COOLING WATER RESOURCES OF UPPER MISSISSIPPI RIVER FOR POWER GENERATION

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ABSTRACT

Thermal regime analyses were performed for the Upper Mississippi River lying in the Mid-Continent Area Power Pool (MAPP) geographical area (reach above River Mile 364.2 at Keokuk, Iowa) using a predictive computational model to determine the cooling water resources of the river for power generation. The thermal effects of the future power plants - new power plants as well as additions to existing units - projected to the year 1993 on seasonal temperatures of the river were determined. The locations of river reaches with under-utilized heat asismilation capacities on the basis of the existing and likely thermal criteria and standards of the various regulating agencies of the state governments in the study region were identified, and the allowable plant capacities that can use once-through cooling at those locations were determined. For the range of plant capacities projected for installation up to 1993 along the river in the MAPP area, alternative cooling modes to open-cycle cooling were investigated, along with an analysis of possible consumptive water use and investment costs of the alternative systems.

INTRODUCTION

Thermal power plants with total capacities of several thousand megawatts have been proposed and projected for installation along the portion of the Upper Mississippi River lying upstream from River Mile 364.2 at Keokuk, Iowa by the Mid-Continent Area Power Pool (MAPP)-member utilities through the year 1993. When selecting the plant sites along the river for these future capacities, the following questions are relevant: Is there adequate flow of water available in the river to provide for the condenser cooling water needs of the future installations if they are to use open-cycle cooling systems? What part of the water withdrawn for condenser cooling needs will be lost by evaporation? If complete open-cycle cooling is not possible, what are the economically most feasible alternate cooling modes, and what are the associated consumptive water uses for which water has to be withdrawn from the river? In order to find answers to these questions, and also to develop a suitable model and a tool for planning related to the present and projected use of the Upper Mississippi River water for electric power generation, a comprehensive study was initiated under the sponsorship of the Environmental Committee of Mid-Continent Area Power Pool. The basic objectives of the study included an evaluation of cooling water uses and needs for power generation, siting and sizing of future power plants based solely on thermal regime analyses, and economic evaluation of wet cooling towers as alternative cooling modes to open-cycle cooling. The results of these studies applicable to Upper Mississippi River are summarized in the following Sections.

COOLING WATER USES AND NEEDS

The condenser cooling water required by a power plant depends upon several factors, including the type of plant (fossil or nuclear), number of units, age and size of each unit, overall plant efficiency, and the temperature rise of the cooling water. For both once-through and recirculating systems with blowdown discharge, the thermal characteristics of the receiving waterbody may be a deciding factor, due to environmental impact considerations, in determining both the permissible temperature rise and the rate of withdrawal of cooling water from the natural waterbody.

The required condenser cooling water discharge, Q_e, for a plant of specified capacity, P (MW), depends upon the rate of heat rejection, and can be determined from

$$Q_e = K_1\left(\frac{P}{\Delta T_e}\right)\left[\left(1-\frac{\eta_I}{100}\right)\frac{1}{(\eta_p/100)} - 1\right],$$

where $k_1 = 0.86\times10^9$, for Q_e in cm^3/hr, with (ΔT_e) in °C, or

$k_1 = 0.547\times10^5$, for Q_e in ft^3/hr, with (ΔT_e) in °F

The condenser-water discharge required by a plant of specific capacity, P (MW), thus can be determined, if allowable temperature rise, ΔT_e, is specified and the in-plant losses, η_I, and the overall plant efficiency, η_p are known. Figure 1 shows the condenser cooling water requirements as a function of the condenser temperature rise for different plant heat rates. The practical ranges of values for the various terms in Eq. (1) are as follows:

1. In-plant Losses. The average in-plant and stack losses for a fossil plant can be taken as about 15 percent. For nuclear plants, these losses are much less - generally less than 5 percent [6].

2. Plant Heat Rates or Plant Efficiency. The amount of fuel energy required to produce one kilowatt-hour of generated energy is plant heat rate. The average efficiency of all steam-electric plants in the nation in 1971 was about 33 percent (heat rate of 10,478 BTU/kwh [3]. Nuclear plants reject about 50 percent more heat to the cooling water per kwh than fossil plants. Even under ideal conditions, well-designed nuclear plants may not have thermal efficiencies exceeding 34 percent. On the other hand, fossil plants have achieved thermal efficiencies up to 39 percent as an average for an entire year's operation [6]. Average thermal efficiencies of 36 percent (heat rate of 9480 BTU/kwh) for fossil-fueled plants and 32 percent (heat rate of 10,700 BTU/kwh) for nuclear plants are reasonable values to use in the analysis of heat rejection from power plants.

3. Temperature Rise. For a given heat transfer rate in the condensers, the cooling water temperature rise is inversely proportional to the cooling water discharge through the condenser. Hence, the allowable temperature rise varies with both cooling water availability and plant heat rate. In addition, factors such as economics, ambient water temperature, and water quality requirements also influence the magnitude of the temperature rise. Federal Power Commission Plant Data for 1969 indicate that average temperature rises have centered about 15°F (8.3°C) and are fixed mainly by economic and process considerations [6].

The total installed thermal plant capacity along the Mississippi River in the MAPP area as of 1975 was about 7295 MW, of which 5820 MW used once-through cooling, and 1475 MW used cooling towers. The locations of the existing plants, which include 19 plants with a total of 59 units, are shown in Figure 2. The existing, proposed*, and projected* total plant capacities along the Mississippi River

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* Proposed plants are those which the utilities have committed to construction as well as those future plants which have been sited. Projected plants are those required to meet future demands for which either locations or condenser cooling systems or both have not been selected.

are listed in Table 1. The total water discharge required for condenser cooling at the existing and proposed plants, obtained from the data reported by the utilities, is tabulated in Table 2. The condenser cooling water requirements, calculated using Eq.(1), also are listed in Table 2. The results indicate that for the existing plants, an average in-plant loss of 10 percent, and an average plant efficiency of 33 percent, with a temperature-rise of 18°F (10°C) give calculated water requirements in close agreement with the reported values. However, for the newer proposed plants, the agreement is better with efficiencies of 36 percent for the fossil plants and 32 percent for nuclear plants and with in-plant efficiencies of 15 percent and 5 percent, respectively. Hence these latter efficiency values were applied in determining the cooling water needs for the proposed and projected plant capacities. The total plant capacity proposed for installation along the Mississippi River within the next few years is about 4260 MW, of which 3660 MW is planned for cooling towers. The locations of the proposed plants are shown in Figure 3. Of the total proposed capacity, 1960 MW will be fossil-fuel plants, and 2300 MW will be nuclear. Compared to this, 8755 MW of the total capacity of 15,955 MW projected through the year 1993 will use nuclear fuel according to present plans. The total condenser cooling water needs calculated for the sum of proposed and projected capacities is about 23,510 cfs (666 cu.m/s).

Consumptive Water Use

In closed-cycle cooling systems, cooling process itself causes loss of water by evaporation; the amount of evaporative loss is determined by the system design characteristics. In open-cycle systems, the temperature rise of the cooling water leads to accelerated evaporation from receiving waterbodies. The amount of heat lost by evaporation in once-through cooling systems can be taken as about 50 percent of the heat discharge [3], so that the quantity of water evaporated is 0.5 $[HR]/L_o$, where [HR] is the heat rejection rate, and L_o is the latent heat of vaporization (L_o = 1050 BTU/lb = 597 cal/gm = 2500 Joules/gm). Note, however, that the fraction of heat loss that is due to evaporation will vary widely with type of cooling system and with meteorological conditions. Since the cooling water discharge is $[HR]/\Delta T_e$, the ratio of consumptive water loss to total withdrawal is given by,

$$\frac{\text{consumptive water loss}}{\text{total withdrawal}} = \frac{\Delta T_e}{2L_o} \quad \text{(for once-through cooling)}$$

The total average rate of withdrawal of fresh water and saline water for cooling purposes in the nation for the years 1969, 1970, and

1971 are given in Table 3. These data were obtained from the Federal Power Commission and represent a summary of the data submitted on FPC Form 67 for the respective years [3]. The 172,392 cfs of fresh water withdrawn for the year 1971 is equivalent to about 9 percent of the average annual runoff of all streams in the conterminous United States. Table 3 also lists the consumptive use of fresh water by both open-cycle and closed-cycle systems. The average evaporative loss of fresh water amounts to about 1 percent of the annual use of water for condenser cooling. Using this value, the amount of evaporative loss corresponding to the cooling water requirement in the MAPP area will be about 235 cfs (6.7 cu.m/s).

