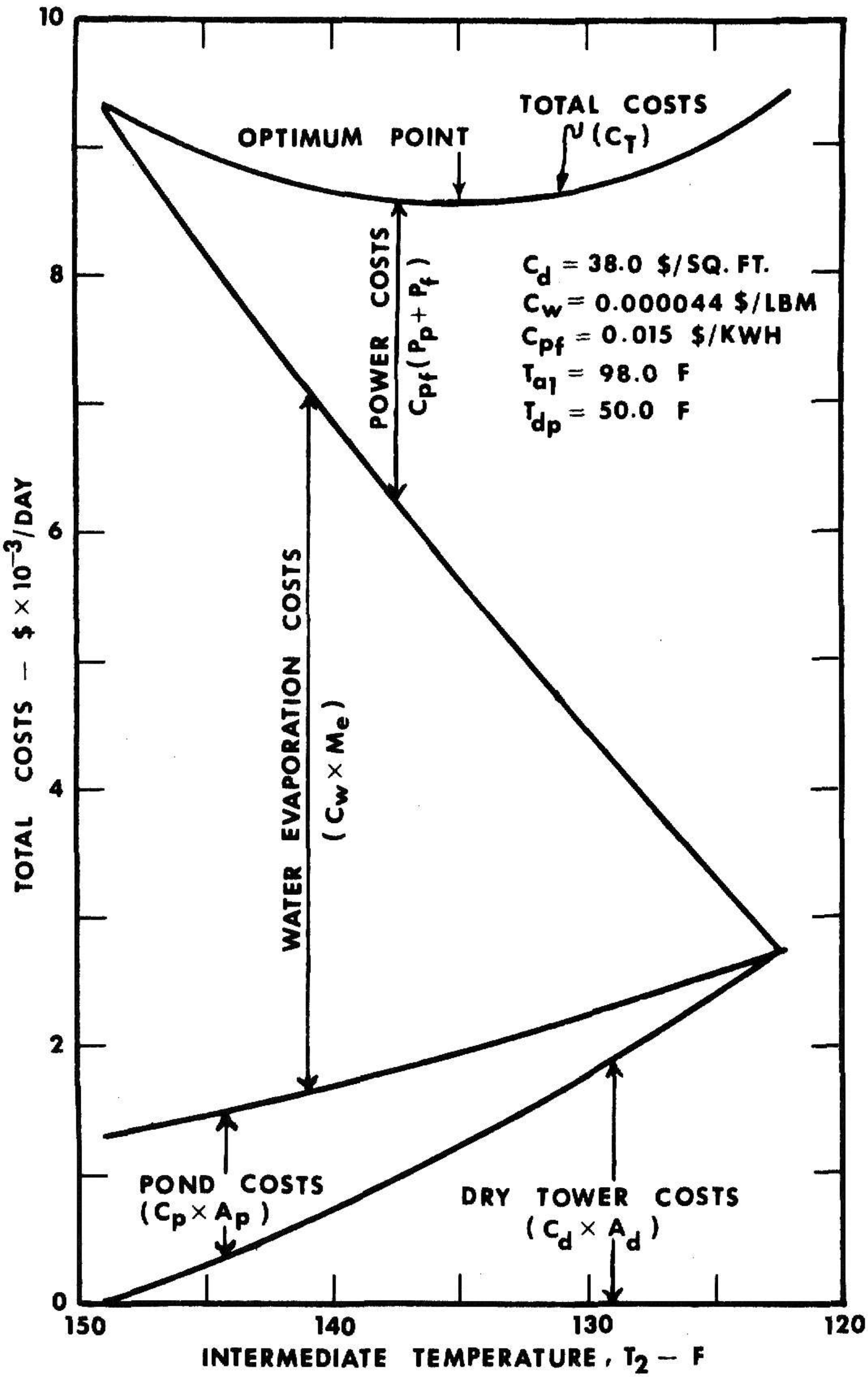


Figure 3. Breakdown of Various Costs for the Reference Case

Table 1

Summary of Typical Results

C_w \$/day	C_d \$/day	C_{pf} \$/day	T_{dp} °F	T_2 °F	Combined System costs \$/day	Only Dry Tower Cooling \$/day	Only Pond Cooling \$/day	% Saving if Combined Cooling used instead of dry tower	pond
				T_{a1} = 90°F, C_p = \$0.5					
0.000052	54.0	0.0175	50	130	9291	9635	10790	3.57	13.89
0.000044	46.0	0.0150	65	132	7989	8242	9333	3.07	14.40
0.000036	30.0	0.0125	80	131	6180	6373	6978	3.03	11.45
				T_{a1} = 98°F, C_p = \$0.5					
0.000044	38.0	0.015	50	135	8524	9423	9284	9.54	8.19
0.000060	46.0	0.020	65	137	10830	12230	11600	11.45	6.64
0.000052	30.0	0.010	80			6619	9578	dry cooling cheapest	
				T_{a1} = 106°F, C_p = \$0.5					
0.000036	38.0	0.0175	50			13390	7829	pond cooling cheapest	
0.000044	38.0	0.0150	65	145	8816	11980	8891	26.41	0.84
0.000060	54.0	0.0125	80	138	10320	12030	10970	14.21	5.93

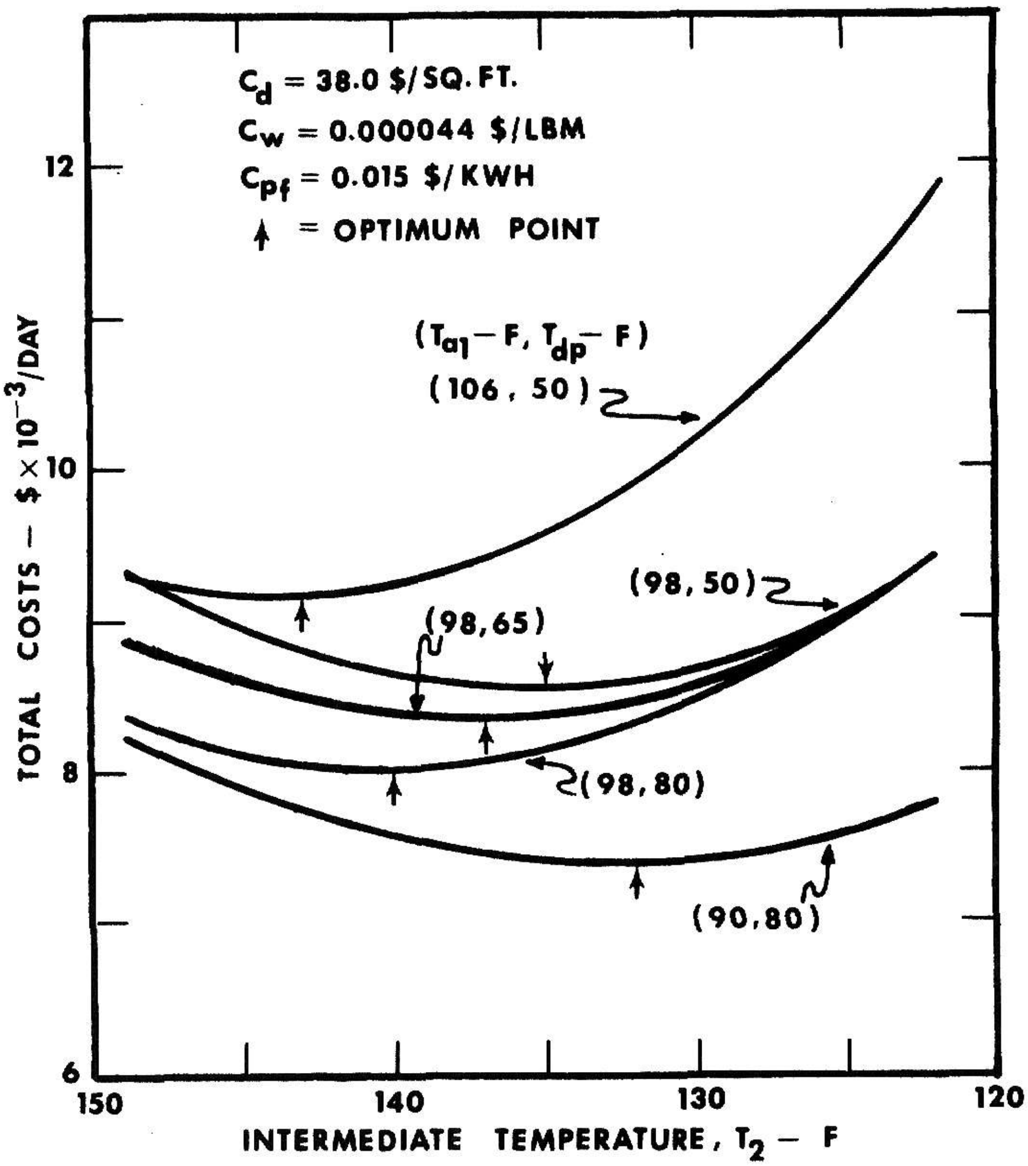


Figure 4. Effects of Dry Bulb and Dew Point Temperatures on the Optimum T_2.

and dew point temperatures. The dry bulb was varied from 98°F to 90°F and 106°F. As the dry bulb temperature goes up, the curves suggest that more and more pond cooling should be used. For instance the optimum point for the condition T_{a1} = 98°F and T_{dp} = 50°F, occurs at 135°F while for the condition T_{a1} = 106°F and T_{dp} = 50°F it occurs at 143°F. The dew point was varied from 50°F to 80°F in increments of 15°F. For a fixed dry bulb temperature, the change in dew point temperatures suggest that lower the dew-point, the greater is the proportion of dry cooling in a combined system. This stems from the fact that a lower dew point means more water evaporation which means higher water costs. In Figure 4 with T_{a1} of 98°F, for a T_{dp} of 80°F, the minimum point is at 140°F while at T_{dp} of 50°F the minimum shifts to 135°F.

