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Energy Laboratory Report No. MIT-EL 79-035
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Leon R. Glicksman

Energy Laboratory
and
Heat Transfer Laboratory
Department of Mechanical Engineering

Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

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Abstract

There is a projected water shortage problem in the electrical power industry by the end of this century. Dry and wet-dry cooling towers are going to be the solution of this problem. Our previous study on the combination of separate dry and wet cooling towers indicated that wet-dry cooling is an economical choice over all-dry cooling when some water is available but the supply is insufficient for an evaporative tower. An advanced wet-dry cooling tower concept was experimentally studied at MIT's Heat Transfer Laboratory and a computer model was developed for predicting the performance of this cooling concept. This study has determined the cost of the cross-flow type of this cooling concept in conjunction with steam electrical power plants. Aluminum is found to be economically preferable to galvanized steel as the cooling plate material. In our base case study using aluminum plates for a 1094 MWe nuclear plant at Middletown, the MIT advanced cooling concept is comparable to conventional wet-dry towers at water makeups larger than 45% and is slightly more economical at makeup larger than 50%. The incremental costs over the power production cost, 32.3 mills/Kwhr, of zero condenser system are 14, 13 and 12 percent for makeups of 45, 60 and 55 percent, respectively. For an 800 MWe fossil plant at Moline, this cooling concept is more economical than conventional wet-dry towers at water makeups larger than 27%. The incremental costs over 20.8 mills/Kwhr of zero condenser system are 12.2 and 10.6 percent for makeups of 37 and 50 percent, respectively. For these two makeups, going from conventional wet-dry to MIT advanced concept results in 13 and 21 percent, respectively, savings in the incremental cost. When the water makeup exceeds 30%, the MIT advanced wet-dry concept is preferable to conventional wet-dry towers for a 1200 MWe nuclear plant at Moline, Ill. The incremental costs over zero condenser system of 21.1 mills/Kwhr are 12.8 and 11.5 percent for makeups of 40 and 50 percent, respectively. Using the MIT advanced concept instead of conventional wet-dry towers results in 28 and 33 percent reduction of incremental power production cost for these two makeups, respectively.

ACKNOWLEDGMENTS

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"Computer Optimization of Dry and Wet/Dry Cooling Tower Systems for Large Fossil and Nuclear Plants," by Choi, M., and Glicksman, L.R., MIT Energy Laboratory Report No. MIT-EL 79-034, February 1979.

"Computer Optimization of the MIT Advanced Wet/Dry Cooling Tower Concept for Power Plants," by Choi, M., and Glicksman, L.R., MIT Energy Laboratory Report No. MIT-EL 79-035, September 1979.

"Operational Issues Involving Use of Supplementary Cooling Towers to Meet Stream Temperature Standards with Application to the Browns Ferry Nuclear Plant," by Stolzenbach, K.D., Freudberg, S.A., Ostrowski, P., and Rhodes, J.A., MIT Energy Laboratory Report No. MIT-EL 79-036, January 1979.

"An Environmental and Economic Comparison of Cooling System Designs for Steam-Electric Power Plants," by Najjar, K.F., Shaw, J.J., Adams, E.E., Jirka, G.H., and Harleman, D.R.F., MIT Energy Laboratory Report No. MIT-EL 79-037, January 1979.

"Economic Implications of Open versus Closed Cycle Cooling for New Steam-Electric Power Plants: A National and Regional Survey," by Shaw, J.J., Adams, E.E., Barbera, R.J., Arntzen, B.C., and Harleman, D.R.F., MIT Energy Laboratory Report No. MIT-EL 79-038, September 1979.

"Mathematical Predictive Models for Cooling Ponds and Lakes," Part B: User's Manual and Applications of MITEMP by Octavio, K.H., Watanabe, M., Adams, E.E., Jirka, G.H., Helfrich, K.R., and Harleman, D.R.F.; and Part C: A Transient Analytical Model for Shallow Cooling Ponds, by Adams, E.E., and Koussis, A., MIT Energy Laboratory Report No. MIT-EL 79-039, December 1979.

"Summary Report of Waste Heat Management in the Electric Power Industry: Issues of Energy Conservation and Station Operation under Environmental Constraints," by Adams, E.E., and Harleman, D.R.F., MIT Energy Laboratory Report No. MIT-EL 79-040, December 1979.

Table of Contents

Chapter 1

1.1 Introduction

A modern-day fossil-fueled electrical power plant has an efficiency of about 40%; approximately one-half of the heat from the fuel burnt in the boiler is rejected to the circulating water. The efficiency of a Pressurized Water Reactor or Boiling Water Reactor nuclear power plant is about 33%; two-thirds of the nuclear heat generated is rejected as waste heat. Therefore, in the electrical power industry, the amount of waste heat discharged to the environment is enormous, and this must be handled safely, economically and without causing damage to the environment.

For power plants located at a river, ocean or lake where large quantities of water are available, once-through cooling is often employed. In once-through cooling, the hot water from the condenser is discharged into the waterway, resulting in an increase of water temperature which may have adverse effects on the ecology of the water bodies.

Conventionally, when water is not sufficient for once-through cooling, evaporative towers are used. The circulating hot water is broken into small droplets by splashing it down the fill in the cooling tower. More than 75% of the heat rejection is by evaporation. One major disadvantage of evaporative towers is the comsumption of a huge amount of water. A 1000 MWe LWR nuclear plant operating at rated load with an evaporative tower requires about 20,000,000 gallons of make-up water every twenty-four hours [6].

Because of high cost, dry cooling towers have not been broadly used by the utility in the United States. By supplementing the dry towers with evaporative towers the cost of all-dry cooling can be significantly reduced. The first wet-dry towers have been purchased by Public Service Co, of New Mexico for use at their San Juan site. These units, 450 MWe each, are designed to save 60% of the water consumed by evaporative cooling towers.

Several years ago ERDA (now the DOE) sponsored a study by Westinghouse Hanford Co. to determine the regional requirements for dry cooling. The study concluded that there are economic alternatives to dry and wet-dry cooling up to 1990. From 1990 to 2000, the combined effects of restrictions on coastal siting, state regulations of the purchase and transfer of water rights from agriculture or other uses to cooling supply, together with the rapid and continuous growth in electricity demands, will have the potential of bringing wet-dry or dry cooling to increased use. Nationally, a total of 21,000 to 39,000 MWe will require dry or wet-dry cooling at that time [7].

The development of the MIT advanced wet-dry cooling concept is to meet such needs. Although this concept was experimentally studied in the past several years, no cost optimization was done at MIT. United Engineers [2] has performed cost optimization on this MIT concept and reported that this concept is comparable to conventional wet-dry towers only at water makeup of about 50%. However, neither tower performance nor detailed comparison between aluminum and steel were reported. In our present work attempt has been made to compare our results with those of United Engineers. Since it is difficult to compare the results of one study to another if the method of analysis, economic factors and site metereological conditions differ, effort has been made to use these the same as the United Engineers in our computer program. However, cost alogrithyms of most cooling components are those originally in our program [1]. In addition, the detailed information of the cost of the cooling plates has now been added. Aluminum is about 25% more expensive than galvanized steel. Detailed cost data are given in the Appendix A.

1.2 Scope of This Study

The cost optimization of the MIT advanced wet/dry for a LWR nuclear plant at the Middletown site was performed so that comparisons can be made between the results of this study and those reported by United Engineers [2]. In addition, our present work also covers the economic optimization of this cooling concept in both fossil and nuclear power plants at the Moline site. Economics of the advanced MIT wet-dry concept will be compared to conventional wet-dry towers. This is a continuation of our previous study prepared for the Division of Environmental Control Technology, U.S. Department of Energy.

1.3 Outline of Presentation

The material in this report is presented in the following sequence. Chapter 2 is a presentation of power plant model, method of analysis and basic economic factors for the Middletown site. These are reported in Chapter 3 for the Moline site. Chapter 4 presents the MIT advanced wet/dry cooling tower model. The optimization procedures are given in Chapter 5 and the results are reported in Chapter 6. Chapter 7 compares the results of this study with the United Engineers. A sensitivity study of the effect of plate cost on the economic optimization is presented in Chapter 8. Finally, Chapter 9 gives conclusions and recommendations.

Chapter 2

This chapter presents the power plant model, method of analysis and base case sconomic factors for the Middletown site. These are the same as those used by United Engineers [2].

2.1 Method of Analysis

The method of analysis is a fixed steam source and fixed demand approach. It assumes a constant heat source of 3173 MWT to be coupled to a conventional low back pressure steam turbine and there is a fixed demand of electrical output from the power plant. The reference plant is assumed to operate at 2 inch HgA all year round with an output of 1094 MWe which is then assumed to be the fixed demand. Any deficit between the plant net capacity and the fixed demand is replaced by incremental base load plant. No load profile is scheduled for the power plant. It assumes that the average annual capacity factor is 75%.

2.2 Plant Model

The nuclear power plant assumed for the cooling system evaluation at Middletown is a Light Water Reactor (LWR). As mentioned in the previous section the steam source is fixed and is coupled to a low back pressure turbine. The turbine-generator is a General Electric Tantum Compound Six Flow (TC6F) 38" turbine. The turbine inlet steam condition is 965 psig saturated. The full-load turbine net heat rate vs. exhaust pressure is plotted in Fig. 2.1.

2.3 Base Economic Factors

The base economic factors for the Middletown site are given in Table 2.1. All the costs are in 1985 dollars.

2.4 Meteorological Condition

The dry bulb and wet bulb temperature distributions at the Middletown site are shown in Fig. 2.2.

Table 2.1 Base Case Economic Factors for Middletown

Year of Pricing	1985
Power Plant Cost	$600/KW
Fuel Cost	$1.53/MM BTU
Fixed Charge Rate	18%
Average Annual Capacity Factor	75%
Capacity Penalty (Incremented Base Load Plant)	$600/KW
Energy Penalty (Base Load Plant Fuel Cost)	$1.53/MM BTU
Water Cost	27¢/1000 gallons
Indirect Cost	25% of direct capital cost

FIG. 2.1

NET HEAT RATE VS. EXHAUST PRESSURE FOR 3173 MWt NUCLEAR TURBINE

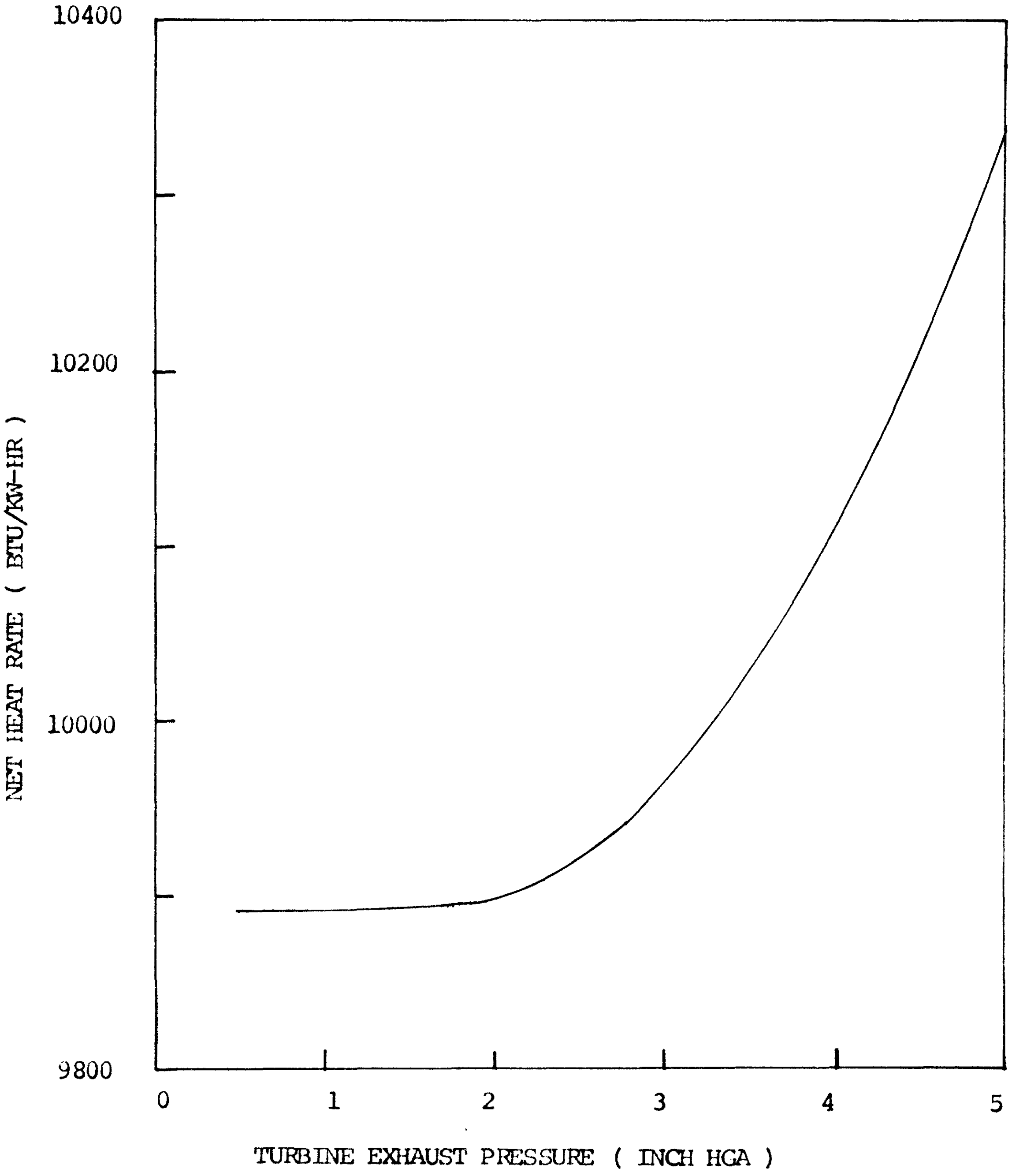
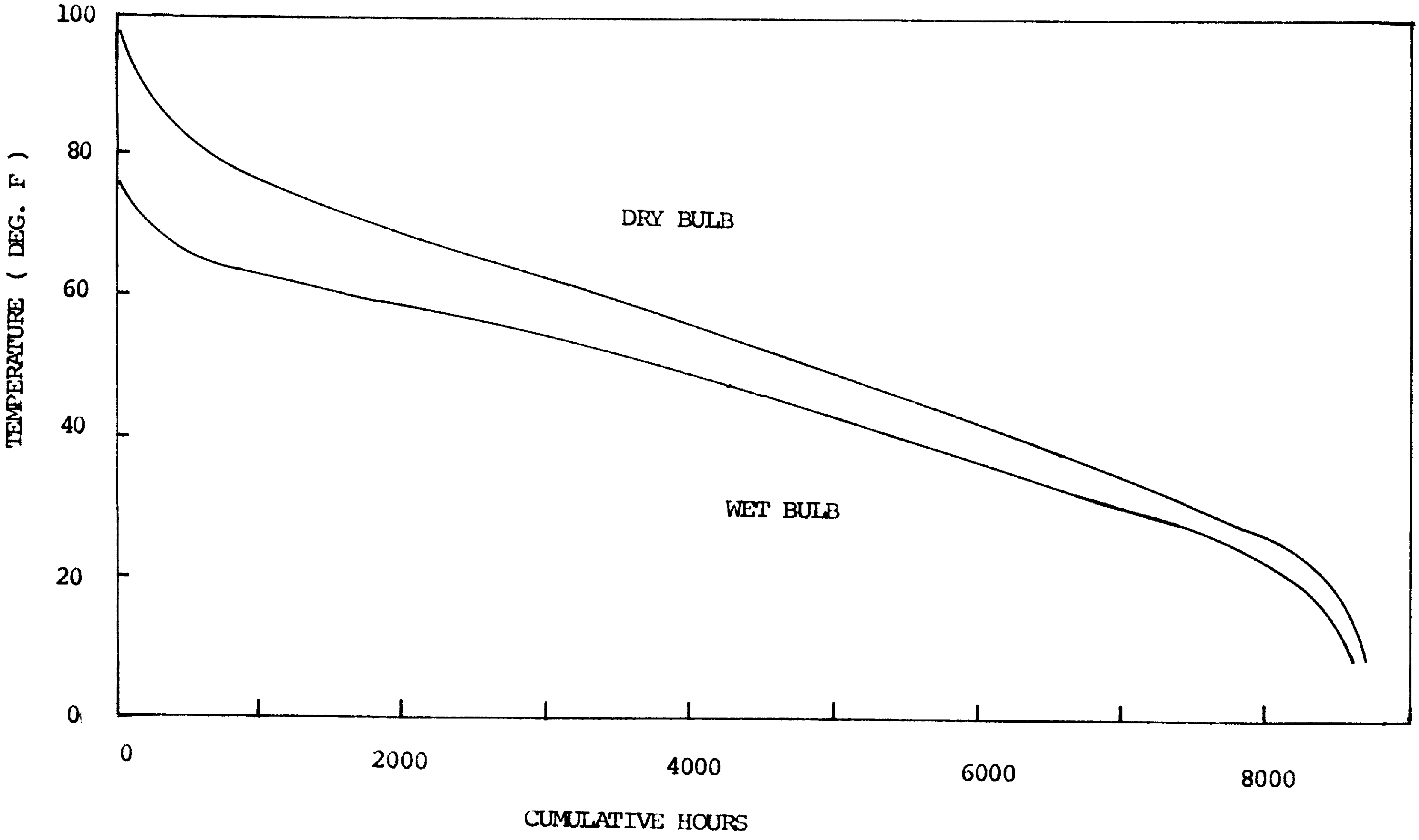


FIG. 2.2

DRY BULB AND WET BULB TEMPERATURE DISTRIBUTIONS AT MIDDLETOWN SITE



Chapter 3

The power plant model, method of analysis and base economic factors for the Moline site are presented in this chapter.

3.1 Method of Analysis

The method of analysis is a constant steam source and fixed demand approach. It assumes a constant heat source to be coupled to a low back pressure turbine. This heat source is 1862 MWt for the fossil plant and 3577 MWt for the nuclear plant. There is a fixed demand of electrical output from the power plant. This is 800 MWe for the fossil plant and is 1200 MWe for the nuclear plant. Any deficit between the net plant capacity and the fixed demand is replaced by gas turbines. There is no load profile scheduled for the power plant. The annual capacity factor is 75%.

3.2 Plant Model

The nuclear plant assumed for the cooling system evaluation is a Boiling Water Reactor (BWR). The turbine-generator is a General Electric TC6F-38 turbine with its full-load net heat rate vs. exhaust pressure shown in Fig. 3.1. The turbine inlet steam condition is 965 psig saturated. The fossil plant is assumed to be coal-fired. Its turbine-generator is a General Electric Cross Compound Six Flow (CC6F) with reheat cycle; its inlet steam conditions are 3500 psig 1000°F/1000°F. The full-load net heat rates vs. exhaust pressure of the fossil turbine is shown in Fig. 3.2.

3.3 Base Economic Factors

The base economic factors for the Moline site are given in Table 3.1. All the costs are in 1977 dollars.

3.4 Meteorological Conditions

The dry bulb and wet bulb temperature distributions at Moline are shown in Fig. 3.3.

Table 3.1 Base Economic Factors for Moline

Year of Pricing		1977
Power Plant Cost:		
	Fossil	$500/KW
	Nuclear	$600/KW
Fuel Cost:		
	Fossil (coal)	$0.90/MM BTU
	Nuclear	$0.47/MM BTU
Fixed Charge Rate		17%
Annual Capacity Factor		75%
Replacement Capacity (gas turbines)		$160/KW
Replacement Energy (gas turbines)		30 mills/KWhr
Operation and Maintenance		1% of all capital costs
Indirect Cost		20% of direct capital cost
Water Cost		20¢/1000 gallons

NET HEAT RATE VS. EXHAUST PRESSURE FOR 1862 MWt FOSSIL TURBINE

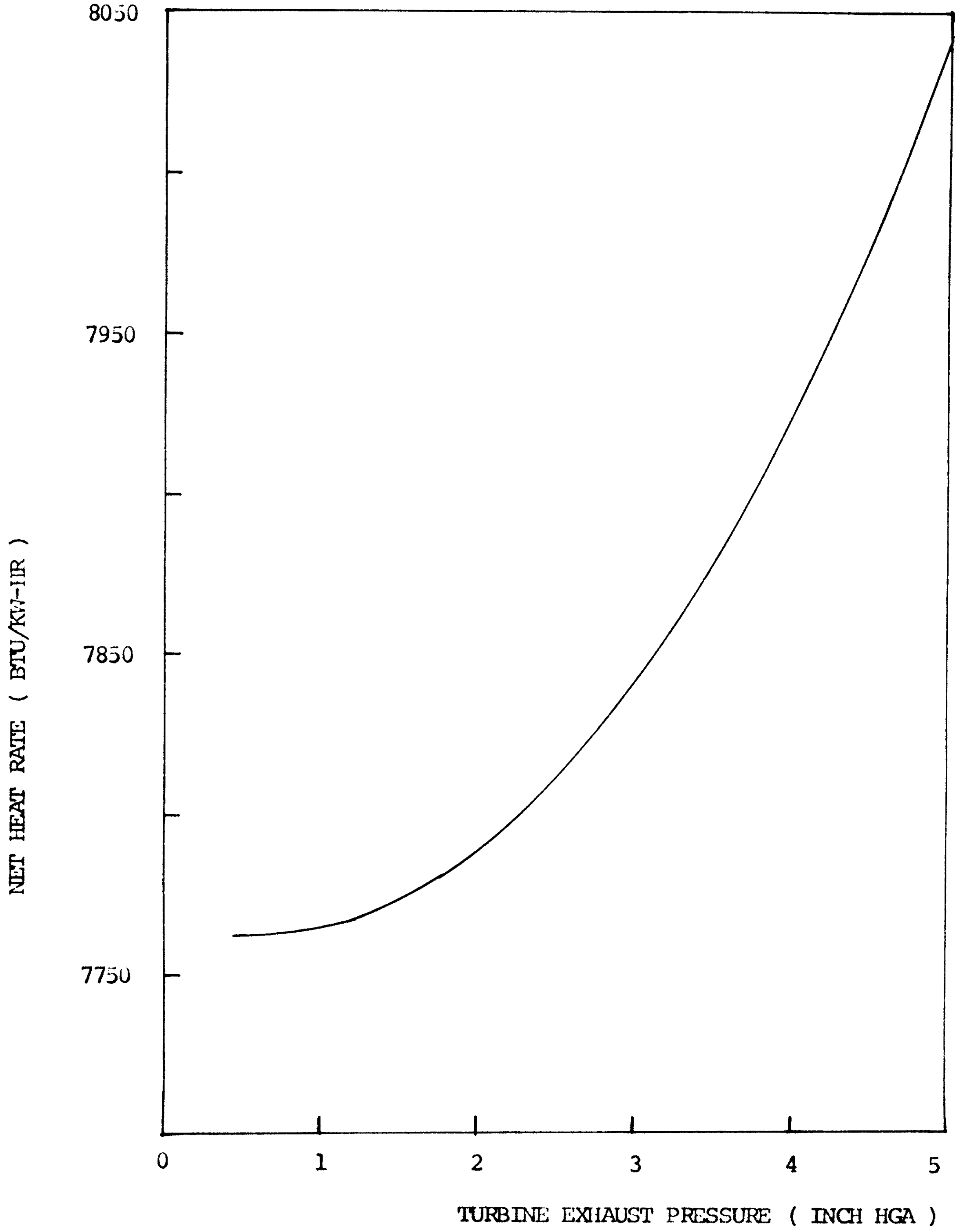


FIG. 3.1

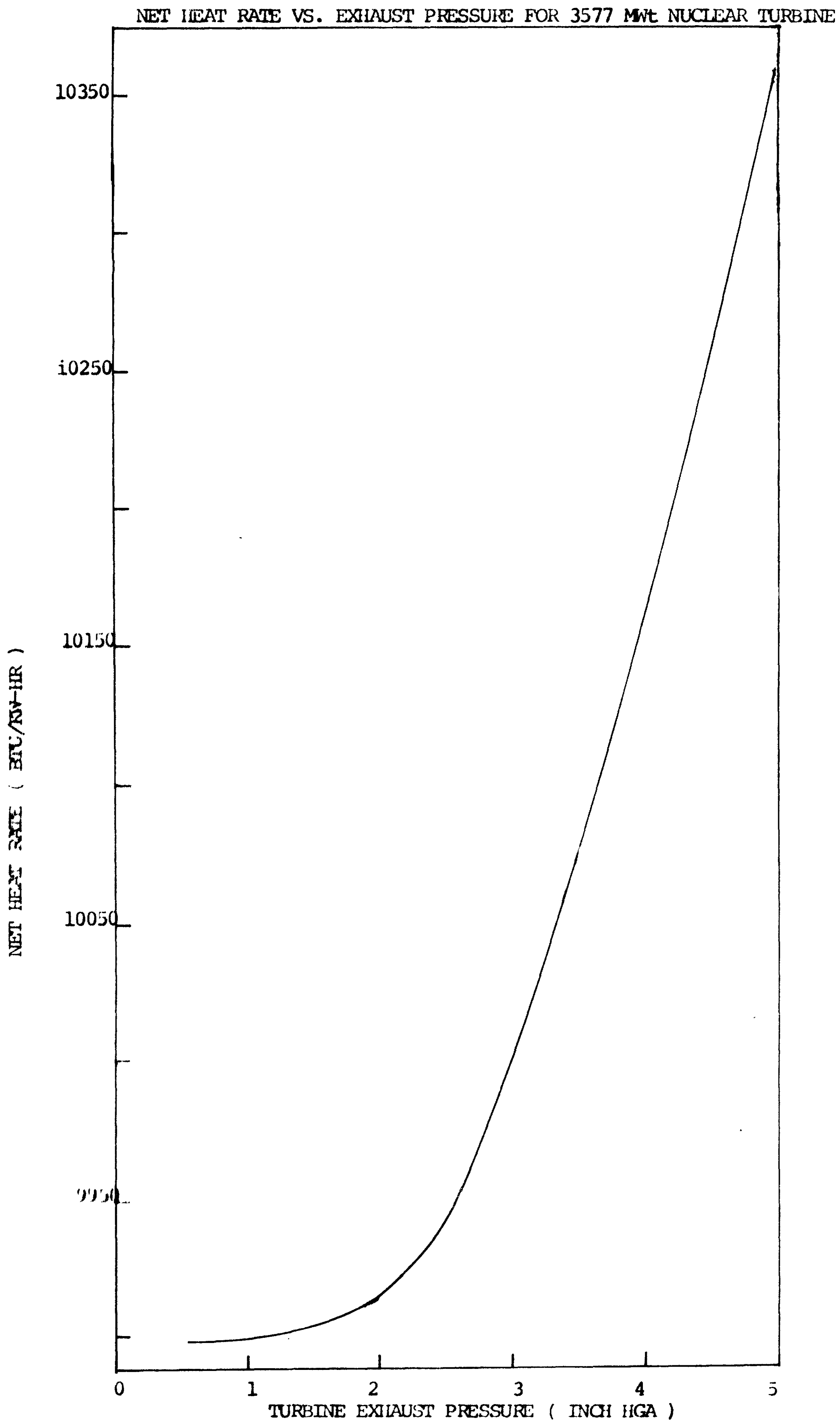
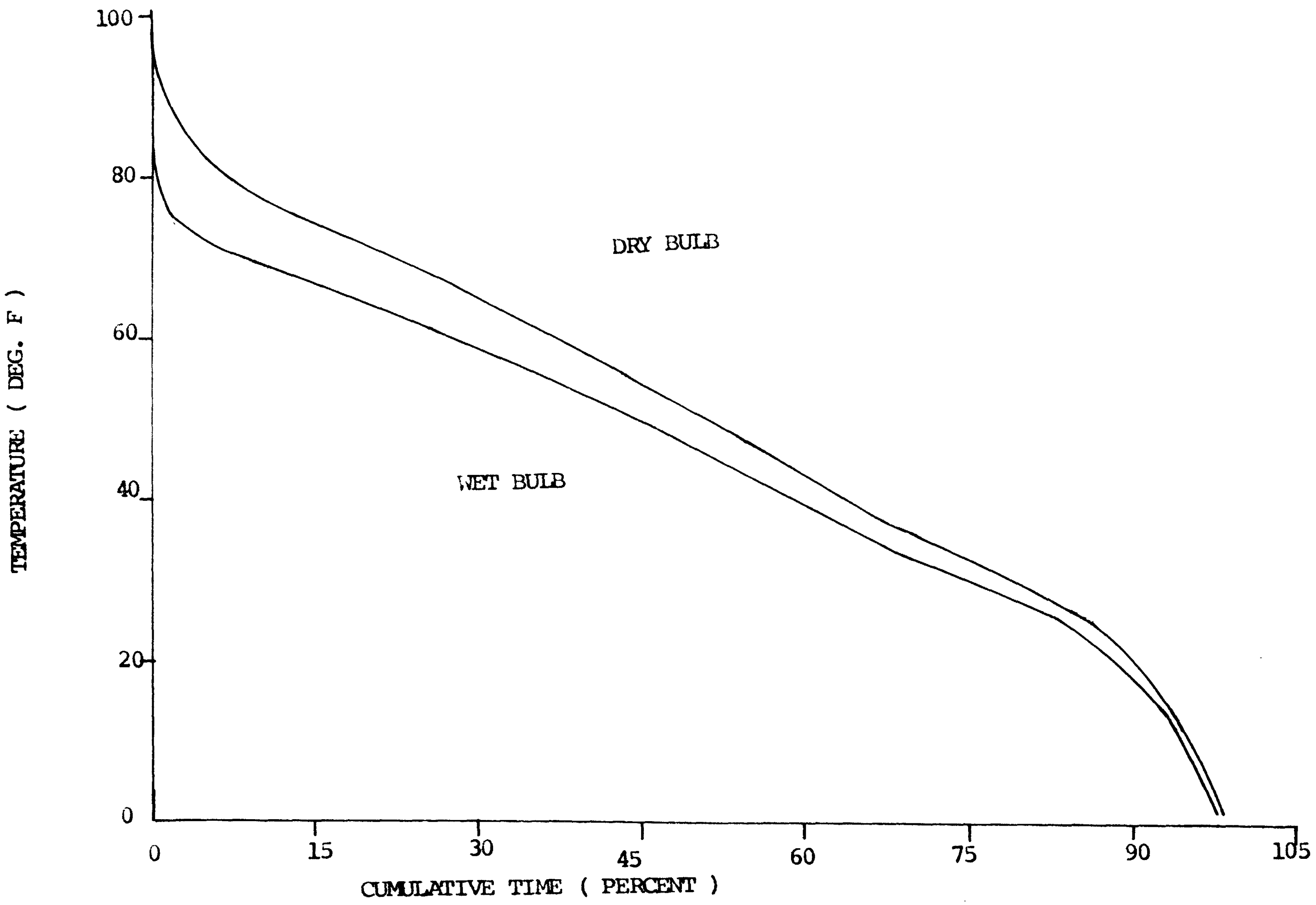

NET HEAT RATE VS. EXHAUST PRESSURE FOR 3577 MWt NUCLEAR TURBINE

FIG. 3.2

FIG. 3.3

CUMULATIVE DISTRIBUTIONS OF DRY BULB AND WET BULB TEMPERATURES AT MOLINE SITE



Chapter 4

MIT Advanced Wet/Dry Cooling Tower System Model

4.1 Introduction

In this study the MIT advanced wet/dry cooling tower system is taken to be an indirect type with surface condensers and tower heat exchangers are packing plates with V-shape water troughs. The air flow in the cooling tower is mechanically induced by fans. The piping system is considered in detail. The various components of the cooling tower system are shown in Fig. 4.1.