SITING AND SIZING OF FUTURE POWER PLANTS

Iowa Thermal Regime Model

In order to evaluate the cooling water resources of the Upper Mississippi River available for power generation, over and above the cooling water needs of the capacities already proposed and projected, thermal regime analyses were performed using a predictive computational model for steady-state temperature distributions ("Iowa Thermal Regime Model") developed by Paily and Kennedy [5]. The model is based on a numerical solution of the one-dimensional convection-diffusion equation, and predicts the longitudinal distribution of cross-sectional average temperature within the entire river length. The total river length is divided into smaller reaches, and solution for the temperature distribution in each reach is obtained separately; the solutions for adjacent reaches being linked by the common conditions at the junction or node points connecting them. Each reach of the river can have multiple thermal inputs and tributary inflows. The formulation allows for changes in the channel characteristics and the river flow rate from station to station. Variations in weather date afrom place to place are also taken into account.

The reliability of the model for predicting the the thermal regime of the Mississippi River was tested by comparing computed results with field measurements obtained along a 110-mile reach of the river between Becker, Minnesota (River Mile 906), and Lock and Dam No. 3 (River Mile 796). The results, presented in Figure 4, indicate that the predicted temperature is accurate within the measured temperature variations that occur along the river channel cross-section.

Thermal Regime Analysis of the Upper Mississippi River

The thermal regime model was used to determine the temperature distributions along the Upper Mississippi River lying in the MAPP area corresponding to average flow and weather conditions during typical months of the four seasons: February (winter), May (spring), August (summer), and November (fall). The input data used for the computations are the following:

1. Heat loads from power plants of rated capacity greater than 25 MW, industries, and municipalities located on the main-stem of the river and on major tributaries within 25 miles of their mouths;
2. Monthly mean values of daily flow rates measured at 12 U.S. Geological Survey gaging stations along the river;
3. Monthly mean values of daily weather conditions including air temperature, wind speed, relative humidity, atmospheric pressure, cloud cover and solar radiation measured at 8 first order weather stations of the National Weather Service; and
4. Channel cross-sectional geometrical parameters at approximately one mile intervals determined from flow profiles developed by the U.S. Army Corps of Engineers.

It was assumed that the river discharge, climatological variables, and channel geometrical parameters varied linearly between adjacent data points. The predicted temperature profiles for each month included the following:

- natural thermal regime of the river;
- temperature distributions with existing heat loads;
- temperature distributions with existing heat loads plus those from proposed and projected power plants;
- temperature distributions with permissible new power plants that could be installed without violating present thermal standards.

In addition, temperature profiles also were determined for the case of 7-day, 10-year low flows at all the gaging stations along the river, combined with average weather condltions for the months of August and November.

The locations and capacities of permissible new plants with once-through cooling sited along the Mississippi River were determined on the basis of the thermal criteria, summarized in Table 4 and 5. In applying the thermal standards, the limiting criterion was found to be a maximum allowable temperature excess of 5°F (2.78°C). However, there is some ambiguity as to what base this 5°F excess should be added to in order to obtain the limiting temperatures. Minnesota and Illinois standards specify this excess to be "above natural," while Wiscoonsin specifies "above existing natural," and Iowa and Missouri standards do not address this point. Hence, the thermal regime calculations to determine the permissible new plant capacity were made in two ways. In the first case, the predicted natural temperature distribution was assumed to be the base, and the 5°F excess was added thereto to obtain the limiting values. For the second case, the predicted temperature distribution with the existing heat loads was treated as the base, and the 5°F excess was added to it. The first case, with "natural-temperature base" is more definite, because it will be the same even after many years; the second case, with "existing-temperature base", will have a different base whenever a new plant is added to the system. The second case would permit the addition of more and more heat loads to the river, until the criteria specifying the maximum allowable temperatures, given in Table 5, become the limiting factors.

The predicted temperature distributions, assuming that all the existing, proposed, and projected power plants are operating at their full-load capacities, are shown for average and low flow conditions in August in Figures 5 and 6 for the case of natural temperature base, and in Figures 7 and 8 for the case of existing temperature base. During the low flow periods, it can be seen that even the existing plants will be in violation of the 5°F temperature-rise criterion at certain reaches of the river. The locations of the permissible new plants and the resulting temperature distributions are also shown in Figures 5 to 8. The locations of the permissible new plants were selected so as to obtain the highest allowable capacity in each case. The capacities of the permissible new plants during average and low flows with natural temperature base are tabulated in Tables 6 and 7, and with existing temperature base are tabulated in Tables 8 and 9 for both fossil-fuel (F) and nuclear-fuel (N) plants. Capacities of fossil-fuel plants were computed assuming η_P = 36 percent, and η_I = 15 percent, while for the nuclear-fuel plants, η_P = 32 percent and η_I = 5 percent were adopted. These capacities were determined such that at each of the selected locations, the temperature rise would be 5°F or less for the four months considered. The temperature rise criterion rather than the maximum temperature was found to be the limiting factor in all cases. If the natural temperature is adopted as the base, and if all existing plants are considered to have full-load operation, only four additional locations are available for new once-through plants, with a total possible capacity of about 5840 MW (F) or 4030 MW (N), as shown in Table 6 during average river flows. Compared to this, Table 7 shows that the total possible capacity is only 2476 NW (F) or 1708 MW (N) during low flow conditions. However, if existing temperature base is considered, it is possible to site plants at ten locations with a total capacity of 15,900 MW (F) or 10,970 MW (N) during average flows (Table 8); during low-flows the permissible plant capacities decrease to 7072 MW (F) or 4877 MW (N), as shown in Table 9.

WET COOLING TOWERS AS ALTERNATE COOLING MODES

The data presented in Table 1 show that projected plant capacities along the Mississippi River in the MAPP area include 15,000 MW for which specific sites have not been selected, and 955 MW for which locations but not cooling systems have been selected. Based on the results of the thermal regime analysis presented in the previous section it is clear that bulk of these projected capacities will have to use alternate cooling systems.

Mechanical draft wet cooling towers are considered as logical alternatives to once-through cooling in the MAPP area. The optimum sizes of these towers for the range of fossil and nuclear plant capacities projected for installation by the MAPP-member utilities, were determined using the methodology developed by Croley, Patel, and Cheng [1, 2]. In addition to the plant capacity, the heat rejection rate and plant heat rate associated with each power level comprise the major input information required for the computations. The meteorological data (chiefly dry-bulb temperature, wet-bulb temperature, and their frequency distributions) utilized for the analysis are those used by Giaquinta et al. [4]. These data are based on conditions for Chicago, Illinois, and represent typical conditions in the north-central area of the United States. For sizing of cooling towers the design values of these temperatures generally used are those which are not exceeded more than 5 percent of the time during the warmest period of a year (from June through September). Operation of the plant for the entire possible range of meteorological conditions was evaluated, and the total capacity loss associated with operation at conditions other than the design condition was determined. The cost equivalent of this capacity loss was added to the capital and operating costs to determine the total system costs.