Figure 5 shows the effects of variation of dry tower costs, C_d. At low dry tower costs, dry cooling definitely is more attractive and the optimum T_2 shifts towards a greater percent of dry cooling in the combined system. As C_d increases, the minimum moves towards all pond cooling. Effects of dry tower costs with changing dry bulb are also shown in Figure 5. Combination of both high dry bulb and high dry tower costs can drive the optimum point to nearly all pond cooling as shown in the topmost curve of Figure 5. The lower-most curve shows the other extreme of almost all dry cooling for low dry bulbs and low dry tower costs.

The effects of the water costs, C_w, variations are shown in Figure 6. The results support the obvious. The higher the water costs, the greater is the shift of optimum T_2 towards 122°F, implying total dry system. It can also be deduced by comparing Figure 6 and Figure 4 that high water costs and high dew point tend to act against each other i.e. the high costs would try to shift the minimum towards dry cooling while high dew point would try to shift it in the other direction; towards wet cooling.

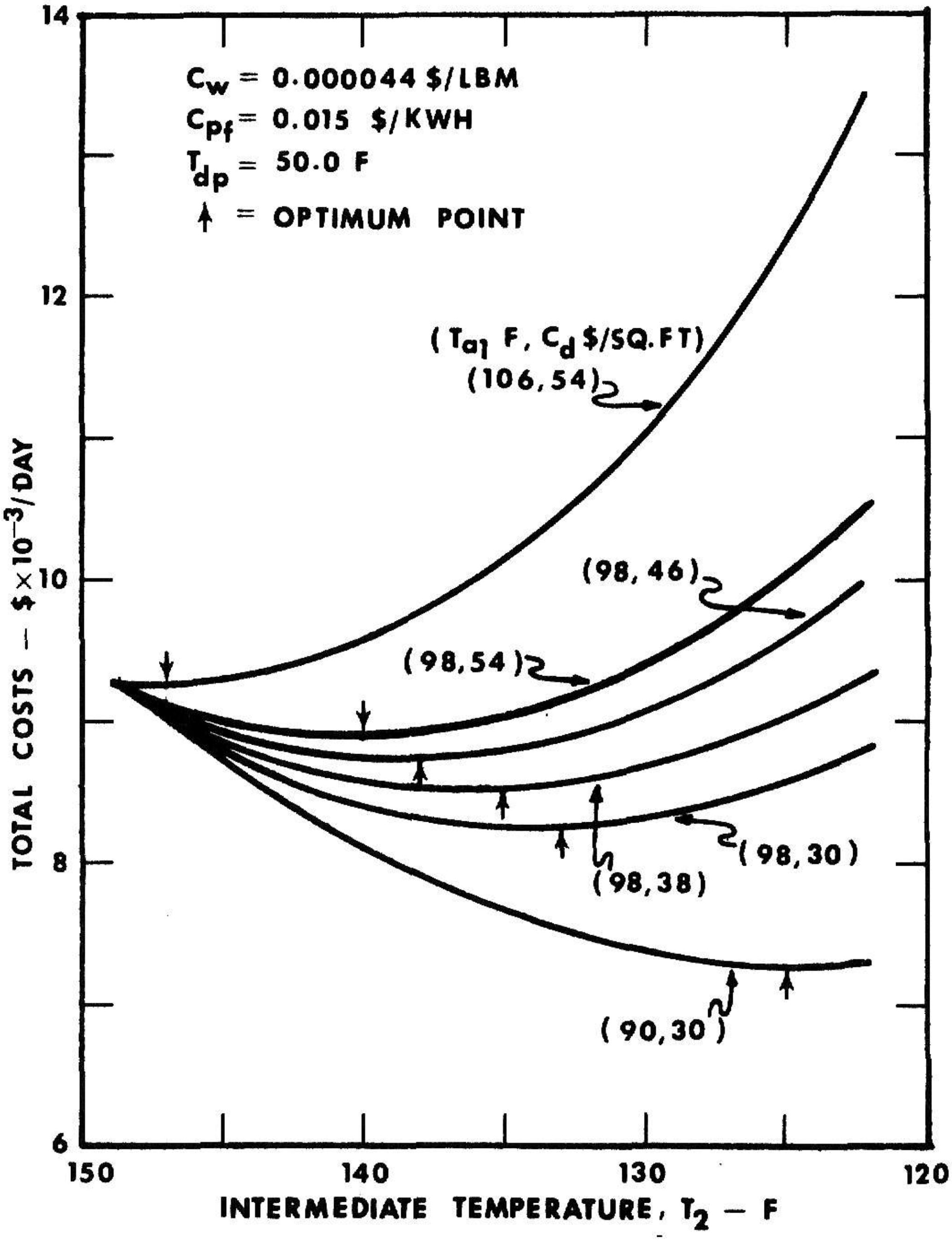


Figure 5. Effects of Dry Tower Costs on the Optimum T_2.

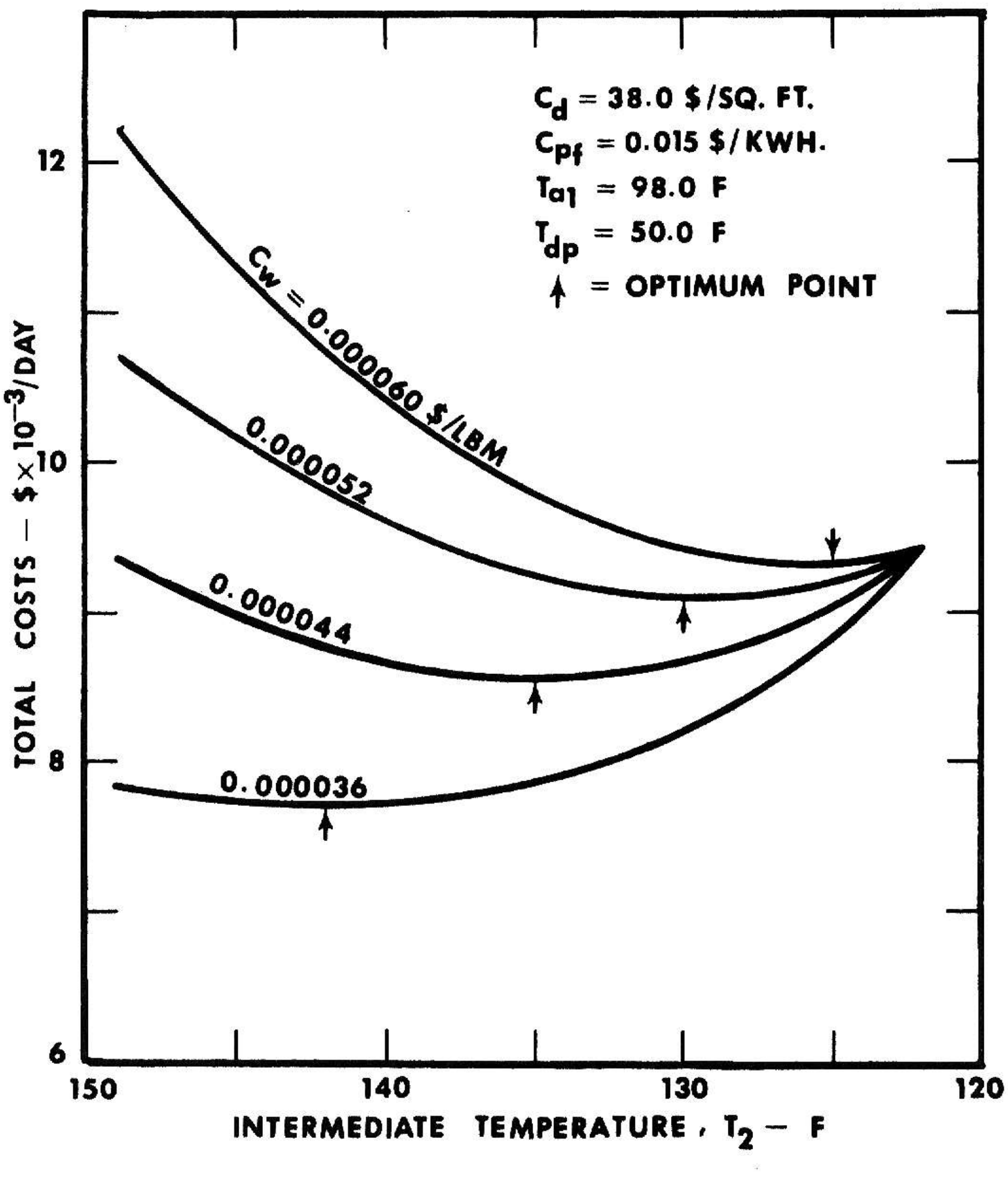


Figure 6. Effects of Water Costs on the Optimum T_2.

The set of curves shown in Figure 7 are for different power costs. These illustrate the extreme importance of power costs in the total daily cooling costs in a power plant. An increase of one cent in power costs from one cent per KWh to two cents per KWh results in almost fifty percent increase in cooling costs, and the minimum cost shifts from (almost all dry cooling at) 125°F to 144°F (almost all pond cooling).