Condensation of turbine exhaust steam takes place at the saturated steam temperatures corresponding to a given turbine exhaust pressure. The condensate is returned to the feedwater circuit. Cooling water entering the condenser at a temperature T_1^w is heated to a temperature T_2^w on leaving the condenser. The difference between the saturated steam temperature and the hot water temperature is the terminal temperature difference (TTD). The temperature difference between T_1^w and T_2^w is the water range. On leaving the condenser, the hot water is circulated through the piping system to the wet/dry tower. The plates are folded at the top to direct water into the V-troughs and prevent water from wetting the fins [4,8]. This is illustrated in Fig. 4.6 on the header plate into the V-shape troughs running from the top to the bottom of the plates. The plates are tilted at 10° to the vertical so that the water flows down the troughs under gravity.

Evaporation takes place at the air-water interface. Furthermore, convective heat transfer takes place on the dry plate surface where air flows across the plate. On the wetted side of the plates, the dry surface is roughened with flow disturbers which serve two purposes. First, they break up the boundary layers to increase the heat transfer coefficient and second, they direct the air-water mixing at both ends of the plates back to the troughs.

Because the MIT advanced wet/dry tower has only a single structure, no infinite control of water and air flow rates is required. This is an important advantage over the conventional wet-dry towers which consist of separate wet and dry towers.

The difference between the temperature of the hot water entering the cooling tower and the dry bulb temperature of the incoming ambient air is the initial temperature difference (ITD). After cooling, the water is collected in a water basin and returned to the condenser. The difference between the cool water temperature ,T_1^w, and the ambient wet bulb temperature is the approach. The temperature relationships are illustrated in Fig. 4.2

The wet/dry towers considered in this study are circular in shape. The cooling plates are arranged around the base of the towers. These are illustrated in Fig. 4.3.

Crossflow is preferrable to counterflow because of the water-air mixing above and below the plates in the latter which could increase the water evaporation. Therefore, only the crossflow type of this cooling concept is considered in this study.

Han's correlations [3] are employed in determining the heat transfer coefficient and friction factor for the roughened surface of the cooling plates. They are the following:

$$e^{+} = \frac{e\ R_{e}}{D_{h}\sqrt{2/f}}$$

$$R_{e}^{+} = \sqrt{\frac{2}{f}} - 2.5\ \ln \frac{2e}{D_{h}} - 3.75$$

$$R_{e}^{+} * \frac{10}{P/e}^{n} (\phi/90)^{0.35} (\alpha/45)^{0.57} = 4.9\ (e^{+}/35)^{m}$$

where $m = \begin{cases} -0.4 & \text{for } e^{+} < 35 \\ 0 & \text{for } e^{+} \geq 35 \end{cases}$

$n = \begin{cases} 0.13 & \text{for } P/e < 10 \\ 0.53\ (\alpha/90)^{0.71} & \text{for } P/_{\theta} \geq 10 \end{cases}$

and where Re = Reynold's number

ρ = density of air

μ = viscosity of air

V = air velocity

D_h = hydraulic diameter

f = friction faction

e = right height

P = pitch of ribs

α = angle of attack

and ϕ = angle of inclination of ribs

For $e^{+} > 35$, then $H^{+} = C\ (\frac{e+}{35})^{0.28}$

where C - constant which depends on the surface characteristics

The Stanton number is given by:

The Nusselt number is given by:

$$Nu = 0.72\ St\ Re$$

Heat transfer coefficient $h + Nu\ k/_{Dh}$

where k = conductivity of air.

Note that each cooling plate has two distinct sides. On the wetted side, the ribs are the flow separators. On the unwetted side, the protrusions of the V-troughs naturally become ribs themselves. Therefore, there are two different convective heat transfer coefficients, one for each side of the plate. Similarly, this is also true for the friction factor. In this study the overall convective heat transfer coefficient is taken to be the mean value. The friction factor is the mean friction factors.

In the above correlations, we have the following:

$$e = \begin{cases} 0.25 \text{ inch for the wetted side} \\ 0.2706 \text{ inch for the unwetted side} \end{cases}$$

$$\alpha = \begin{cases} 45^\circ \text{ for the wetted side} \\ 90^\circ \text{ for the unwetted side} \end{cases}$$

$$\phi = \begin{cases} 90^\circ \text{ for the wetted side} \\ 60^\circ \text{ for the unwetted side} \end{cases}$$

$$c = \begin{cases} 10. \quad \text{for the wetted side} \\ 13.6604 \text{ for the unwetted side} \end{cases}$$

For $e^+ < 35$, then $H^+ = C$.

By using these correlations, a comparison between several runs of experimental results [8] and theoretical predictions is made in Table 4.1. In general, good agreement is achieved between the data the theoretical results.

Table 4.1 Comparison of Experimental and Theoretical Results

	(1)		(2)		(3)		(4)	
	+	*	+	*	+	*	+	*
Air Velocity ft/sec	10.69		10.69		11.09		11.0	
Inlet Air Temperature °F	79.3		78.9		76.8		70.8	
Inlet Air Humidity lb/lb	3.103		2.85		3,849		3.505	
Inlet Water Temperature °F	144.5		129.4		123.4		138.2	
Total Heat Transfer Btu/min	502.4	594.9	371.8	432.8	386.7	407.1	593.0	619.7
Percent Evaporative Heat Transfer	41.	43.2	39.	43.2	45.	39.3	43.	40.5

\+ Experimental

* Theoretical

4.2 Packing Plates

As mentioned in the previous section, the cooling plates are folded at the top to direct water into the V-troughs. In manufacturing these plates, a structure of ten of these plates is bolted together to form a fill pack [2]. These fill packs are shipped to the construction site where a number of these fill packs form the necessary number of modules. These cooling modules are supported above the water basin by an "I" beam structure. The plates are held at 10^{o} to the vertical by a wedge-shape structure formed from pipes [2].

4.3 Evaluation of Off-Design Tower Performance

The evaluation of the heat rejection capability of the MIT advanced wet/dry tower at off-design condition is discussed in this section.

At thermodynamical equilibrium the condenser heat load must be equal to the tower heat rejection rate. Also, the condenser heat load is equal to the rate of heat discharged by the turbine. The determination of the condenser equilibrium temperature requires trial and error. The bulky calculation can be readily handled by the computer. To do this, for each ambient condition under consideration, first, a file of tower heat rejection vs. turbine exhaust steam temperature is created. Second, the turbine heat rejection vs. exhaust steam temperature is determined. Then trial and error is used to determine the equilibrium temperature at which the tower heat rejection rate is equal to the turbine heat rejection rate. This is illustrated in Fig. 4.5.

In this study, the performance of the MIT advanced wet/dry tower is evaluated over a yearly cycle of temperature and air humidity.

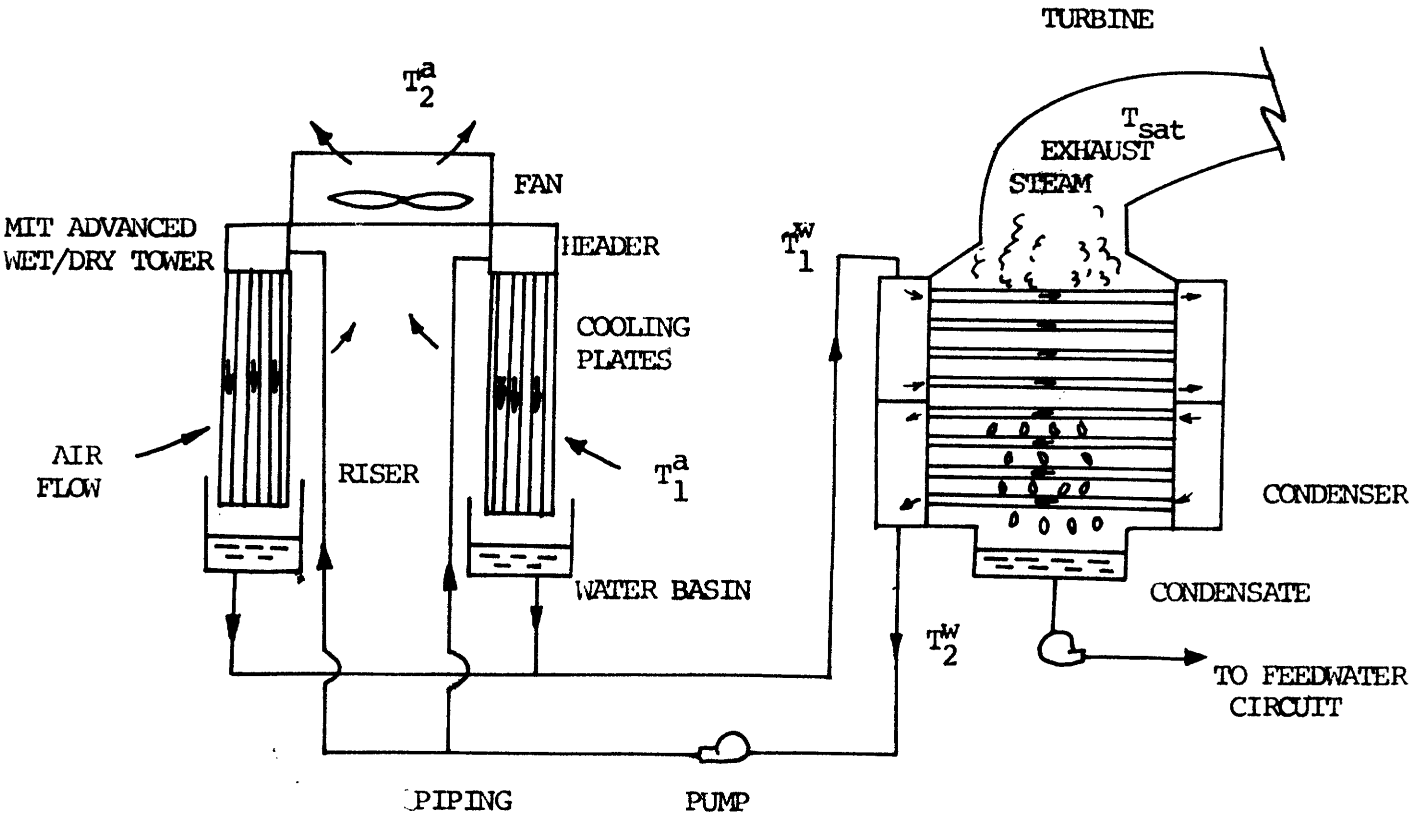
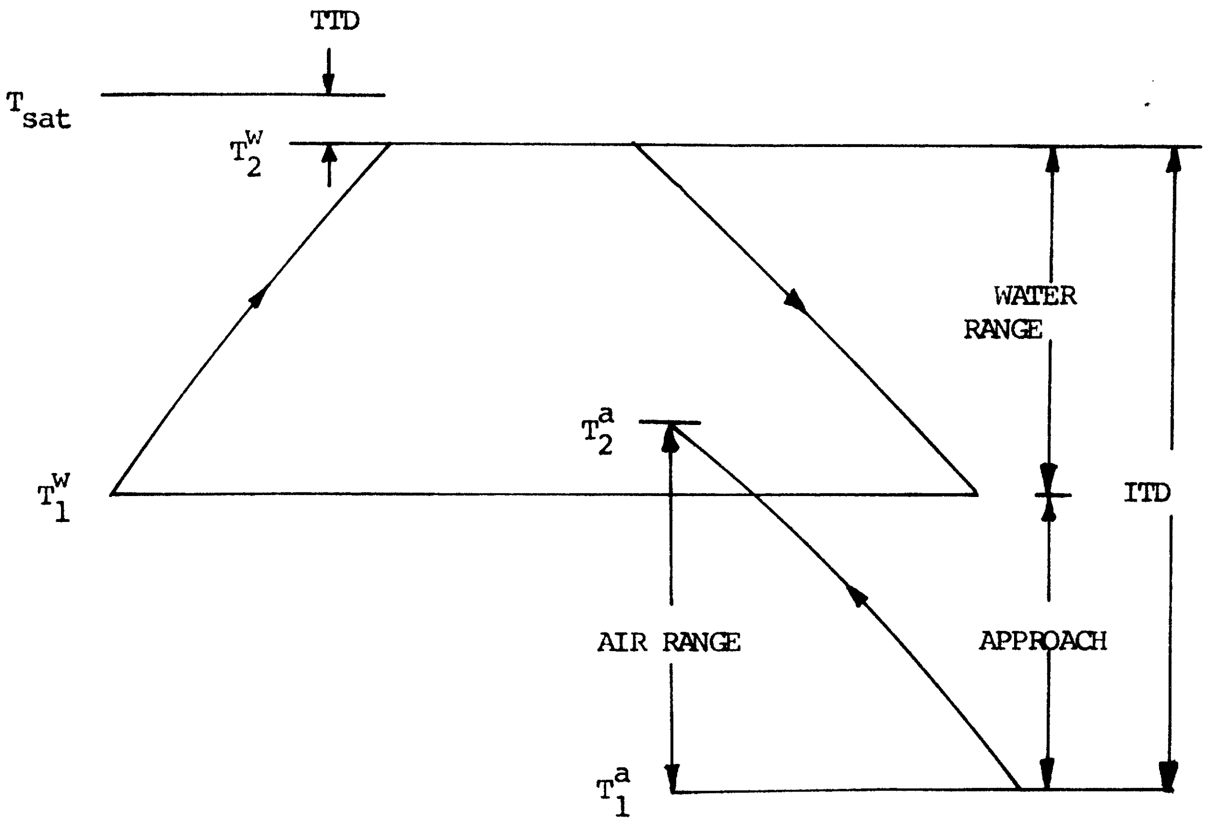


FIG. 4.1 MIT ADVANCED WET/DRY COOLING TOWER SYSTEM



T_{sat} = SATURATED STEAM TEMPERATURE AT TURBINE OUTLET

TTD = CONDENSER TERMINAL TEMPERATURE DIFFERENCE

ITD = INITIAL TEMPERATURE DIFFERENCE

T_1^w = COOL WATER TEMPERATURE

T_2^w = HOT WATER TEMPERATURE

T_1^a = TEMPERATURE OF AMBIENT AIR ENTERING WET/DRY TOWER

T_2^a = TEMPERATURE OF AIR LEAVING TOWER

FIG. 4.2 TEMPERATURE RELATIONSHIPS

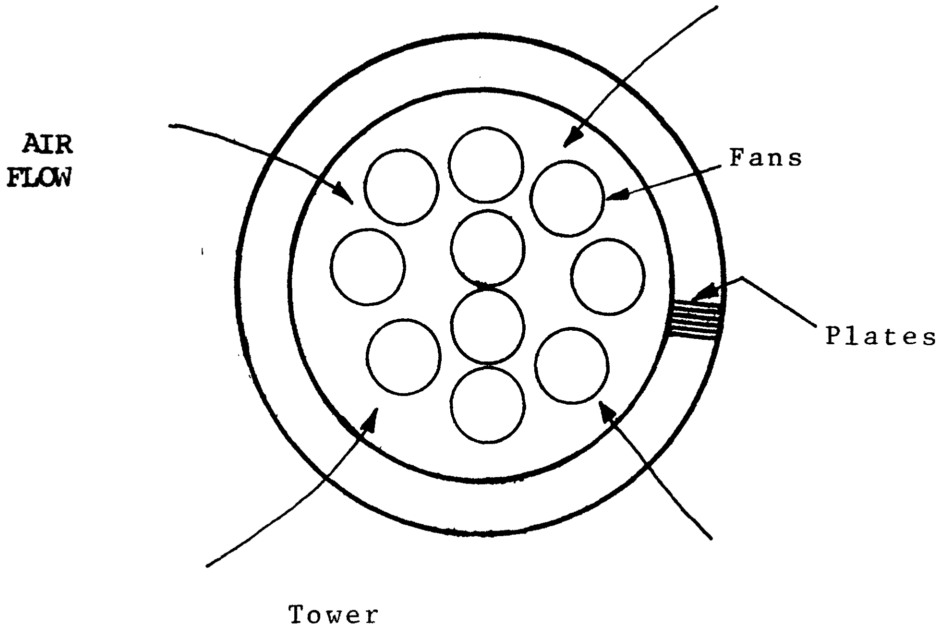

AIR FLOW
Fans
Plates
Tower

FIG. 4.3

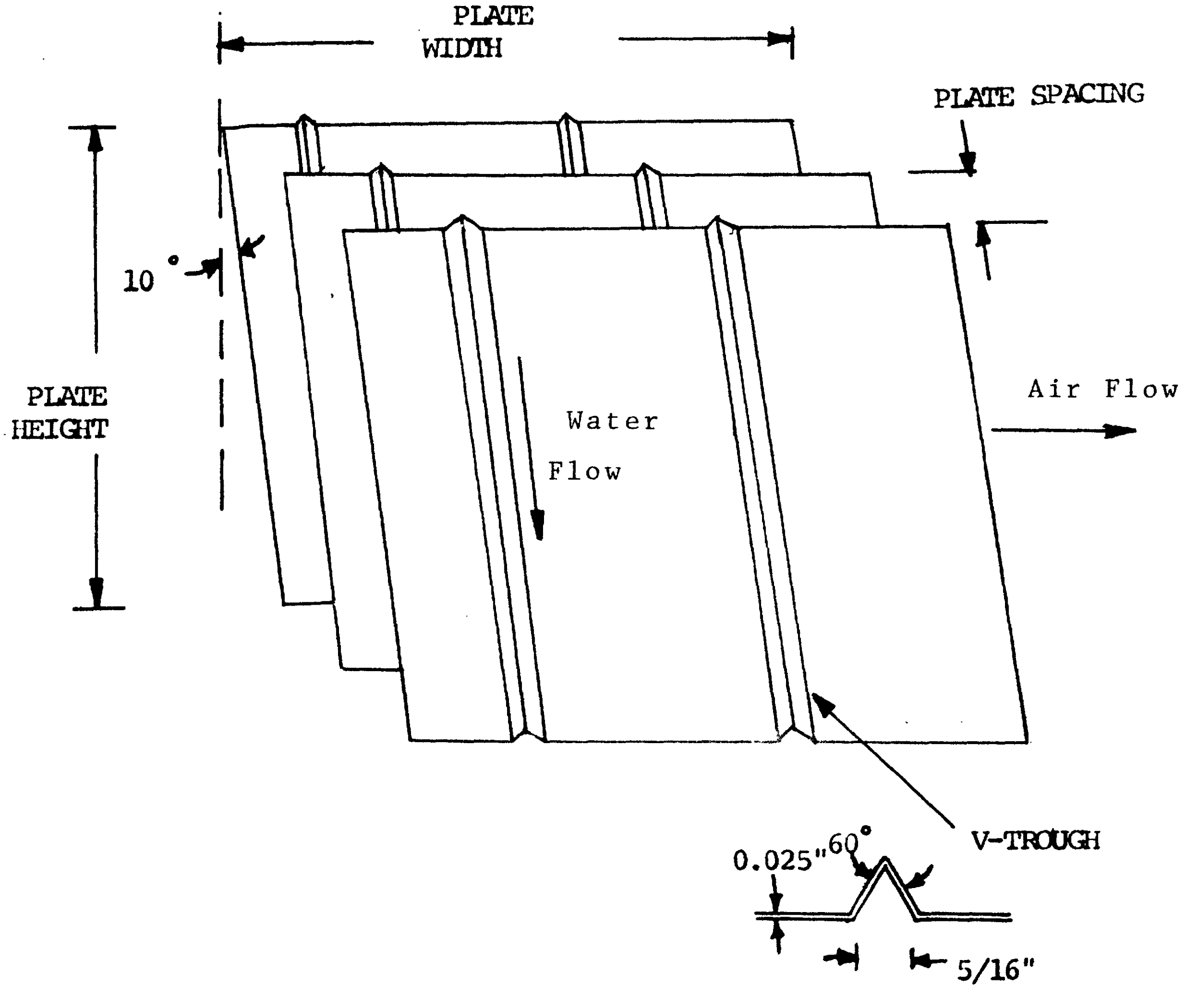


PLATE WIDTH
PLATE SPACING
10 °
PLATE HEIGHT
Water Flow
Air Flow
V-TROUGH
0.025"
60°
5/16"

FIG. 4.4

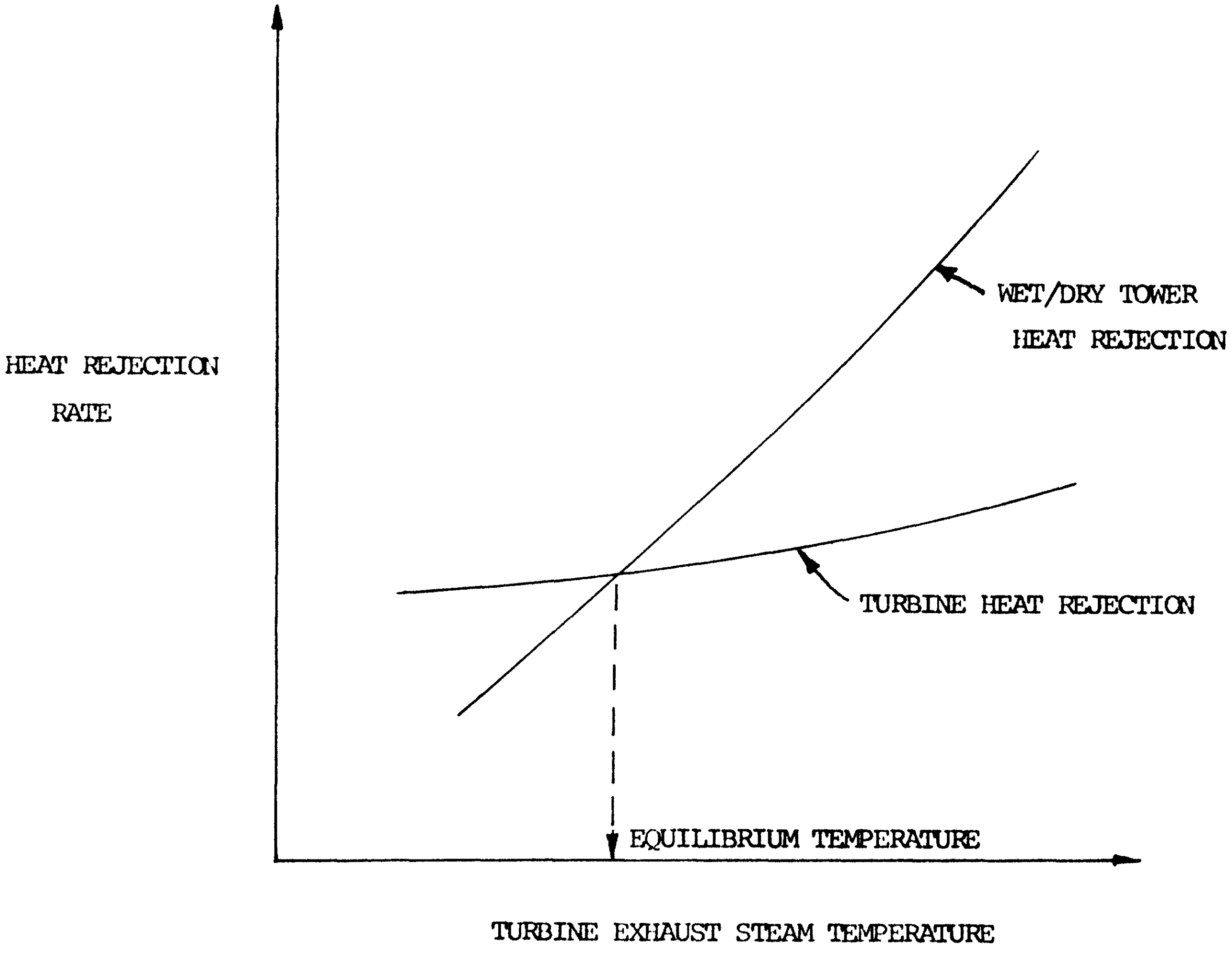
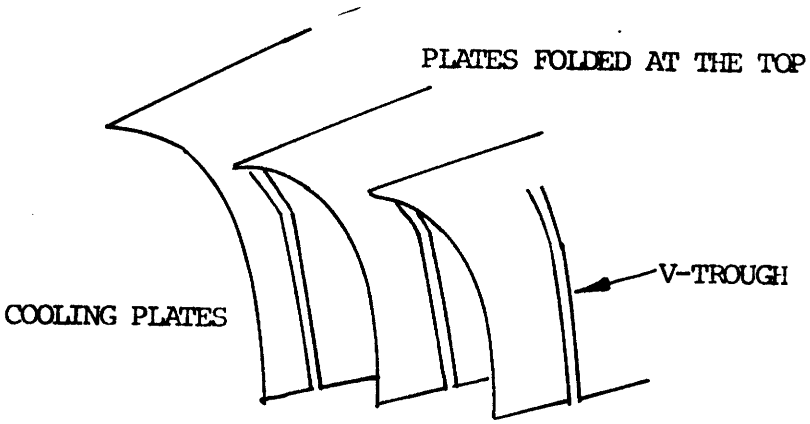
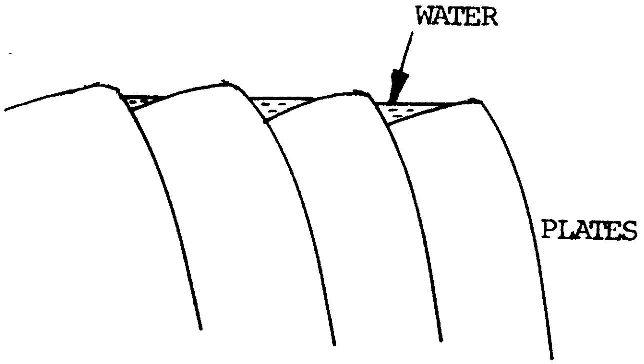

HEAT REJECTION RATE
WET/DRY TOWER HEAT REJECTION
TURBINE HEAT REJECTION
EQUILIBRIUM TEMPERATURE
TURBINE EXHAUST STEAM TEMPERATURE

FIG. 4.5





SIDE VIEW

FIG. 4.6

Chapter 5

Optimization Procedure

The optimization program optimizes the plate spacing, plate packing width, plate height, air flow rate and water flow rate. The number of water troughs per plate is varied to give various water makeup requirements. Illustration of the meaning of the above variables has been given in Fig. 4.4.

5.1 Optimization Procedure

With a given plate material, a given turbine heat rate characteristic, a specified net capacity, a given set of economic parameters, a given set of meteorological data and the variables mentioned above, optimization can then be performed. The optimization involves sequentially varying one variable while keeping the others constant. The procedures are as follows:

(1) Select a design ambient condition and a design turbine exhause steam saturated temperature. Although these are rather arbitrary, they should be chosen so that they are economical to the utility. By selecting the maximum ambient and the maximum backpressure of a low back pressure turbine, steam throttling can be avoided. In other words, the power plant can run at full-load all year long. The difference between the saturated steam temperature and the design condenser terminal temperature difference gives the hot water temperature.

(2) Pick a combination of reasonable values of plate spacing, packing width, plate height, air flow mass velocity (V) and water flow rate for a given number of plates.

(3) Vary the number of troughs per plate to give different water makeup systems.

(4) Find the power production cost for the various water makeups.

(5) Change the plate spacing while keeping the other variables constant.

(6) Plot the power production cost vs. the water makeup for the various spacings.

(7) Select the rough optimum spacing that gives the least power production cost for a given makeup.

(8) Repeat the above procedures for the other variables.

(9) Repeat the above with smaller changes in the variables.

(10) Use further smaller step sizes if noticeable changes in the cost is observed. This gives the final optimum values.

The computer program listing is given in Appendix B.

Chapter 6

Results of Optimization

This chapter presents the results of optimization for both the Middletown site and the Moline site. They are given in sections 6.1 and 6.2, respectively.

6.1 Results for Middletown Using United Engineers Approach and Base Economic Factors

The power production cost vs. water makeup requirement were plotted in Figs. 6.1 - 6.5 for aluminum plates. In Fig 6.1 we see the effect of plate spacing on the power production cost is quite significant. Bearing in mind that plate spacing should be limited to a minimum of 0.75 inch and to a maximum of 1.5 inches to avoid any manufacturing problems [2], only values within these limits were considered. In this figure we see that for water makeup larger than about 41%, among the three spacings considered, 1 inch is the best. For water makeup less than 41%, 0.75 inch spacing is slightly better than 1 inch. Fig. 6.2 shows the effect of the air velocity. In general, a higher air velocity would result in a higher heat transfer coefficient but a larger pressure drop. Among the three air flow rates considered, a value of 3000 $lb/hr/ft^2$ is the most economical. It corresponds to a velocity of about 12 ft/sec. Because pressure drop is proportional to the square of the air velocity, a high air velocity gives a very large pressure drop or fan power.

Fig. 6.3 is a plot of power production cost vs. water makeup for three different packing widths. It appears that a packing width of 5 ft. is the best in almost all water makeups. The number of troughs per foot of packing width might be limited to a maximum of eight to avoid any manufacturing problem [2]. If this is the case, then the maximum number of troughs for a 5 ft.

packing width is limited to 40. For packing widths of 7 ft. and 9 ft., the maximum number of troughs are 56 and 72, respectively.

Fig. 6.4 shows the effect of the plate height on the cost. Among the three heights considered, 28 ft. is the most economical. Note that a larger plate height would result in a higher pumping head.

The effect of the water flow rate on the cost can be seen in Fig. 6.5 For makeups larger than about 46%, a water flow rate of 3000 lb/hr/plate is the best. For makeups less than 46%, 2000 lb/hr/plate is the most preferrable.

After using smaller changes in the variables, the fine optimum power production cost vs. water makeup curve was plotted in Fig. 6.11.

Using galvanized steel plates, the results were plotted in Figs. 6.6 - 6.10, and the fine optimum curve is also shown in Fig. 6.11.

In employing the Han's correlations, the total heat transfer area should be larger is all the faces of the ribs on the wetted side of the plates were included. It would increase the dry surface area by about 10%. The effect of this increase in surface area can be seen in Fig. 6.11. Because an increase in the heat transfer area results in a higher convective heat transfer, the effect is economically very favorable.

A comparison between aluminum plates and steel plates can be made in Fig. 6.11. Because the thermal conductivity of aluminum is six times that of steel, the fin efficiency of aluminum plates is much higher for low water makeups.

Note that for aluminum plates, although the MIT advanced wet/dry concept is more economical than conventional wet-dry towers only at water makeups larger than about 50%, it does not differ much in cost from the conventional wet-dry towers at makeups between 40 and 50 percent.

The optimum design parameters for the MIT advanced wet/dry concept using aluminum plates are shown in Table 6.1 for water makeups of 45, 50 and 55 percent. The cost breakdowns are shown in Table 6.2. Note that for these three water makeups, the incremental power production costs over zero-condenser systems are 11.6, 13.2 and 12.4 percent, respectively. Using conventional wet-dry towers, these incremental costs are 13.2, 13.0 and 12.6 percent. Therefore, for makeup between 45 and 55 percent, the cost of the MIT advanced wet/dry concept would be essentially the same as the conventional wet-dry towers.