A summary of the design conditions and unit values used for the economic analysis of wet cooling towers is presented in Table 10. Using these values, the optimum total unit costs of cooling for fossil and nuclear plants at various power levels are given in Tables 11 and 12, respectively. The variations with plant capacity of the optimum sizes and the corresponding minimum costs for wet cooling towers are illustrated in Figures 9 and 10 for fossil plants and nuclear plants, respectively. Tables 11 and 12 also list the annual evaporation loss and the annual blowdown discharge associated with each optimum tower size at each power level. Depending upon the power level, the total unit costs for optimum sized plants vary from 2.890 to 2.943 mills per kilowatt-hour for fossil plants, and from 2.957 to 2.978 mills per kilowatt-hour for nuclear plants. (These total unit costs can be converted to annual costs in dollars by multiplying the unit costs by 8760 P, where P is the plant capacity in MW.)

The costs of constructing and operating closed-cycle cooling systems should be compared to the costs of open-cycle cooling. The differential costs may then be interpreted as cost penalties for the closed-cycle system. This interpretation becomes important when evaluating the costs in light of the environmental and other benefits accruing to closed-cycle systems. Tables 11 and 12 include the total unit costs of open-cycle cooling for comparison with the cost of cooling by a wet cooling tower of optimum size. Costs of open-cycle cooling were obtained by the method used by Giaquinta et al. [4] for mechanical draft cooling towers with appropriate revisions. The range of total unit costs for optimum sized plants using once-through cooling is from 2.694 to 2.717 mills per kilowatt-hour for fossil plants and from 2.426 to 2.445 mills per kilowatt-hour for nuclear plants. Differences between these unit costs and the ones mentioned earlier for wet cooling towers give the cost penalties associated with closed-cycle cooling. These differential unit costs are seen to range from 0.196 to 0.226 mills per kilowatt-hour for fossil plants and from 0.531 to 0.533 mills per kilowatt-hour for nuclear plants.

For the plants represented in Tables 11 and 12 annual penalties resulting from the use of closed-cycle rather than open-cycle cooling range from \$0.396 x 10^6 per year to \$1.373 x 10^6 per year for fossil plants, and from \$1.868 x 10^6 per year to \$6.977 x 10^6 per year for nuclear plants.

CONCLUSIONS

The analysis of the thermal regimes of the Mississippi River lying in the MAPP geographical area indicates that the river have, under existing environmental and thermal regulations, heat transfer and assimilation capacities adequate for handling much of the waste heat from power plants planned for installation through 1993. However, certain reaches of the river (specifically the sections of the river lying adjacent to and extending some distance downstream from Minneapolis-St. Paul) can not accomodate additional thermal loads under existing thermal regulations.

An analysis of the capital and operating costs of mechanical draft wet cooling towers needed to dissipate the waste heat corresponding to the projected plant capacities was made. The total unit cost of these closed-cycle cooling systems was found to range from 2.810 to 2.943 mills per kilowatt-hour for fossil plants, and from 2.957 to 2.978 mills per kilowatt-hour for nuclear plants. The corresponding values for open-cycle cooling were found to range from 2.694 to 2.717 mills per kilowatt-hour for fossil plants and from 2.426 to 2.445 mills per kilowatt-hour for nuclear plants. The resultant cost penalties resulting from the use of closed-cycle cooling were found to range from \$0.396 x 10^6 per year to \$1.373 x 10^6 per year for fossil plants and from \$1.868 x 10^6 per year to \$6.977 x 10^6 per year for nuclear plants.

Finally, it should be noted that in many instances, particularly in relation to definition of natural temperature, the existing thermal standards are imprecise, and the various reasonable interpretations lead to a wide variation in estimating the remaining heat assimilation capacity.

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Asheville, North Carolina in providing various segments of data is gratefully acknowledged. Part of the computer time was provided by the University of Iowa.

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TABLE 1

EXISTING, PROPOSED, AND PROJECTED TOTAL PLANT CAPACITIES IN MW ALONG UPPER MISSISSIPPI RIVER

Case	Fossil		Nuclear	
	OTF[a]	WCT[a]	OTF	WCT
Existing	3600	350	2220	1125
Proposed	600	1360	0	2300
Projected:[b]				
Location Specified	0		955	
Location Unspecified[c]	7200		7800	

[a] OTF = Once-Through Fresh; WCT = Wet Cooling Tower

[b] Cooling System not specified

[c] Only capacities that could possibly be installed along the river considered.

TABLE 2

COOLING WATER USES AND NEEDS FOR POWER PLANTS ALONG THE MISSISSIPPI RIVER

Category	Plant Capacity, (MW) F = Fossil N = Nuclear	Cooling Water Required in cfs(cu·m/s): Calculated, (Eq. 1) η_I = 15%(F), 5%(N); η_p = 36%(F), 32%(N)	Calculated, (Eq. 1) η_I = 10%(F,N); η_p = 33%(F,N)	Reported by (Utilities[c])
Existing Plants	350[a] (F)	--	--	--
	1125[b] (N)	188.0 (5.3)	188.0 (5.3)	188.0 (5.3)
	3600 (F)	4135.8 (117.1)	5248.0 (148.6)	5339.9 (151.2)
	2220 (N)	3689.8 (104.5)	3236.3 (91.7)	3048.6 (86.4)
sum:	7295	8013.6 (226.9)	8672.3 (245.6)	8576.5 (242.9)
Proposed Plants	1360[a] (F)	--	--	--
	600 (F)	689.3 (19.5)	874.8 (24.8)	757.8 (21.5)
	2300[a] (N)	--	--	--
sum:	4260	689.3 (19.5)	874.8 (24.8)	757.8 (21.5)
Projected Plants	7200 (F)	8271.6 (234.2)	10496.0 (297.2)	--
	8755 (N)	14551.3 (412.1)	12762.9 (361.4)	--
sum:	15955	22822.9 (646.3)	23258.9 (658.6)	--

[a]Cooling water data not available

[b]Closed-cycle cooling system, make-up water requirement

[c]From FPC Form 67

TABLE 3

PERCENTAGE OF TOTAL COOLING WATER WITHDRAWAL LOST BY EVAPORATION [3]*

year	Quantity of Water, (cfs)		
	1969	1970	1971
I. Rate of Withdrawal			
Fresh Water	165232	172005	172392
Saline Water	68391	73439	72564
II. Consumptive Use (Fresh Water)			
As Reported by Utilities	1058	881	1267
Including Calculated Loss for Once-through	1933	1830	2129
Percentage Consumptive Use (%)	1.17	1.06	1.23

* It is assumed that the amount of heat lost by evaporation in once-through cooling systems is 50 percent of the heat rejection.

TABLE 4

SUMMARY OF THERMAL STANDARDS FOR MISSISSIPPI RIVER

River Reach	State, and Controlling Agency	Classification of Reach	Allowable Temperature Rise Above Natural Conditions	Maximum Allowable Water Temperature
Lake Itasca to Lock and Dam No. 2, Hastings (RM 815)	Minnesota State Pollution Control Agency	Fish and Recreation Class B and Class C	5°F	86°F, and/or as specified for each month (Table 10), except 90°F-max. from outlet of Metro Wastewater Treat. Works to L & D No. 2
Lock and Dam No. 2, Hastings (RM 815) to Illinois border (RM 581)	Minnesota State Pollution Control Agency; and Wisconsin State Department of Natural Resources; and Iowa State Department of Environmental Quality	Fish and Recreation Class B; Waters for Fish and Aquatic Life; Class A	5°F	Specified for each month (Table 10)
Wisconsin border (RM 581) to Missouri border (RM 361)	Iowa State Department of Environmental Quality; and Illinois State Pollution Control Board	Class A; --	5°F	3°F above the limits specified for each month (Table 10)
Iowa border (RM 361) to Alton Lock and Dam (RM 203); and downstream of Alton Lock and Dam	Illinois State Pollution Control Board; and Missouri State Clean Water Commission	--	5°F	3°F above the limits specified for each month (Table 10)