In Table 1, are shown nine different cases selected to illustrate that depending on the local environmental and cost factors, savings up to 26 percent can be made by using a combined system. Out of 720 different sets of conditions generated by the computer program, 80 showed that all dry cooling was cheapest. These were mainly for conditions where dry tower and power costs were low and dry bulb temperature was low. 105 sets showed that all pond cooling was cheapest. These cases were again for the extreme cases where water costs and the dew point temperature were low. However for average conditions and cost factors, distinct optimum temperatures (T_2's) were obtained.

The results for the reference case of Figure 3 also show (see sample results in Appendix B) that while 232 acres of land area would be required for all pond cooling, only 130 acres are required with the optimum combination. Land area of 232 acres for all pond cooling for a 1000 MW plant seems small compared to the areas of at least 1000 acres generally noted in the literature. The difference in the two figures is due to two facts. First, the cooling range used typically for all pond cooling is 15 to 20°F. The range for the system under study is 27°F. For the same thermal load and for low cooling range, this implies greater cooling water rate and larger ponds for total pond systems. Secondly, the water approach temperature is usually very close to the equilibrium temperature, thus decreasing the temperature

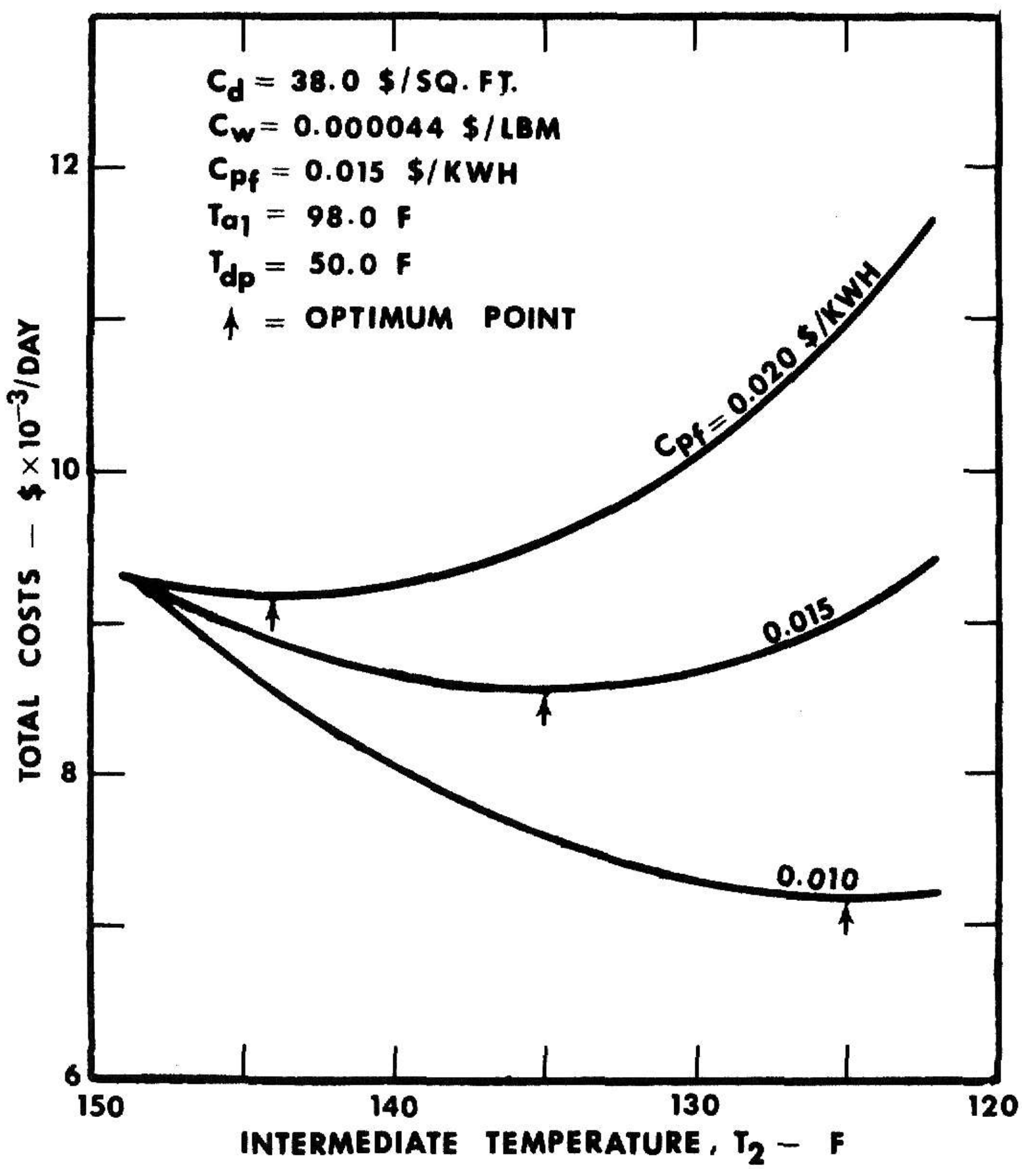


Figure 7. Effects of Power Costs on the Optimum T_2.

Table 2

Summary of Heat Exchanges between the Pond and the Environment

T_{al}	T_{dp}	E	K	H_a	H_{br}	H_e	H_c
°F	°F	°F	Btu/ft^{2}day°F	Btu/ft^{2}day	Btu/ft^{2}day	Btu/ft^{2}day	Btu/ft^{2}day
90	50	79.69	181.63	3157.78	3404.93	2438.49	-388.80
90	65	85.11	202.64	3268.04	3543.89	2202.96	-184.40
90	80	92.46	235.47	3402.28	3739.07	1860.44	92.76
98	50	82.22	191.40	3345.69	3469.28	2763.05	-595.07
98	65	87.41	212.20	3462.52	3604.13	2545.31	-399.35
98	80	94.49	245.27	3604.74	3794.38	2228.24	-132.37
106	50	84.67	200.86	3541.86	3532.45	3100.16	-804.36
106	65	89.65	221.90	3665.54	3663.53	2900.22	-616.57
106	80	96.46	255.27	3816.10	3848.62	2604.69	-359.76

and the heat transfer takes place at the expense of greater required pond area. In the present case under study the approach is large. Table 2 shows a minimum approach (122°F - E) of at least 25.5°F.

One more point needs to be discussed. For the same heat load to be dissipated at a low dew point temperature the water evaporation costs are high compared to the evaporation costs at a high dew point. However a question may arise as to how the extra heat formerly dissipated (at low dew points) by evaporation is dissipated and how much does it cost to dissipate this extra heat. Table 2 shows the heat exchanges taking place between the environment and the pond water surface for different dry bulb and dew point temperatures. As the dew point goes up, E and K also go up. All this results in less heat dissipation by evaporation and increased dissipation by conduction and back radiation. Thus more sensible heat dissipation takes place (at no cost for water replacement) resulting in total savings.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

The results of the study show that optimum dry tower - cooling pond combinations can be found which are more economical than either all dry or all wet systems. The combinations are dependent on the local meterological conditions and cost factors.

Low dry bulb and dew point temperatures suggest greater proportions of dry cooling. High dry bulb and high dew point imply greater proportions of wet cooling. The various cost factors alone can influence the optimum combination. Operational power costs and water evaporation costs are the critical factors in determination of the optimum system. The various cost factors combined with different environmental conditions can either negate or enhance the effects of each other.

Dry tower and cooling ponds both have their advantages and disadvantages. The combined system, while retaining all the advantages of the individual systems, will minimize the disadvantages of each. In the case of all pond cooling, the two main disadvantages are the high land usages and water loss due to evaporation. The optimum combination can greatly reduce the land area and water loss. An all dry cooling system involves loss of generating capacity with increasing dry bulb temperatures. Thus the additional benefits (though not studied in this report) of the combined system can be the minimization of this loss, since a pond is less sensitive to ambient conditions and has a stabilizing effect. With proper design a combined system can result in no loss of generating capacity in a power plant.

The addition of a small pond to a dry system as a result of a combination may also mean better public relations for the power plant in the community. It can provide an excellent public recreational area. It will also give a more neat look to the plant by reducing the area of heat exchangers to be installed.

This study just scratches the surface of a highly complicated and interesting problem. As pointed out in the introduction, this study was very limited in scope. The problem can be advanced in several different directions. The effects of seasonal variations were not studied. Cold weather favors dry cooling while hot weather favors pond cooling, thus from seasonal variation point of view the combined system should prove even more advantageous. Another area of study can be normalizing and combining of different variables thus making it easier for the designers to pick the right system. It is felt that true equilibrium temperature E may be modified to be used as the only meterological parameter by combining all the other ambient conditions. The ultimate step from this study is to study the optimum cooling process considering the whole plant and its various components such as the condenser size, turbine design etc. as variables.

It can be recommended from the results of this study that the power plant designers should not make arbitrary decisions to go either all pond (wet) or all dry cooling. Careful study of all processes and local conditions is required which may lead to a more economically optimum combination system.