The heat rejection capabilities of the MIT advanced wet/dry concept are illustrated in Figs. 6.12 - 6.14, with the heat rejection rate vs. condenser saturated steam temperature for various ambient conditions. The tower heat rejection curve intersects the turbine heat rejection curves at the equilibrium condenser steam temperature. Because the turbine is allowed to operate at the maximum allowable back pressure (5 inch HgA) at the maximum ambient temperature, the condenser steam temperature for all makeups is the same at the highest ambient, namely 133.76°F. Note that for a given condenser steam temperature, the tower heat rejection rate increases as the ambient temperature decreases.

Fig. 6.15 shows how the water makeup rate increases with ambient dry bulb temperature for water makeups of 45, 50 and 55 percent. For a given ambient temperature, the water evaporation rate of a larger makeup system is higher because of less dry surface and more wet surface.

The power plant net capacity vs. ambient dry bulb temperature for three different water makeup cooling systems is shown in Table 6.3. The net capacity is the difference between the gross capacity and the auxiliary power for fans and pumps.

6.2 Results of Optimization for the Moline Site

The results in the previous section are for the Middletown site using the base economic factors presented in Chapter 2. In this section, the results of optimization for the Moline site will be presented separately.

Starting with the optimum values of plate spacing, plate packing width, plate height, air flow rate and water flow rate obtained in the previous section, optimization for the Moline site were similarly performed. The optimum power production cost vs. water makeup curves were plotted in Fig. 6.16 for the fossil plant and in Fig. 6.17 for the nuclear plant. Again, we see that aluminum is significantly advantageous to galvanized steel as the plate material. Using aluminum plates, the MIT advanced wet/dry concept is more economical than conventional wet-dry towers at water makeups larger than 30% for either the fossil or the nuclear plant. Using steel, this is 40% for the fossil plant and 41% for the nuclear plant.

For the fossil plant, the incremental power production costs of this MIT concept using aluminum plates over zero condenser cost system are 14.8, 12.2 and 10.6 percent for water makeups of 25, 37 and 50 percent because the power production cost of the zero-condenser system is 20.8 mills/Kwhr. These incremental costs are 14.4, 14.0 and 13.5 percent for conventional wet-dry towers. Therefore, the savings obtained by using the MIT advanced wet/dry tower are rather significant.

For the nuclear plant, the power production cost of the zero-condenser system is 21.1 mills/Kw-hr. The incremental power production costs for water makeups of 30, 40 and 50 percent are 15.9, 12.8 and 11.5 percent, respectively. These incremental costs are 15.9, 15.2 and 14.8 percent for the conventional wet-dry towers. Again, the savings obtained by using the MIT advanced concept are significant.

The optimum design parameters for these three water makeups are shown in Table 6.4 for the fossil plant and in Table 6.5 for the nuclear plant. The cost breakdowns are given in Tables 6.6 and 6.7. The plant net capacity vs. ambient temperature is presented in Table 6.8 for the fossil plant and in Table 6.9 for the nuclear plant.

TABLE 6.1 - Optimum Design Parameters
of MIT Advanced Wet/Dry Tower for 1094
MWe Nuclear Plant at Middletown

Plate Material is Aluminum

		Makeup (%)	
	45	50	55
Dssign Ambient Dry Bulb Temperature (^{o}F)	99	99	99
Design Ambient Wet Bulb Temperature (^{o}F)	77	77	77
Design Turbine Back Pressure (inch HgA)	5	5	5
Design Heat Rejection Rate (10^9 Btu/hr)	7.255	7.255	7.255
Design Water Range (^{o}F)	24.3	26.7	28.6
Design Approach (^{o}F)	27.5	25.0	23.1
Plate Spacing (inch)	1.00	1.00	1.00
Packing Width (ft)	5	5	5
Plate Height (ft)	28	28	28
Air Flow Rate (10^9 lb/hr)	0.60	0.54	0.57
Water Flow Rate (10^9 lb/hr)	0.30	0.27	0.25
Number of Troughs per Plate	30	38	45
Total Number of Plates	95256	86316	58776
Evaporative/Convective Heat Transfer at Highest Ambient	61%/39%	65.6%/34.4%	68.7%/31.3%
Gross Output at Pmax (MWe)	1047.1	1047.1	1047.1
Net Output at Pmax (MWe)	1024.3	1026.9	1028.9
Fin Efficiency	0.90	0.94	0.96
Dry Surface Convective Heat Transfer Coefficient (	7.68	7.61	7.56
Plate Friction Factor	0.13	0.13	0.12

TABLE 6.2 - Cost breakdown for
Optimum Design 45%, 50% and 55%
Water Makeup Tower System for 1094
MWe Nuclear Plant at Middletown

All costs are in million dollars except the power production cost

	Makeup (%)		
	45	50	55
Cooling System Capital Cost:			
Condenser	15.05	14.27	13.75
Piping	17.64	17.05	15.13
Pumping and Elect. Equip.	6.44	6.24	5.91
Cooling Tower (Plates, Fan, Fan Elect. Equip. Structure and Foundation)	46.80	45.98	42.83
Indirect Cost	19.87	20.88	19.40
Total Capital Cost	111.86	104.42	97.02
Replacement Capacity	41.82	40.25	39.07
Replacement Energy	3.03	2.86	2.69
Annual Fuel Cost	108.86	108.86	108.86
Power Plant Cost	656.4	656.4	656.4
Power Production Cost (mills/Kwhr)	36.89	36.68	36.34

TABLE 6.3 - Plant Net Capacity vs. Ambient Temperature for 45, 50, 55 Percent Water Makeup Tower Systems

Ambient Dry Bulb (^{o}F)	Net Capacity (MWE)		
	Makeup (%)		
	45	50	55
20	1070.2	1072.8	1074.8
30	1070.2	1072.8	1074.8
37	1070.2	1072.8	1074.6
42	1070.0	1072.2	1073.9
47	1069.3	1071.5	1073.2
52	1068.4	1070.7	1072.4
57	1067.5	1069.0	1071.0
62	1065.6	1066.4	1067.5
67	1061.9	1063.4	1065.4
72	1058.3	1059.7	1061.7
77	1055.8	1057.1	1057.5
82	1051.2	1051.9	1053.9
87	1044.9	1045.4	1047.5
92	1037.5	1035.7	1037.7
96	1028.0	1030.6	1032.6
98	1024.3	1026.9	1028.9

TABLE 6.4 - Optimum Design Parameters of 25, 37 and 50 Percent Makeup Tower Systems for 800 MWe Fossil Plant at Moline

	Makeup (%)		
	25	37	50
Design Ambient Dry Bulb Temperature (^oF)	98	98	98
Design Ambient Wet Bulb Temperature (^oF)	84	84	84
Design Turbine Back Pressure (inch HgA)	5	5	5
Design Heat Rejection Rate (10^9 Btu/hr)	3.657	3.657	3.657
Design Water Range (^oF)	14.2	20.9	26.1
Design Approach (^oF)	30.6	23.9	18.7
Plate Spacing (inch)	1.00	1.00	1.00
Packing Width (ft)	5	5	5
Plate Height (ft)	28	28	28
Air Flow Rate (10^9 lb/hr)	0.52	0.35	0.28
Water Flow Rate (10^9 lb/hr)	0.26	0.17	0.14
Number of Water Troughs per Plate	11	23	40
Total Number of Plates	83154	56112	44744
Evaporative/Convective Heat Transfer at Highest Ambient	39.1%/60.9%	51.4%/48.6%	62.5%/37.5%
Gross Output at Pmax (MWe)	790.2	790.2	790.2
Net Output at Pmax (MWe)	773.9	776.9	780.7
Fin Efficiency	0.57	0.84	0.95
Dry Surface Convective Heat Transfer Coefficient (	7.13	7.76	7.58
Plate Friction Factor	0.09	0.14	0.12

TABLE 6.5 - Optimum Design Parameters of 30, 40 and 50 Percent of Makeup Tower Systems for 1200 MWe Nuclear Plant at Moline

	Makeup (%)		
	30	40	50
Design Ambient Dry Bulb Temperature (°F)	98	98	98
Design Ambient Wet Bulb Temperature (°F)	84	84	84
Design Turbine Back Pressure (inch HgA)	5	5	5
Design Heat Rejection Rate (10^9 Btu/hr)	8.187	8.187	8.187
Design Water Range (°F)	17.5	22.6	25.8
Design Approach (°F)	27.2	22.2	18.9
Plate Spacing (inch)	1.00	1.00	1.00
Packing Width (ft)	5	5	5
Plate Height (ft)	28	28	28
Air Flow Rate (10^9 lb/hr)	0.95	0.73	0.64
Water Flow Rate (10^9 lb/hr)	0.47	0.36	0.32
Number of Troughs per Plate	16	28	40
Total Number of Plates	150460	116104	101120
Evaporative/Convective Heat Transfer at Highest Ambient	44.6%/55.4%	55.1%/44.9%	62%/38%
Gross Output at Pmax (MWe)	1160.4	1160.4	1160.4
Net Output at Pmax (MWe)	1139.5	1149.1	1154.6
Fin Efficiency	0.72	0.89	0.95
Dry Surface Convective Heat Transfer Coefficient (	7.45	7.70	7.59
Plate Friction Factor	0.11	0.13	0.12

TABLE 6.6 - Cost Breakdown for 25,
37 and 50 Percent Makeup Tower Systems
for 800 MWe Fossil Plant at Moline

All costs are in millon dollars except the power production cost

	Makeup (%)		
	25	37	50
Cooling System Capital Cost:			
Condenser	5.57	4.97	4.43
Piping	9.10	5.69	4.33
Pumping and Elect. Equip.	3.43	2.82	2.46
Cooling Tower (Plates, Fan, Fan Elect. Equip. Structure and Foundation)	23.51	17.07	13.44
Indirect Cost	8.51	6.25	5.02
Total Captial Cost	51.01	37.48	30.32
Replacement Capacity (Gas Turbine)	4.18	3.73	3.08
Replacement Energy (Gas Turbine)	0.73	0.52	0.32
Annual Fuel Cost	41.70	41.64	41.52
Power Plant Cost	403.10	403.10	403.10
Power Production Cost (mills/Kwhr)	23.88	23.33	23.01

TABLE 6.7 - Cost Breakdown for 30, 40 and 50 Percent Makeup Tower Systems for 1200 MWe Nuclear Plant at Moline

	Makeup (%)		
	30	40	50
Cooling System Capital Cost:			
Condenser	11.92	10.37	9.63
Piping	21.46	18.10	17.27
Pumping and Elect. Equip.	6.73	4.68	4.13
Cooling Tower (Plate, Fan, Fan Elect. Equip. Structure and Foundation)	43.81	36.09	31.16
Indirect Cost	27.07	14.08	12.65
Total Captial Cost	102.40	84.47	75.88
Replacement Capacity (Gas Turbine)	9.68	8.14	7.27
Replacement Energy (Gas Turbine)	2.80	1.24	0.92
Annual Fuel Cost	37.67	37.64	37.55
Power Plant Cost	727.4	727.4	727.4
Power Production Cost (mills/Kwhr)	24.45	23.80	23.53

TABLE 6.8 - Net Capacity vs. Ambient Temperature for 25, 37 and 50 Percent Makeup Tower Systems for 800 MWE Fossil Plant at Moline

Ambient Dry Bulb (°F)	Net Capacity (MWe)		
	Makeup (%)		
	25	37	50
20	800.1	802.9	807.0
30	800.1	802.9	806.6
37	800.1	802.6	806.1
42	799.8	802.2	805.7
47	799.2	801.5	805.2
52	798.7	801.1	804.5
57	798.1	800.5	803.9
62	797.0	799.0	802.4
67	795.9	798.3	801.2
72	793.8	795.6	798.9
77	790.3	791.7	795.0
82	785.8	787.6	789.8
87	782.9	784.7	788.8
92	779.5	782.4	784.4
96	775.0	777.8	781.9
98	773.8	776.7	780.7

TABLE 6.9 - Net Capacity vs. Ambient Temperature for 30, 40 and 50 Percent Makeup Tower Systems for 1200 MWe Nuclear Plant at Moline

Ambient Dry Bulb Temperature (^{o}F)	Net Capacity (MWe)		
	Makeup (%)		
	30	40	50
20	1192.1	1201.7	1207.2
30	1192.1	1207.7	1207.0
37	1192.1	1201.5	1206.8
42	1192.0	1201.2	1206.3
47	1191.4	1200.6	1205.8
52	1190.9	1200.3	1205.2
57	1190.4	1199.4	1204.4
62	1188.8	1197.2	1201.8
67	1186.8	1194.1	1198.2
72	1181.2	1190.1	1194.3
77	1174.3	1182.2	1185.5
82	1165.5	1170.4	1173.5
87	1158.5	1165.7	1171.2
92	1150.7	1156.5	1162.0
96	1142.1	1151.7	1157.2
98	1139.5	1149.1	1154.6

6.3 Wet Topping

From the results in sections 4.1 and 4.2, it can been seen that the cost goes up very rapidly when the plate surface becomes very dry, that is, when the number of troughs on each plate is small such that the fin efficiency becomes very small. Attempt was made to see if there would be any savings by topping this tower with a conventional evaporative tower. The results are shown in Fig. 6.17. Using wet topping there are savings obtained but still are not cost competitive with conventional wet-dry towers.

MIDDLETOWN SITE 1094 MWe NET CAPACITY NUCLEAR PLANT ALUMINUM PLATE

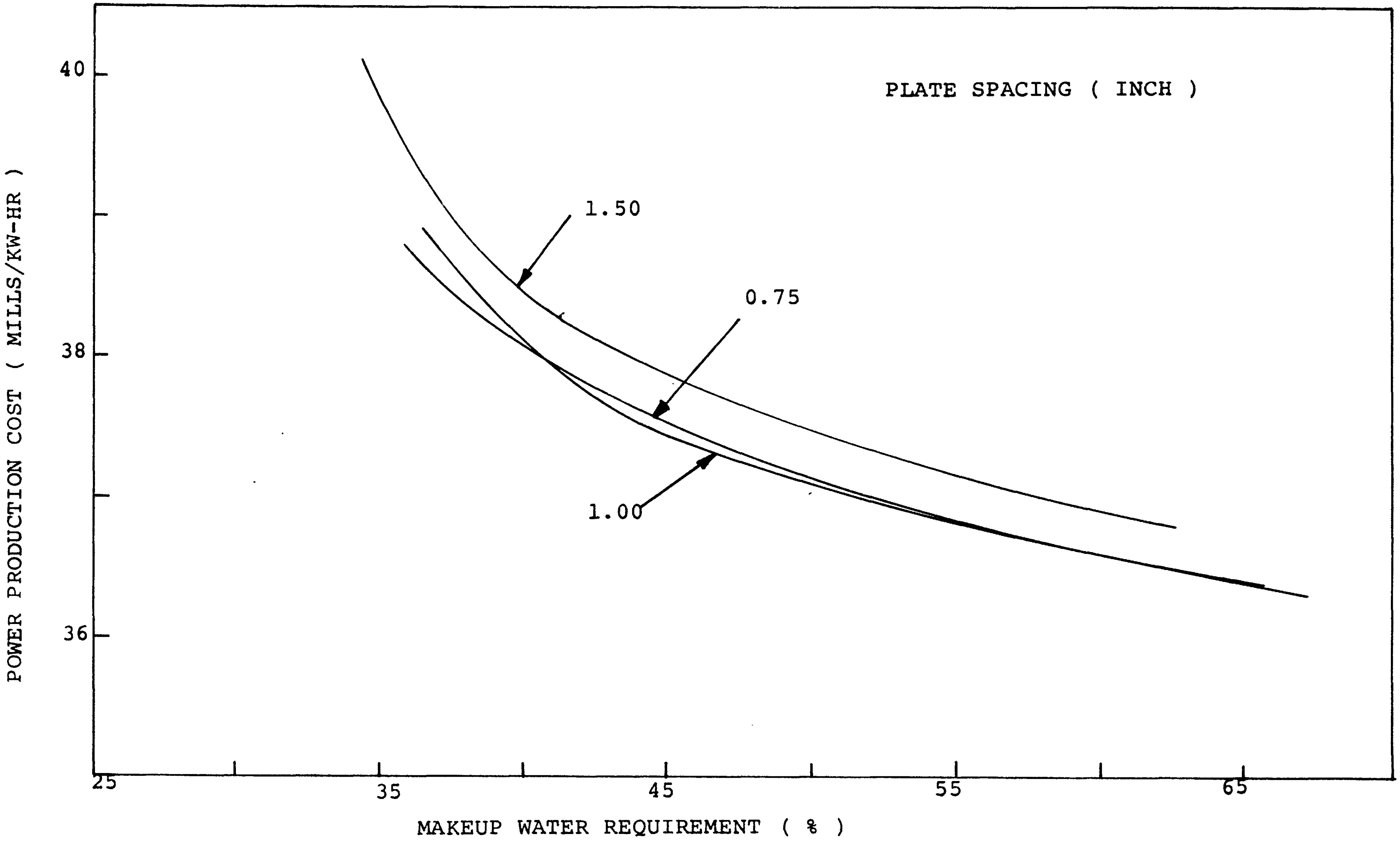


FIG. 6.1

MIDDLETOWN SITE 1094 MWe NET CAPACITY NUCLEAR PLANT

ALUMINUM PLATE

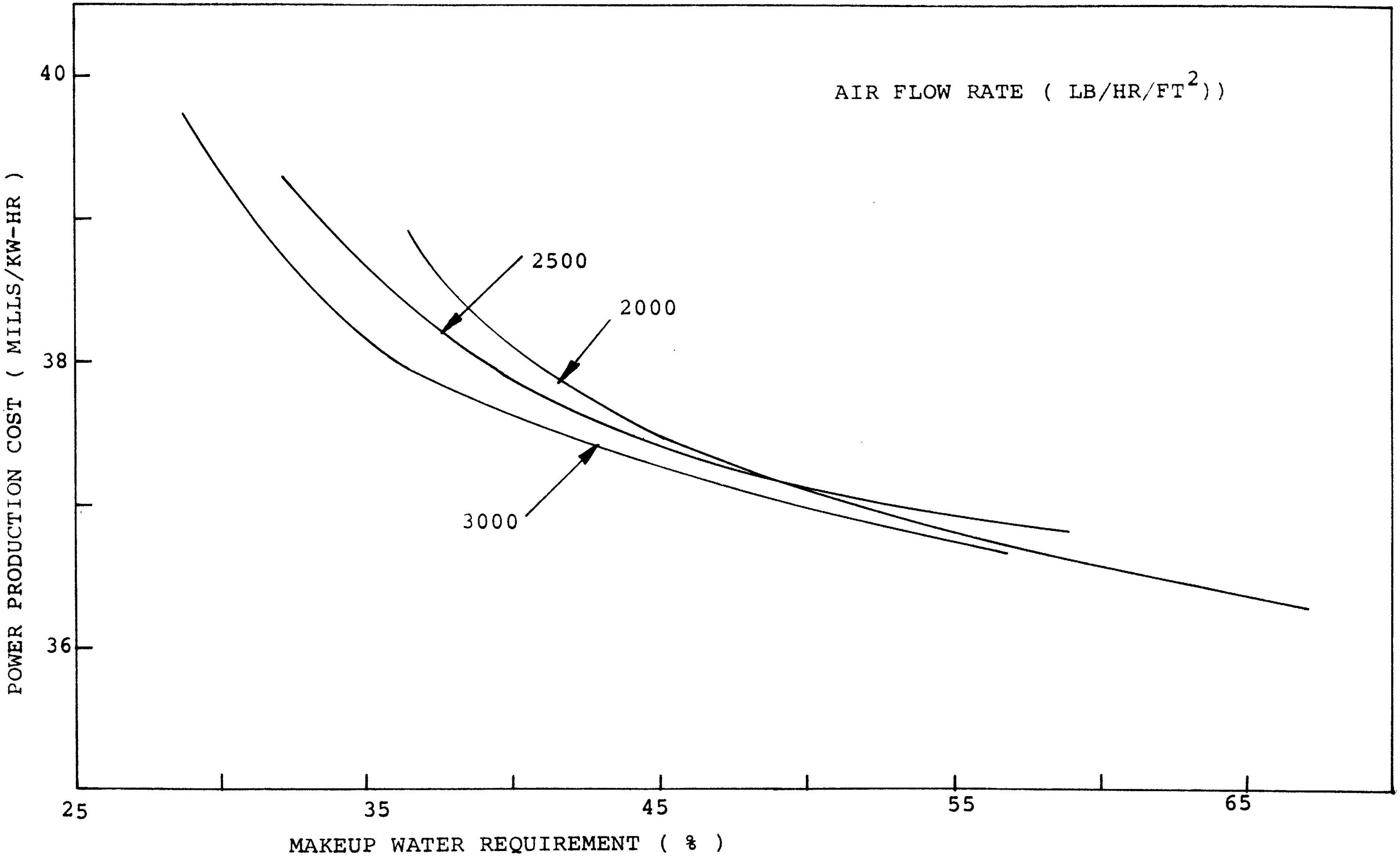


FIG. 6.2

MIDDLETOWN SITE 1094 MWe NET CAPACITY NUCLEAR PLANT ALUMINUM PLATE

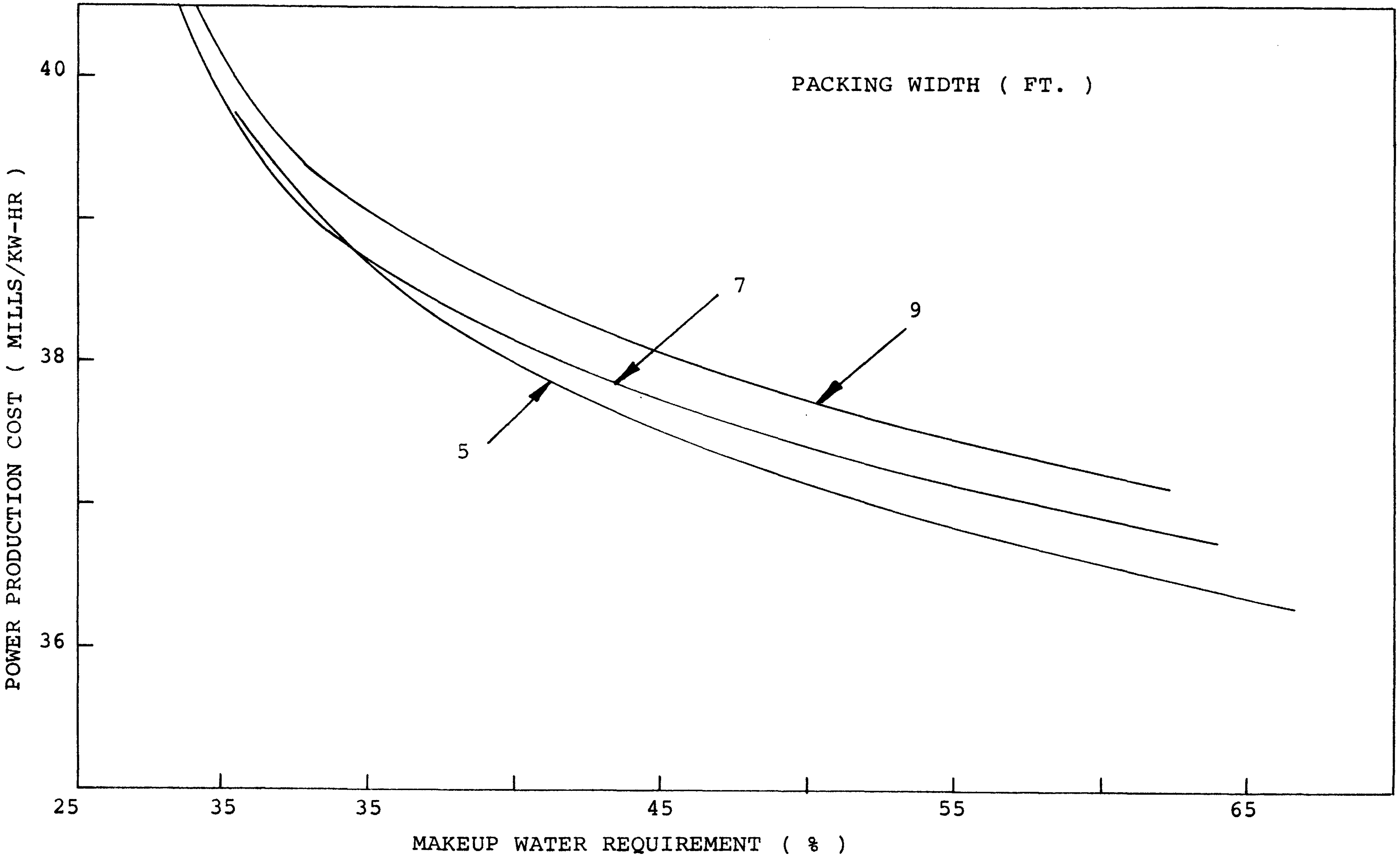


FIG. 6.3

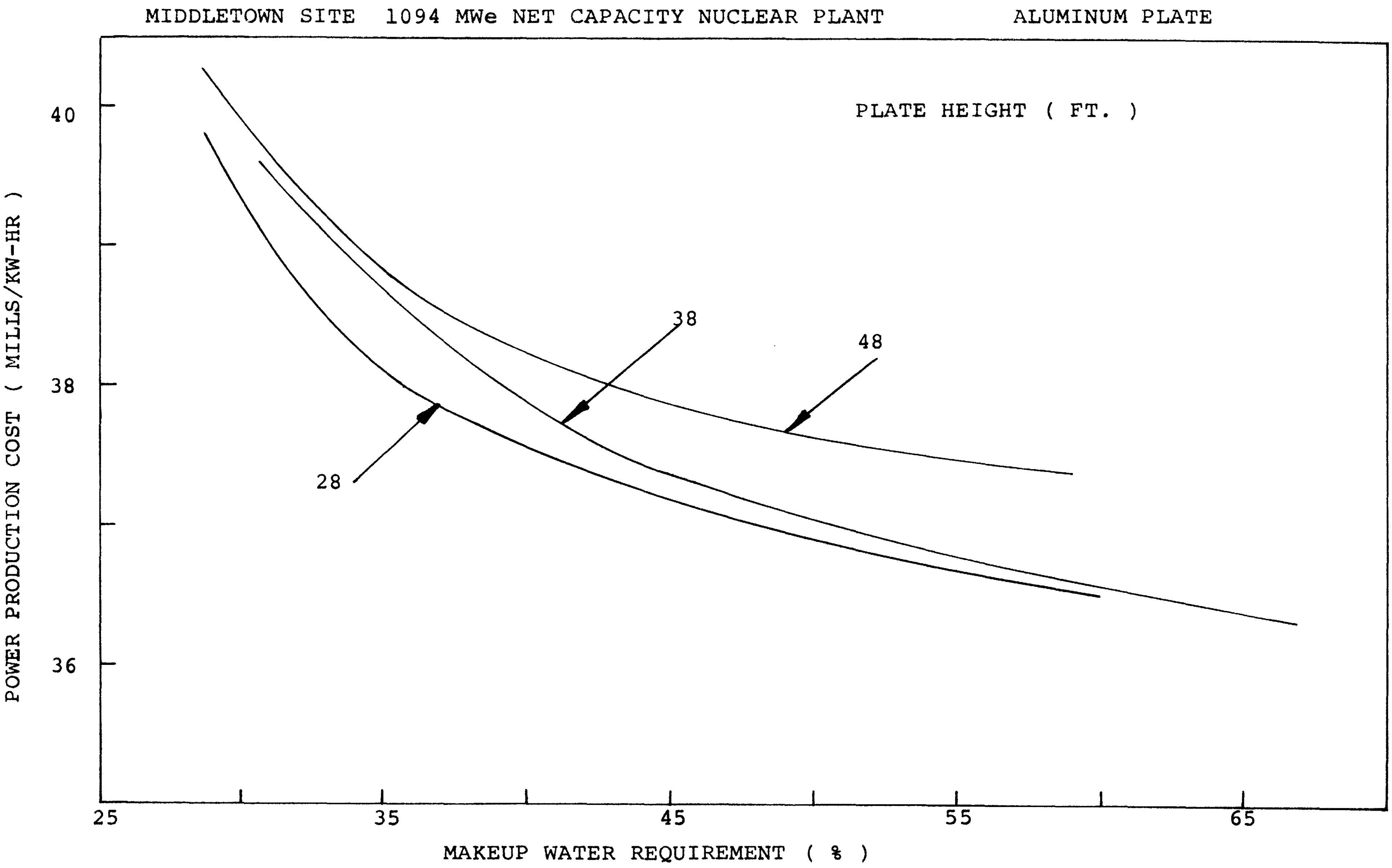

MIDDLETOWN SITE 1094 MWe NET CAPACITY NUCLEAR PLANT
ALUMINUM PLATE
PLATE HEIGHT (FT.)
48
38
28
40
38
36
POWER PRODUCTION COST (MILLS/KW-HR)
25
35
45
55
65
MAKEUP WATER REQUIREMENT (%)