TABLE 5

MAXIMUM ALLOWABLE WATER TEMPERATURES*
IN MISSISSIPPI RIVER

Month	Reach 1	Reach 2	Reach 3	Reach 4	Reach 5
January	40	40	45	45	50
February	40	40	45	45	50
March	48	54	57	57	60
April	60	65	68	68	70
May	72	75	78	78	80
June	78	84	85	86	87
July	83	84	86	88	89
August	83	84	86	88	89
September	78	82	85	86	87
October	68	73	75	75	78
November	50	58	65	65	70
December	40	48	52	52	57

Reach 1: Lake Itasca to Lock and Dam No. 2, Hastings (RM 815)

Reach 2: Lock and Dam No. 2, Hastings (RM 815) to Illinois border (RM 581)

Reach 3: Wisconsin border (RM 581) to Missouri border (RM 361)

Reach 4: Iowa border (RM 361) to Alton Lock and Dam (RM 203)

Reach 5: Alton Lock and Dam (RM 203) to Arkansas border

* Temperatures are weekly average values for Minnesota; monthly averages of daily maximum values for Wisconsin; and the values that shall not be exceeded during more than one percent of the hours in the 12-month period ending with any month, for Iowa, Illinois, and Missouri.

TABLE 6

LOCATIONS AND CAPACITIES OF PERMISSIBLE POWER PLANTS BASED ON PREDICTED NATURAL TEMPERATURES AND FULL-LOAD OPERATION -- MISSISSIPPI RIVER (AVERAGE FLOW)

River	River Flow, Q(cfs)				Mixed Temp. Increase ΔT (°C)				Permissible Plant Capacity - Fossil (MW)				Permissible Plant Capacity - Nuclear (MW)			
Mile	Feb	May	Aug	Nov	Feb	May	Aug	Nov	Feb	May	Aug	Nov	Feb	May	Aug	Nov
1150.3	1654	2312	1491	1687	2.78	2.45	2.50	2.78	399	491	324	408	275	339	223	281
1113.0	1700	3564	1829	2000	2.78	1.42	2.03	2.78	411	441	323	483	283	304	222	333
700.0	15332	51016	22217	22702	2.78	1.43	1.98	0.65	3705	6337	3834	1283	2555	4370	2644	885
339.4	40369	97984	42642	45428	2.78	1.44	1.97	0.99	9763	12275	7308	3912	6733	8465	5040	2698

Summary of Permissible Plant Capacities:

Location (River Mile)	1150.3	1113.0	700.0	399.4
Fossil (MW)	324	323	1283	3912
Nuclear (MW)	223	222	885	2698

TABLE 7

LOCATIONS AND CAPACITIES OF PERMISSIBLE POWER PLANTS BASED ON PREDICTED NATURAL TEMPERATURES AND FULL-LOAD OPERATION -- MISSISSIPPI RIVER (LOW FLOW)

River	River Flow, Q(cfs)		Mixed Temp. Increase ΔT (°C)		Permissible Plant Capacity - Fossil (MW)		Permissible Plant Capacity - Nuclear (MW)	
Mile	Aug	Nov	Aug	Nov	Aug	Nov	Aug	Nov
1150.3	192	192	2.78	2.78	46	46	32	32
1113.0	192	192	2.78	2.78	46	46	32	32
1075.8	364	364	2.78	2.78	88	88	60	60
1038.5	499	499	2.78	2.78	120	120	83	83
1001.2	547	547	2.68	2.78	127	132	88	91
964.0	596	596	2.63	2.78	136	144	94	99
399.4	10678	10678	2.51	2.06	2331	1913	1608	1319

Summary of Permissible Plant Capacities:

Location (River Mile)	1150.3	1113.0	1075.8	1038.5	1001.2	964.0	399.4
Fossil (MW)	46	46	88	120	127	136	1913
Nuclear (MW)	32	32	60	83	88	94	1319

TABLE 8

LOCATIONS AND CAPACITIES OF PERMISSIBLE POWER PLANTS BASED ON TEMPERATURES WITH EXISTING PLANTS AND FULL-LOAD OPERATION -- MISSISSIPPI RIVER (AVERAGE FLOW)

River	River Flow, Q(cfs)				Mixed Temp. Increase ΔT (°C)				Permissible Plant Capacity - Fossil (MW)				Permissible Plant Capacity - Nuclear (MW)			
Mile	Feb	May	Aug	Nov	Feb	May	Aug	Nov	Feb	May	Aug	Nov	Feb	May	Aug	Nov
1150.3	1654	2312	1491	1687	2.78	2.78	2.78	2.78	399	559	361	408	275	385	249	281
1113.0	1700	3564	1829	2000	2.78	1.43	2.03	2.78	411	443	323	483	283	305	222	333
1075.8	1770	4662	2199	2215	2.78	1.09	1.86	2.78	428	443	354	536	295	305	244	370
1038.5	1981	5984	2715	2629	2.78	0.85	1.63	2.78	479	441	386	635	331	304	266	438
1001.2	2346	7598	3385	3292	2.78	0.62	1.43	2.58	568	411	423	739	391	283	291	510
964.0	2712	9211	4056	3955	2.78	0.54	1.23	1.90	656	429	432	655	452	296	298	451
700.0	15332	51016	22217	22702	2.78	1.74	2.48	2.59	3705	7714	4784	5116	2555	5320	3299	3528
599.4	20347	61853	27819	28691	2.78	0.50	1.28	0.83	4917	2698	3100	2065	3391	1860	2138	1424
500.0	28695	75706	34982	37369	2.78	0.64	1.43	0.88	6934	4198	4359	2855	4782	2895	3006	1969
399.4	40369	97984	42642	45428	2.31	0.82	1.82	1.27	8107	7009	6769	5025	5591	4834	4668	3465

Summary of Permissible Plant Capacities

Location (River Mile)	1150.3	1113.0	1075.8	1038.5	1001.2	964.0	700.0	599.4	500.0	399.4
Fossil (MW)	361	323	354	386	411	429	3705	2065	2855	5025
Nuclear (MW)	249	222	244	266	283	296	2555	1424	1969	3465

TABLE 9

LOCATIONS AND CAPACITIES OF PERMISSIBLE POWER PLANTS BASED ON TEMPERATURES WITH EXISTING PLANTS AND FULL-LOAD OPERATION -- MISSISSIPPI RIVER (LOW FLOW)

River Mile	River Flow, Q(cfs)		Mixed Temp. Increase ΔT (°C)		Permissible Plant Capacity - Fossil (MW)		Permissible Plant Capacity - Nuclear (MW)	
	Aug	Nov	Aug	Nov	Aug	Nov	Aug	Nov
1150.3	192	192	2.78	2.78	46	46	32	32
1113.0	192	192	2.78	2.78	46	46	32	32
1075.8	364	364	2.78	2.78	88	88	60	60
1038.5	499	499	2.78	2.78	120	120	83	83
1001.2	547	547	2.68	2.78	127	132	88	91
964.0	596	596	2.63	2.78	136	144	94	99
700.0	6421	6421	2.57	2.40	1437	1340	991	924
599.4	8941	8941	2.31	1.80	1799	1403	1241	967
500.0	9894	9894	2.17	1.61	1872	1388	1291	957
399.4	10678	10678	2.73	2.56	2533	2378	1746	1640

Summary of Permissible Plant Capacities:

Location (River Mile)	1150.3	1113.0	1075.8	1038.5	1001.2	964.0	700.0	599.4	500.0	399.4
Fossil (MW)	46	46	88	120	127	136	1340	1403	1388	2378
Nuclear (MW)	32	32	60	83	88	94	924	967	957	1640

TABLE 10

DESIGN CONDITIONS AND UNIT COSTS FOR DETERMINING SIZES, AND CAPITAL AND OPERATING COSTS OF WET COOLING TOWERS IN THE MAPP AREA