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APPENDIX

APPENDIX A

Derivation of Equilibrium Temperature E

The natural heat exchanges taking place between the pond and environment are shown schematically in Figure 8. The corresponding heat balance equation is

$$\Delta H = H_s + H_a - H_{sr} - H_{ar} - H_{br} \pm H_c + H_e \tag{12}$$

The individual terms are given below as developed by Patterson et.al. [17] from Edinger and Geyer's [7] theory

$$H_s = H_o(0.615S + 0.35)$$

$$H_a = 4.15 \times 10^{-8}(T_{a1} + 460)^4(C + 0.031\sqrt{e_{a1}})$$

where C, the Brunt's coefficient is determined from the air temperature and ratio of the measured solar radiation to the clear sky solar radiation

$$H_{br} = \gamma_w \sigma\, (T_s + 460)^4$$

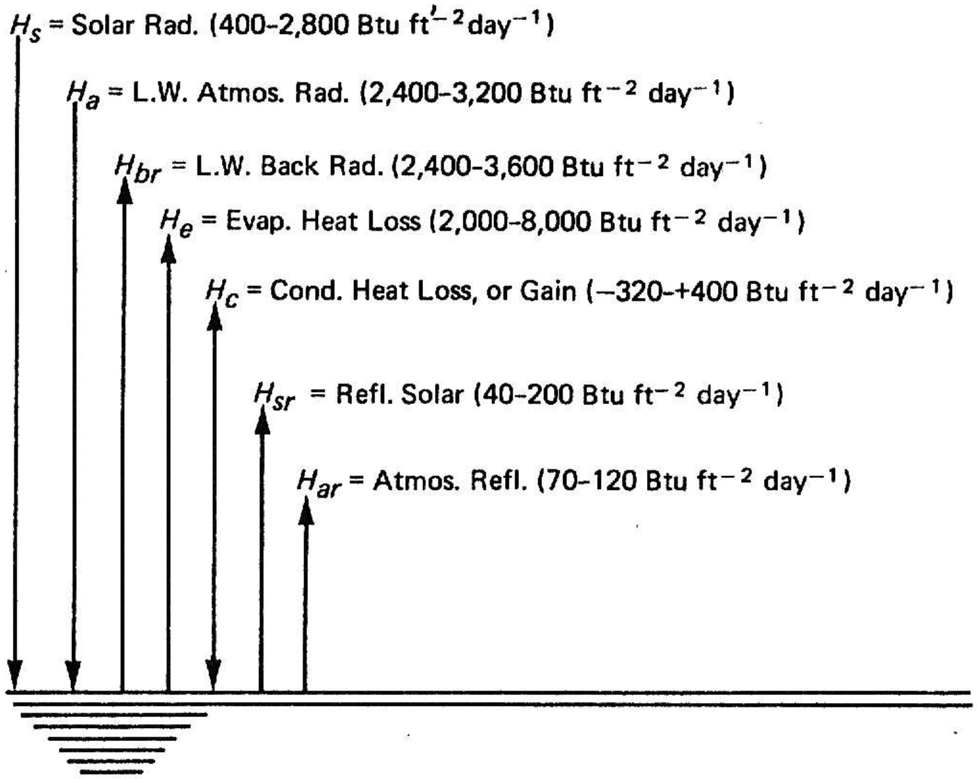
$$H_e = (73 + 7.3W)(e_s - e_{a1})$$

$$H_{sr} = 0.05\, H_s \quad \text{and} \quad H_{ar} = 0.03\, H_a$$

$$H_c = 0.26\,(73 + 7.3W)(T_s - T_{a1})(P/760)$$

For $\Delta H = 0$, $E = T_s$.

E is calculated as a function of environmental variables T_{a1} and T_{dp} by a trial and error iteration method in the computer program subroutine EQT (see Appendix B).



NET RATE AT WHICH HEAT CROSSES WATER SURFACE

$$\Delta H = (H_s + H_a - H_{sr} - H_{ar}) - (H_{br} \pm H_c + H_e) \text{ Btu ft}^{-2} \text{ day}^{-1}$$

H_R	Temp. Dependent Terms
Absorbed Radiation Independent of Temp.	$H_{br} \sim (T_s + 460)^4$ $H_c \sim (T_s - T_a)$ $H_e \sim W(e_s - e_a)$

Figure 8. Mechanisms of Heat Transfer Exchanger Between the Pond Water Surface and the Environment. (taken from reference [18])

Derivation of A_p as a Function of T_2

The heat transfer equation for the pond can be written as

$$m_w C_{pw}(T_2 - T_3) = \int_0^{A_p} K(T_A - E)\, dA_p \tag{13}$$

where K is defined in $\Delta H = K(T_s - E)$

Also

$$-\rho_w C_{pw} Q \frac{dT}{dA_p} = K(T_A - E) \tag{14}$$

which has as a solution, when $T_A = T_2$ for $A = 0$ and T_3 for $A = A_p$:

$$(T_3 - E) = (T_2 - E)\, e^{-r} \tag{15}$$

where $r = K\, A_p/\rho_w C_{pw} Q$

or $$e^{-r} = \left(\frac{T_3 - E}{T_2 - E}\right)$$

which gives

$$A_p = \frac{\rho_w C_{pw} Q}{K} \log_e \left(\frac{T_2 - E}{T_3 - E}\right) \tag{8}$$

Derivation of an Equation of M_e

The expression given for M_e ($lbm/ft^2 day$) in this appendix is simply the same as used that for H_e($Btu/ft^2 day$) after dividing it by latent heat of evaporation 971 Btu/lbm. Rewriting the expression

$$M_e = (73 + 7.3W)(e_s - e_{a1})/971.0$$

The unknown parameter in the above equation is e_s since T_s is not known in the problem. Hence an expression for T_s was derived in terms of T_2.

Average value of T_s can be written, from equation (15), as

$$T_s = \frac{1}{A_p} \int_0^{A_p} [(T_2 - E)e^{-r} + E]\, dA$$

where $r = KA/\rho_w C_{pw} Q$

which on integration and substitution of limits gives

$$T_s = (T_2 - T_3) \Big/ \log_e \left(\frac{T_2 - E}{T_3 - E}\right) + E \qquad (9a)$$

hence

$$M_e = A_p\ (73 + 7.3W)\{VP[(T_2 - T_3) \Big/ \log_e (\frac{T_2 - E}{T_3 - E}) + E] - VP(T_{a1})\} \qquad (9)$$

where VP is the vapor pressure (of the temperature inside the brackets) calculated in function program VPP in the computer program (see Appendix B).

Derivation of A_d as a Function of T_2

Rewriting equations (1), (2), (3) and (4) after substituting $A_p = 0$

$$Q_a = m_w C_{pw}(T_1 - T_2) \qquad (1a)$$

$$Q_a = m_a C_{pa}(T_{a2} - T_{a1}) \qquad (2a)$$

$$Q_a = \frac{UA_b}{2}[(T_1 - T_{a2}) + (T_2 - T_{a1})] \qquad (3a)$$

$$m_a = \frac{\rho_a}{\beta_a} V_d A_b \qquad (4)$$

Eliminating Q_a from equations (1a) and (2a) and eliminating Q_a, m_a and T_{a2} from equations (1a), (3a) and (4) A_d is obtained as

$$A_d = \frac{m_w C_{pw}(T_1 - T_2)(1 + \frac{\beta_a U}{2\rho_a V_d C_{pa}})}{0.5\ \beta_a U(T_1 + T_2 - 2T_{a1})} \qquad (7)$$

Derivation of Fan and Pump Power Comsumption Terms P_f and P_p

Fan Power $P_f = A_d V_f \Delta P$

$$\Delta P = f(V_m)$$

From the expression given by Cook [8]

$$\Delta P = \frac{3.24}{10^8 \rho_a} R F_s V_m^{1.725}$$

Cook uses a value of 1.1 for F_s, a safety factor.

Then

$$P_f = (A_d V_f)\left(\frac{3.24}{10^8 \rho_a}\right) R F_s V_m^{1.725} \qquad (16)$$

For a triangular tube spacing of 2-3/8" fin height of 5/8" and 8 fins per inch with a thickness of 0.014"

$$\frac{V_m}{V_f} = \text{(flow area fraction between tubes) x (fraction flow between fins)}$$

$$\frac{V_m}{V_f} = \frac{1.375}{2.375} \times \frac{0.111}{0.125}$$

$$V_m = 1.945\ V_f$$

Substituting the above value of V_m in equation (17)

$$P_f = \frac{A_d F_s R V_f}{10^8 \rho_a} (1.945 V_f)^{1.725} \times 3.24 \times 60 \times 24 \times 5.20218 \times 3.66 \times 10^{-7} \qquad (10)$$

Power for the Pump, $P_p = \Delta P \times Q$

From Kreith [9]

$$\Delta P = f \frac{L}{D_i} \frac{\rho_w V_w^2}{2 g_c}$$

$$= 0.184\ R_e^{-0.2} \times \frac{L}{D_i} \frac{\rho_w V_w^2}{2 g_c}$$

Also

$$Q = \frac{N\pi D_i^{2}V_w}{4}$$

then

$$P_p = \frac{0.184R_e^{-0.2}V_w^{3}\ N\pi D_iL}{2g_c \times 4}$$

Since

$$R_a \times N\pi D_iL = A_b\text{, and } A_b = \beta_aA_d$$

where $R_a = D_o/D_i$

$$P_p = \frac{0.184\ R_e^{-0.2}}{2 \times 4 \times R_ag_c}\rho_wV_w^{3}\beta_aA_d \times 3600 \times 24 \times 3.766 \times 10^{-7} \qquad (11)$$

Derivative of the Cost Equation

Differentiating with respect to T_2 equation (6) becomes:

$$\frac{dC_T}{dT_2} = \frac{C_d A_d}{dT_2} + C_p \frac{dA_p}{dT_2} + C_w \frac{dM_e}{dT_2} + C_{pf} \frac{d(P_f + P_p)}{dT_2} \qquad (6a)$$

The individual terms differentiated are as follows:

$$\frac{dA_d}{dT_2} = \frac{2m_w C_{pw}\left(1+\dfrac{\beta_a U}{2\rho_a V_d C_{pa}}\right)}{\beta_a \times 0.5U(T_1 + T_2 - 2T_{a1})^2} \qquad \text{(from equation 7)}$$

$$\frac{dA_p}{dT_2} = \frac{\rho_w C_{pw} Q}{K(T_2 - E)} \qquad \text{(from equation 8)}$$

$$M_e = \frac{A_p(73 + 7.3W)}{971.0}\{VP[(T_2 - T_3)/\log_e(\frac{T_2 - E}{T_3 - E}) + E] - VP(T_{dp})\} \qquad (9)$$

In the above equation it was assumed that the vapor pressure terms could be written as $\beta\,(T_s - T_{a1})$ where β was the slope of the saturated vapor pressure curve (w.r.t. temperature) and for small ranges of temperatures β was assumed constant. The value of T_s in terms of T_2 is given in equation (9a).