FIG. 6.4

MIDDLETOWN SITE 1094 MWe NET CAPACITY NUCLEAR PLANT ALUMINUM PLATE

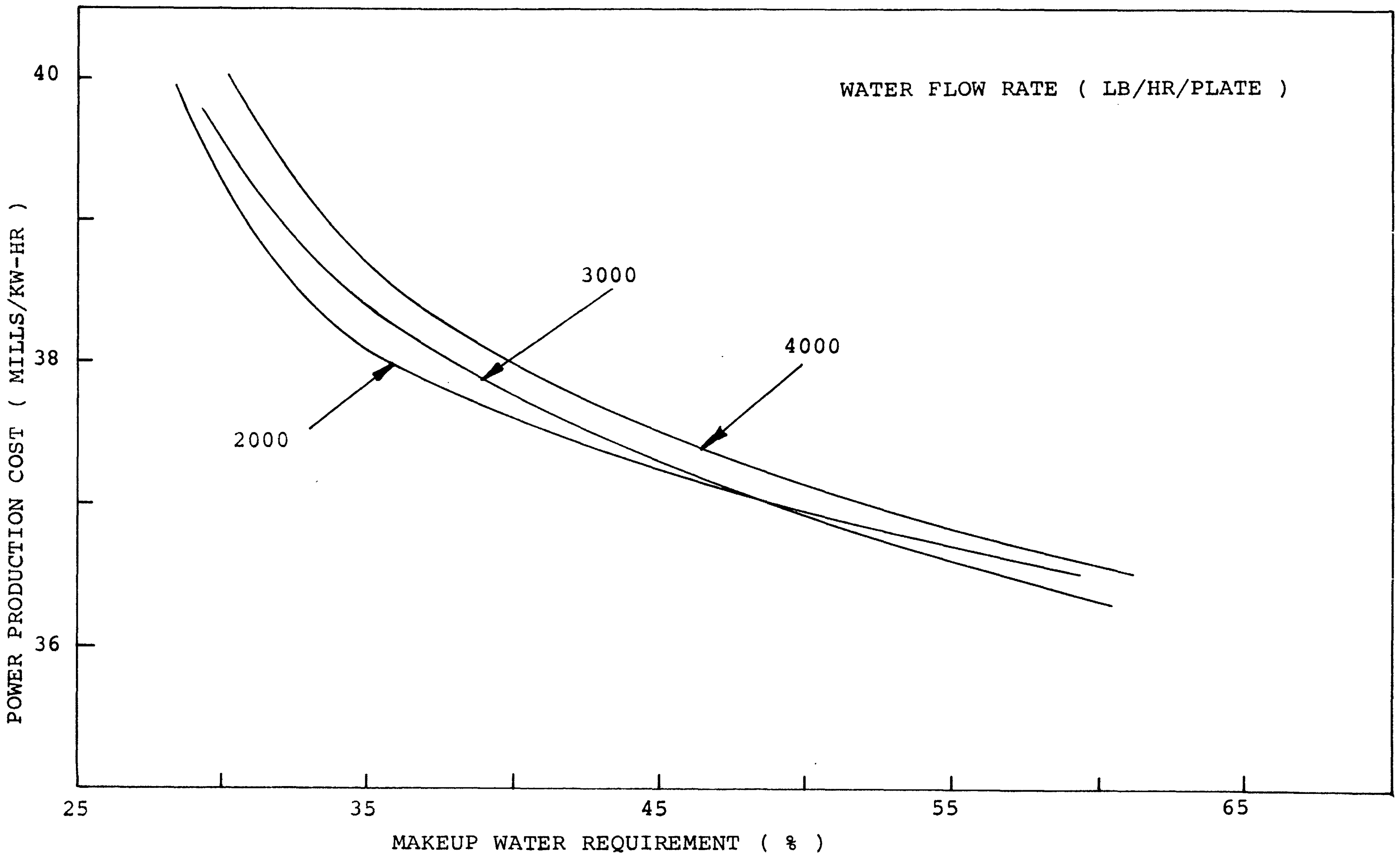


FIG. 6.5

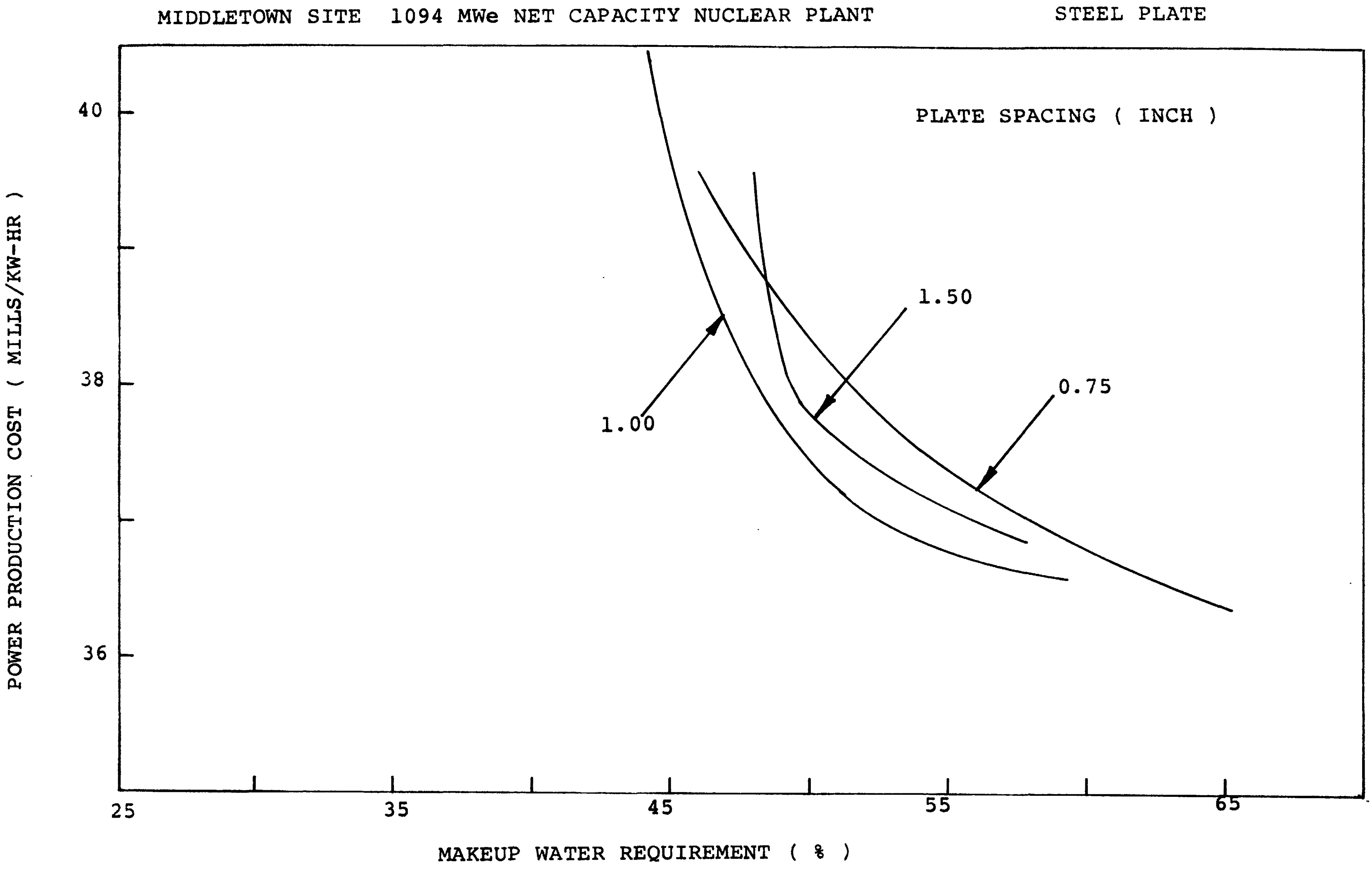

MIDDLETOWN SITE 1094 MWe NET CAPACITY NUCLEAR PLANT
STEEL PLATE
PLATE SPACING (INCH)
1.50
0.75
1.00
POWER PRODUCTION COST (MILLS/KW-HR)
40
38
36
25
35
45
55
65
MAKEUP WATER REQUIREMENT (%)

FIG. 6.6

MIDDLETOWN SITE 1094 MWe NET CAPACITY NUCLEAR PLANT STEEL PLATE

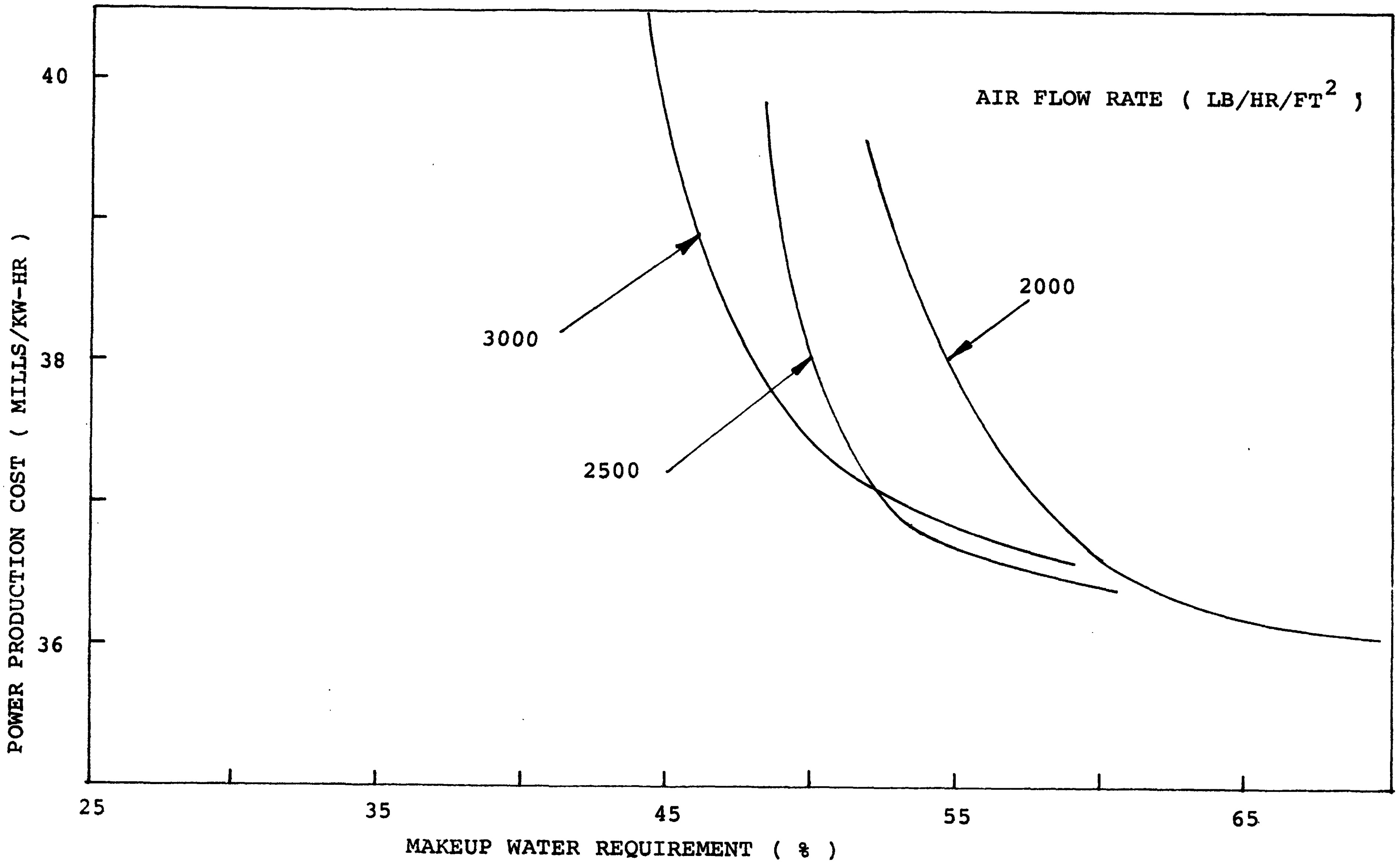


FIG. 6.7

MIDDLETOWN SITE 1094 MWe NET CAPACITY NUCLEAR PLANT STEEL PLATE

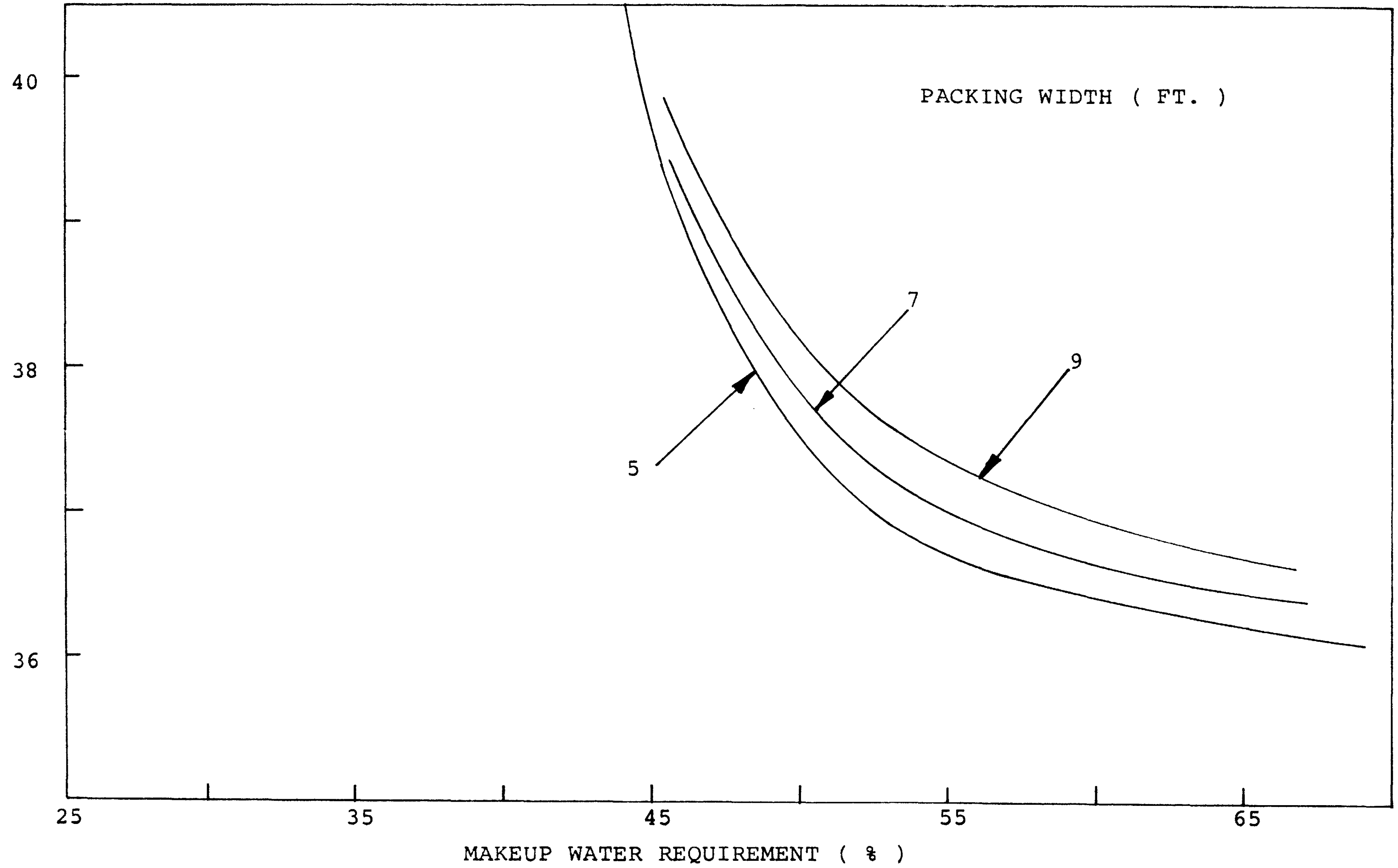


FIG. 6.8

MIDDLETOWN SITE 1094 MWe NET CAPACITY NUCLEAR PLANT STEEL PLATE

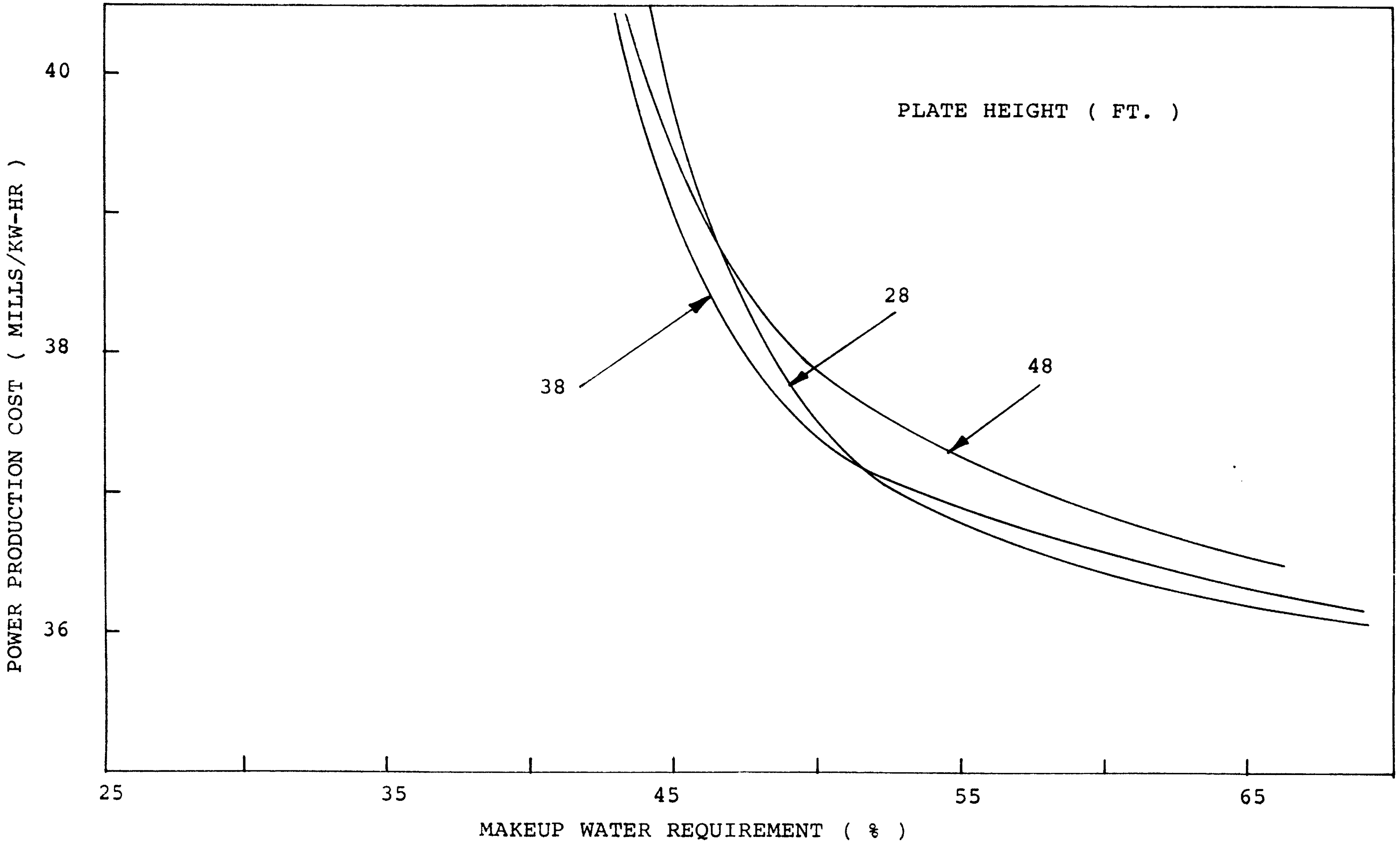


FIG. 6.9

MIDDLETOWN SITE 1094 MWe NET CAPACITY NUCLEAR PLANT STEEL PLATE

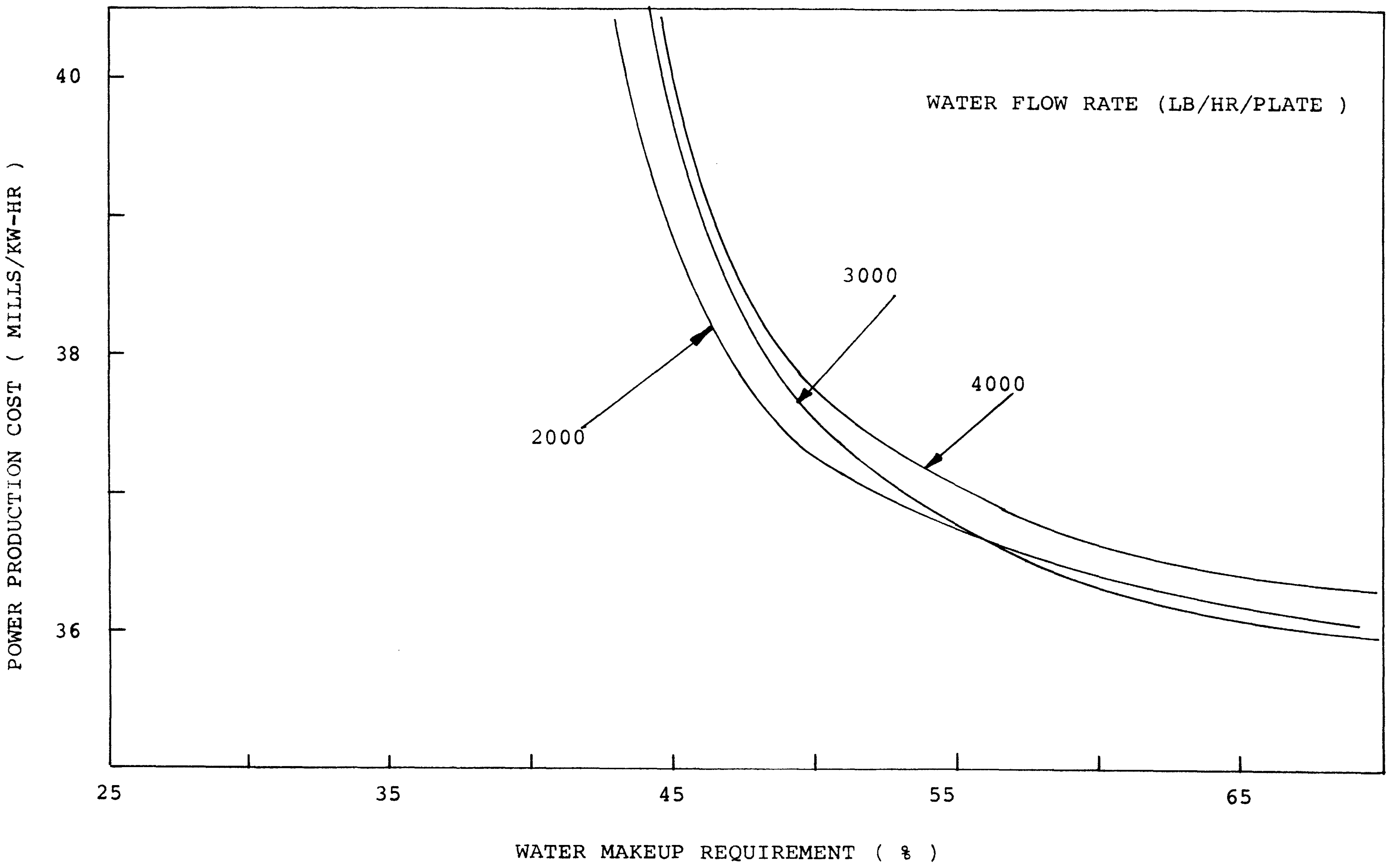


FIG. 6.10

FIG. 6.11

MIDDLETOWN SITE 1094 MWe NET CAPACITY NUCLEAR PLANT

OPTIMUM CURVES

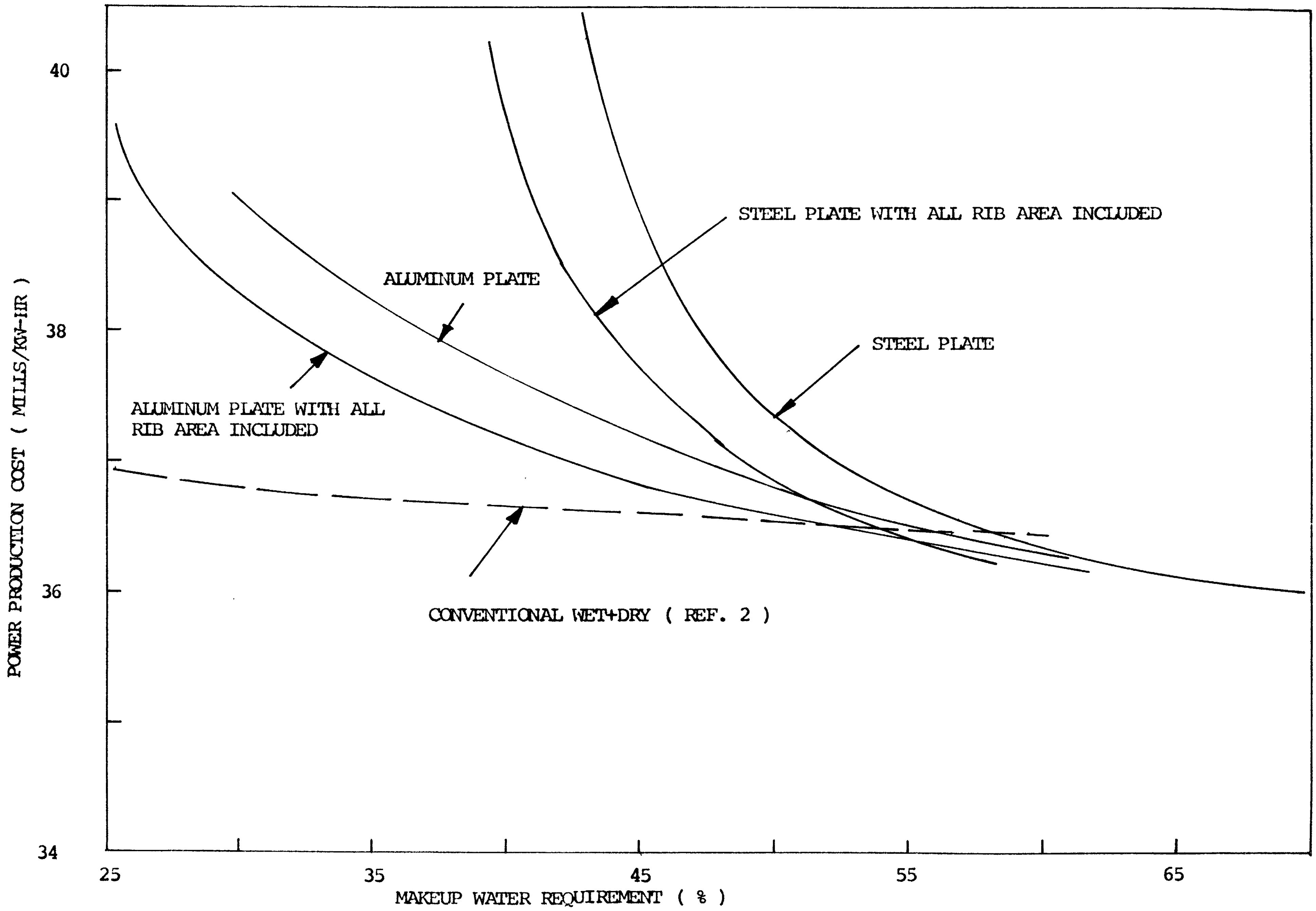


FIG. 6.12

HEAT REJECTION CAPABILITY OF A 45% WATER MAKEUP MIT ADVANCED WET/DRY TOWER.

MIDDLETOWN SITE 1094 MWe NET CAPACITY NUCLEAR PLANT ALUMINUM PLATE

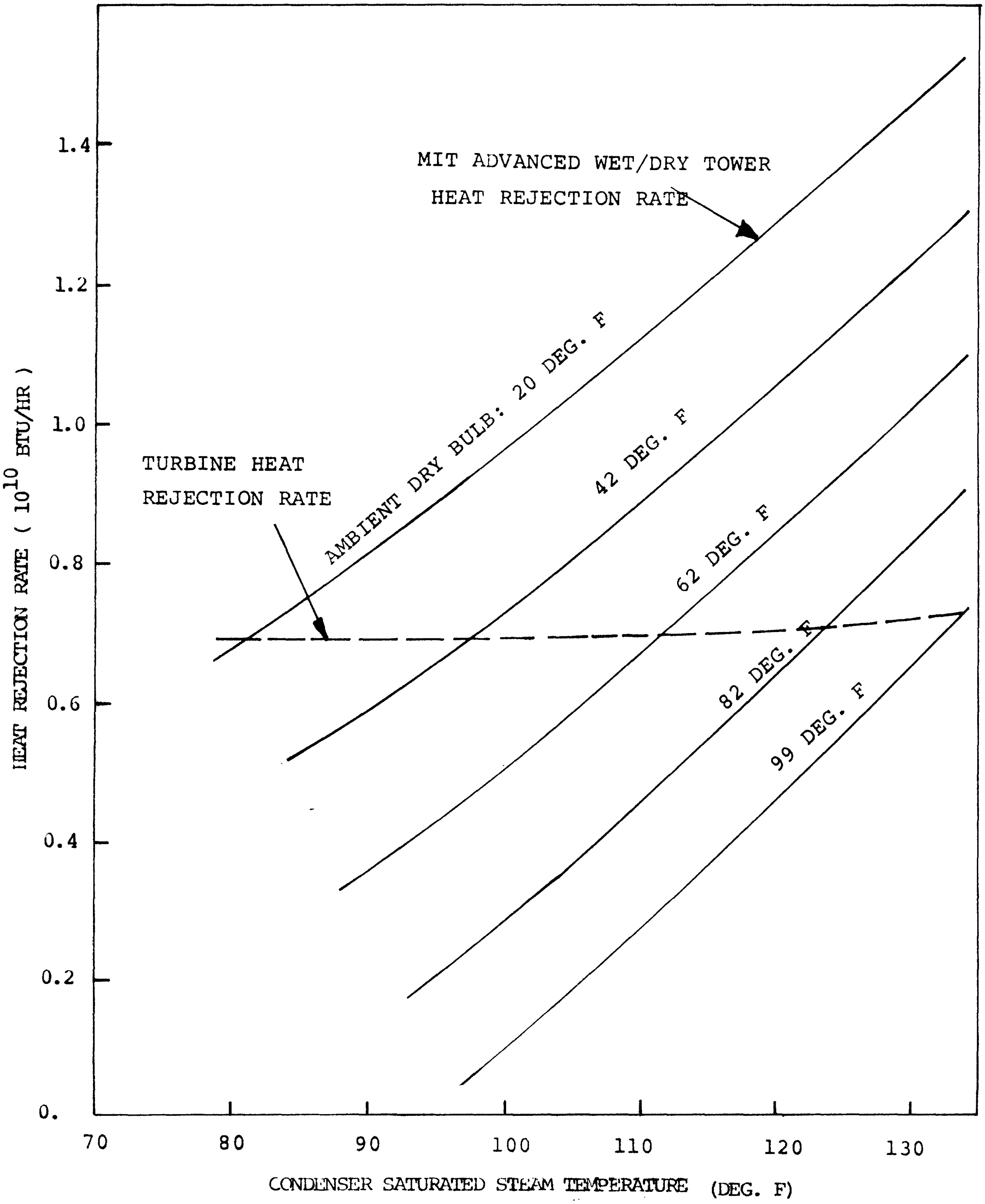


FIG. 6.13

HEAT REJECTION CAPABILITY OF A 50% WATER MAKEUP MIT ADVANCED WET/DRY TOWER.