I. Design Conditions:	
Design wet-bulb temperature	75°F
Design dry-bulb temperature	89°F
Fan diameter	28 ft
Distance between fan centers	32 ft
Width of the tower pile on each of two sides	18 ft
Pumping height of water through towers	75 ft
Pumping efficiency	78.2%
Condenser heat transfer coefficient	630 BTU/hr/ft^2/°F
Specific land area	0.10 acre/MW
Concentration ratio of contaminants in cooling water	3.3
Water loading	12.5 gpm/ft^2 plan area
Air loading	1800 lbs/hr/ft^2 face area
II. Unit Costs:	
Unit fuel cost	$0.000751/kwh
Unit supply water cost	$0.10/1000 gal.
Unit blowdown treatment cost	$0.05/1000 gal.
Unit tower cost	$7.50/Tower Unit
Unit cost of replacement capacity	$90/kw
Unit cost of energy loss	$0.01/kwh
Unit condenser cost	$4/$ft^2$ area
Unit land cost	$3000/acre
Annual maintenance cost	$200/cell/year

TABLE 11

OPTIMUM SIZES AND TOTAL UNIT COSTS OF OPEN-CYCLE COOLING AND WET COOLING TOWERS -- FOSSIL PLANTS

Power Level,* (MW)	Optimum Tower Height, H (ft)	Optimum Tower Length L (ft)	Total Unit Cost mills/kwh		Total Annual Blowdown, (acre-ft /year)	Total Annual Evaporation Loss, (acre-ft /year)
			Cooling Tower	Open Cycle		
200	55	200	2.94291	-	1138	2618
	50	200	2.91771	-	1147	2638
	45	200	2.91714	2.7171	1158	2663
400	55	350	2.89960	2.7050	2285	5255
	50	350	2.90052	-	2305	5302
	45	400	2.90503	-	2316	5327
600	55	500	2.89518	-	3431	7892
	50	550	2.89367	2.6982	3452	7939
	45	600	2.89822	-	3474	7990
800	55	700	2.88970	2.6939	4570	10511
	50	750	2.89020	-	4599	10577
	45	800	2.89358	-	4632	10653

* Rated capacity

TABLE 12

OPTIMUM SIZES AND TOTAL UNIT COSTS OF OPEN-CYCLE COOLING AND WET COOLING TOWERS--NUCLEAR PLANTS

Power Level,* (MW)	Optimum Tower Height, H (ft)	Optimum Tower Length, L (ft)	Total Unit Cost mills/kwh		Total Annual Blowdown, (acre-ft /year)	Total Annual Evaporation Loss, (acre-ft /year)
			Cooling Tower	Open Cycle		
400	55	400	2.97936	2.4452	2710	6233
	50	450	2.97976	-	2723	6264
	45	450	2.98424	-	2751	6328
600	55	600	2.97256	-	4065	9349
	50	650	2.97114	2.4384	4091	9409
	45	700	2.97565	-	4119	9475
1100	60	1100	2.97049	-	7390	16998
	55	1100	2.96263	-	7452	17141
	50	1200	2.96191	2.4299	7498	17245
1300	60	1250	2.96619	-	8739	20100
	55	1350	2.96047	-	8799	20238
	50	1400	2.95965	2.4276	8865	20390
1500	60	1400	2.96549	-	10087	23199
	55	1500	2.95787	-	10162	23374
	50	1600	2.95748	2.4258	10233	23535