Thus

$$\frac{dT_s}{dT_2} = \frac{d}{dT_2}[(T_2 - T_3)/\log_e(\frac{T_2 - E}{T_3 - E}) + E]$$

$$= \frac{\log_e(\frac{T_2 - E}{T_3 - E}) - (\frac{T_2 - T_3}{T_2 - E})}{[\log_e(\frac{T_2 - E}{T_3 - E})]^2}$$

and

$$\frac{dM_e}{dT_2} = \frac{73 + 7.3W}{971.0} \beta \frac{\left\{\frac{dA_p}{dT_2}\left[(T_2 - T_3)/\log_e\left(\frac{T_2 - E}{T_3 - E}\right) + E - T_{a1}\right] + A_p\left[\log_e\left(\frac{T_3 - E}{T_2 - E}\right) - \left(\frac{T_2 - T_3}{T_2 - E}\right)\right]\right\}}{\left[\log_e\left(\frac{T_2 - E}{T_3 - E}\right)\right]^2} = 0 \qquad (17)$$

From equations (10) and (11) it can be seen that $\frac{dP_f}{dT_2}$ and $\frac{dP_p}{dT_2}$ are equal to the constant terms in those equations times $\frac{dA_d}{dT_2}$.

The solution of equation (6a) is not simple. The problem lies in finding a representative temperature from among the several possible (T_2, T_3, E) for evaluation of β in equation (17).

THIS BOOK CONTAINS NUMEROUS PAGES THAT WERE BOUND WITHOUT PAGE NUMBERS.

THIS IS AS RECEIVED FROM CUSTOMER.

APPENDIX B

145 pages of (results) output data was obtained through the computer program. The two pages of the sample results included here following the program show the general format of the output and also include the values obtained for the reference case.