MIDDLETOWN SITE 1094 MWe NET CAPACITY NUCLEAR PLANT
ALUMINUM PLATE

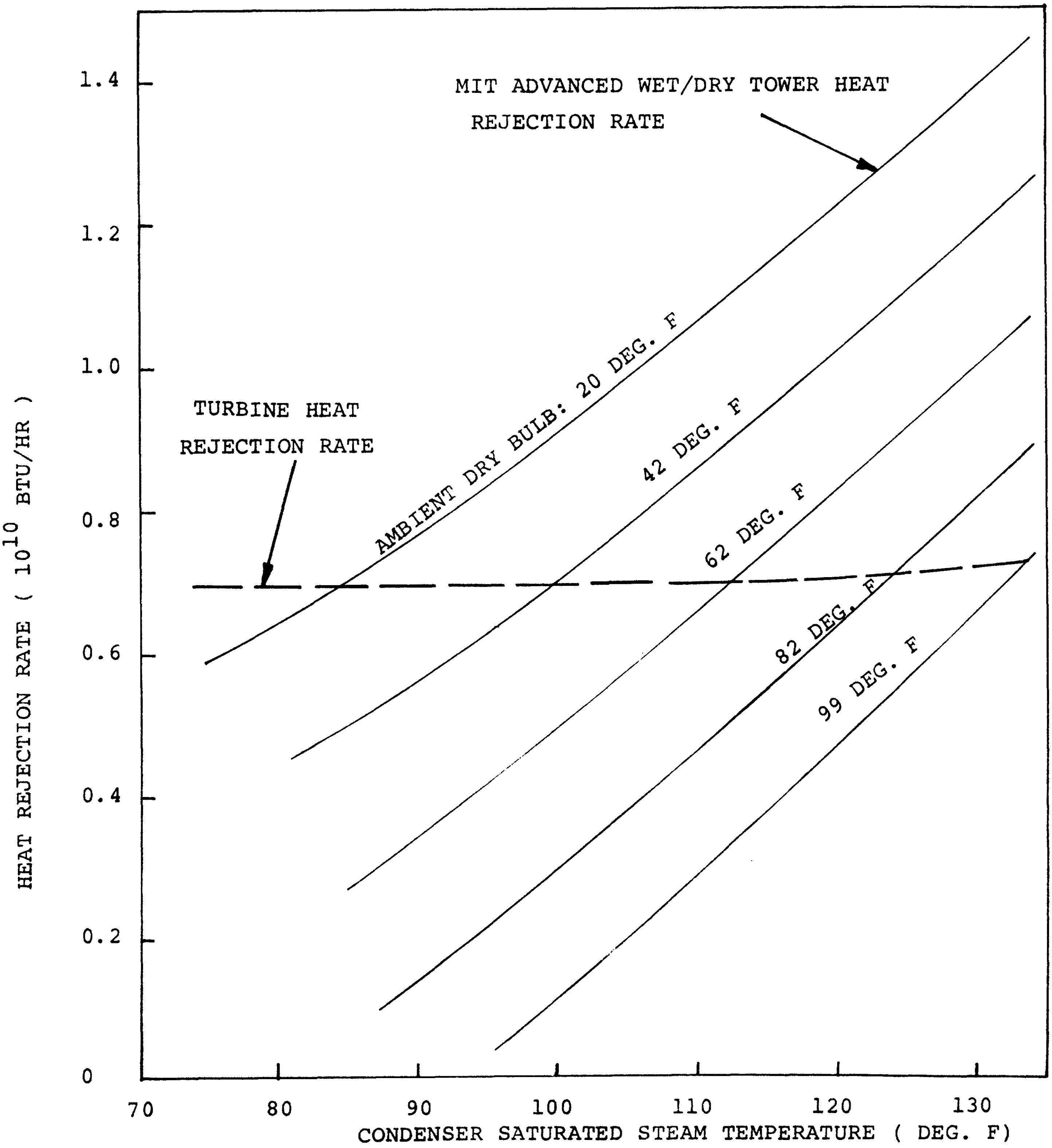
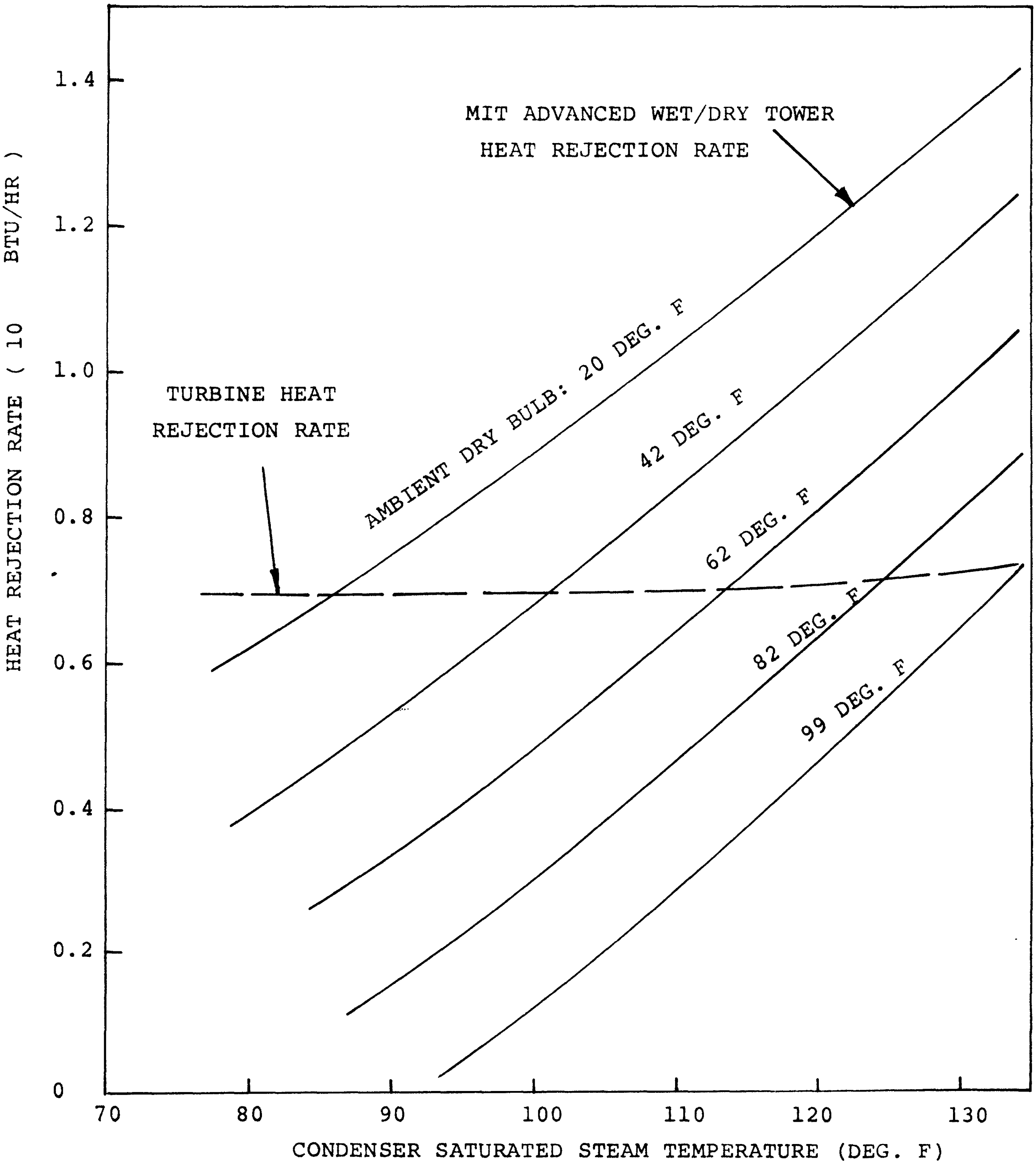


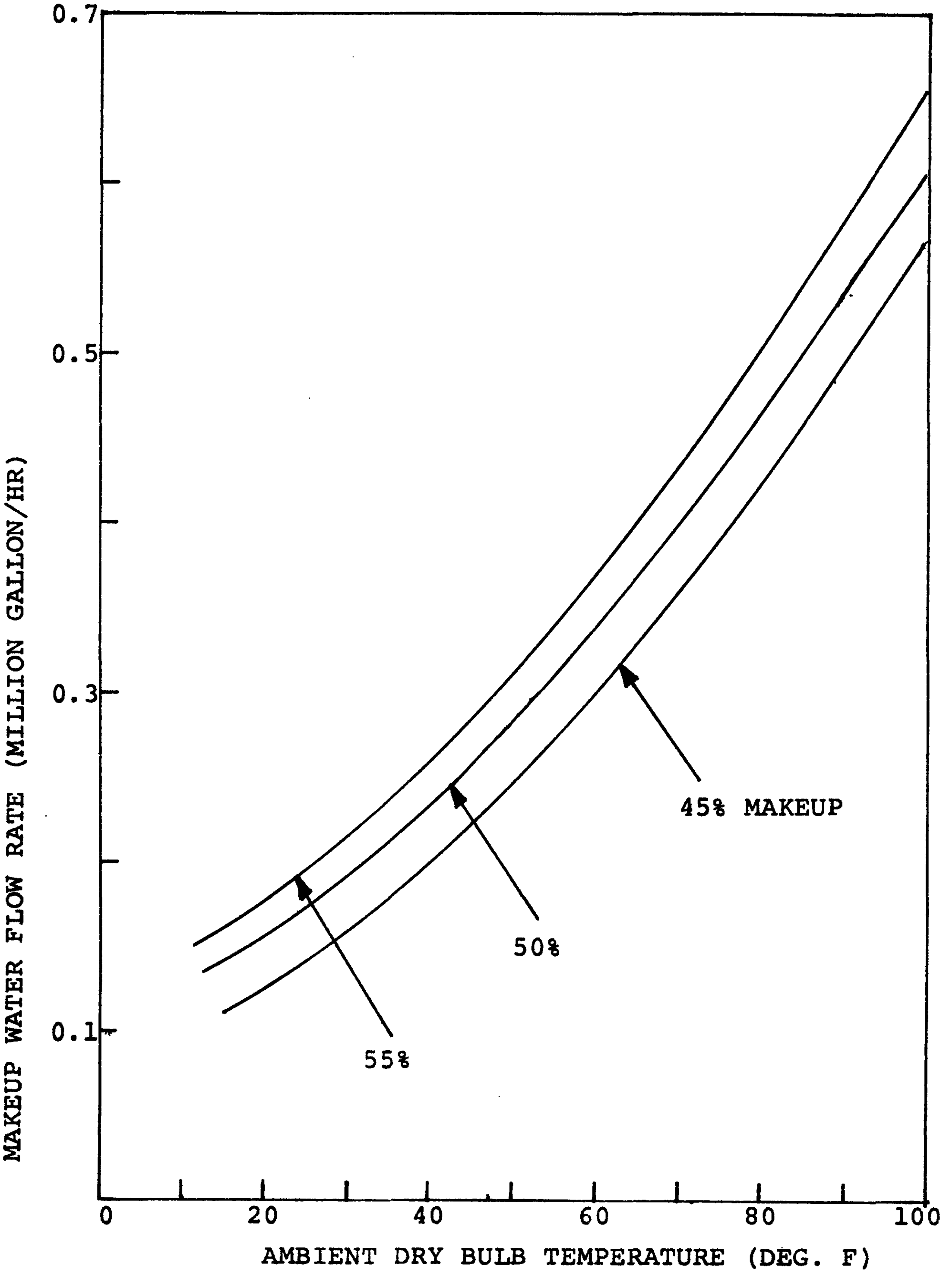
FIG. 6.14

HEAT REJECTION CAPABILITY OF A 55% WATER MAKEUP MIT ADVANCED WET/DRY TOWER.

MIDDLETOWN SITE 1094 MWe NET CAPACITY NUCLEAR PLANT
ALUMINUM PLATE

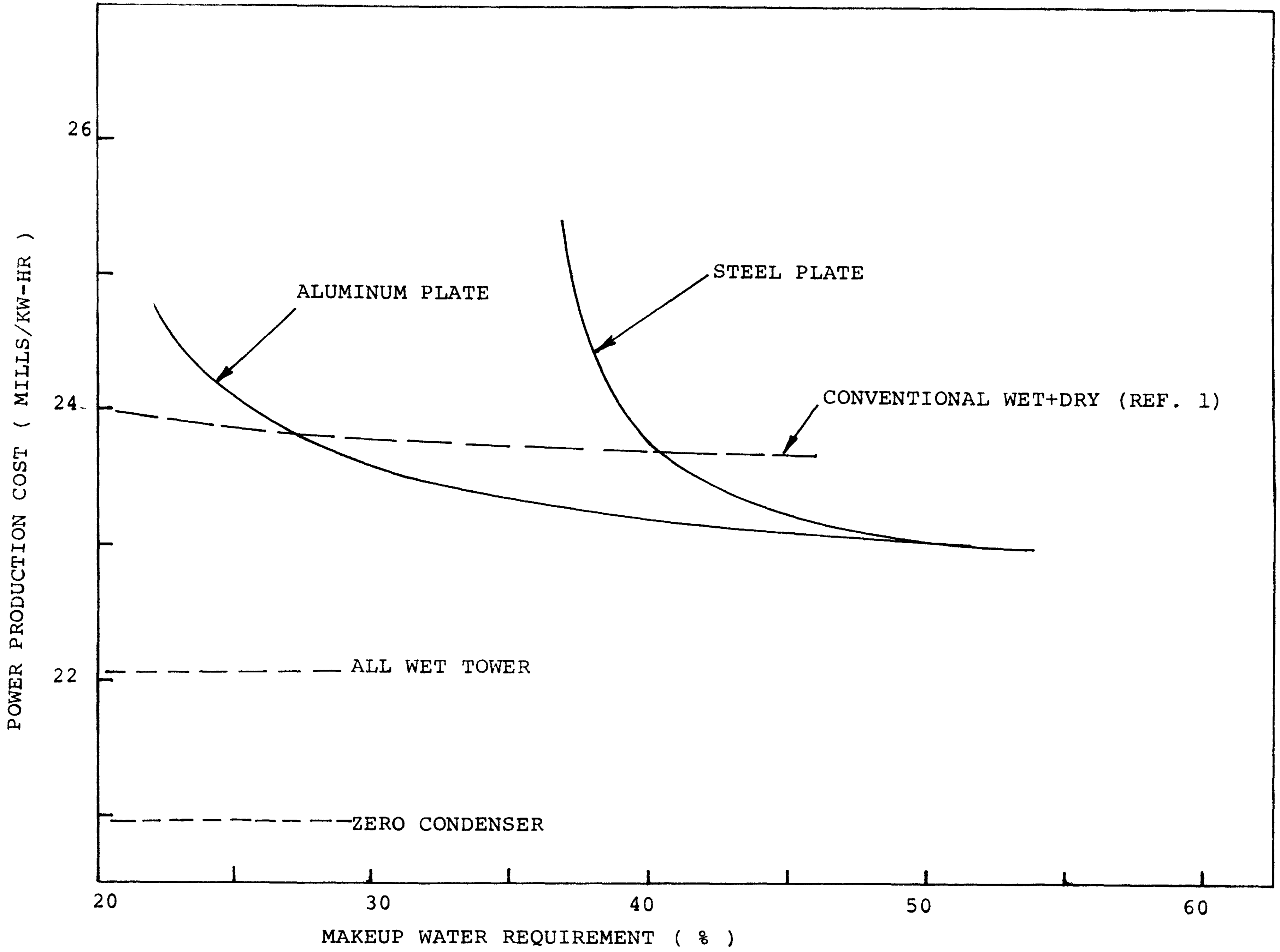


MIDDLETOWN SITE   1094 MWe NET CAOACITY NUCLEAR PLANT



MAKEUP WATER FLOW RATE VS. AMBIENT DRY BULB TEMPERATURE

FIG. 6.15



MOLINE SITE 800 MWe NET CAPACITY FOSSIL PLANT

FIG. 6.16

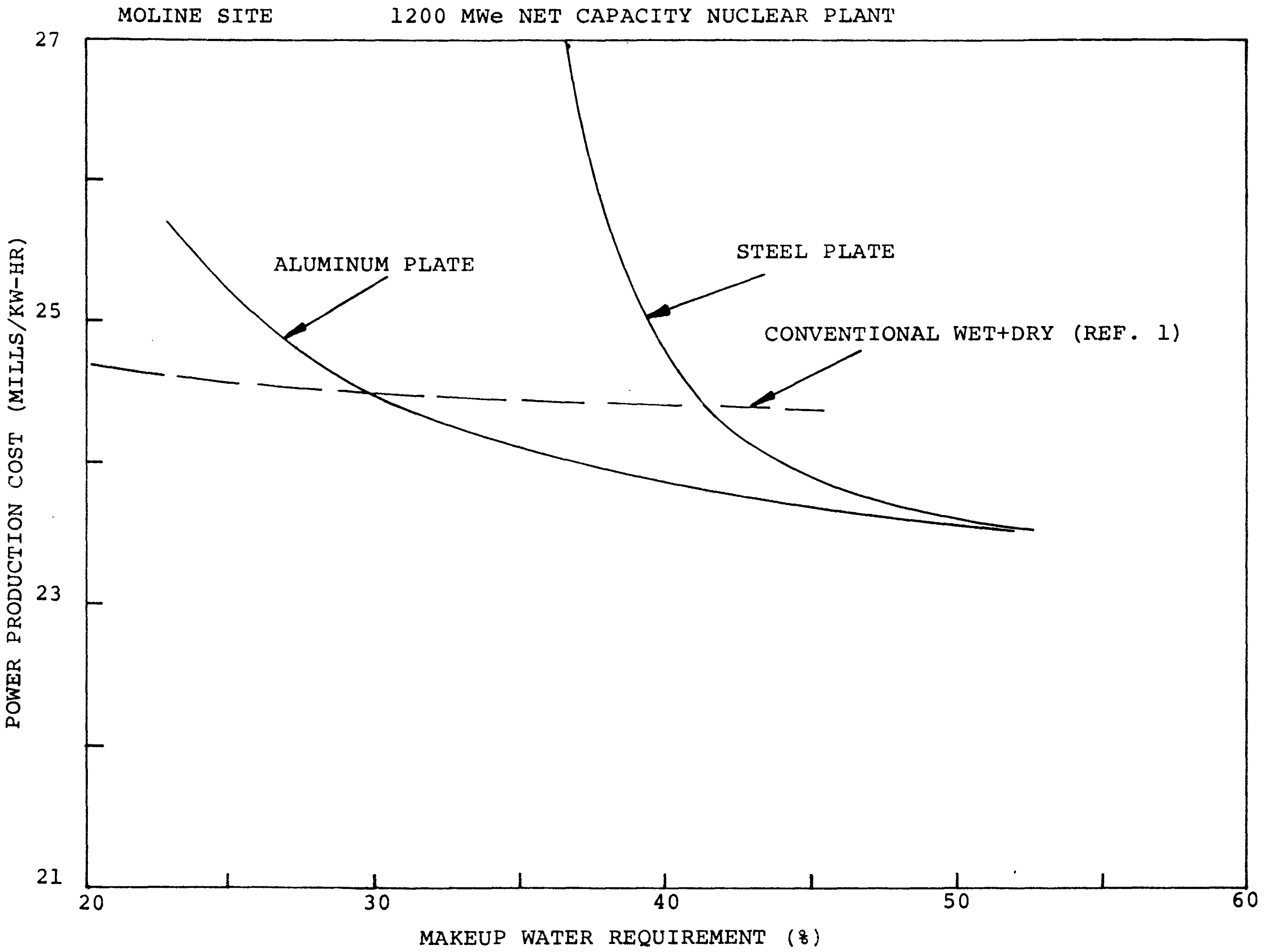

MOLINE SITE
1200 MWe NET CAPACITY NUCLEAR PLANT
27
25
23
21
20
30
40
50
60
POWER PRODUCTION COST (MILLS/KW-HR)
MAKEUP WATER REQUIREMENT (%)
ALUMINUM PLATE
STEEL PLATE
CONVENTIONAL WET+DRY (REF. 1)

FIG. 6.17

MIDDLETOWN SITE 1094 MWe NET CAPACITY NUCLEAR PLANT ALUMINUM PLATE

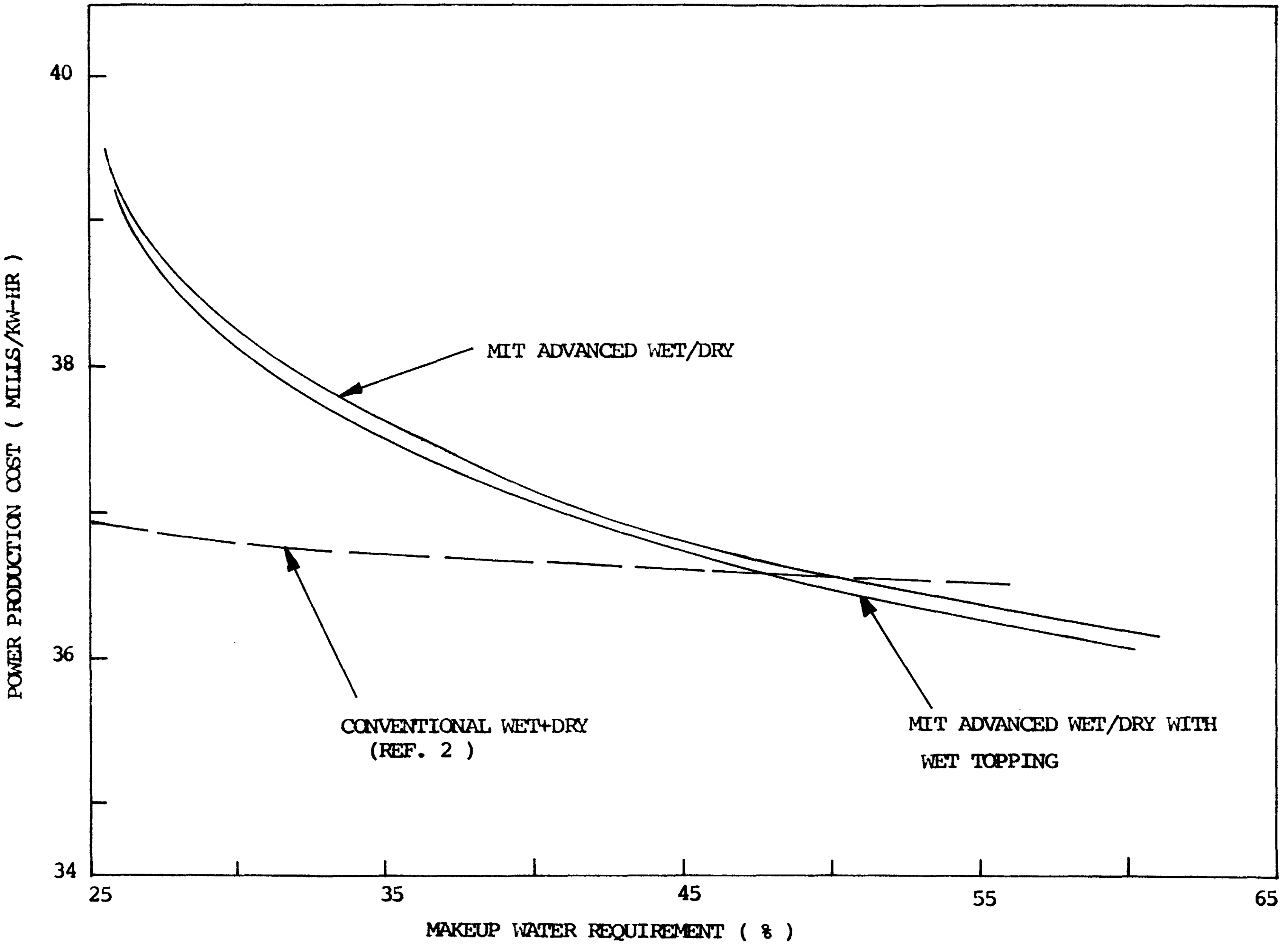


FIG. 6.18

Chapter 7

Comparison with United Engineer's Study

As mentioned in earlier chapters one major task in this study is to compare our results with those reported by United Engineers. This will be done in this chapter.

According to United Engineers [2], galvanized steel plate is preferrable to aluminum. However, the results in our study indicate that aluminum is much more economical than steel, especially for low water makeups. Since they only reported the results of optimization for steel, we are only able to compare these results for the MIT advanced wet/dry tower concept using steel plates.

A comparison of the optimum design parameters for a 50% makeup tower system between these two studies are shown in Table 7.1. Note that the results are rather comparable.

The cost breakdowns are compared in Table 7.2 We see that the capital costs of the condenser and cooling tower in these two studies are close. However, the costs of the water circulating system in our study is much higher because piping design is considered in detail. On the other hand, only main circulating pipe cost was considered in United Engineers' study. Our piping cost included main pipes, tower distribution pipes, risers, as well as all pipe fittings. As a result, our power production cost is higher than United Engineers.

The penalty cost in this study is essentially the same as United Engineers.

In comparing the capital cost of the cooling tower per square foot of plate area, we see that it is \$1.8/ft^2 for United Engineers and is \$2.3/ft^2 for this study. Therefore, it is 30% higher in this study.

TABLE 7.1 - Comparison of Optimum Design Parameters between United Engineers and this study for Middletown

	United Engineers	This Study
Water Makeup (%)	50	50
Design Ambient Dry Bulb Temperature (^{o}F)	99	99
Design Ambient Wet Bulb Temperature (^{o}F)	77	77
Design Turbine Back Pressure (inch HgA)	5	5
Design Heat Rejection Rate (Btu/hr)	$7.25\text{x}10^{9}$	$7.25\text{x}10^{9}$
Plate Spacing (inch)	1.00	1.00
Packing Plate Width (ft)	7	5.86
Plate Height	30	28
Air Flow Rate (lb/hr)	not clear	$5.90\text{x}10^{8}$
Water Flow Rate (lb/hr)	unknown	$2.95\text{x}10^{8}$
Number of Water Channels per Plate	not clear	33
Total Number of Plates	78120	93728
Evaporative Heat Transfer/Convective Heat Transfer at Highest Ambient	61%/31%	64.9%/35.1%
Gross Output at Pmax, MWe	1048.4	1047.2
Net Output at Pmax, MWe	1025.4	1025.0
Annual Makeup Water (gall)	$21.58\text{x}10^{8}$	$21.58\text{x}10^{8}$
Fan and Pump Power (MWe	23.03	23.81
Design Water Range (^{o}F)	unknown	24.6
Design Approach (^{o}F)	unknown	27.1

TABLE 7.2 - Comparison of Cost Breakdowns
between United Engineers and this Study for
Middletown for Steel Plate

All the costs are in million dollars except last three items

	50% Water Makeup	
	United Engineers	This Study
Cooling System Capital Cost:		
Condenser	14.74	14.94
Piping and Pumping	11.36 (Elect, Equip. not included)	23.77 (Elect. Equip. not included)
Cooling Tower (Plates, Fan, Structure and Foundation)	33.91	35.17
Electrical Equipment	4.92 (Fan & Pump)	35.17
Indirect Cost	16.23	20.50
Total Cooling System Capital Cost	81.46	102.50
Penalty Cost:		
Capacity	27.36	27.08
Fan and Pump Power	13.82	14.29
Replacement Energy and Auxiliary Energy	15.69	16.22
Make-up Water	3.20	3.20
Cooling System Maintenance	4.24	5.37
Total Penalty	64.32	66.16
Incremental Power Production Cost (mills/Kwhr)	3.80	4.33
Incremental Power Production Cost (%)	11.7	13.4
Cooling Tower per ft^2 of Plate ($/$ft^2$)	1.8	2.3

Chapter 8

Sensitivity Study

The cooling plates in the MIT advanced wet/dry concept are not currently offered by manufacturers. Therefore, the cost of these plates is uncertain. In the base case study, the total plate cost is assumed to be twice the plate material cost. However, if the cost changes the results of optimization would also change. Therefore, a sensitivity study of the plate cost is necessary and is given in this chapter.

The sensitivity parameters are 2 and 3 times the base case plate cost for the Moline site. The results are shown in Fig. 8.1 for the fossil plant and in Fig. 8.2 for the nuclear plant using aluminum plates. From these two figures we can see that the MIT advanced wet/dry concept would entirely not be cost competitive with conventional wet-dry towers only when the plate cost is more than two times the base case cost. Although the plate cost is rather uncertain at this step, it is very unlikely that the plate cost would be more than twice the base cost. Hence, this MIT advanced wet/dry concept is economically rather encouraging. Of course, a lower plate cost would make this MIT concept further favorable.

Chapter 9

Conclusions and Recommendations

9.1 Conclusions

This study has determined the cost of the MIT advanced wet/dry cooling concept in both fossil and nuclear power plants. Aluminum is superior to galvanized steel as the cooling plate material. In our base case study for the Middletown site 1094 MWe nuclear plant and using aluminum plates, the MIT concept is slightly more economical than conventional wet-dry towers at water makeups larger than 50%. For a 55% water makeup system, for instance, using the MIT advanced concept reduces the incremental power production cost from the conventional wet-dry towers by about 0.15 mills/Kwhr.

In our base case study at the Moline site, for an 800 MWe fossil plant the MIT advanced wet/dry tower with aluminum plates is more economical than conventional wet-dry towers when water makeup is larger than 27%. For makeups of 25, 37 and 50 percent, the optimum power production costs are 23.88, 23.33 and 23.01 mills/Kwhr, respectively, compared to 23.82, 23.70 and 23.6 mills/Kwhr. for conventional wet-dry towers. When these are compared to 20.8 mills/Kwhr. for zero-condenser system, the incremental costs for makeups of 37 and 50 percent using MIT advanced wet/dry instead of conventional wet-dry would be reduced by 13 and 21 percent, respectively.