* Rated capacity

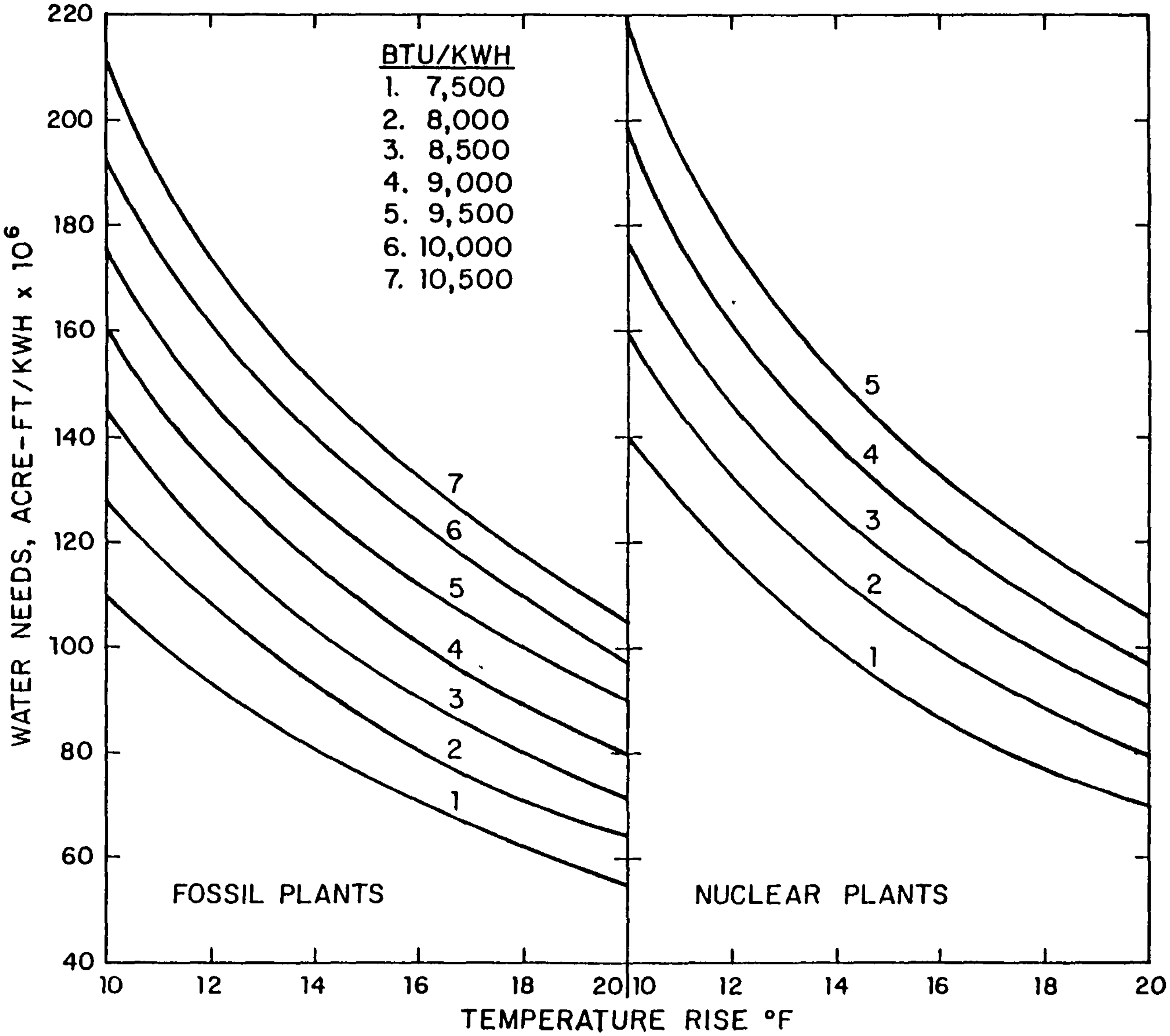

Figure 1. Cooling Water Requirements of Fossil and Nuclear Plants

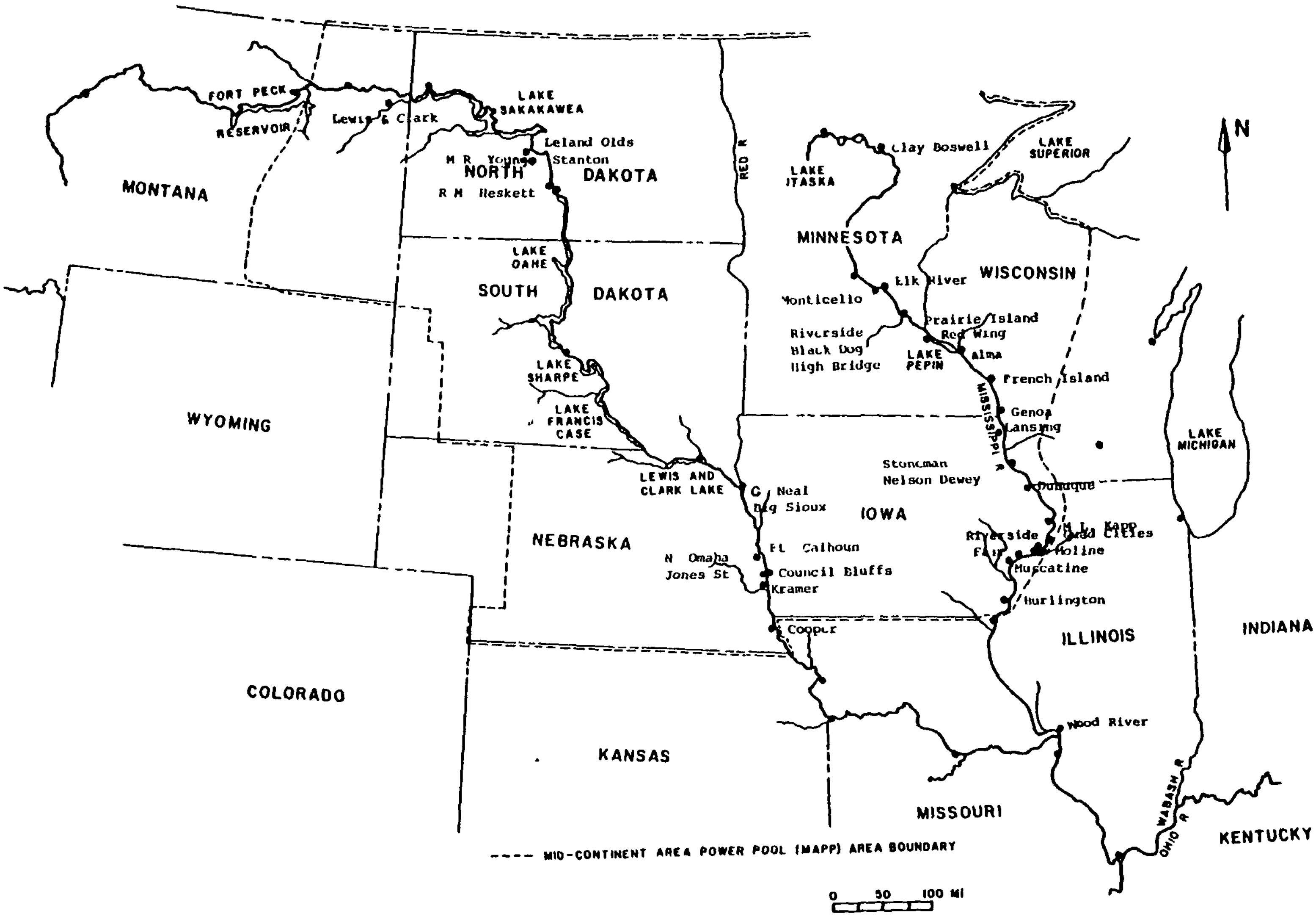

Figure 2. Locations of Existing Thermal Power Plants Along the Mississippi and Missouri Rivers in the MAPP Area

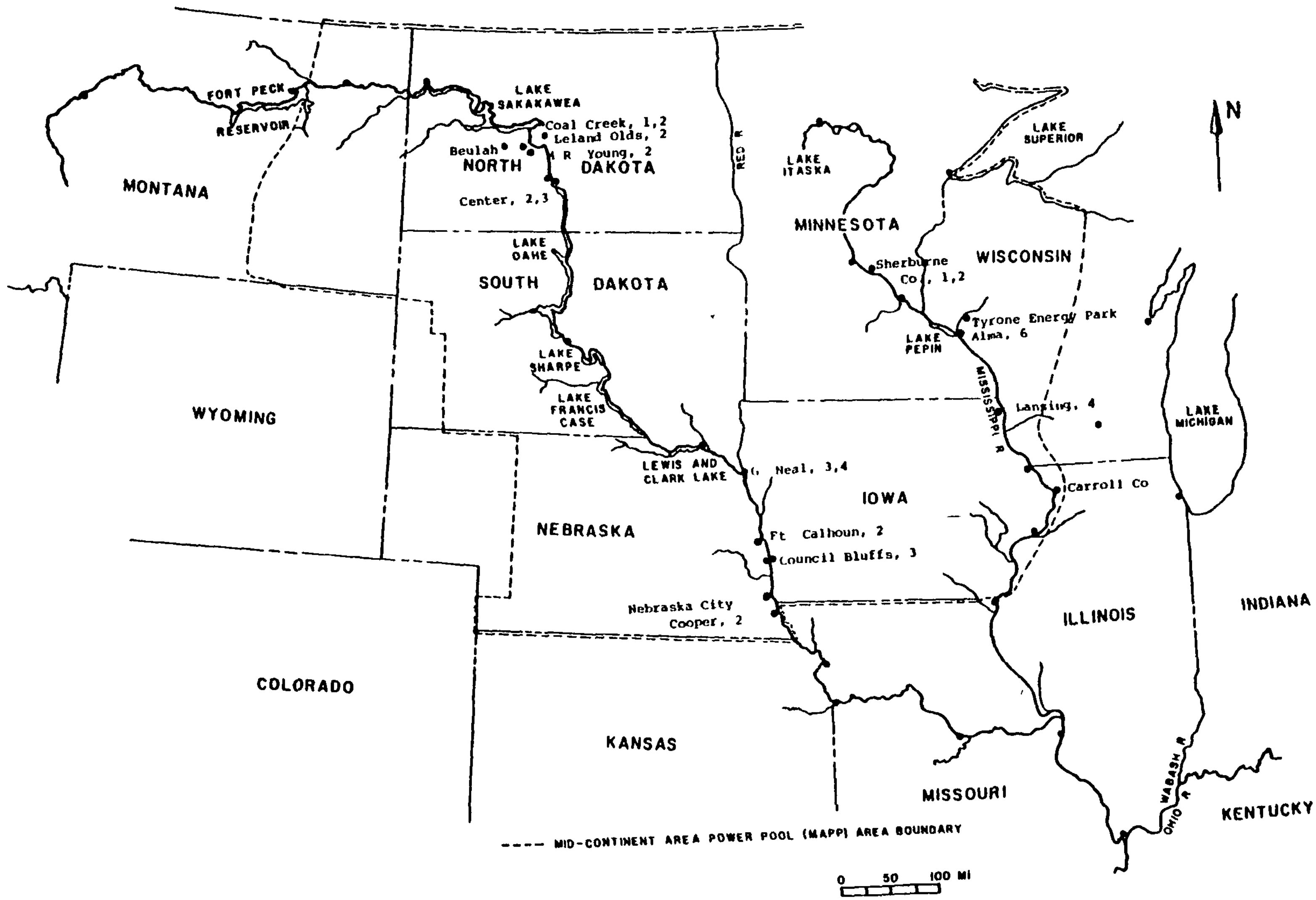

Figure 3. Locations of Proposed and Projected Thermal Power Plants Along the Mississippi and Missouri Rivers in the MAPP Area