ILLEGIBLE DOCUMENT

THE FOLLOWING DOCUMENT(S) IS OF POOR LEGIBILITY IN THE ORIGINAL

THIS IS THE BEST COPY AVAILABLE

```
$JOB            AKG,RUN=CHECK,TIME=6,PAGES=155
C  THIS FORTRAN WATFIV PROGRAM IS WRITTEN TO CALCULATE THE COOLING COSTS PER DAY
C  OF A POWER PLANT, BY A DRY TOWER OR A COOLING TOWER OR A COMBINATION OF BOTH.
C  INPUTS TO THE PROGRAM ARE THE DIFFERENT COST FACTORS,THE POWER PLANT OUTPUT
C  AND EFFICIENCY, THE COOLING RANGE AND THE AMBIENT ATMOSPHERIC CONDITIONS.
C      NOMENCLATURE -- AND -- UNITS
C         AP -- AREA OF THE POND -- FT**2
C         ADT -- FACE AREA OF THE DRY TOWER -- FT**2
C         AN -- OVERALL EFFICIENCY OF THE POWER PLANT
C         AMU -- DYNAMIC VISCOSITY OF WATER -- LBM/FT*SEC
C         A -- COEF. USED IN MEYER'S EVAPORATION EQN.
C         B -- COEF. USED IN MEYER'S EVAPORATION EQN.
C         BC -- BRUNT'S COEF. USED IN FINDING HRLW
C         BETA -- PROPORTIONALITY FACTOR USED IN FINDING TK -- MMHG/F
C         BETA1 -- LINEARIZATION FACTOR USED IN FINDING TK
C         CPA --SPECIFIC HEAT OF AIR -- BTU/LBM*F
C         CPW --SPECIFIC HEAT OF WATER -- BTU/LBM*F
C      BELOW ARE COST FACTORS IN DOLLARS PER DAY
C         CDT -- DRY TOWER COSTS PER FT**2 OF FACE AREA
C         CD -- TOTAL DRY TOWER COSTS
C         CP -- POND COSTS PER FT**2 OF AREA (AVE. DEPTH OF 5 FEET)
C         CWP -- TOTAL POND COSTS
C         CF -- WATER COSTS PER LBM
C         CWF -- TOTAL EVAPORATED WATER COSTS
C         CPF -- POWER COSTS PER KWH
C         CFP -- TOTAL POWER COSTS FOR FAN AND PUMP OPERATION
C         CT -- TOTAL COOLING COSTS USING COMBINATION
C         CCP -- TOTAL COOLING COSTS DUE TO POND
C         DI -- INSIDE DIA. OF HT. EXCHANGER TUBES -- IN.
C         DIF -- INSIDE DIA OF HT. EXCHANGER TUBES -- FT
C         EC -- HEAT LOAD FROM THE TURBINE TO BE DISSIPATED -- BTU/DAY
C         ET -- TOTAL HEAT INPUT TO GENERATOR -- BTU/HR
C         FE -- FUEL ENERGY TO THE BOILER -- BTU/HR
C         FPK -- POWER CONSUMPTION BY FAN -- BTU
C         FPK -- POWER CONSUMPTION BY FAN -- KWH/DAY
C         FS -- SAFETY FACTOR USED IN FAN CALCULATIONS
C         GC -- ACCN. DUE TO GRAVITY -- LBM*FT/LBF*SEC*SEC
C         GN -- GENERATOR EFFICIENCY
C         HB -- HEAT LOSS IN THE BOILER -- BTU/HR
C      BELOW ARE HEAT LOAD TERMS IN BTU/FT**2*DAY
C         HRSW -- SHORTWAVE RADIATION GIVEN BY SUN AND SKY
C         HABRSW -- AMOUNT OF HRSW ABSORBED BY THE WATER IN POND
C         HCOND -- HEAT LOSS DUE TO CONDUCTION (CONVECTION) BY POND
C         HEVAP -- HEAT LOSS BY EVAPORATIO OF POND WATER
C         HRBW -- HEAT RADIATED BY THE POND WATER (AS A BLACK BODY)
C         HRLW -- ATMOSPHERIC LONGWAVE RADIATION TO THE POND
C         HRRLW -- FRACTION HRLW REFLECTED BACK BY THE POND
C         HRRSW -- FRACTION OF HABRSW REFLECTED BY WATER
C         NO -- COOLING RANGE + 1 -- F
C         P -- AMBIENT ATMOSPHERIC PRESSURE -- MMHG
C         Q -- COOLING WATER REQUIRED -- FT**3/DAY
C         RA -- RATIO OF OUTSIDE DIA./INSIDE DIA. OF H.E. TUBES
C         REP -- REYNOLD'S NUMBER RAISED TO -0.2
C         RHOA -- DENSITY OF AIR -- LBM/FT**3
C         RHOW -- DENSITY OF WATE -- LBM/FT**3
C         ROW -- NUMBER OF ROWS IN BUNDLE OF HE TUBES
C         SIGMA -- STEPHAN BOLTZMAN CONSTANT -- BTU/FT**2*DAY*R**4
C         SUN -- FRACTION SUNSHINE
C         T1 -- TEMP. OF HOT WATER WATER COMING OUT OF CONDENSER -- F
C         T2 -- INTERMEDIATE TEMP. (T2 MAY BE T3) -- F
```

```
C         T3 -- TEMP OF COOLED WATER (T1 - T3 = COOLING RANGE) -- F
C         TEQ -- EQUILIBRIUM TEMP OF POND (WITH NO PLANT LOAD) -- F
C         TAMB -- AMBIENT AIR TEMP. -- F
C         TDP -- AMBIENT DEW POINT TEMP. -- F
C         TK -- HEAT EXCHANGE COEF. FOR THE POND -- BTU/DAY*F*FT**2
C         UDT -- OVERALL H.T. COEF. OF DRY TOWER EXCHANGER -- BTU/DAY*F*FT**2BARE
C         VF -- AIR FACE VELOCITY -- FT/MIN
C         VFD -- AIR FACE VELOCITY -- FT/DAY
C         VW -- WATER VELOCITY IN HE TUBES --FT/SEC
C         WIND -- AMBIENT WIND VELOCITY -- MPH
C         WK -- POWER PLANT OUTPUT -- KW/HR
C         WM -- COOLING WATER REQUIRED -- LBM/DAY
C         YW -- EMMISSIVITY OF WATER
  190 FORMAT(' ',5X,5X,'TAMB',6X,'TDP',7X,'TEQ',7X'TK',8X,'DELH'4X,'HABR
     1SW',4X,'HRLW'6X,'HRRW ',5X,'HEVAP',6X,'HCOND')
  200 FORMAT(' ',5X,10F10.2,/)
  411 FORMAT(' ',5X,F4.0,9E11.3,2E12.4)
  419 FORMAT(' ',1X,'WK ='E11.3,5X,'AN =',F4.2,5X,'EC =',F12.4,5X,'WM ='
     1,F12.4,5X,'D =',E12.4,/)
  420 FORMAT(' ',1X,'CPE',' T2 ',5X,'ADT',8X,'CD',09X,'AP',9X,'CWP',8X,
     1'HEM',8X,'CWF',6X,'FPK'8X,'PPK',6X,'CFP',8X,'CCP',09X,'CT')
  421 FORMAT(' ',7,1X,'CPE =',F7.4)
  431 FORMAT(' ',1X,'CP =',F5.2,5X,'CE ='F10.7,5X,'CDT =',F5.2,/)
  441 FORMAT('1')
  902 FORMAT(' ', 50X,'COOLING BY POND IS CHEAPEST')
  903 FORMAT(' ', 50X,'DRY TOWER COOLING IS CHEAPEST')
      DIMENSION ADT(28),AP(28),HEM(28),FPK(28),PPK(28),T2(28),CD(28),CWP
     1(28),CWF(28),CFP(28),CCP(28),CT(28) ,ALMTD(28)
      COMMON YW,SIGMA,A,B,WIND,AVP,P,TAMB,HABRSW,HRRSW,HRLW,HRRLW
      A = 73.0
      AMU = 0.0003232
      AN = 0.40
      B = 7.3
      BA = 5.04
      BC = 0.74
      CP = 0.5
      CPA = 0.2405
      CPW = 0.999
      DI = 0.782
      DIF = 0.782/12.0
      FS = 1.1
      GC = 32.2
      GN=0.975
      HRSW = 2800.0
      ND = 29
      P = 755.0
      RHOA =  0.071
      RA =1.0/0.782
      RHOW =61.45
      ROW =4.0
      SIGMA =0.000415/10000.0
      SUM = 0.0
      T1 =149.0
      T3 = 122.0
      UDT = 24.0*120.
      VF = 595.0
      VFD = 595.0*60.0*24.0
      VW =10.0
      WIND = 10.0
      WK = 1000000.0
```

```
      VW = 0.97
      FAN = (VF*1.945)**1.725*ROW*FS*VF*5.20218/(100000000.0*RHOA)*3.240
     1*6.*1.24*0.0003766/0.75
      RED =(VW*DIF*RHOW/AMU)**(-0.2)
      PUMP = 0.184*RED*RHOW*VW*VW*VW*BA/(2.0*GC*RA*4.0)*36.0*24.0*0.0000
     13766/0.75
      HK=1.0 +UDT*BA/(2.0*RHOA*CPA*VFD)
      FE=3413.0/AN *WK
      HB=FE *0.10
      ET =3413.0*WK/GN
      HLG = .025*ET
      EC = (FE-HB-ET+HLG)*24.0
      WM = EC/27.0
      Q = WM/62.37
      WRITE(6,441)
      WRITE(6,419) WK,AN,EC,WM,Q
      HABRSW = HRSW*(0.61*SUN +0.35)
      HRBSW = 0.05*HABRSW
      IC = 0
      DO 100 II = 122,149
      IC = IC+1
  100 T2(IC) = II
      DO 400 I = 90,106,8
      TAMB = I
      DO 500 I1 = 1,NO
      ADT(I1) = WM*CPW*(T1- T2(I1))* HK/(BA*0.5*UDT*(T1+T2(I1)-2.*TAMB))
      FPK(I1) = FAN*ADT(I1)
  500 PPK(I1) = PUMP*ADT(I1)
      DO 400 J = 50,80,15
      TDP = J
      AVP  = VPP(TDP)
      HRLW = SIGMA*(TAMB+459.6)**4*(BC+0.031*SQRT(AVP))
      HRRLW =0.03*HRLW
      TEQ = 55.0
      CALL EQT(TEQ,DELH,HRBW,HEVAP,HCOND,1.0,50)
      IF (DELH.EQ.0.0) GO TO 300
      TEQ = TEQ - 1.0
      CALL EQT(TEQ,DELH,HRBW,HEVAP,HCOND,0.1,10)
      IF (DELH.EQ.0.0) GO TO 300
      TEQ = TEQ - 0.1
      CALL EQT(TEQ,DELH,HRBW,HEVAP,HCOND,0.01,10)
      IF(TEQ.GT.50.0.AND.TEQ.LT.60.0) BETA1=1.1901
      IF(TEQ.GT.60.0.AND.TEQ.LT.70.0) BETA1 = 1.2294
      IF(TEQ.GT.70.0.AND.TEQ.LT.80.)  BETA1 = 1.2684
      IF(TEQ.GT.80.0.AND.TEQ.LT.90.0) BETA1 = 1.3086
      IF(TEQ.GT.90.0) BETA1 = 1.3508
      VP1 =VPP(TEQ-0.5)
      VP2 =VPP(TEQ+0.5)
      BETA = VP2-VP1
  300 TK = BETA1*15.7 + (0.26 + BETA)*(A+ B*WIND)
      WRITE(6,190)
      WRITE(6,200) TAMB,TDP,TEQ,TK,DELH,HABRSW,HRLW,HRBW,HEVAP,HCOND
      POND = RHOW*CPW*Q/TK
      DO 600 I2 = 1,NO
      ALMTD(I2) = ALOG((T2(I2) - TEQ)/(T3 -TEQ))
      AP(I2) = POND*ALMTD(I2)
      IF(AP(I2).EQ.0.0) GO TO 401
      HEM(I2)=AP(I2)*(A+B*WIND)*(VPP((T2(I2)-T3)/ALMTD(I2)+TEQ)-AVP)/971
     1.
      GO TO 600
```

```
  401 HEM(I2) = 0.0
  600 CONTINUE
      DO 400 K =  36,60,8
      CE = K/100000.0
      DO 700 I3 = 1,NO
      CWP(I3) = CP*AP(I3)*0.0937/365.0
      CWE(I3) = CE*HEM(I3)
  700 CCP(I3) = CWE(I3) +CWP(I3)
      DO 400 L=30,54,8
      CDT = L
      WRITE(6,431) CP,CE,CDT
      DO 800 I4 = 1,NO
  800 CD(I4) = CDT*ADT(I4) *0.0937/365.0
      WRITE(6,420)
      DO 400 M =100,200,25
      CPF = M/10000.0
      WRITE(6,421) CPF
      DO 450 N =1,NO
      CFP(N)= CPF*(FPK(N) +PPK(N))
  450 CT(N) = CD(N)+ CFP(N)+ CCP(N)
      SMALCT = CT(1)
      I6 = 1
      DO 900 I5 =1,NO
      IF(CT(I5) -SMALCT) 901,900,900
  901 SMALCT = CT(I5)
      I6 = I5
  900 CONTINUE
      WRITE(6,411)     T2(1),ADT(1),CD(1),AP(1),CWP(1),HEM(1),CWE(1),FPK
     1(1),PPK(1),CFP(1),CCP(1),CT(1)
      DO 1000 IN = 4,24,5
 1000 WRITE(6,411) T2(IN),ADT(IN),CD(IN),AP(IN),CWP(IN),HEM(IN),CWE(IN),
     1FPK(IN),PPK(IN),CFP(IN),CCP(IN),CT(IN)
      WRITE(6,411) T2(NO),ADT(NO),CD(NO),AP(NO),CWP(NO),HEM(NO),CWE(NO),
     1 FPK(NO),PPK(NO),CFP(NO),CCP(NO),CT(NO)
      IF (I6.EQ.1)  GO TO 904
      IF (I6.EQ.NO) GO TO 905
      WRITE(6,411) T2(I6),ADT(I6),CD(I6),AP(I6),CWP(I6),HEM(I6),CWE(I6),
     1FPK(I6),PPK(I6),CFP(I6),CCP(I6),CT(I6)
      GO TO 440
  904 WRITE(6,903)
      GO TO 440
  905 WRITE(6,902)
  440 IF(M.EQ.200) WRITE(6,441)
  400 CONTINUE
      STOP
      END

      SUBROUTINE EQT(TEQ,DELH,HRBW,HEVAP,HCOND,DT,N)
C  THIS SUBROUTINE CALCULATES THE EQUILIBRIUM TEMP OF POND WATER WITH NO LOAD
      COMMON YW,SIGMA,A,B,WIND,AVP,P,TAMB,HABRSW,HRRSW,HRLW,HRRLW
      DO 100 I = 1,N
      HRBW = YW*SIGMA*(TEQ+459.6)**4
      HEVAP = (A+B*WIND)*(VPP(TEQ) -AVP)
      HCOND= 0.26*P/760.0*(A+B*WIND)*(TEQ-TAMB)
      DELH = HABRSW-HRRSW+HRLW-HRRLW -HRBW-HEVAP-HCOND
      IF (DELH) 200,200,100
  100 TEQ = TEQ +DT
      WRITE(6,50) TEQ
   50 FORMAT('  TEQ NOT WITHIN DESIRABLE LIMITS , TEQ =',F6.2)
      STOP
```

```
  200 RETURN
      END
      FUNCTION VPP(T)
C  THIS FUNCTION CALCULATES SATURATED VAPOR PRESSURE AT A GIVEN TEMP -- MMHG
      X = 647.27 - (T +459.6)/1.8
      TEMP = X*1.8/(T+459.6)*(3.244 +0.005868*X+0.117/10000000.0*X**3)/(
     11.0+0.002188*X)
      VPP = 3207.0/10.0**TEMP*51.7149
      RETURN
      END
   $ENTRY
```