For a 1200 MWe nuclear plant the MIT advanced wet/dry tower with aluminum plates is more economical than conventional wet-dry towers when water makeup is larger than 30%. For makeups of 30, 40 and 50 percent, the optimum power production costs are 24.45, 23.80 and 23.53 mills/Kwhr., respectively, compared with 24.95, 24.84 and 24.75 mills/Kwhr. for the conventional wet-dry

FIG. 8.1

MOLINE SITE 800 MWe NET CAPACITY FOSSIL PLANT

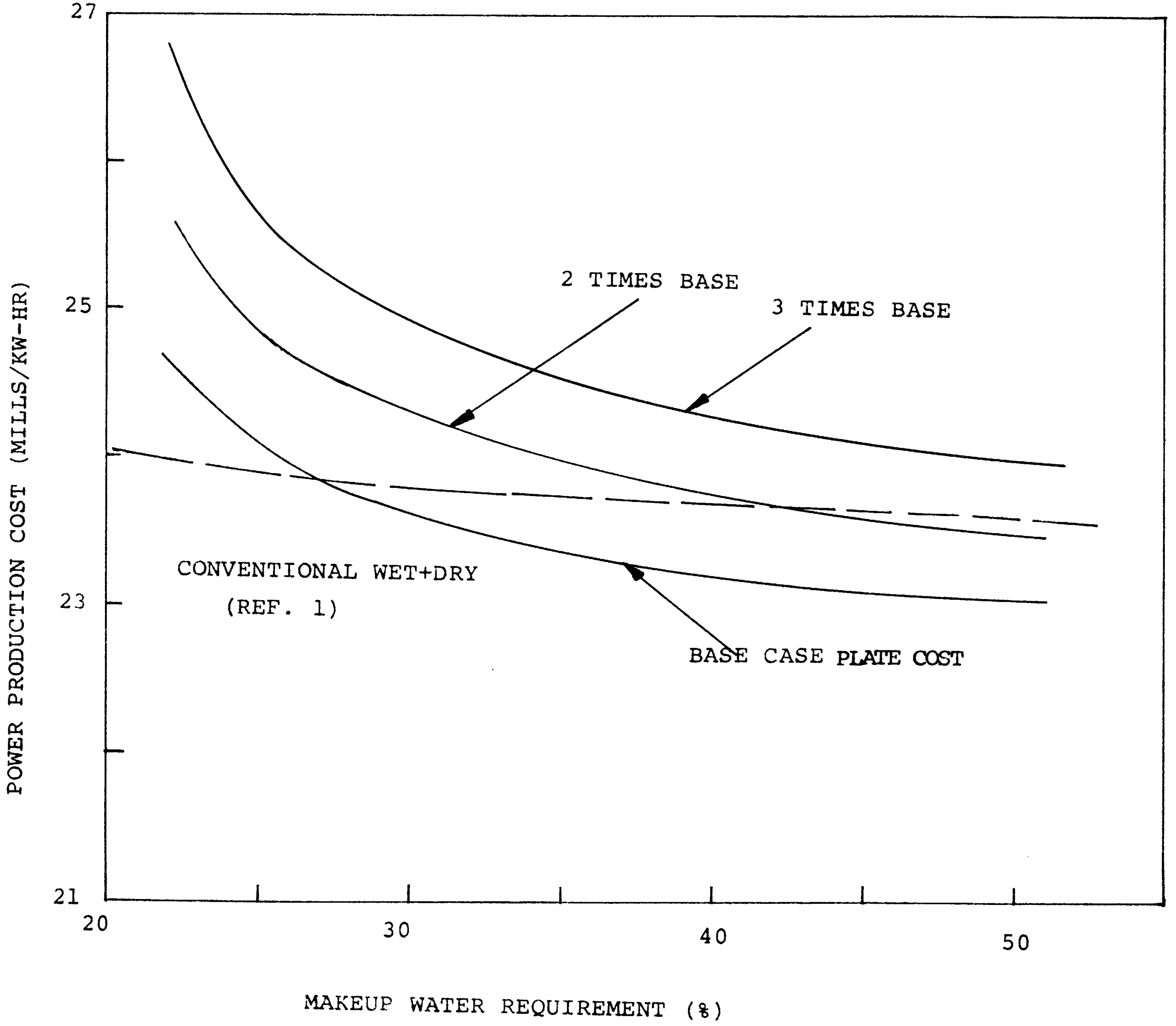
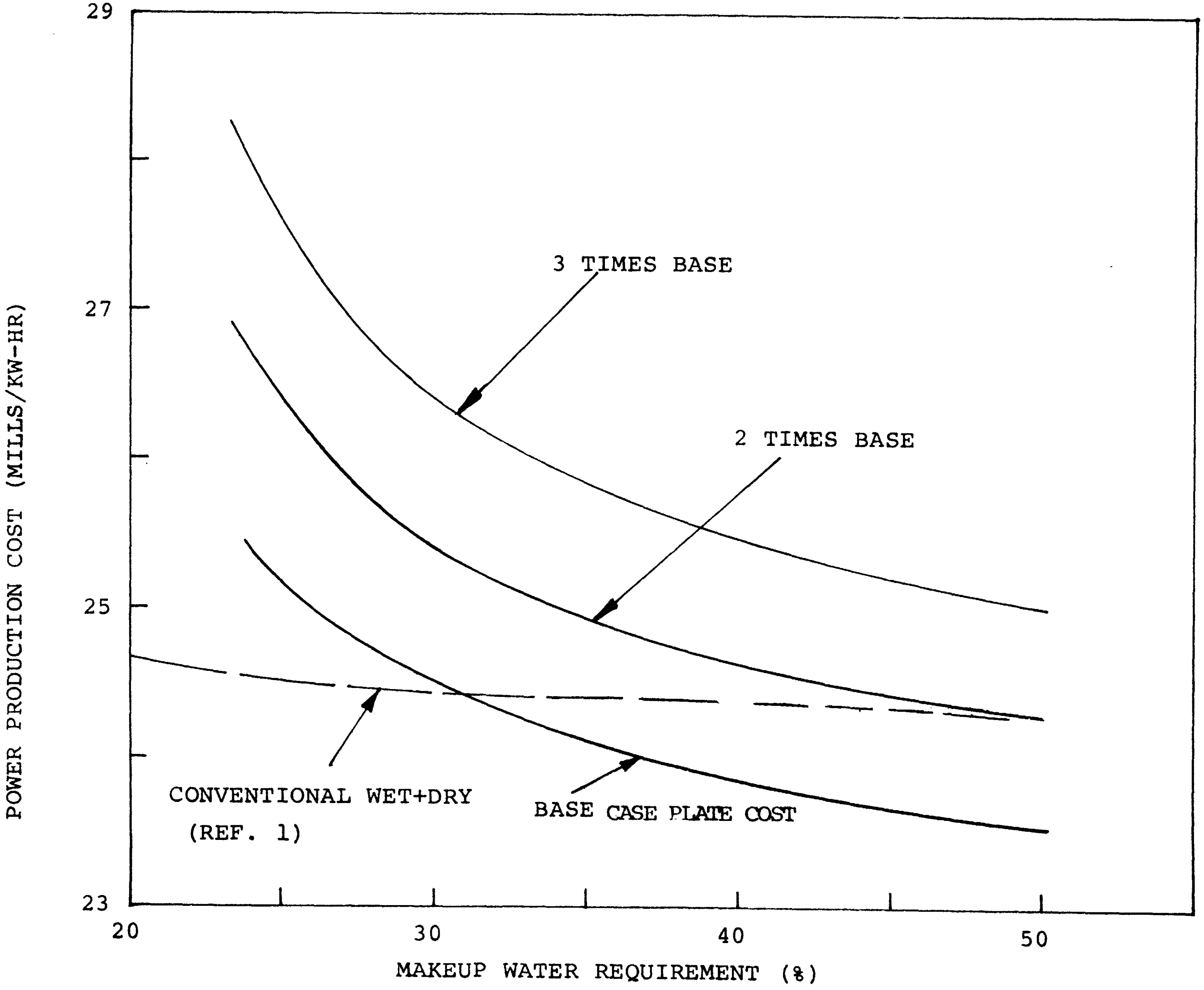


FIG. 8.2

MOLINE SITE 1200 MWe NET CAPACITY NUCLEAR PLANT



towers. When these are compared to 21.1 mills/Kwhr for zero-condenser system, the incremental costs for makeups of 40 and 50 percent using MIT advanced wet/dry instead of conventional wet-dry would be reduced by 28 and 33 percent, respectively.

Our sensitivity study indicates that only when the plate cost is higher than twice the base case cost would the MIT advanced tower entirely not be competitive with conventional wet-dry towers.

Soon the water shortage problem would be common in the electrical power industry. If this is the case, then the MIT advanced wet/dry cooling tower concept provides the utility a useful tool in the heat sink problem.

9.2 Recommendations

Pressure drop measurements were not experimentally done in the previous studies. In future work, this should be performed and compared with theoretical results. The thermal performance of the MIT advanced wet/dry tower presented in the previous chapters have to be verified by operating such a cooling module in existing plants. Finally, the cost of manufacturing the packing plates has to be ascertained before this cooling concept can be recommended for vendors.

9.3 Acknowledgement

This study is supported by the Division of Environmental Technology, U.S. Department of Energy under contract No. EY-76-S-02-4114-A001. It is much appreciated.

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Appendix A

Plate Cost

In 1979, the material cost of 0.025 inch thick aluminum plates is \$0.45/ft^2. The total plate cost is assumed to be twice the material cost. It is the sum of plate material, manufacture and erection costs. Therefore, it is \$0.90/ft^2. Allowing 10% for the contractors profit and 4% for shipping, then the total direct cost is \$1.03/ft^2. This is \$0.81/ft^2 for galvanized steel plates of the same thickness. To estimate these costs in years other than 1979, an inflation of 7% per year is allowed. Cost algorithms of other cooling system components are given in Ref. 1.

Appendix B

Computer Program Listing

The computer program with input data for the 1200 MWe nuclear plant at Moline site is given. Also, several samples of the computer ourput are presented. To execute this program for the 800 MWe fossil plant at Moline, some numerics have to be changed. In the data inputs, turbine heat rates at lines 5 and 6 have to be changed to $\left\{\begin{array}{l}7777,7782,7789,7809,7841\\7882,7930,7984,8012,8040\end{array}\right.$. The value of boiler efficiency EFFE in line 22 has to be changed from 1.0 to 0.9. In line 24, the number representing the plant capacity 1200, has to be replaced by 800. In line 25, the numbers 0147, 600 and 200 represent the fuel cost, plant cost, turbine-generator cost and steam-generator cost, respectively, they have to be replaced by 0.90, 500, 167 and 167, respectively. In line 93 to 95, the numbers are turbine heat rates, they have to be replaced by 7770, 7770, 7770, 7770, 7777, 7783, 7789, 7800, 7809, 7825, 7841, 7862, 7882, 7907, 7930, 7955, 7984, 8012, 8040. In the main program, to determine the make-water requirement in the statement AWLOSS = AWLOSS x 7.48 *100./(62.4*5.9628E09) the number 5.9628E09 has to be replaced by 2.6187E09 because this is the all-evaporative tower annual water makeup.