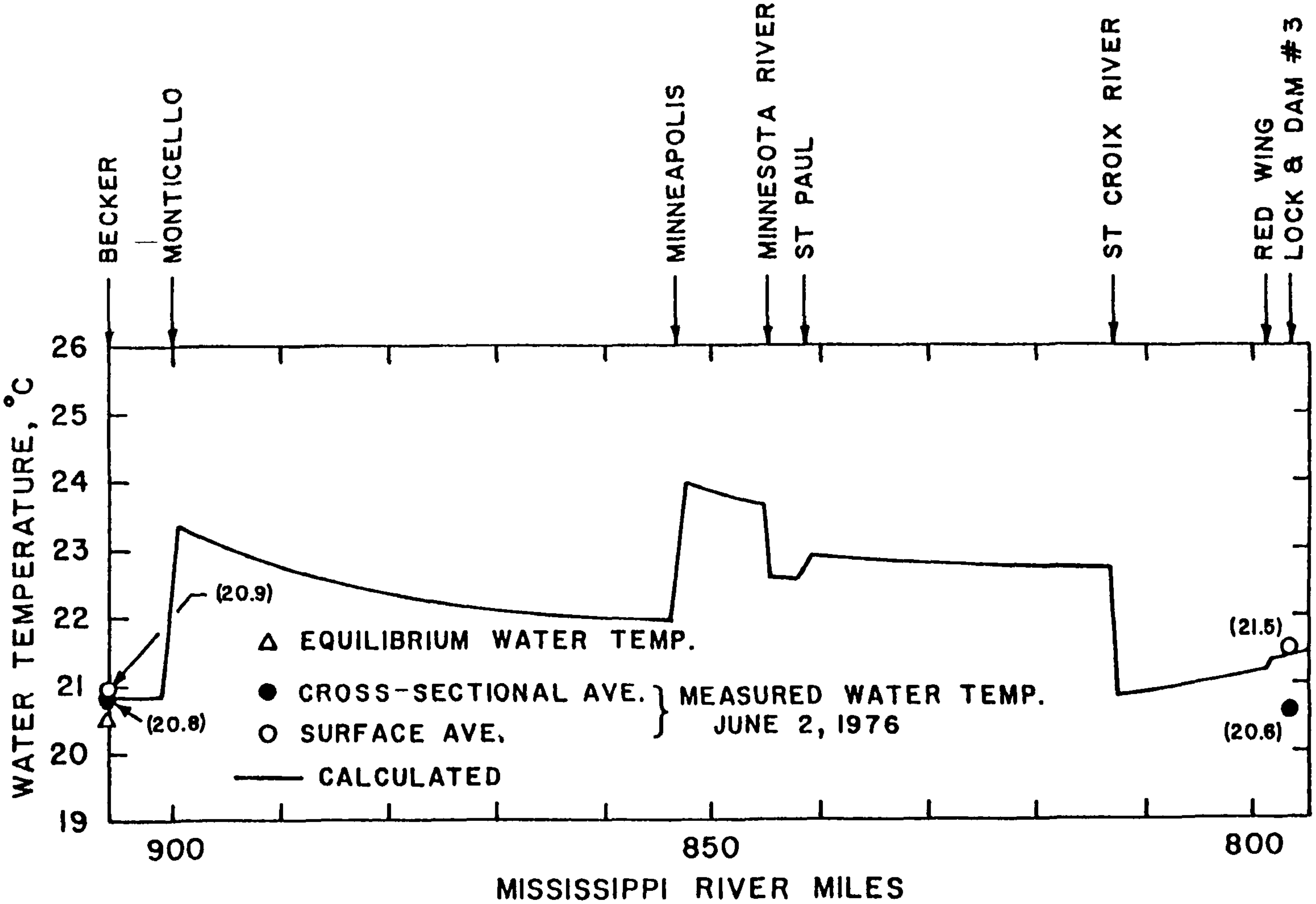

Figure 4. Comparison of Calculated and Measured Temperatures - Mississippi River Between Becker, Minnesota, and Lock and Dam No. 3

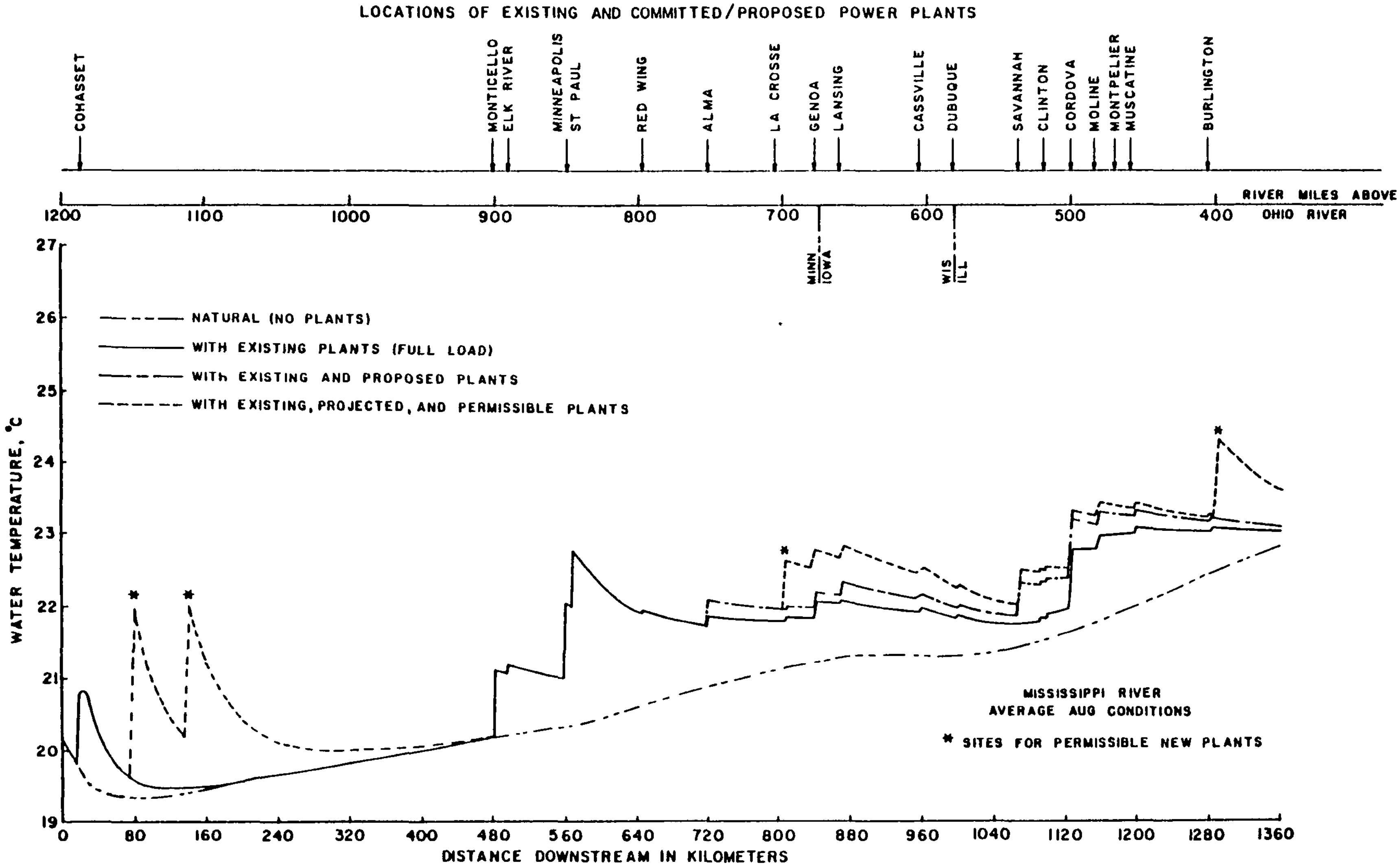

Figure 5. Temperature Distributions Along the Mississippi River for Average Flow Conditions With Full-Load Operation and Permissible New Plants Based on Predicted Natural Temperatures.