TAMB	TDP	TEQ	TK	DELH	HARRSW	HRLW	HRBW	HEVAP	HCOND
98.00	50.00	82.22	191.40	-0.60	2517.20	3345.69	3469.28	2763.05	-595.07

CP = 0.50 CE = 0.0000360 CDT =30.00

CPF T2	ADT	CD	AP	CWP	HFM	CWE	FPK	PPK	CFP	CCP	CT
CPF = 0.0100											
122.	0.281E 06	0.217E 04	0.000E 00	0.000E 00	0.000E 00	0.000E 00	0.243E 06	0.202E 06	0.445E 04	0.0000E 00	0.6619E 04
125.	0.240E 06	0.185E 04	0.142E 07	0.182E 03	0.185E 08	0.667E 03	0.208E 06	0.173E 06	0.381E 04	0.8495E 03	0.6506E 04
130.	0.179E 06	0.138E 04	0.357E 07	0.459E 03	0.502E 08	0.181E 04	0.155E 06	0.129E 06	0.283E 04	0.2267E 04	0.6475E 04
135.	0.124E 06	0.957E 03	0.551E 07	0.708E 03	0.830E 08	0.299E 04	0.107E 06	0.893E 05	0.197E 04	0.3696E 04	0.6621E 04
140.	0.756E 05	0.582E 03	0.728E 07	0.934E 03	0.117E 09	0.421E 04	0.654E 05	0.543E 05	0.120E 04	0.5146E 04	0.6925E 04
145.	0.319E 05	0.245E 03	0.890E 07	0.114E 04	0.152E 09	0.548E 04	0.276E 05	0.229E 05	0.505E 03	0.6624E 04	0.7375E 04
149.	0.000E 00	0.000E 00	0.101E 08	0.130E 04	0.182E 09	0.653E 04	0.000E 00	0.000E 00	0.000E 00	0.7832E 04	0.7832E 04
129.	0.202E 06	0.156E 04	0.274E 07	0.352E 03	0.374E 08	0.135E 04	0.175E 06	0.146E 06	0.321E 04	0.1629E 04	0.6465E 04
CPF = 0.0125											
122.	0.281E 06	0.217E 04	0.000E 00	0.000E 00	0.000E 00	0.000E 00	0.243E 06	0.202E 06	0.557E 04	0.0000E 00	0.7732E 04
125.	0.240E 06	0.185E 04	0.142E 07	0.182E 03	0.185E 08	0.667E 03	0.208E 06	0.173E 06	0.476E 04	0.8495E 03	0.7458E 04
130.	0.179E 06	0.138E 04	0.357E 07	0.459E 03	0.502E 08	0.181E 04	0.155E 06	0.129E 06	0.354E 04	0.2267E 04	0.7183E 04
135.	0.124E 06	0.957E 03	0.551E 07	0.708E 03	0.830E 08	0.299E 04	0.107E 06	0.893E 05	0.246E 04	0.3696E 04	0.7113E 04
140.	0.756E 05	0.582E 03	0.728E 07	0.934E 03	0.117E 09	0.421E 04	0.654E 05	0.543E 05	0.150E 04	0.5146E 04	0.7224E 04
145.	0.319E 05	0.245E 03	0.890E 07	0.114E 04	0.152E 09	0.548E 04	0.276E 05	0.229E 05	0.631E 03	0.6624E 04	0.7501E 04
149.	0.000E 00	0.000E 00	0.101E 08	0.130E 04	0.182E 09	0.653E 04	0.000E 00	0.000E 00	0.000E 00	0.7832E 04	0.7832E 04
134.	0.135E 06	0.104E 04	0.514E 07	0.660E 03	0.763E 08	0.275E 04	0.116E 06	0.968E 05	0.267E 04	0.3408E 04	0.7111E 04
CPF = 0.0150											
122.	0.281E 06	0.217E 04	0.000E 00	0.000E 00	0.000E 00	0.000E 00	0.243E 06	0.202E 06	0.668E 04	0.0000E 00	0.8845E 04
125.	0.240E 06	0.185E 04	0.142E 07	0.182E 03	0.185E 08	0.667E 03	0.208E 06	0.173E 06	0.571E 04	0.8495E 03	0.8410E 04
130.	0.179E 06	0.138E 04	0.357E 07	0.459E 03	0.502E 08	0.181E 04	0.155E 06	0.129E 06	0.425E 04	0.2267E 04	0.7891E 04
135.	0.124E 06	0.957E 03	0.551E 07	0.708E 03	0.830E 08	0.299E 04	0.107E 06	0.893E 05	0.295E 04	0.3696E 04	0.7605E 04
140.	0.756E 05	0.582E 03	0.728E 07	0.934E 03	0.117E 09	0.421E 04	0.654E 05	0.543E 05	0.180E 04	0.5146E 04	0.7524E 04
145.	0.319E 05	0.245E 03	0.890E 07	0.114E 04	0.152E 09	0.548E 04	0.276E 05	0.229E 05	0.757E 03	0.6624E 04	0.7627E 04
149.	0.000E 00	0.000E 00	0.101E 08	0.130E 04	0.182E 09	0.653E 04	0.000E 00	0.000E 00	0.000E 00	0.7832E 04	0.7832E 04
140.	0.756E 05	0.582E 03	0.728E 07	0.934E 03	0.117E 09	0.421E 04	0.654E 05	0.543E 05	0.180E 04	0.5146E 04	0.7524E 04
CPF = 0.0175											
122.	0.281E 06	0.217E 04	0.000E 00	0.000E 00	0.000E 00	0.000E 00	0.243E 06	0.202E 06	0.779E 04	0.0000E 00	0.9959E 04
125.	0.240E 06	0.185E 04	0.142E 07	0.182E 03	0.185E 08	0.667E 03	0.208E 06	0.173E 06	0.666E 04	0.8495E 03	0.9361E 04
130.	0.179E 06	0.138E 04	0.357E 07	0.459E 03	0.502E 08	0.181E 04	0.155E 06	0.129E 06	0.496E 04	0.2267E 04	0.8599E 04
135.	0.124E 06	0.957E 03	0.551E 07	0.708E 03	0.830E 08	0.299E 04	0.107E 06	0.893E 05	0.344E 04	0.3695E 04	0.8097E 04
140.	0.756E 05	0.582E 03	0.728E 07	0.934E 03	0.117E 09	0.421E 04	0.654E 05	0.543E 05	0.210E 04	0.5146E 04	0.7823E 04
145.	0.319E 05	0.245E 03	0.890E 07	0.114E 04	0.152E 09	0.548E 04	0.276E 05	0.229E 05	0.884E 03	0.6624E 04	0.7754E 04
149.	0.000E 00	0.000E 00	0.101E 08	0.130E 04	0.182E 09	0.653E 04	0.000E 00	0.000E 00	0.000E 00	0.7832E 04	0.7832E 04
144.	0.403E 05	0.310E 03	0.858E 07	0.110E 04	0.145E 09	0.522E 04	0.348E 05	0.289E 05	0.112E 04	0.6326E 04	0.7752E 04
CPF = 0.0200											
122.	0.281E 06	0.217E 04	0.000E 00	0.000E 00	0.000E 00	0.000E 00	0.243E 06	0.202E 06	0.891E 04	0.0000E 00	0.1107E 05
125.	0.240E 06	0.185E 04	0.142E 07	0.182E 03	0.185E 08	0.667E 03	0.208E 06	0.173E 06	0.761E 04	0.8495E 03	0.1031E 05
130.	0.179E 06	0.138E 04	0.357E 07	0.459E 03	0.502E 08	0.181E 04	0.155E 06	0.129E 06	0.566E 04	0.2267E 04	0.9307E 04
135.	0.124E 06	0.957E 03	0.551E 07	0.708E 03	0.830E 08	0.299E 04	0.107E 06	0.893E 05	0.394E 04	0.3696E 04	0.8589E 04
140.	0.756E 05	0.582E 03	0.728E 07	0.934E 03	0.117E 09	0.421E 04	0.654E 05	0.543E 05	0.239E 04	0.5146E 04	0.8122E 04
145.	0.319E 05	0.245E 03	0.890E 07	0.114E 04	0.152E 09	0.548E 04	0.276E 05	0.229E 05	0.101E 04	0.6624E 04	0.7880E 04
149.	0.000E 00	0.000E 00	0.101E 08	0.130E 04	0.182E 09	0.653E 04	0.000E 00	0.000E 00	0.000E 00	0.7832E 04	0.7832E 04