In subroutine POWER P, in the statement HEATIN = 3577.5 * 1000. * 3413., the number 3577.5 has to be replaced by 1861.8 because this is the heat source. Also, in the statement PS1 NW = 1212.4, the number 1212.4 has to be changed to 806.5 because it is the plant capacity at the turbine rating back pressure.

```
 DIMENSION AL(5),ANPL(5),ANG(7),AMA(7),AMLIN(7),WPACK(5),VAM(6)
 DIMENSION TA(17),AWIN(17),TPER(17),FUELCS(17),CCCST(17),ECCST(17)
 DIMENSION WLOSS(17)
 DIMENSION TST(3),TITDS(3)
 COMMON/DTOW1/ VAS(6),KCONV,JCONS,XDEPA
 COMMON/DTOW2/ TCOS,DELPA
 COMMON/DTOW3/ TSAT,TTDZ,TD,WIN
 COMMON/COST1/ CSTEAM,CPLN,CPIPE,CCOND,CPUMP,CWDTS,CSTFN,CPLNNW,
1COSM,CTURB,CFAN,CEEQ,CSCOOL,CFUEL,CCSYS,CCWQC,OPCWQC
 COMMON/DTOW4/ MTOW,AMPT,DIAMT,W3,W4,VAIR,
1QIN,QREJ,HRFAC,T4,NFAN,NLM,FLOSS,
2DPCON,DPPIP,SCPOW,PPOW,FPOW,XNPASS,TLSH,AREAPS,XNTS
 COMMON/DTOW6/ CONK
 COMMON/DTOW8/ QRJMX(4),POWMX(4)
 COMMON/INPUT1/ HRFACB,HRFMIN,HRFMAX,T1MAX,TSMIN,TSMAX,TEFF,
1TPO(13),BP1,BP2,BP3
 COMMON/INPUT2/ ECCOS,CCCOS,CAPF,FCOS,FCR,PSIZE,PLANC,STEAMC,
1TURBC,PER,PTTURB,CSCCM,CWQCC,CWQCOP,SUPCC,SUPCP
 COMMON/INPUT3/ EFFP,EFFF,RFCOV,VELCON,VELW,PFACT,EFFB
 COMMON/INPUT5/ THROTT(4),EFFMX(4)
 COMMON/INPUT6/ DIST,CU,GCF,CF,CPMPC1,CPMPC2,GPMPF,AREAPF,
1TOD,TID,DFAN
 COMMON/INPUT7/T11,T11ST
 COMMON/PIPING/ TWP(23),DIA(23),CPC1(23),CPC2(23,2),CPC3(23),
1CRC1(23),CRC2(23,2),CTC1(23),CTC2(23,2),CE1C1(23),CE2C1(23),
2CE1C2(23,2),CE2C2(23,2),VALCST(23),FLCST(23)
 COMMON/INPUT8/ITRACK
 COMMON/IN1/ T1T(10),HR1T(10),QTUR(10),TLIN1T(10)
 COMMON/IN5/CSFPL,DENSPL
 COMMON/IN8/SP
 COMMON/DTOW9/ FF1,FF2,FAIR
 COMMON/INA/TSTM(21),PSTM(21),HR(19)
 ITRACK=0
 ID=1
 READ(53,77) (TST(I),I=1,3)
 READ(53,77) (TITDS(I),I=1,3)
 READ(53,77) (T1T(I),I=1,5)
 READ(53,77) (T1T(I),I=6,10)
 READ(53,76) (HR1T(I),I=1,5)
 READ(53,76) (HR1T(I),I=6,10)
 READ(53,67) (TA(I),I=1,2)
 READ(53,67) (TA(I),I=3,17)
 READ(53,30)(AWIN(I),J=1,8)
 READ(53,30)(AWIN(I),I=9,17)
 READ(53,69) (TPER(I),I=1,2)
 READ(53,69) (TPER(I),I=3,10)
 READ(53,69) (TPER(I),I=11,17)
 READ(53,77) (EFFMX(I),I=1,3)
 READ(53,77) (THROTT(I),I=1,3)
 READ(53,77) DIST,CU,GCF,CF,GPMPF,AREAPF
 READ(53,77) T11ST
 READ(53,77) TOD,TID,DFAN
 READ(53,45) CPMPC1,CPMPC2
 READ(53,77) VELCON,VELW,PFACT
 READ(53,76) VAS(1),VAS(2),VAS3ST,VAS(4),VAS(5),VAS(6)
 READ(53,77) TEFF,EFFP,EFFF,XDEPA,RFCOV,EFFB,CSCCM
 READ(53,70) CWQCC,CWQCOP,SUPCC,SUPCP
 READ(53,77) PSIZE,PER,PTTURB
 READ(53,77) FCOS,FCR,PLANC,STEAMC,TURBC,CCCOS,ECCOS,CAPF
 READ(53,77) TSTAR,TEND,TSATST,TSATEN
 READ(53,77) BP1,BP2,BP3,HRFMIN,HRFMAX,HRFACB
 READ(53,72) (TPO(I),I=1,8)
 READ(53,72) (TPO(I),I=9,13)
 READ(53,77) ITD2,TITDMX,TSMIN,T1MAX
 READ(53,40) (DIA(I),I=1,12)
 READ(53,40) (DIA(I),I=13,23)
```

```
READ(53,41)  (TWP(I),I=1,10)
READ(53,41)  (TWP(I),I=11,20)
READ(53,41)  (TWP(I),I=21,23)
READ(53,42)  (CPC3(I),I=1,10)
READ(53,42)  (CPC3(I),I=11,20)
READ(53,42)  (CPC3(I),I=21,23)
READ(53,42)  (CPC1(I),I=1,10)
READ(53,42)  (CPC1(I),I=11,20)
READ(53,42)  (CPC1(I),I=21,23)
READ(53,42)  (CPC2(I,1),I=1,10)
READ(53,42)  (CPC2(I,1),I=11,20)
READ(53,42)  (CPC2(I,1),I=21,23)
READ(53,42)  (CPC2(I,2),I=1,10)
READ(53,42)  (CPC2(I,2),I=11,20)
READ(53,42)  (CPC2(I,2),I=21,23)
READ(53,43)  (CRC1(I),I=1,8)
READ(53,43)  (CRC1(I),I=9,16)
READ(53,43)  (CRC1(I),I=17,23)
READ(53,43)  (CRC2(I,1),I=1,8)
READ(53,43)  (CRC2(I,1),I=9,16)
READ(53,43)  (CRC2(I,1),I=17,23)
READ(53,43)  (CRC2(I,2),I=1,8)
READ(53,43)  (CRC2(I,2),I=9,16)
READ(53,43)  (CRC2(I,2),I=17,23)
READ(53,43)  (CTC1(I),I=1,8)
READ(53,43)  (CTC1(I),I=9,16)
READ(53,43)  (CTC1(I),I=17,23)
READ(53,43)  (CTC2(I,1),I=1,8)
READ(53,43)  (CTC2(I,1),I=9,16)
READ(53,43)  (CTC2(I,1),I=17,23)
READ(53,43)  (CTC2(I,2),I=1,8)
READ(53,43)  (CTC2(I,2),I=9,16)
READ(53,43)  (CTC2(I,2),I=17,23)
READ(53,43)  (CE1C1(I),I=1,8)
READ(53,43)  (CE1C1(I),I=9,16)
READ(53,43)  (CE1C1(I),I=17,23)
READ(53,43)  (CE1C2(I,1),I=1,8)
READ(53,43)  (CE1C2(I,1),I=9,16)
READ(53,43)  (CE1C2(I,1),I=17,23)
READ(53,43)  (CE1C2(I,2),I=1,8)
READ(53,43)  (CE1C2(I,2),I=9,16)
READ(53,43)  (CE1C2(I,2),I=17,23)
READ(53,43)  (CE2C1(I),I=1,8)
READ(53,43)  (CE2C1(I),I=9,16)
READ(53,43)  (CE2C1(I),I=17,23)
READ(53,43)  (CE2C2(I,1),I=1,8)
READ(53,43)  (CE2C2(I,1),I=9,16)
READ(53,43)  (CE2C2(I,1),I=17,23)
READ(53,43)  (CE2C2(I,2),I=1,8)
READ(53,43)  (CE2C2(I,2),I=9,16)
READ(53,43)  (CE2C2(I,2),I=17,23)
READ(53,43)  (FLCST(I),I=1,8)
READ(53,43)  (FLCST(I),I=9,16)
READ(53,43)  (FLCST(I),I=17,23)
READ(53,43)  (VALCST(I),I=1,8)
READ(53,43)  (VALCST(I),I=9,16)
READ(53,43)  (VALCST(I),I=17,23)
READ(53,30)  WIN
READ(53,77)  CSFPL,DENSPL
READ(53,77)  SP
READ(53,76)  (HR(I),I=1,7)
READ(53,76)  (HR(I),I=8,14)
READ(53,76)  (HR(I),I=15,19)
READ(53,77)  (TSTM(I),I=1,8)
READ(53,77)  (TSTM(I),I=9,16)
READ(53.77)(TSIM(I).I=17.21)
```

```
    READ(53,77) (PSTM(I),I=1,8)
    READ(53,77) (PSTM(I),I=9,16)
    READ(53,77)(PSTM(I),I=17,21)
    IF(IE.EQ.1) GO TO 888
    WRITE(6,79)
    WRITE(6,67) (TA(I),I=1,2)
    WRITE(6,67) (TA(I),I=3,17)
    WRITE(6,30)(AWIN(I),I=1,8)
    WRITE(6,30)(AWIN(I),I=9,17)
    WRITE(6,69) (TPER(I),I=1,2)
    WRITE(6,69) (TPER(I),I=3,10)
    WRITE(6,69) (TPER(I),I=11,17)
    WRITE(6,77) (EFFMX(I),I=1,4)
    WRITE(6,77) (THROTT(I),I=1,4)
    WRITE(6,77) DIST,CU,GCF,CF,GPMPF,AREAPF
    WRITE(6,77) T11ST
    WRITE(6,77) (T1T(I),I=1,5)
    WRITE(6,77) (T1T(I),I=6,10)
    WRITE(6,76) (HR1T(I),I=1,5)
    WRITE(6,76) (HR1T(I),I=6,10)
    WRITE(6,77) TOD,TID,DFAN
    WRITE(6,45) CPMPC1,CPMPC2
    WRITE(6,77) VELCON,VELW,PFACT
    WRITE(6,76) VAS(1),VAS(2),VAS3ST,VAS(4),VAS(5),VAS(6)
    WRITE(6,77) TEFF,EFFP,EFFF,XDEPA,RFCOV,EFFB,CSCCM
    WRITE(6,70) CWQCC,CWQCOP,SUPCC,SUPCP
    WRITE(6,77) PSIZE,PER,PTTURB
    WRITE(6,77) FCOS,FCR,PLANC,STEAMC,TURBC,CCCOS,ECCOS,CAPF
    WRITE(6,77) TSTAR,TEND,TSATST,TSATEN
    WRITE(6,77) BP1,BP2,BP3,HRFMIN,HRFMAX,HRFACB
    WRITE(6,72) (TPO(I),I=1,8)
    WRITE(6,72) (TPO(I),I=9,13)
    WRITE(6,77) TTD2,TITDMX,TSMIN,T1MAX
    WRITE(6,30) WIN
    WRITE(6,77) CSFPL,DENSPL
    WRITE(6,77) SP
    WRITE(6,76) (HR(I),I=1,7)
    WRITE(6,76) (HR(I),I=8,14)
    WRITE(6,76)(HR(I),I=15,19)
    WRITE(6,77) (TSTM(I),I=1,8)
    WRITE(6,77) (TSTM(I),I=9,16)
    WRITE(6,77)(TSTM(I),I=17,21)
    WRITE(6,77)(PSTM(I),I=1,8)
    WRITE(6,77)(PSTM(I),I=9,16)
    WRITE(6,77)(PSTM(I),I=17,21)
888 WRITE(6,76) VAS(1),VAS(2),VAS3ST,VAS(4),VAS(5),VAS(6)
 40 FORMAT(12F6.0)
 41 FORMAT(10F8.4)
 42 FORMAT(10F8.2)
 43 FORMAT(10F8.2)
 30 FORMAT(10F8.5)
 45 FORMAT(5F16.4)
 70 FORMAT(8F10.2)
 72 FORMAT(8F10.7)
 77 FORMAT(8F10.4)
 76 FORMAT (8F10.1)
 67 FORMAT(15F5.1)
 69 FORMAT(10F10.7)
 79 FORMAT('1')
    TD=TSTAR
    TSATT=TSATST
555 WRITE(6,81) TD
 81 FORMAT('0DESIGN DRY BULB TEMPERATURE TD =',F8.3,' DEGREE F')
    WRITE(6,77) VAS(4)
    VAS(3)=VAS3ST
666 WRITE(6,76) VAS(3)
```

```
444 TITD=TSATT-TTD2-TD
121 WRITE(6,181) TITD
181 FORMAT(' DESIGN ITD=',F7.3,' DEGREE F')
    TLIN=TSATT-TTD2
    TSAT=TSATT
    CALL POWERP(VAS(1),VAS(2),VAS(3),VAS(4),VAS(5),VAS(6))
    WRITE(6,77) FF1,FF2,FAIR
    WRITE(6,77) DELPA,FAIR,FLOSS
    CAPIT=CCSYS+CSTEAM+CTURB+CPLNNW
    IF(IL.EQ.1) GO TO 999
    WRITE(6,84) NLM,NFAN
 84 FORMAT(10X,' NUMBER OF MAIN CIRCULATION LINES=',I3/10X,'NUMBER OF
   1FANS =',I6)
    WRITE(6,85) QREJ
 85 FORMAT(10X,' DESIGN HEAT REJECTION RATE =',E15.5,' BTU/HR')
    WRITE(6,74) NTOW,AMPT
 74 FORMAT(10X,' NUMBER OF WET/DRY TOWERS =',I5/10X,
   1' NUMBER OF MODULES PER TOWER =',F6.1)
    WRITE(6,88) DPPIP,DPCON,PPOW,FPOW
 88 FORMAT(10X,' PRESSURE DROP OF PIPING SYSTEM =',F10.3,' FEET H2O'/
   110X,' PRESSURE DROP THROUGH CONDENSER =',F10.3,' FEET H2O'/
   210X,' PUMPING POWER =',E10.3, ' MWE'/10X,' FAN POWER =',E10.3,
   3' MWE')
    WRITE(6,97) XNPASS,TLSH,AREAPS,XNTS,W3,W4
 97 FORMAT(10X,' NUMBER OF CONDENSER TUBE PASSES =',F10.4/10X,
   1' LENGTH OF CONDENSER SHELL =',F10.4,' FEET'/10X,
   2' HEAT TRANSFER AREA PER CONDENSER SHELL =',E15.5,' FT2'/10X,
   3' NUMBER OF CONDENSER TUBES PER SHELL =',E15.5/10X,
   4' WATER FLOW RATE =',E15.5,' LB/HR'/10X,
   5' AIR FLOW RATE =',E15.5,' LB/HR')
    WRITE(6,82) HRFAC,T4
 82 FORMAT(10X,' DESIGN HEAT RATE FACTOR =',F7.4/10X,' TOWER EXIT
   1AIR TEMPERATURE =',F8.3,' DEGREE F')
    WRITE(6,83) VAIR
 83 FORMAT(10X,'DESING AIR VELOCITY =',F10.3,' FT/SEC')
    WRITE(6,86) CPIPE,CPUMP,CCOND,CWDTS,CSTFN,CFAN,CEEQ
 86 FORMAT(10X,' CAPITAL COST OF PIPING SYSTEM =$',E12.5/10X,
   1' CAPITAL COST OF PUMPING SYSTEM =$',E12.5/10X,
   2' CAPITAL COST OF CONDENSER =$',E12.5/10X,
   3' CAPITAL COST OF HEAT EXCHANGER =$',E12.5/10X,
   4' CAPITAL COST OF TOWER STRUCTURE AND FOUNDATION =$',E12.5/10X,
   5' CAPITAL COST OF FAN SYSTEM =$',E12.5/10X,
   6' CAPITAL COST OF FAN SYSTEM ELECTRICAL EQUIPMENT =$',E12.5)
    WRITE(6,80) CCSYS,CPLNNW,CFUEL,CSTEAM,CTURB
 80 FORMAT(10X,' TOTAL DIRFCT AND INDIRFCT COST OF COOLING SYSTEM =$'
   1,E12.5/10X,' POWER PLANT CONSTRUCTION COST =$',E12.5/10X,
   2' FUEL COST AT DESIGN POINT =$',E12.5/10X,
   3' CAPITAL COST OF ADDITIONAL STEAM SUPPLY SYSTEM =$',E12.5/10X,
   4' CAPITAL COST OF EXTRA TURBINE =$',E12.5)
999 WRITE(6,102)
102 FORMAT(5X,' TDB',10X,' TSAT',8X,' TTD',10X,' ITD',2X,' NET POWER'
   1,5X,' FRACTION OF FULL-',2X,' ENERGY CHARGE',10X,' WATER LOSS'/
   268X,' LOAD THROTTLE')
    DO 178 I=1,3
    POWMX(I)=QIN*THROTT(I)*EFFMX(I)/(3413.*1000.)
    QRJMX(I)=QIN*THROTT(I)*(1.-EFFMX(I))
178 CONTINUE
    DO 170 I=1,10
    QTUR(I)=QIN*(1.-3413./HRIT(I))
    TLINIT(I)=TIT(I)-QTUR(I)*CONK
170 CONTINUE
    AFUEL=0.
    ACSEC=0.
    AWLOSS=0.
    T11=T11ST
    DO 3 I=2,17
```

```
      CALL PERFORM (TA(I),AWIN(I),TPER(I),ECCST(I),CCCST(I),FUELCS(I),
     1WLOSS(I))
      AFUEL=AFUEL+FUELCS(I)
      ACSEC=ACSEC+ECCST(I)
      AWLOSS=AWLOSS+WLOSS(I)
    3 CONTINUE
      CAPAC=CCCST(17)
      H2OC=AWLOSS*7.48*0.20/(62.4*1000.)
      ACAPIT=(CAPIT+CAPAC)*FCR
      AOPER=COSM+CAPAC*PER+AFUEL+ACSEC+OPCWQC+H2OC
      ACAPCS=ACAPIT/(8760.*CAPF*PSIZE)
      AOPCS=AOPER/(8760.*CAPF*PSIZE)
      ANNCOS=AOPCS+ACAPCS
      AWLOSS=AWLOSS*7.48*100./(62.4*5.9628E09)
      WRITE(6,87) CAPAC,ACSEC,AFUEL,ANNCOS,AWLOSS
   87 FORMAT(10X,' CAPITAL COST OF REPLACEMENT CAPACITY =$',E12.5/10X,
     1' REPLACEMENT ENERGY COST =$',E12.5/10X,
     2' ANNUAL FUEL COST =$',E12.5/10X,
     3' POWER PRODUCTION COST =',F12.4,' MILLS/KW-HR',
     410X,' ANNUAL WATER LOSS=',F12.4,' %')
      VAS(3)=VAS(3)+6.
      IF(VAS(3).LE.45.) GO TO 666
  222 VAS(5)=VAS(5)+10000.
      IF(VAS(5).EQ.30000.) GO TO 222
      IF(VAS(5).LE.40000.) GO TO 555
      TSATT=TSATT+10.
      IF(TSATT.LE.TSATEN) GO TO 444
      TD=TD+10.
      IF(TD.LE.TEND) GO TO 555
      STOP
      END
      SUBROUTINE POWERP(AL,ANPL,ANG,AMA,AMLIN,WPACK)
      DIMENSION GPMA(100),NLA(100),VELA(100),DIAA(100),PIPCSA(100),
     1VCSA(100),CRCA1(100),CRCA2(100),TWPA(100),CPC3A(100),TCSA(100),
     2PIPCA(100),REDCA(100),TCA(100),DPRA(100),DPA(100),EL1CSA(100),
     3EL2CSA(100),ELA(100),FLCSA(100)
      COMMON/DTOW1/ VAS(6),KCONV,JCONS,XDEPA
      COMMON/DTOW2/ TCOS,DELPA
      COMMON/DTOW3/ TSAT,TTD2,TD,WIN
      COMMON/COST1/ CSTEAM,CPLN,CPIPE,CCOND,CPUMP,CWDTS,CSTFN,CPLNNW,
     1COSM,CTURB,CFAN,CEEQ,CSCOOL,CFUEL,CCSYS,CCWQC,OPCWQC
      COMMON/DTOW4/MTOW,AMPT,DIAMT,W3,W4,VAIR,
     1QIN,QREJ,HRFAC,T4,NFAN,NLM,FLOSS,
     2DPCON,DPPIP,SCPOW,PPOW,FPOW,XNPASS,TLSH,AREAPS,XNTS
      COMMON/DTOW6/ CONK
      COMMON/INPUT1/ HRFACB,HRFMIN,HRFMAX,T1MAX,TSMIN,TSMAX,TEFF,
     1TPO(13),BP1,BP2,BP3
      COMMON/INPUT2/ ECCOS,CCCOS,CAPF,FCOS,FCR,PSIZE,PLANC,STEAMC,
     1TURBC,PER,PTTURB,CSCCM,CWQCC,CWQCOP,SUPCC,SUPCP
      COMMON/INPUT3/ EFFP,EFFF,RFCOV,VELCON,VELW,PFACT,EFFB
      COMMON/INPUT6/ DIST,CU,GCF,CF,CPMPC1,CPMPC2,GPMPF,AREAPF,
     1TOD,TID,DFAN
      COMMON/INPUT8/ITRACK
      COMMON/DTOW9/ FF1,FF2,FAIR
      COMMON/IN5/CSFPL,DENSPL
      COMMON/IN8/SP
      COMMON/INA/TSTM(21),PSTM(21),HR(19)
      KCONV=0
      CALL TABLE(TSAT,TSTM,PSTM,21,P)
      CALL TABLE(P,PSTM,HR,19,HRATE)
      HRFAC=HRATE/HR(19)
      TEFFM=3413./HRATE
      HEATIN=3577.5*1000.*3413.
      POUT=HEATIN*TEFFM/(3413.*1000.)
      QHEAT=HEATIN
      QREJ=QHEAT*(1.-TEFFM)
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```
      TOUT=TSAT-TTD2
      TLIN=TOUT
   58 CALL WDTOW(AL,ANPL,ANG,AMA,TD,WIN,AMLIN,TLIN,WPACK,RANGE,
     1QREJM,DMLM,T4,1)
      IF(QREJM.EQ.0.) GO TO 10
      ANOM=QREJ/QREJM
      TWL=ANOM*DMLM
   20 TIN=TOUT-RANGE
      TMEAN=(TIN+TOUT)/2.
      DENM=EXP(-1.3656E-4*TMEAN+4.1413)
      IF(RANGE.LE.0.) GO TO 10
      W3=QREJ/RANGE
      GPMCON=W3*7.48/(60.*DENM)
      XNSH=2.
      GPMSH=GPMCON/XNSH
      TDLM=RANGE/ALOG((RANGE+TTD2)/TTD2)
   59 IF(TIN-100.) 60,60,61
   60 IF(TIN.LT.75.) GO TO 67
      TCF=1.03+0.0028*(TIN-75.)
      GO TO 62
   67 TCF=-0.19+0.0275*TIN-0.00015*TIN**2
      GO TO 62
   61 TCF=1.10+0.001888*(TIN-100.)
   62 US=CU*SQRT(VELCON)*TCF*GCF*CF
      AREAPS=(QREJ/XNSH)/(US*TDLM)
      TL=AREAPS*VELCON*GPMPF/(AREAPF*GPMSH)
      XNPASS=1.
      IF(TL.GT.50.) XNPASS=2.
      TLSH=TL/XNPASS
      XNTS=XNPASS*AINT(GPMSH/(VELCON*GPMPF)+0.5)
      CALL DELP(TID,VELCON,TMEAN,PCONT,1)
      DPCONT=PCONT*TL
      DPENT=(-0.0633+0.03766*VELCON+0.01133*VELCON**2+0.0003333*VELCON
     1**3)*XNPASS
      DPWB=(-0.1434+0.04204*VELCON+0.01733*VELCON**2)*XNPASS
      DPCON=DPENT+DPWB+DPCONT
   63 CALL SUPCON(TLSH,XNTS,AREAPS,XNSH,CCOND)
      SCPOW=SUPCP/1000.
      CSCOOL=SUPCC
   21 W4=ANOM*AMA*AL*(ANPL-1.)*SP/12.
      GO TO 11
   10 KCONV=1
      RETURN
   11 GPMTOT=W3*7.48/(60.*62.)
      CALL PIPE(1,GPMTOT,NLTOT,VELTOT,DIATOT,PIPTOT,VCSTOT,DUMY,DUMMY,
     1DUM,DUMM,TCSTOT,EL1TOT,EL2TOT,FLCTOT)
      IF (NLTOT.LT.5) GO TO 39
      GO TO 10
   39 XTOW=2.*NLTOT
   40 AMPT=ANOM/XTOW
      ELENI=AMPT*SP*(ANPL-1.)/12.
      DIAMI=ELENI/3.1416
      IF(DIAMI.GT.350.) GO TO 41
      IF(DIAMI.GT.30.) GO TO 42
      DIAMI=30.
      GO TO 42
   41 XTOW=XTOW+2.*NLTOT
      GO TO 40
   42 MTOW=XTOW
   43 MTOW=XTOW
   44 NXTOW=MTOW/2
      DIAMO=DIAMI+2.*WPACK
      DIAMT=DIAMI
      GPMM=GPMTOT/NLTOT
      NFAN=3.1416*MTOW*DIAMT/(2.*32.)
      NLM=NLTOT
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      GPMR=GPMM/(2*NXTOW)
   45 PIPEA=0.
      DPIPA=0.
      RFCSTA=0.
      TCSTA=0.
      ELCSTA=0.
      DO 70 I=1,NXTOW
      GPMA(I)=GPMM-2*(I-1)*GPMR
      CALL PIPE(1,GPMA(I),NLA(I),VELA(I),DIAA(I),PIPCSA(I),VCSA(I),
     1CRCA1(I),CRCA2(I),TWPA(I),CPC3A(I),TCSA(I),EL1CSA(I),EL2CSA(I),
     2FLCSA(I))
      PIPCA(I)=PIPCSA(I)*1.5*DIAMT*2
      IF(I.GT.1) GO TO 71
      REDCA(I)=0.
      GO TO 72
   71 REDCA(I)=2.*(TWPA(I-1)*CRCA1(I-1)+CRCA2(I-1)+1.67*(1.+DIAA(I-1)
     1/DIAA(I))*CPC3A(I-1)*DIAA(I-1))*1.1
   72 IF(I.EQ.NXTOW) GO TO 73
      ELA(I)=0.
      TCA(I)=TCSA(I)*4
      GO TO 74
   73 TCA(I)=TCSA(I)*2
      ELA(I)=EL2CSA(I)*2
   74 PIPEA=PIPEA+PIPCA(I)
      TCSTA=TCSTA+TCA(I)
      ELCSTA=ELCSTA+ELA(I)
      RFCSTA=RFCSTA+REDCA(I)
      CALL DELP(DIAA(I),VELA(I),TMEAN,DPRA(I),2)
      DPA(I)=DPRA(I)*1.5*DIAMT*2.*1.45
      DPIPA=DPIPA+DPA(I)
   70 CONTINUE
      IF(NLM-1) 90,90,91
   90 ELCSTA=ELCSTA
      GO TO 98
   91 IF(NLM-2) 92,92,93
   92 ELCSTA=ELCSTA+4*EL1CSA(1)
      GO TO 98
   93 IF(NLM-3) 94,94,95
   94 ELCSTA=ELCSTA+8*EL1CSA(1)/3
      GO TO 98
   95 IF(NLM-4) 96,96,97
   96 ELCSTA=ELCSTA+4*EL1CSA(1)+EL2CSA(1)
      GO TO 98
   97 ELCSTA=ELCSTA+4*EL1CSA(1)+0.8*EL2CSA(1)
   98 TLR=4*DIAMT*NXTOW/6
      CALL PIPE(1,GPMR,NLR,VELR,DIAR,PIPCSR,VCSR,CRCR1,CRCR2,TWPR,
     1CPC3R,TCSR,EL1CSR,EL2CSR,FLCSR)
      PIPCR=PIPCSR*TLR
      TCR=TCSR*2*NXTOW*2
      CALL DELP(DIAR,VELR,TMEAN,DPRR,2)
      DPR=DPRR*DIAMT*2./6.
      GPMH=GPMR/4.
      CALL PIPE(1,GPMH,NLH,VELH,DIAH,PIPCSH,VCSH,CRCH1,CRCH2,TWPH,
     2CPC3H,TCSH,EL1CSH,EL2CSH,FLCSH)
      PIPCH=PIPCSH*(3.5*DIAMT*2.+AL)*2.*NXTOW
      TCH=TCSH*4*4*NXTOW
      VCH=VCSH*16*NXTOW
      FCH=FLCSH*NXTOW*32
      EL1CH=EL1CSH*2*4*NXTOW
      EL2CH=EL2CSH*24*NXTOW
      CALL DELP(DIAH,VELH,TMEAN,DPRH,2)
      DPH=DPRH*(2.*DIAMT+AL)*1.45
      DPPIP=DPIPA+DPRA(1)*2.0*1.45*(DIST-DIAMC)+DPR+DPH
      CPIB=PIPEA+PIPCSA(1)*2.0*(DIST-DIAMC)+PIPCR+PIPCH
      CPTOT=NLTOT*CPIB
      CRFCE=NLTOT*RFCSTA
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      CT=NLTOT*(TCSTA+TCR+TCH)
      CELBW=(EL1CH+EL2CH+ELCSTA)*NLTOT
      CVALV=VCH*NLTOT
      CFLN=FCH*NLTOT
      CPIPE=CPTOT+CT+CELBW+CRFCE+CVALV+CFLN
      AREAT=3.1416*DIAMO**2/4
      AV4AR=(T4+460.)/(TD+460.)
      AVMAR=((T4+TD)/2.+460.)/(TD+460.)
      DHYD=4.*AL*SP/(2.*(AL+SP/12.))/12.
      FAIR=SQRT(0.5*(FF1**2+FF2**2))
      AAT=(T4+TD)/2.
      VA=53.35*(AAT+460.)/(14.7*144.)
      VE=VA*AMA*(ANPL-1.)*AL*SP*AMPT*MTOW*4./(12.*3.1416*
     1NFAN*3600.*DFAN**2)
      AFRON=AL*SP*(ANPL-1.)/12.
      GAIR=AMA
      VAIR=GAIR*VA/3600.
      DELPA=4.*FAIR*WPACK*VAIR*VAIR/(64.4*VA*DHYD)
      SIGMA=1.0
      FLOSS=(1.-RFCOV)*VE*VE/(64.*VA)
      HPAIR=W4*VA*(DELPA+FLOSS)/(3600.*550.)
      FBHP=HPAIR/EFFF
      CALL FANSYS(FBHP,NFAN,DFAN,CSTFAN)
      CFAN=CSTFAN*NFAN
      CALL ELECEQ(FBHP,NFAN,CEQFAN)
      HPWAT=(DPPIP+DPCON+AL)*W3/(3600.*550.)
      PBHP=HPWAT/EFFP
      PPOW=PBHP/1341.
      CPUMP=CPMPC1+PPOW*1000.*CPMPC2
      CEEQ=CEQFAN
      FPOW=FBHP/1341.
      QIN=QHEAT
      QREJ=QIN*(1.-TEFFM)
      CONK=TTD2/QREJ
      CFUEL=FCOS*QIN*8760.*CAPF/(EFFB*1000000.)
      CSTEAM=(PSIZE+PPOW+FPOW+SCPOW)*HRFAC*(HRFACB-1.)*STEAMC*1000.
     1/HRFACB
      CTURB=(PSIZE+PPOW+FPOW+SCPOW)*HRFAC*1000.*TURBC*PTTURB/HRFACB
      CPLN=PLANC*PSIZE*1000.
      PSIZNW=1212.4
      CPLNNW=PLANC*PSIZNW*1000.
      AREAT=3.1416*DIAMO**2/4.
      WTFAN=NFAN*7600.
      WTWAT=62.*3.1416*(DIAMO**2-DIAMI**2)/12.
      WTPP=1.4*AL*WPACK*0.025*62.4*DENSPL/12.
      WTPLT=ANPL*AMPT*WTPP
      WTRF=((WTFAN+WTWAT)/(AFRON*AMPT))+40.
      CSTFN=(0.2458*AREAT*AL*MTOW*(0.00305*WTRF+0.878)+0.019*(WTPLT+
     1WTWAT)+0.82*AREAT*MTOW)*1.1
      CCWQC=CWQCC*GPMTOT
      OPCWQC=CWQCOP*GPMTOT
      CWDTS=CSFPL*AL*(WPACK+ANG*5./12./16.)*ANPL*AMPT*MTOW
      CCSYS=CSTFN+CWDTS+CFAN+CEEQ+CCOND+CPIPE+CPUMP+CCWQC+CSCOOL
      CCSYS=CCSYS*1.20*CSCCM
      COSM=(CCSYS+CSTEAM+CTURB+CPLNNW)*PER
      TCOS=((CCSYS+CSTEAM+CTURB+CPLNNW)*FCR+COSM+
     1OPCWQC+CFUEL)/(PSIZE*8760.*CAPF)
  341 RETURN
      END
      SUBROUTINE WDTOW(AL,ANPL,ANG,AMA,TD,WIN,AML1N,TLIN,WPACK,RANGE,
     1QREJM,DMLM,T4,IP)
C     THIS COMPUTER PROGRAM MODELS THE PERFORMANCE OF THE M.I.T
C     CROSSFLOW ADVANCED WET/DRY COOLING TOWER BY MEANS OF A FINITE
C     ELEMENT TECHNIQUE.
      COMMON/INPUT8/ITRACK
      COMMON/IND/PITCH
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      COMMON/IN8/SP
      COMMON/INL/HDP,HD
      INTEGER AIRHUM,AIRTEM,AIRFLO
      REAL OUTAIR(50),OUTHUM(50),OUTLIQ(50),OUTFLO(50),NU
      REAL KP,L,NG,NPL,MLIN,MLOUT,DATA(30,30,5),MA,NOMIX
      LOGICAL LMIX
      DATA YESMIX/'  '/,NOMIX/'ON'/
    7 LMIX=.FALSE.
      PITCH=(WPACK*12.+5./16.)/(ANG+1.)
      RIBHT=0.25
      L=12.*AL
      NPL=ANPL
      THETA=10.0
      TP=0.025
      KP=120.
      NG=ANG
      MA=AMA*(ANPL-1.)*AL*SP/(60.0*12.)
      TIN=TD
      MLIN=AMLIN/60.0
      P=30.0
      PACKW=12.0*WPACK
      B=PACKW+NG*(5./16.)
      ATOT=2.*B*L
      AWET=(5./16.)*NG*L
      ADRY=ATOT-2.*AWET+L*(PACKW+5./16.)*2.*0.25/2.5
      RATIO=AWET/ADRY
C     THE FOLLOWING ARBITRARILY SELECTED INDEX IXX ESTABLISHES THE
C     NUMBER OF ROWS AND COLUMNS INTO WHICH THE WHOLE PACKING SECTION
C     WILL BE DIVIDED FOR PURPOSES OF ANALYSIS.
  206 IXX=5
      XX=IXX
C     THE NEXT FIVE CARDS DEFINE THE VALUES OF FIVE IDENTIFICATION
C     PARAMETERS FOR THE STORING OF INPUT PARAMETERS PER FINITE
C     ELEMENT OF PACKING SECTION.
      LIQTEM=1
      AIRTEM=2
      LIQFLO=3
      AIRFLO=4
      AIRHUM=5
C     NEXT CARD CALCULATES THE AREA FOR AIR FLOW INTO FINITE ELEMENT
C     OF PACKING.
      AFABLK=L*NPL*SP/144./XX
C     THE NEXT STATEMENT DEFINES THE REFERENCE TEMPERATURE IN DEGREES
C     ABSOLUTE.
      T0=TLIN+459.67
C     DO LOOP TO ASSIGN THE INLET CONDITIONS OF WATER AND AIR INTO THE
C     COOLING TOWER.
      DO 11 I=1,IXX
      DATA(1,I,LIQTEM)=TLIN+459.67
      DATA(I,1,AIRTEM)=TIN+459.67
      DATA(1,I,LIQFLO)=MLIN*60./XX
      DATA(I,1,AIRFLO)=MA*60./XX
      DATA(I,1,AIRHUM)=WIN
   11 CONTINUE
C     IF STATEMENT TO ESTABLISH IF COOLING TOWER IS OF THE TOTALLY
C     DRY KIND.
      IF(RATIO.EQ.0.)ABLIQ=0.
C     IF STATEMENT TO CALCULATE TOTAL AREA FOR CONVECTIVE HEAT TRANSFER
C     FROM WATER TO AIR PER FINITE ELEMENT OF PACKING.
      IF(RATIO.GT.0.) ABLIQ=B/(.5/RATIO+1.)*L*NPL/XX**2.
     1 /144.
      IF(RATIO.EQ.1.) ABLIQ=2.*B*L*NPL/144./XX**2.
C     ABDRY IS THE DRY AREA PER FINITE ELEMENT OF PACKING ON THE
C     SIDE OF THE WATER CHANNELS ONLY.
      ABDRY=L*NPL*B/XX**2./144. -2.*ABLIQ
C     STATEMENT TO FIND EQUIVALENT DISTANCE BETWEEN CHANNELS.
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      D=ABDRY/L*XX/NG*XX*12./NPL
      ABDRY=ABDRY+L*(PACKW+5./16.)*0.25*2.*NPL/(2.5*144.*XX**2.)
      SOP=1.0
      RIB1=RIBHT
C     CALL TO SUBROUTINE HAN TO CALCULATE THE CONVECTIVE HEAT TRANSFER
C     COEFFICIENTS FOR SENSIBLE AND EVAPORATIVE HEAT TRANSFER.
      CALL HAN (RIB1,SP,L,NPL,P,TIN,MA,HDP1,SOP)
      IF(HDP1.GE.0.) GO TO 15
      HDP1=.01
   15 RIB2=0.2706
      SOP=2.0
      CALL HAN (RIB2,SP,L,NPL,P,TIN,MA,HDP2,SOP)
      IF(HDP2.GE.0.) GO TO 16
      HDP2=.01
   16 HDP=(HDP1**2+HDP2**2)/(HDP1+HDP2)
      IF(HDP.GE.6.5) H=HDP+2.125
      IF(HDP.LT.6.5) H=HDP+3.50
      IF(HDP.LE.6.0) H=HDP+4.50
C     NESTED DO LOOP TO DETERMINE PROPERTIES OF WATER AND AIR AT THE
C     INLET AND OUTLET OF EACH FINITE ELEMENT USING SUBROUTINE BLOCK
   17 DO 33 J=1,IXX
      DO 22 I=1,IXX
      II=I+1
      JJ=J+1
  211 CALL BLOCK(DATA(I,J,AIRTEM),DATA(I,J,LIQTEM),DATA(I,J,AIRHUM),
     1DATA(I,J,LIQFLO),DATA(I,JJ,AIRTEM),DATA(II,J,LIQTEM),
     2DATA(I,JJ,AIRHUM),DATA(II,J,LIQFLO),IXX,AFABLK,ABLIQ,ABDRY,P,
     3DATA(1,1,4),TE,KP,TP,RATIO,NU,H,D)
   22 CONTINUE
   33 CONTINUE
C     OUTAIR,OUTHUM,OUTLIQ,AND OUTFLO.
C     OUTLET PROPERTIES OF THE AIR AND WATER ARE STORED ALSO IN ARRAYS
C     OUTAIR,OUTHUM,OUTLIQ,AND OUTFLO.
      DO 18 I=1,IXX
      OUTAIR(I)=DATA(I,IXX+1,AIRTEM)-459.67
      OUTHUM(I)=DATA(I,IXX+1,AIRHUM)
      OUTLIQ(I)=DATA(IXX+1,I,LIQTEM)-459.67
      OUTFLO(I)=DATA(IXX+1,I,LIQFLO)/60.
   18 CONTINUE
      FL=0.
      ATL=0.
C     DO LOOP TO FIND TOTAL ATL AND FL.
      DO 31 I=1,IXX
      ATL=ATL+DATA(IXX+1,I,LIQTEM)
      FL=FL+DATA(IXX+1,I,LIQFLO)
   31 CONTINUE
C     OUTLET WATER MASS FLOW RATE AND OUTLET WATER TEMPERATURE ARE
C     COMPUTED.
      MLOUT=FL/60.
      TLOUT=ATL/XX-459.67
      J=IXX+1
C     CALL MIX TO FIND AVERAGE OUTLET AIR TEMPERATURE AND AVERAGE
C     OUTLET SPECIFIC HUMIDITY.
      CALL MIX(DATA,IXX,J,DATA(1,1,4),WOUT,TAV)
      TOUT=TAV-459.67
C     TOTAL ENERGY TRANSFER FROM WATER.
      QTOT=(TLIN-TLOUT)*MLOUT+MA*(WOUT-WIN)*(TLIN-32.)
C     TOTAL EVAPORATIVE HEAT TRANSFER FROM WATER.
      QEL=(MLIN-MLOUT)*(-.5942*(TLIN+460.)+1370.16
     1 -(.240)*(TLIN-TOUT))
C     RATIO OF EVAPORATIVE HEAT TRANSFER TO TOTAL HEAT TRANSFER.
      QRAT=QEL/QTOT*100.
C     NET CHANGE IN AVERAGE AIR TEMPERATURE.
      DELT=TOUT-TIN
C     NET CHANGE IN AVERAGE WATER TEMPERATURE
      DELTL=TLOUT-TLIN
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C      PERCENTAGE OF WATER THAT VAPORIZES.
       FML=(MLIN-MLOUT)/MLIN*100.
       RANGE=TLIN-TLOUT
       QREJM=60.0*QTOT
       DMLM=60.0*(MLIN-MLOUT)
       T4=TOUT
   44 OUTMIX=NOMIX
       IF(LMIX)OUTMIX=YESMIX
C      FOLLOWING ARE THE STATEMENTS TO PRINT OUT THE RESULTS OF THE
C      MODELING.
       IF(IP.NE.1) GO TO 100
       WRITE(6,48) H,HDP,HD,NU
   48 FORMAT(5X,' H=',F8.2,' HDP=',F8.2,' HD=',F8.2,' NU=',F8.2)
       WRITE(6,50)RATIO,L,B,PACKW,NPL,NG,SP,THETA
       WRITE(6,60)TP,KP,T0,MA,P,TIN,TOUT,WIN,WOUT,MLIN,MLOUT
       WRITE(6,70)TLIN,TLOUT,DELTL,FML,DELT,QTOT,QEL,QRAT
   50 FORMAT(2X,'TOWER GEOMETRY' /2X,'WET-DRY SURFACE ',
     *'RATIO=',F6.3 /2X,'PACKING HEIGHT=',F7.2,' IN.' /2X,'TOTAL ',
     *'HEAT TRANSFER SURFACE WIDTH=',F8.2,' IN.' /2X,'PACKING ',
     *'WIDTH=',F7.2,' IN.' /2X,'NUMBER OF PLATES=',F9.0 /2X,'NUMBER',
     *' OF CHANNELS PER PLATE=',F6.2 /2X,'PLATE SPACING=',F5.2
     *,' IN.' /2x,'PLATE ANGLE FROM VERTICAL=',F4.1,' DEGREES'/)
   60 FORMAT(2X,'PLATE THICKNESS=',F5.3,' IN.' /2X,'PLATE CONDUCTIVITY
     *=',F7.3,' BTU/HR FT F'/ 2X,'REFERENCE TEMPERATURE=',F7.2,
     *' R'/   30X,'INLET',17X,'OUTLET'/ 2X,'AIR FLOW RATE',6X,E9.3
     *,' LBM/MIN'/ 2x,'AIR PRESSURE',9X,F5.2,' IN. HG'/ 2X,
     *'AIR TEMPERATURE',5X,2(F7.2,' F',13X)/ 2X,'HUMIDITY',13X,2(F8.6,
     *' LBM/LBM',7X)/ 2X,'WATER FLOW RATE',4X,2(E9.3,' LBM/MIN',6X)/)
   70 FORMAT(2X,'WATER TEMPERATURE',3X,2(F7.2,' F',14X)/// 2X,'WATER '
     *,'TEMPERATURE CHANGE=',F7.2,' F'/ 2X,'PERCENT WATER LOSS=',
     *F8.2,' %'/ 2X,'AIR TEMPERATURE CHANGE=',
     *F7.2,' F'/ 2X,'TOTAL HEAT TRANSFER=',E11.3,' BTU/MIN'//
     *2X,'EVAPORATIVE HEAT TRANSFER=',E11.3,' BTU/MIN'/ 2X,
     *'PERCENT EVAPORATIVE HEAT TRANSFER=',F4.1,' %')
  100 RETURN
       END
       SUBROUTINE HAN(RIBHT,SP,L,NPL,P,TIN,MA,HDP,SOP)                    HAN100
\c0
C      THIS SUBROUTINE CALCULATES THE HEAT TRANSFER COEFFICIENTS BETWEEN HAN200
\c0
C      THE AIR AND THE DRY AREA OF THE PLATE USING THE J.C. HAN           HAN300
\c0
C      CORRELATIONS FOR RIB-ROUGHENED SURFACES.                           HAN400
\c0
       COMMON/INPUT8/ITRACK
       COMMON/IND/PITCH
       COMMON/DTOW9/ FF1,FF2,FAIR
       REAL L,NPL,MA,MUA,NUN,K,NLHP                                       HAN500
\c0
       TA=TIN+460.                                                        HAN600
\c0
       DH=SP/6.0                                                          HAN700
\c0
       AFA=L*NPL*SP/144.                                                  HAN800
\c0
       ROA=(70.727*P)/(53.35*TA)                                          HAN900
\c0
       VA=MA/(60.0*ROA*AFA)                                               HAN10.0
\c0
       MUA=7.42E-07*SQRT(TA)/(1.0+(205.2/TA))                             HAN1100
\c0
       RE=ROA*VA*DH/MUA                                                   HAN1200
\c0
       IF(SOP.EQ.2.0) GO TO 44
       POE=10.
       IF(POE.LT.10.) RFC=4.9*(10./POE)**0.13
```

```
      IF(POE.GE.10.) RFC=4.9/(10./POE)**0.324
      GO TO 55
   44 POE=PITCH/RIBHT
      IF(POE.LT.10.) RFC=4.9*(10./POE)**0.13*0.7763
      IF(POE.GE.10.) RFC=4.9/(10./POE)**0.53*0.7763
   55 REP=RFC
      FFF=REP-2.5*ALOG(2.*RIBHT/DH/12.0)-3.75
\c0
      FF=2./(FFF**2)
\c0
      EPLUS=(RIBHT*RE)/(12.0*DH*FFF)
\c0
      IF (EPLUS.GE.35.0) GO TO 20
\c0
      DO 5 J=1,20
\c0
      EPLUS1=EPLUS
\c0
      REP=RFC*((EPLUS1/35.0)**(-.40))
\c0
      FFF=REP-2.5*ALOG(RIBHT/SP)-3.75
\c0
      FF=2.0/(FFF**2)
\c0
      EPLUS2=(RIBHT*RE)/(12.0*DH*FFF)
\c0
      EPLUS=(EPLUS1+EPLUS2)/2.0
\c0
      IF(ABS(EPLUS2-EPLUS1) .GT. 0.50) GO TO 5
      GO TO 20
\c0
    5 CONTINUE
\c0
      WRITE(6,10) EPLUS
\c0
   10 FORMAT (5X,'EPLUS=',F8.2)
\c0
   20 IF (SOP.EQ.1.)CONST=10.00000
\c0
      IF (SOP.EQ.2.) CONST=13.66040
\c0
      NLHP=ALOG(CONST)+0.28*ALOG(EPLUS/35.)
\c0
      IF (EPLUS .LT. 35.0) NLHP=ALOG(CONST)
\c0
      HPLUS=EXP(NLHP)
\c0
      STN=FF/((HPLUS-REP)*SQRT(2.*FF)+2.0)
\c0
      NUN=0.72*STN*RE
\c0
      K=0.0008946*SQRT(TA)/(1.+(205.2/TA))
\c0
      HDP=NUN*K/DH
\c0
      IF(SOP.EQ.1.) FF1=FF
      FF2=FF
   30 RETURN
\c0
      END
\c0
      SUBROUTINE BLOCK(TIN,TLIN,WIN,MLIN,TOUT,TLOUT,WOUT,MLOUT,IXX,
\c0
     1 AFABLK,ABLIQ,ABDRY,PP,MAG,T0,KP,TP,RATIO,NU,H,D)
      COMMON/INL/HDP,HD
C     THIS SUBROUTINE ANALYSES THE TRANSPORT PROCESSES TAKING PLACE
```

```
\c0
C      INSIDE THE COOLING TOWER PER FINITE ELEMENT OF PACKING.               BLOCK4
\c0
       REAL K,KP,MAG,MUA,MUL,MV,NU,MLIN,MLOUT,ML                             BLOCK5
\c0
C      BELOW THE QUANTITIES NEEDED TO DETERMINE THE INCREMENTAL              BLOCK6
\c0
C      TRANSFERS OF HEAT AND MASS PER FINITE ELEMENT ARE EVALUATED.          BLOCK70
\c0
       COMMON/INPUT6/ITRACK
       IF(TLIN.GT.0.AND.TIN.GT.0.) GO TO 1
       IF(TLIN.GT.0.) GO TO 2
       TLIN=460.
       WRITE(6,55) TLIN
    55 FORMAT(' TLIN IS DEFAULTED TO',F10.2,' DEG R')
     2 IF(TIN.GT.0.) GO TO 1
       TIN=460.
       WRITE(6,56) TIN
    56 FORMAT(' TIN IS DEFAULTED TO',F10.2,' DEG R')
     1 CA=.241
       CL=1.                                                                 BLOCK90
\c0
       PR=.72                                                                BLOCK10
\c.
       RV=85.775                                                             BLOCK11
\c0
       P=PP*70.727                                                           BLOCK12
\c0
       RA=53.35                                                              BLOCK13
\c0
       HFG0=-.5942*T0+1370.16                                                BLOCK14
\c0
       MV=WIN*MAG                                                            BLOCK15
\c0
       ROA=P/((WIN*RV+RA)*TIN)                                               BLOCK16
\c0
       ROV=WIN*ROA                                                           BLOCK17
\c0
       IF(TLIN-500.)3,3,4                                                    BLOCK18
\c0
     3 ROL=62.4                                                              BLOCK19
\c0
       GO TO 6                                                               BLOCK20
\c.
     4 ROL=62.4-2.4792E-04*((TLIN-500.0)**1.8)                               BLOCK21
\c0
     6 PA=ROA*RA*TIN                                                         BLOCK22
\c0
       PV=P-PA                                                               BLOCK23
\c0
       HFG=1370.16-0.5942*TLIN                                               BLOCK24
\c0
       PVSAT=1.44E+26*(0.0006369*TLIN+2.0883)*EXP(-12386./TLIN)*             BLOCK25
\c0
      1(TLIN**(-5.387))                                                      BLOCK26
\c0
       ROVSAT=PVSAT/RV/TLIN                                                  BLOCK27
\c0
       ROMIX=(ROA+ROV*WIN)/(1.+WIN)
   101 K=.0008946*SQRT(TIN)/(1.+(205.2/TIN))                                 BLOCK29
\c0
       CV=((19.86)-(597./SQRT(TIN))+(7500.0/TIN))/18.0                       BLOCK30
\c.
       CMIX=(CA+CV*WIN)/(1.+WIN)                                             BLOCK31
\c0
C   CALCULATION OF MASS DIFFUSIVITY COEFFICIENT OF VAPOR INTO AIR.           BLOCK32
```

```
\c0
      REAL DATA(30,30,5)
\c0
      AIRTEM=2
\c0
      AIRHUM=5
\c0
C     INITIALIZATION VALUES OF TOTAL ENTHALPY OF MIXTURE AND TOTAL
\c0
C     SPECIFIC HUMIDITY.
\c0
      HAIR=0.
\c0
      WAIR=0.
\c0
C     DO LOOP TO FIND TOTAL HAIR AND TOTAL WAIR.
\c0
      DO 1 I=1,IXX
\c0
      HAIR=HAIR+((.241)+(.45)*DATA(I,J,AIRHUM))*AIRFLO*
\c0
     1  DATA(I,J,AIRTEM)
\c0
    1 WAIR=WAIR+DATA(I,J,AIRHUM)
\c0
      XX=IXX
\c0
C     AVERAGE OUTLET SPECIFIC HUMIDITY.
\c0
      WOUT=WAIR/XX
\c0
C     AVERAGE OUTLET MIXTURE TEMPERATURE.
\c0
      TOUT=HAIR/XX/AIRFLO/(.241+.45*WOUT)
\c0
      RETURN
\c0
      END
\c0
      SUBROUTINE PEFORM(TAIR,WAIR,TFREQ,ECCST,CCCST,FUELCS,WLOST)
      DIMENSION          RANGIT(10),QREMIT(10),DMLMIT(10),T4T(10),
     1QREJT(10),WLOSS(10)
      COMMON/DTOW1/ VAS(6),KCONV,JCONS,XDEPA
      COMMON/DTOW2/ TCOS,DELPA
      COMMON/DTOW3/ TSAT,TTD2,TD,WIN
      COMMON/COST1/ CSTEAM,CPLN,CPIPE,CCOND,CPUMP,CWDTS,CSTFN,CPLNNW,
     1COSM,CTURB,CFAN,CEEQ,CSCOOL,CFUEL,CCSYS,CCWQC,OPCWQC
      COMMON/DTOW4/MTOW,AMPT,DIAMT,W3,W4,VAIR,
     1QIN,QREJ,HRFAC,T4,NFAN,NLM,FLOSS,
     2DPCON,DPPIP,SCPOW,PPOW,FPOW,XNPASS,TLSH,AREAPS,XNTS
      COMMON/DTOW6/ CONK
      COMMON/INPUT1/ HRFACB,HRFMIN,HRFMAX,T1MAX,TSMIN,TSMAX,TEFF,
     1TPO(13),BP1,BP2,BP3
      COMMON/INPUT2/ ECCOS,CCCOS,CAPF,FCOS,FCR,PSIZE,PLANC,STEAMC,
     1TURBC,PER,PTTURB,CSCCM,CWQCC,CWQCOP,SUPCC,SUPCP
      COMMON/DTOW8/ QRJMX(4),POWMX(4)
      COMMON/INPUT5/ THROTT(4),EFFMX(4)
      COMMON/INPUT7/ T11,T11ST
      COMMON/INPUT8/ITRACK
      COMMON/IN1/ T1T(10),HR1T(10),QTUR(10),TLIN1T(10)
      COMMON/INA/TSTM(21),PSTM(21),HR(19)
      ID=1
      HRMIN=HR(1)
      TEFFMI=3413./HRMIN
      T1=T11ST
      DO 171 I=1,10
```

```
      CALL WDTOW( VAS(1),VAS(2),VAS(3),VAS(4),TAIR,WAIR,VAS(5),
     1TLINIT(I),VAS(6),RANGIT(I),QREMIT(I),DMLMIT(I),T4T(I),2)
      QREJT(I)=QREMIT(I)*AMPT*MTOW
      WLOSS(I)=DMLMIT(I)*AMPT*MTOW
  171 CONTINUE
      IF(TAIR.EQ.TD) GO TO 1000
    1 CALL TABLE(T1,TSTM,PSTM,21,P)
      CALL TABLE(P,PSTM,HR,19,HRATE)
      TEFFMT=3413./HRATE
      HREJT=QIN*(1.-TEFFMT)
      TTDT=CONK*HREJT
      TWIN=T1-TTDT
      CALL TABLE(TWIN,TLINIT,QREJT,10,TQREJ)
      IF(ABS((HREJT-TQREJ)/HREJT).LT.0.03) GO TO 4
      T1=T1+1.
      T11=T1
      IF(T1.GT.TSMIN.AND.T1.LT.134.) GO TO 1
    4 IF(T11.GT.T1MAX) GO TO 12
      IF(T11.GT.TSMIN) GO TO 16
   33 HRATE=HRMIN
      T11=TSMIN
      TEFFMT=TEFFMI
      HREJT=QIN*(1.-TEFFMI)
      TTDT=HREJT*CONK
      TWIN=T11-TTDT
      GO TO 16
 1000 T1=TSAT
      T11=TSAT
      TEFFMT=3419./HR(19)
      HREJT=QIN*(1.-TEFFMT)
      TWIN=T11-TTD2
      GO TO 16
   12 IF(TQREJ.GT.HREJT) GO TO 33
      T11=T1MAX
      CALL WDTOW( VAS(1),VAS(2),VAS(3),VAS(4),TAIR,WAIR,VAS(5),
     1TLINIT(10),VAS(6),RANGTT,QRMMAX,DMLMTT,T4TT,2)
      QREMAX=QRMMAX*AMPT*MTOW
      HREJT=QREMAX
      TTDT=HREJT*CONK
      CALL TABLE(HREJT,QRJMX,THROTT,3,PTTHRO)
      CALL TABLE(PTTHRO,THROTT,POWMX,3,POUT)
      CSFUEL=CFUEL*PTTHRO
      GO TO 17
   16 POUT=QIN*TEFFMT/(3413.*1000.)
      PTTHRO=THROTT(1)
      CSFUEL=CFUEL
   17 RANGT=HREJT/W3
      TINN=T11-TTDT-RANGT
      SUCPOW=SCPOW
      IF(TINN.LE.95.) SUCPOW=0.
      PGEN=POUT-PPOW-FPOW-SUCPOW
      IF(PGEN.GE.PSIZE) GO TO 5
      CSTEC=(PSIZE-PGEN)*8760.*CAPF*1000.*ECCOS
      CSTCC=(PSIZE-PGEN)*1000.*CCCOS
      GO TO 6
    5 CSTEC=0.
      CSTCC=0.
      CSFUEL=CFUEL*PSIZE/PGEN
    6 FUELCS=TFREQ*CSFUEL
      ECCST=TFREQ*CSTEC
      CCCST=CSTCC
      TITDT=T11-TAIR-TTDT
      TWIN=T11-TTDT
      CALL TABLE(TWIN,TLINIT,WLOSS,10,WLOST)
      WLOST=WLOST*TFREQ*8760.*CAPF
      BLODN=WLOST*0.40
```

```
      WLOST=WLOST+BLODN
      IF(ID.EQ.1) GO TO 99
      WRITE(6,8) TAIR,T11,TTDT,TITDT,PGEN,PTTHRO,ECCST,WLOST
    8 FORMAT(F10.2,4X,F10.2,2X,F10.2,4X,F10.2,1X,F10.2,6X,F10.2,10X,
     1E12.5,10X,E12.5)
   99 RETURN
      END
      SUBROUTINE TABLE(X,XA,YA,M,ANSWER)
      DIMENSION XA(200),YA(200)
      COMMON/INPUT8/ITRACK
      IF((XA(1)-X)*(XA(M)-X)) 2,2,1
    1 IF(ABS(X-XA(1)).LT.ABS(X-XA(M))) N=1
      IF(ABS(X-XA(1)).GT.ABS(X-XA(M))) N=M-2
      GO TO 8
    2 N=M-1
      DO 4 I=1,N
      IF(X.NE.XA(I)) GO TO 3
      ANSWER=YA(I)
      RETURN
    3 IF((X.GT.XA(I)).AND.(X.LT.XA(I+1))) GO TO 5
      IF((X.LT.XA(I)).AND.(X.GT.XA(I+1))) GO TO 5
    4 CONTINUE
      N=M-2
      GO TO 8
    5 IF(I-3) 6,7,7
    6 N=1
      GO TO 8
    7 N=I-1
    8 X1=XA(N)
      X2=XA(N+1)
      X3=XA(N+2)
      Y1=YA(N)
      Y2=YA(N+1)
      Y3=YA(N+2)
      X11=X1*X1
      X22=X2*X2
      X33=X3*X3
      DETM=X22*X3-X33*X2-X11*X3+X33*X1+X11*X2-X22*X1
      A=(Y2*X3-X2*Y3-Y1*X3+Y3*X1+Y1*X2-Y2*X1)/DETM
      B=(X22*Y3-X33*Y2-X11*Y3+X33*Y1+X11*Y2-X22*Y1)/DETM
      C=(Y1*(X22*X3-X33*X2)-Y2*(X11*X3-X33*X1)+Y3*(X11*X2-X22*X1))/DETM
      ANSWER=A*X*X+B*X+C
      RETURN
      END
      SUBROUTINE DELP(DIA,VEL,TWAT,DPR,IR)
      DIMENSION ROUGH(2)
      COMMON/INPUT8/ITRACK
      DATA ROUGH/0.00006,0.0018/
      VISC=7.3283E-4/TWAT
      REYN=VEL*DIA/(12.*VISC)
      IF(REYN-2000.) 1,2,2
    1 F=16./REYN
      GO TO 8
    2 RELR=DIA/ROUGH(IR)
      F1=4.*ALOG10(RELR)+2.28
      F2=RELR*F1/REYN
      IF(F2-0.01) 7,3,3
    3 FTRY=F1
    4 FTRYY=F1-4.*ALOG10(1.+4.67*RELR*FTRY/REYN)
      IF((ABS(FTRYY-FTRY))/FTRY-0.001) 6,6,5
    5 FTRY=FTRYY
      GO TO 4
    6 F1=FTRY
    7 F=1./F1**2
    8 DPR=74.594*F*VEL**2/(DIA*100.)
      RETURN
```

```
\c0
      DV=(144.0*14.696*0.000140*((TIN+TLIN)/2.)**2.5)/                    BLOCK33
\c0
     1(((TIN+TLIN)/2.+441.0)*P)                                           BLOCK34
\c0
      HD=(H/(ROMIX*CMIX))*((ROMIX*CMIX*DV/K)**(2./3.))                    BLOCK35
\c0
      ML=SQRT((6.0*D*D*HDP)/(KP*TP))                                      BLOCK36
\c0
      IF(RATIO.GE.0.) NU=(TANH(ML))/ML                                    BLOCK37
\c0
      IF(RATIO.EQ.1.)NU=0.                                                BLOCK38
\c0
      IF(RATIO.EQ.0.)NU=.8                                                BLOCK39
\c0
C     THE CALCULATIONS BELOW ARE TO FIND THE INCREMENTAL CHANGES OF       BLOCK40
\c.
C     MASS, TEMPERATURE, HUMIDITY AND ENERGY PER FINITE ELEMENT.          BLOCK41
\c0
  201 DML=HD*(ROVSAT-ROV)*ABLIQ                                           BLOCK42
\c0
      DQCL=H*(TLIN-TIN)*ABLIQ                                             BLOCK43
\c0
      DQEL=(HFG+CL*(TLIN-T0))*DML                                         BLOCK44
\c0
      DQDP=(NU*HDP*(TLIN-TIN)*ABDRY*2.)+HDP*(TLIN-TIN)                    BLOCK45
\c0
     1  *ABLIQ*2.                                                         BLOCK46
\c0
      IF(RATIO.EQ.1.)DQDP=0.                                              BLOCK47
\c0
      DQ=DQCL+DQEL+DQDP                                                   BLOCK48
\c0
      DTL=((DQ+((MLIN-DML)*CL*(TLIN-T0)))/(MLIN*CL))-TLIN+T0
      DMV=DML                                                             BLOCK50
\c.
      DW= (MV+DMV)/MAG-WIN                                                BLOCK51
\c0
      DT=(-DQ-MAG*CA*(TIN-T0)-WIN*MAG*(CV*(TIN-T0)+HFG0)                  BLOCK52
\c0
     1  +(WIN+DW)*MAG*HFG0)/(-MAG*CA-(WIN+DW)*MAG*CV)                     BLOCK53
\c0
     2  -TIN+T0                                                           BLOCK54
\c0
C     PROPERTIES OF FLUIDS AT THE EXIT OF FINITE ELEMENT.                 BLOCK55
\c0
      MLOUT=MLIN-DML                                                      BLOCK56
\c0
      TLOUT=TLIN-DTL                                                      BLOCK57
\c0
      WOUT=WIN+DW                                                         BLOCK58
\c0
      TOUT=TIN+DT                                                         BLOCK59
\c0
  301 RETURN                                                              BLOCK60
\c.
      END                                                                 BLOCK61
\c0
      SUBROUTINE MIX(DATA,IXX,J,AIRFLO,WOUT,TOUT)                         MIX3000
\c0
C     THIS SUBROUTINE FINDS THE AVERAGE PROPERTIES OF THE AIR AT          MIX1000
\c0
C     THE EXIT OF THE COOLING TOWER.                                      MIX2000
\c0
      COMMON/INPUT8/ITRACK
      INTEGER AIRHUM,AIRTEM                                               MIX4000
```

```
      END
      SUBROUTINE SUFCON(TLA,XTS,AREAS,XNS,COND)
      DIMENSION XLCST(2),TULCF(2)
      COMMON/INPUT8/ITRACK
      DATA TUBOD,IBAC/1.0,18/
      DATA ERTCST/2.5/
      DATA SCC1,SCC2/10.836,102161./
      DATA TUCST,WTPFT/1.3,0.510/
      DATA XLCST/1.07,1.08/
      DATA TULCF/0.0153,0.00042/
      DATA SCF1,SCF2/0.0366,0.15/
      CAX=0.3*AREAS
      TULSUM=TLA*XTS*XNS
      IF(TLA-60.) 7,8,8
    8 ADLCST=XLCST(2)
      GO TO 9
    7 IF(TLA-50.) 10,6,6
    6 ADLCST=XLCST(1)
      GO TO 9
   10 ADLCST=1.0
    9 TUBCST=TULSUM*TUCST*ADLCST*WTPFT*1.1
      TUBLCF=(TULCF(1)+TULCF(2))*TLA+0.58
      CONSCF=(SCF1*ALOG(XTS)-SCF2)
      SHCST=SCC1*XTS+SCC2
      SHLCST=(SHCST*(TUBLCF+CONSCF)+CAX)*XNS
      FECST=ERTCST*AREAS*XNS
      COND=(SHLCST*0.88*1.14+TUBCST+FECST)*1.10*1.1
   21 RETURN
      END
      SUBROUTINE FANSYS(FBHP,NFAN,DFAN,CSTFAN)
      COMMON/INPUT8/ITRACK
      DATA XBLADE/8./
      DATA CFF/472./
      DATA CB1,CB2/25.2,-105./
      DATA CSR/25./
      DATA CER,WER/0.55,4.6/
      DATA CRRS,WRRS/0.55,4.6/
      CFAN=XBLADE*(DFAN*CB1+CB2)+CFF
      HPFAN=FBHP/NFAN
      IF(HPFAN-250.) 1,1,2
    1 CE=1000.
      CM=26.6
      GO TO 3
    2 CE=9000.
      CM=24.3
    3 CFE=HPFAN*(CSR+CM)+HPFAN**1.5+CE
      CFPL=1.08*CER*WER*DFAN**2*1.1*1.1
      CVRS=2.25*CRRS*WRRS*DFAN**2*1.1*1.1
      CSTFAN=(CFAN+CFE+CFPL+CVRS)*1.1*1.1*1.15*1.1
    4 RETURN
      END
      SUBROUTINE ELECEQ(HPX,NX,CSTX)
      COMMON/INPUT8/ITRACK
      HPXX=HPX/NX
      IF(HPXX-250.) 1,1,2
    1 CX=((203.-0.38*HPXX)*HPXX*NX)*1.25
      GO TO 5
    2 IF(HPXX-600.) 3,3,4
    3 CX=5450.*HPXX**0.29*NX*1.25
      GO TO 5
    4 CX=480.*HPXX**0.77*NX*1.25
    5 CSTX=CX*1.125*1.05*1.05*1.1
      RETURN
      END
      SUBROUTINE PIPE(J,GPM,NL,VEL,DIAME,PIPCS,VCS,CRCC1,CRCC2,TW,
     1CPCC3,TCS,EL1CS,EL2CS,FLCS)
```

```
  COMMON/INPUT3/ EFFP,EFFF,RFCCV,VELCON,VELW,PFACT,EFFB
  COMMON/PIPING/ TWP(23),DIA(23),CPC1(23),CPC2(23,2),CPC3(23),
 1CRC1(23),CRC2(23,2),CTC1(23),CTC2(23,2),CE1C1(23),CE2C1(23),
 2CE1C2(23,2),CE2C2(23,2),VALCST(23),FLCST(23)
  COMMON/INPUT8/ITRACK
  XL=1.0
3 DIAME=0.6391*SQRT((GPM/XL)/VELW)
  IF(DIAME-DIA(23)) 1,1,2
2 XL=XL+1.
  GO TO 3
1 DO 5 I=1,23
  IF(DIAME-DIA(I)) 4,4,5
5 CONTINUE
4 NL=XL
  DIAME=DIA(I)
  VEL=0.4085*(GPM/XL)/DIAME**2
  PIPCS=(TWP(I)*CPC1(I)+CPC2(I,J)+0.084*DIA(I)*CPC3(I))*1.1*1.1
  VCS=VALCST(I)*1.1*1.1
  TCS=(TWP(I)*CTC1(I)+CTC2(I,J)+5.01*DIA(I)*CPC3(I))*1.1*1.1
  CRCC1=CRC1(I)*1.1
  CRCC2=CRC2(I,J)*1.1
  TW=TWP(I)
  CPCC3=CPC3(I)*1.1
  EL1CS=(TWP(I)*CE1C1(I)+CE1C2(I,J)+3.34*CPC3(I)*DIA(I))*1.1*1.1
  EL2CS=(TWP(I)*CE2C1(I)+CE2C2(I,J)+3.34*CPC3(I)*DIA(I))*1.1*1.1
  FLCS=FLCST(I)*1.1*1.1
  RETURN
  END
```

```
  50.         65.         80.
  78.3        63.3        48.3
  91.72       96.73       101.14     108.71     115.06
 120.56      125.43       129.78     131.80     133.76
  9904.0      9910.0      9914.0      9943.0     9997.0
 10071.0     10167.0     10270.0     10315.0    10360.0
 10.  20.
 30.0 37.0 42.0 47.0 52.0 57.0 62.0 67.0 72.0 77.0 82.0 87.0 92.0 96.0 98.0
 0.00148 0.00229 0.00347 0.00189 0.00120 0.00359 0.00244 0.00130
 0.00484 0.00369 0.00820 0.01406 0.01992 0.01870 0.01925 0.02048 0.02220
  0.0662630  0.1380760
0.0712860 0.1163020 0.0678710 0.0618820 0.0629430 0.0671650 0.0728000 0.0822140
0.0868330 0.0668970 0.0525040 0.0338970 0.0132470 0.0034920 0.0093760
    0.3200     0.3160     0.2870
    1.         0.7800     0.5400
  500.0000  263.0000     1.0000     0.8500     1.9920     0.2610
      65.0
    1.0000     0.9020    28.0000
    1496500.0000          314.4700
    5.         12.5       2.000
    28.        10.         22.       3000.      20000.        5.
     .336       .8276       .65        0.0        .25       1.0        1.0
      1.24        0.90 250000.0       180.0
1200.          .010      0.
    0.47        .17      600.       200.       200.       160.          .0300      .75
   98.        98.       133.76     133.76
    0.5         1.         2.         0.972      1.025      1.
 0.972      0.972      0.         0.         0.          0.9686     0.0032     0.
 0.         1.0555    -0.096183  0.0346    -0.0033166
    5.         31.        65.00     133.76
  12.   18.   24.   30.   36.   42.   48.   54.   60.   66.   72.   78.
  84.   90.   96.  102.  108.  114.  120.  126.  132.  138.  144.
   .1250    .2500    .3750    .3750    .3750    .3750    .4375    .4375    .5000    .563
\c5
   .5625    .6250    .6250    .6875    .6875    .7500    .8125    .8125    .8750    .875
\c0
   .9375    .9375  1.0000
     .19     2.71     5.23     5.23     5.23     5.23     6.50     7.75     9.15     9.1
\c5
   11.32    11.32    13.50    13.50    15.67    17.85    17.85    20.02    20.02    22.2
\c0
   22.20    22.20    24.37
   86.      122.     159.     190.     222.     264.     306.     334.     362.     367.
  372.      391.     411.     421.     431.     436.     442.     447.     452.     457.
  462.      467.     472.
   64.       82.     100.     119.     139.     169.     199.     222.     245.     265.
  285.      316.     348.     379.     410.     456.     503.     537.     571.     620.
  670.      735.     800.
   28.       34.      41.      49.      58.      72.      87.      97.     108.     128.
  148.      158.     169.     186.     204.     239.     274.     294.     315.     347.
  380.      412.     445.
    342.       673.      1104.      1535.      1966.      3798.      5630.      6436.
   7243.      8187.      9131.     11745.     14360.     16730.     19100.     25606.
  32113.     44119.     56125.     68062.     80000.     92000.    104000.
     20.        47.       110.       173.       236.       300.       364.       404.
    444.       529.       614.       654.       694.       800.       906.      1109.
   1312.      1481.      1651.      1853.      2056.      2228.      2400.
     35.        55.        75.        95.       114.       131.       147.       222.
    297.       370.       443.       469.       495.       585.       675.       861.
   1047.      1202.      1357.      1503.      1650.      1825.      2000.
    853.      2908.      4963.      5248.      5534.      8253.     10972.     21202.
  31432.     36692.     41952.     47611.     53270.     57597.     61924.     67348.
  72772.     83358.     93944.    102472.    111000.    120000.    129000.
    171.       305.       438.       743.      1049.      1344.      1639.      1973.
   2308.      2945.      3582.      4108.      4634.      5427.      6221.      7516.
   8812.      9788.     10764.     11982.     13200.     14450.     15700.
```

```
    262.       404.       546.       831.      1117.      1323.      1530.      1934.
   2338.      2848.      3359.      3976.      4594.      5163.      5733.     77166.
   8600.      9658.     10717.     11358.     12000.     12750.     13500.
   361.      1141.      1921.      2322.      2723.      4753.      6784.     15872.
  24960.     28598.     32237.     36600.     40963.     45349.     49736.     54126.
  58517.     65077.     71638.     78198.     84759.     91320.     97881.
    110.       210.       310.       469.       628.       895.      1163.      1456.
   1773.      2200.      2627.      3074.      3522.      4109.      4697.      5641.
   6586.      7417.      8249.      8900.      9550.      9800.     10659.
    164.       245.       326.       466.       607.       795.       983.      1233.
   1543.      1871.      2200.      2615.      3031.      3401.      3772.      4765
   5639.      6347.      7055.      7705.      8355.      8955.      9555.
    466.      1622.      2759.      3339.      3920.      6688.      9456.     15637.
  29819.     35146.     40474.     59312.     53285.     59312.     65339.     70685.
  76034.     87155.     98277.    101277.    104277.    113288.    122300.
    191.       296.       402.       586.       770.      1045.      1320.      1677.
   3959.      6473.      8986.     11530.     14073.     17802.     21530.     28205.
  23956.     25610.     27264.     31264.     35264.     39132.     43000.
   3966.      5550.      7134.      9815.     12496.      14725.    16954.     20455.
  34880.     38120.     41378.     47486.     53593.     60252.     66910.     72221.
  77531.     82806.     88081.     93356.     98631.    103906.    109181.
    203.       394.       586.       898.      1210.      1722.      2235.      2835.
   3435.      4247.      5059.      5937.      6815.      7930.      9045.     10793.
  12542.     14169.     15797.     16898.     18000.     19800.     21600.
    342.       617.       893.      1145.      1398.      1934.      2471.      3218.
   2035.      2527.      3020.      3538.      4057.      4604.      5151.      6420.
   7690.      8638.      9587.     10543.     11500.     12600.     13700.
  .02220
   0.90       2.6
   1.00
   9902.      9902.      9902.      9902.      9904.      9910.      9914.
   9925.      9943.      9975.      9997.     10030.     10071.     10120.
  10167.     10220.     10270.     10315.     10360.
   58.80      70.43      79.03      85.93      91.72       96.73     101.14     105.09
  108.71     112.01     115.06     117.89     120.56     123.05     125.43     128.05
  129.78     131.80     133.76     140.78     146.86
    .50        .75       1.00       1.25       1.50        1.75       2.00       2.25
   2.50       2.75       3.00       3.25       3.50        3.75       4.00       4.25
   4.50       4.75       5.00       6.00       7.00

r 16:17 0.825 277 level 2
```

```
r 16:54 12.393 1654

     28.0       10.0       22.0     3000.0   30000.0        5.0

DESIGN DRY BULB TEMPERATURE TD =  98.000 DEGREE F
3000.0000
     22.0
DESIGN ITD= 30.760 DEGREE F
     H=     9.90 HDP=     7.78 HD=  674.86 NU=     0.83
 TOWER GEOMETRY
 WET-DRY SURFACE RATIO= 0.052
 PACKING HEIGHT= 336.00 IN.
 TOTAL HEAT TRANSFER SURFACE WIDTH=   66.88 IN.
 PACKING WIDTH=  60.00 IN.
 NUMBER OF PLATES=       10.
 NUMBER OF CHANNELS PER PLATE=   22.00
 PLATE SPACING= 1.00 IN.
 PLATE ANGLE FROM VERTICAL=10.0 DEGREES

 PLATE THICKNESS=0.025 IN.
 PLATE CONDUCTIVITY  =120.000 BTU/HR FT F
 REFERENCE TEMPERATURE= 588.43 R.
                            INLET                    OUTLET
 AIR FLOW RATE       0.105e+04 LBM/MIN
 AIR PRESSURE           30.00 IN. HG
 AIR TEMPERATURE        98.00 F                116.20 F
 HUMIDITY              0.022200 LBM/LBM        0.027250 LBM/LBM
 WATER FLOW RATE     0.500e+03 LBM/MIN       0.495e+03 LBM/MIN

 WATER TEMPERATURE      128.76 F                108.24 F


 WATER TEMPERATURE CHANGE= -20.52 F
 PERCENT WATER LOSS=     1.06 %
 AIR TEMPERATURE CHANGE=  18.20 F
 TOTAL HEAT TRANSFER=  0.107e+05 BTU/MIN

 EVAPORATIVE HEAT TRANSFER=  0.539e+04 BTU/MIN
 PERCENT EVAPORATIVE HEAT TRANSFER=50.6 %
   0.0939    0.1796    0.1433
   2.6579    0.1433    0.9975
     TDB             TSAT            TTD          ITD   NET POWER       FRACTION OF
\cFULL-    ENERGY CHARGE            WATER LOSS
                                                                         LOAD THROTT
\cLE
          CAPITAL COST OF REPLACEMENT CAPACITY =$ 0.90269e+07
          REPLACEMENT ENERGY COST =$ 0.21163e+07
          ANNUAL FUEL COST =$ 0.37666e+08
          POWER PRODUCTION COST =      24.0330 MILLS/KW-HR          ANNUAL WATE
\cR LOSS=     35.8149 %

DESIGN DRY BULB TEMPERATURE TD =  98.000 DEGREE F
3000.0000
     22.0
DESIGN ITD= 30.760 DEGREE F
     H=     9.90 HDP=     7.78 HD=  679.02 NU=     0.83
 TOWER GEOMETRY
 WET-DRY SURFACE RATIO= 0.052
 PACKING HEIGHT= 336.00 IN.
 TOTAL HEAT TRANSFER SURFACE WIDTH=   66.88 IN.
 PACKING WIDTH=  60.00 IN.
 NUMBER OF PLATES=       10.
 NUMBER OF CHANNELS PER PLATE=   22.00
 PLATE SPACING= 1.00 IN.
ANGLE
```

```
r 16:58 12.191 1010

     28.0        10.0        30.0      3000.0   30000.0        5.0

DESIGN DRY BULB TEMPERATURE TD =  98.000 DEGREE F
3000.0000
     30.0
DESIGN ITD= 30.760 DEGREE F
     H=     9.80 HDP=     7.68 HD=  665.51 NU=     0.90
 TOWER GEOMETRY
 WET-DRY SURFACE RATIO= 0.071
 PACKING HEIGHT= 336.00 IN.
 TOTAL HEAT TRANSFER SURFACE WIDTH=    69.38 IN.
 PACKING WIDTH=  60.00 IN.
 NUMBER OF PLATES=       10.
 NUMBER OF CHANNELS PER PLATE=   30.00
 PLATE SPACING= 1.00 IN.
 PLATE ANGLE FROM VERTICAL=10.0 DEGREES

 PLATE THICKNESS=0.025 IN.
 PLATE CONDUCTIVITY  =120.000 BTU/HR FT F
 REFERENCE TEMPERATURE= 588.43 R
                              INLET                    OUTLET
 AIR FLOW RATE        0.105e+04 LBM/MIN
 AIR PRESSURE           30.00 IN. HG
 AIR TEMPERATURE         98.00 F               115.68 F
 HUMIDITY               0.022200 LBM/LBM        0.028586 LBM/LBM
 WATER FLOW RATE      0.500e+03 LBM/MIN       0.493e+03 LBM/MIN

 WATER TEMPERATURE      128.76 F                105.59 F


 WATER TEMPERATURE CHANGE= -23.17 F
 PERCENT WATER LOSS=     1.34 %
 AIR TEMPERATURE CHANGE=  17.68 F
 TOTAL HEAT TRANSFER=  0.121e+05 BTU/MIN

 EVAPORATIVE HEAT TRANSFER=  0.682e+04 BTU/MIN
 PERCENT EVAPORATIVE HEAT TRANSFER=56.5 %
   0.0939     0.1644     0.1338
   2.4816     0.1338     0.9909
    TDB            TSAT            TTD            ITD    NET POWER       FRACTION OF
\cFULL-   ENERGY CHARGE             WATER LOSS
                                                                          LOAD THROTT

\cLE
          CAPITAL COST OF REPLACEMENT CAPACITY =$ 0.80455e+07
          REPLACEMENT ENERGY COST =$ 0.12113e+07
          ANNUAL FUEL COST =$ 0.37635e+08
          POWER PRODUCTION COST =      23.7694 MILLS/KW-HR            ANNUAL WATE
\cR LOSS=      42.4453 %

DESIGN DRY BULB TEMPERATURE TD =  98.000 D

QUIT
r 16:59 18.502 678 level 2




    28.       10.         30.     3000.     30000.        5.

Substitution failed.
```

```
New Fortran 5b
r 17:11 12.274 1594


     28.0       10.0       40.0     3000.0    30000.0        5.0

DESIGN DRY BULB TEMPERATURE TD =  98.000 DEGREE F
3000.0000
     40.0
DESIGN ITD= 30.760 DEGREE F
     H=    9.71 HDP=    7.59 HD=  656.70 NU=    0.95
 TOWER GEOMETRY
 WET-DRY SURFACE RATIO= 0.895
 PACKING HEIGHT= 336.00 IN.
 TOTAL HEAT TRANSFER SURFACE WIDTH=   72.50 IN.
 PACKING WIDTH=  60.00 IN.
 NUMBER OF PLATES=      10.
 NUMBER OF CHANNELS PER PLATE=   40.00
 PLATE SPACING= 1.00 IN.
 PLATE ANGLE FROM VERTICAL=10.0 DEGREES

 PLATE THICKNESS=0.025 IN.
 PLATE CONDUCTIVITY  =120.000 BTU/HR FT F
 REFERENCE TEMPERATURE= 588.43 R
                              INLET                 OUTLET
 AIR FLOW RATE       0.105e+04 LBM/MIN
 AIR PRESSURE          30.00 IN. HG
 AIR TEMPERATURE        98.00 F               114.69 F
 HUMIDITY              0.022200 LBM/LBM        0.030040 LBM/LBM
 WATER FLOW RATE     0.500e+03 LBM/MIN       0.492e+03 LBM/MIN

 WATER TEMPERATURE     128.76 F               102.94 F


 WATER TEMPERATURE CHANGE= -25.82 F
 PERCENT WATER LOSS=    1.65 %
 AIR TEMPERATURE CHANGE=  16.69 F
 TOTAL HEAT TRANSFER=  0.135e+05 BTU/MIN

 EVAPORATIVE HEAT TRANSFER=  0.837e+04 BTU/MIN
 PERCENT EVAPORATIVE HEAT TRANSFER=62.0 %
   0.0939    0.1513    0.1259
   2.3328    0.1259    0.9922
    TDB            TSAT          TTD          ITD   NET POWER      FRACTION OF
\cFULL-   ENERGY CHARGE          WATER LOSS
                                                                   LOAD THROT

\cLE
          CAPITAL COST OF REPLACEMENT CAPACITY =$ 0.72684e+07
          REPLACEMENT ENERGY COST =$ 0.91658e+06
          ANNUAL FUEL COST =$ 0.37546e+08
          POWER PRODUCTION COST =     23.5325 MILLS/KW-HR          ANNUAL WATE
\cR LOSS=     49.3704 %

DESIGN DTEM
QUIT
r 17:13 14.451 979 level 2


MCnoi WetDry logged out 08/29/79  1713.9 edt Wed
CPU usage 3 min 5 sec, memory usage 941.1 units.
hangup
`x
```

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