COOLING BY POND IS CHEAPEST

CP = 0.50   CE = 0.0000440   CDT =38.00

CPF T2	ADT	CD	AP	CWP	HCM	CWE	FPK	PPK	CFP	CCP	CT
CPF = 0.0100											
122.	0.281E 05	0.274E 04	0.000E 00	0.000E 00	0.000E 00	0.000E 00	0.243E 06	0.202E 06	0.445E 04	0.0000E 00	0.7196E 04
125.	0.240E 06	0.234E 04	0.142E 07	0.182E 03	0.185E 08	0.816E 03	0.208E 06	0.173E 06	0.381E 04	0.9979E 03	0.7148E 04
130.	0.179E 06	0.174E 04	0.357E 07	0.459E 03	0.502E 08	0.221E 04	0.155E 06	0.129E 06	0.283E 04	0.2668E 04	0.7244E 04
135.	0.124E 06	0.121E 04	0.551E 07	0.708E 03	0.830E 08	0.365E 04	0.107E 06	0.893E 05	0.197E 04	0.4360E 04	0.7540E 04
140.	0.756E 05	0.737E 03	0.728E 07	0.934E 03	0.117E 09	0.515E 04	0.654E 05	0.543E 05	0.120E 04	0.6082E 04	0.8016E 04
145.	0.319E 05	0.311E 03	0.890E 07	0.114E 04	0.152E 09	0.670E 04	0.276E 05	0.229E 05	0.505E 03	0.7843E 04	0.8659E 04
149.	0.000E 00	0.000E 00	0.101E 08	0.130E 04	0.182E 09	0.799E 04	0.000E 00	0.000E 00	0.000E 00	0.9284E 04	0.9284E 04
125.	0.240E 06	0.234E 04	0.142E 07	0.182E 03	0.185E 08	0.816E 03	0.208E 06	0.173E 06	0.381E 04	0.9978E 03	0.7148E 04
CPF = 0.0125											
122.	0.281E 06	0.274E 04	0.000E 00	0.000E 00	0.000E 00	0.000E 00	0.243E 06	0.202E 06	0.557E 04	0.0000E 00	0.8309E 04
125.	0.240E 06	0.234E 04	0.142E 07	0.182E 03	0.185E 08	0.816E 03	0.208E 06	0.173E 06	0.476E 04	0.9978E 03	0.8100E 04
130.	0.179E 06	0.174E 04	0.357E 07	0.459E 03	0.502E 08	0.221E 04	0.155E 06	0.129E 06	0.354E 04	0.2668E 04	0.7952E 04
135.	0.124E 06	0.121E 04	0.551E 07	0.708E 03	0.830E 08	0.365E 04	0.107E 06	0.893E 05	0.246E 04	0.4360E 04	0.8032E 04
140.	0.756E 05	0.737E 03	0.728E 07	0.934E 03	0.117E 09	0.515E 04	0.654E 05	0.543E 05	0.150E 04	0.6082E 04	0.8315E 04
145.	0.319E 05	0.311E 03	0.890E 07	0.114E 04	0.152E 09	0.670E 04	0.276E 05	0.229E 05	0.631E 03	0.7843E 04	0.8785E 04
149.	0.000E 00	0.000E 00	0.101E 08	0.130E 04	0.182E 09	0.799E 04	0.000E 00	0.000E 00	0.000E 00	0.9284E 04	0.9284E 04
131.	0.167E 06	0.163E 04	0.398E 07	0.511E 03	0.567E 08	0.249E 04	0.145E 06	0.120E 06	0.331E 04	0.3005E 04	0.7951E 04
CPF = 0.0150											
122.	0.281E 06	0.274E 04	0.000E 00	0.000E 00	0.000E 00	0.000E 00	0.243E 06	0.202E 06	0.668E 04	0.0000E 00	0.9423E 04
125.	0.240E 06	0.234E 04	0.142E 07	0.182E 03	0.185E 08	0.816E 03	0.208E 06	0.173E 06	0.571E 04	0.9978E 03	0.9051E 04
130.	0.179E 06	0.174E 04	0.357E 07	0.459E 03	0.502E 08	0.221E 04	0.155E 06	0.129E 06	0.425E 04	0.2668E 04	0.8660E 04
135.	0.124E 06	0.121E 04	0.551E 07	0.708E 03	0.830E 08	0.365E 04	0.107E 06	0.893E 05	0.295E 04	0.4360E 04	0.8524E 04
140.	0.756E 05	0.737E 03	0.728E 07	0.934E 03	0.117E 09	0.515E 04	0.654E 05	0.543E 05	0.180E 04	0.6082E 04	0.8615E 04
145.	0.319E 05	0.311E 03	0.890E 07	0.114E 04	0.152E 09	0.670E 04	0.276E 05	0.229E 05	0.757E 03	0.7843E 04	0.8911E 04
149.	0.000E 00	0.000E 00	0.101E 08	0.130E 04	0.182E 09	0.799E 04	0.000E 00	0.000E 00	0.000E 00	0.9284E 04	0.9284E 04
135.	0.124E 06	0.121E 04	0.551E 07	0.708E 03	0.830E 08	0.365E 04	0.107E 06	0.893E 05	0.295E 04	0.4360E 04	0.8524E 04
CPF = 0.0175											
122.	0.281E 06	0.274E 04	0.000E 00	0.000E 00	0.000E 00	0.000E 00	0.243E 06	0.202E 06	0.779E 04	0.0000E 00	0.1054E 05
125.	0.240E 06	0.234E 04	0.142E 07	0.182E 03	0.185E 08	0.816E 03	0.208E 06	0.173E 06	0.666E 04	0.9978E 03	0.1000E 05
130.	0.179E 06	0.174E 04	0.357E 07	0.459E 03	0.502E 08	0.221E 04	0.155E 06	0.129E 06	0.496E 04	0.2668E 04	0.9368E 04
135.	0.124E 06	0.121E 04	0.551E 07	0.708E 03	0.830E 08	0.365E 04	0.107E 06	0.893E 05	0.344E 04	0.4360E 04	0.9016E 04
140.	0.756E 05	0.737E 03	0.728E 07	0.934E 03	0.117E 09	0.515E 04	0.654E 05	0.543E 05	0.210E 04	0.6082E 04	0.8914E 04
145.	0.319E 05	0.311E 03	0.890E 07	0.114E 04	0.152E 09	0.670E 04	0.276E 05	0.229E 05	0.884E 03	0.7843E 04	0.9037E 04
149.	0.000E 00	0.000E 00	0.101E 08	0.130E 04	0.182E 09	0.799E 04	0.000E 00	0.000E 00	0.000E 00	0.9284E 04	0.9284E 04
140.	0.756E 05	0.737E 03	0.728E 07	0.934E 03	0.117E 09	0.515E 04	0.654E 05	0.543E 05	0.210E 04	0.6082E 04	0.8914E 04
CPF = 0.0200											
122.	0.281E 06	0.274E 04	0.000E 00	0.000E 00	0.000E 00	0.000E 00	0.243E 06	0.202E 06	0.891E 04	0.0000E 00	0.1165E 05
125.	0.240E 06	0.234E 04	0.142E 07	0.182E 03	0.185E 08	0.816E 03	0.208E 06	0.173E 06	0.761E 04	0.9978E 03	0.1095E 05
130.	0.179E 06	0.174E 04	0.357E 07	0.459E 03	0.502E 08	0.221E 04	0.155E 06	0.129E 06	0.566E 04	0.2668E 04	0.1008E 05
135.	0.124E 06	0.121E 04	0.551E 07	0.708E 03	0.830E 08	0.365E 04	0.107E 06	0.893E 05	0.394E 04	0.4360E 04	0.9508E 04
140.	0.756E 05	0.737E 03	0.728E 07	0.934E 03	0.117E 09	0.515E 04	0.654E 05	0.543E 05	0.239E 04	0.6082E 04	0.9213E 04
145.	0.319E 05	0.311E 03	0.890E 07	0.114E 04	0.152E 09	0.670E 04	0.276E 05	0.229E 05	0.101E 04	0.7843E 04	0.9164E 04
149.	0.000E 00	0.000E 00	0.101E 08	0.130E 04	0.182E 09	0.799E 04	0.000E 00	0.000E 00	0.000E 00	0.9284E 04	0.9284E 04
144.	0.403E 05	0.393E 03	0.858E 07	0.110E 04	0.145E 09	0.639E 04	0.348E 05	0.289E 05	0.128E 04	0.7487E 04	0.9155E 04

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VITA

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Master of Science

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OPTIMUM DRY COOLING TOWER-COOLING POND COMBINATIONS FOR POWER PLANT HEAT REJECTIONS

by

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ABSTRACT

Due to recent environmental concerns, limitations on unrestricted use of water for cooling purposes, siting flexibility and water costs, dry cooling towers are receiving increased attention for power plant heat rejections.

For reasonable approach to ambient air dry bulb temperature with dry cooling towers, large (expensive) heat transfer surface area is required because of the low temperature difference between the condenser cooling water and the air.

A system combining a dry tower and a cooling pond, can possibly provide a more economical attainment of the same heat load rejection with only minimal water use. In such a system, condenser cooling water would be received by a dry tower first and cooled to an intermediate temperature, and then transferred to the pond to dissipate the remaining heat load. The system takes the advantages of the relatively high initial water-air dry bulb temperature difference in the dry section. As this difference diminishes, the water is transferred to the pond where the driving temperature difference again increases, becoming essentially that between the water and the air wet bulb.

Optimum dry tower-cooling pond combinations were found for different sets of environmental conditions and cost factors. Effects of different air dry bulb and dew point temperatures, dry tower and cooling pond capital costs, water (evaporation) costs and power consumption (to run the fan and the pumps) costs on the optimum combination were studied.

It was found that on a daily cost basis water and power costs (i.e. operational costs) far exceed the capital costs. Water costs and power costs could

drastically shift the proportions of dry and wet cooling in the optimum combination.

Low dry bulb and dew point temperatures implied greater proportions of dry cooling and high temperatures suggested greater proportions of pond cooling. Depending on the combination of extreme ambient temperatures and various costs, some cases showed that either all dry or all wet cooling was more economical then a combined system.

Summary of results showed that depending on local conditions and cost factors net monetary savings in cooling costs of up to 26 percent and significant amount of land area savings can result by the use of a combination system rather than an all dry or all wet cooling system.