PPP

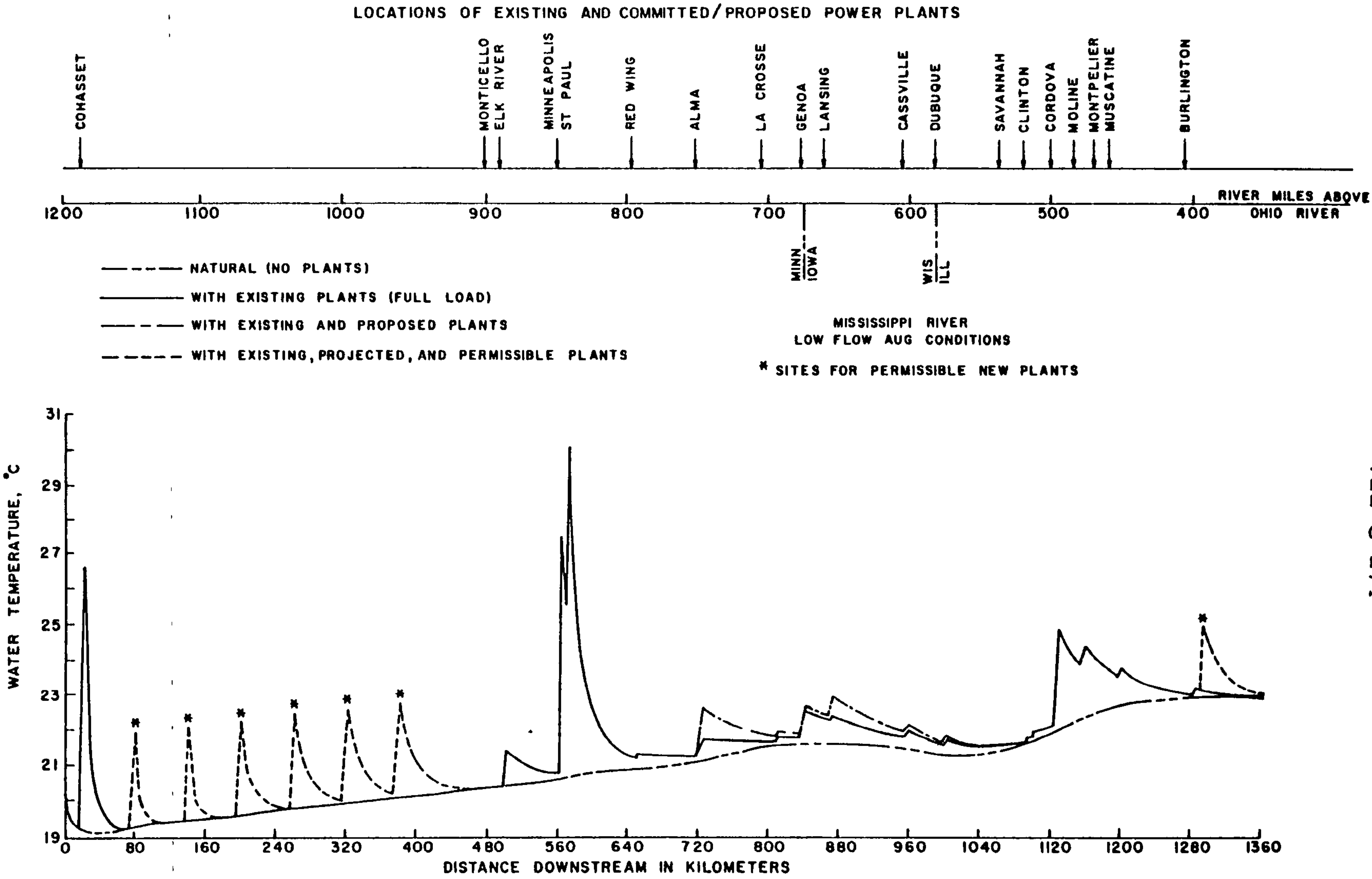

Figure 6. Temperature Distributions Along the Mississippi River for Low Flow Conditions With Full-Load Operation and Permissible New Plants Based on Predicted Natural Temperatures.

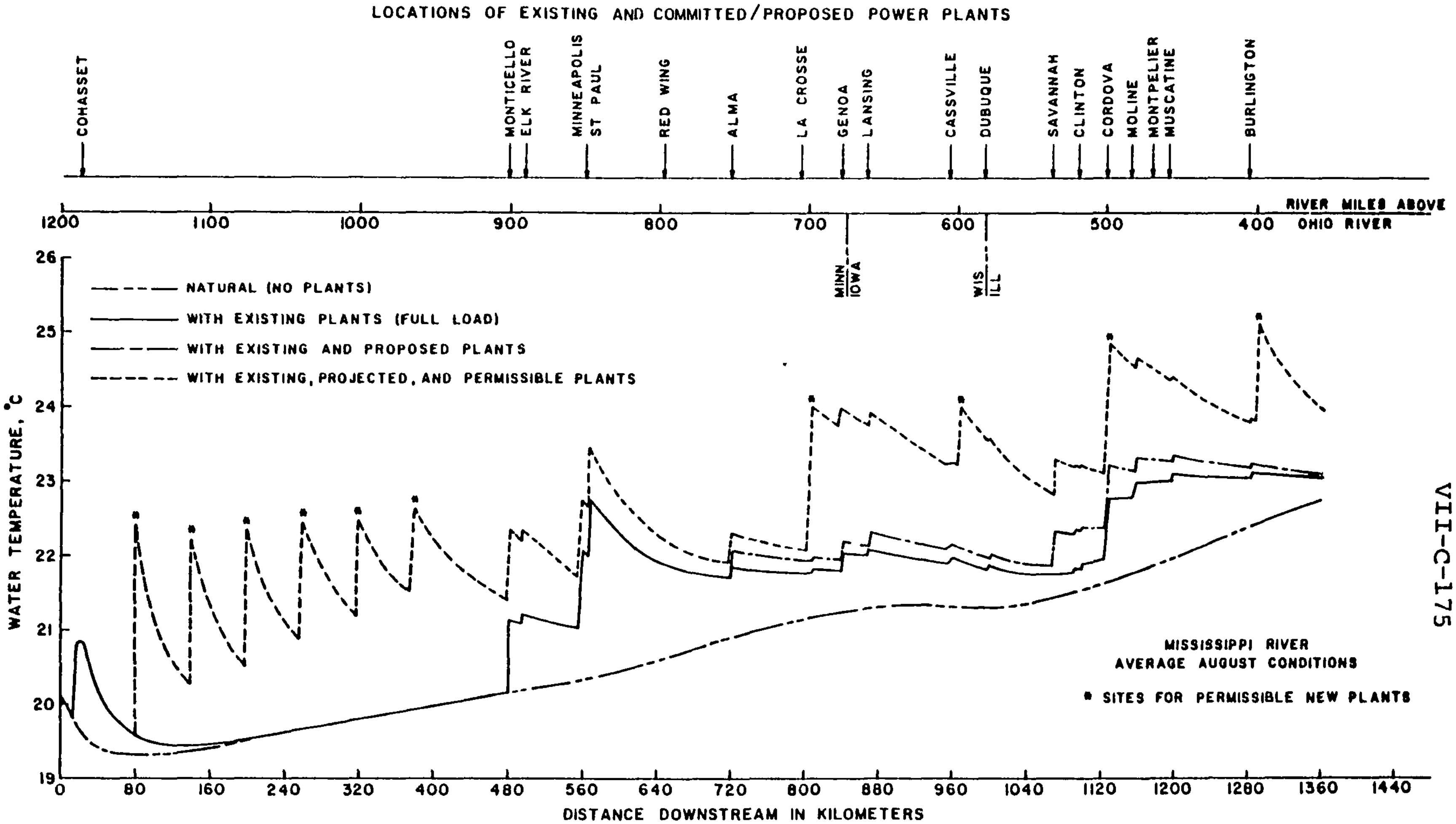

Figure 7. Temperature Distribution Along the Mississippi River for Average Flow Conditions With Full-Load Operation and Permissible New Plants Based on Temperatures With Existing Heat Loads.

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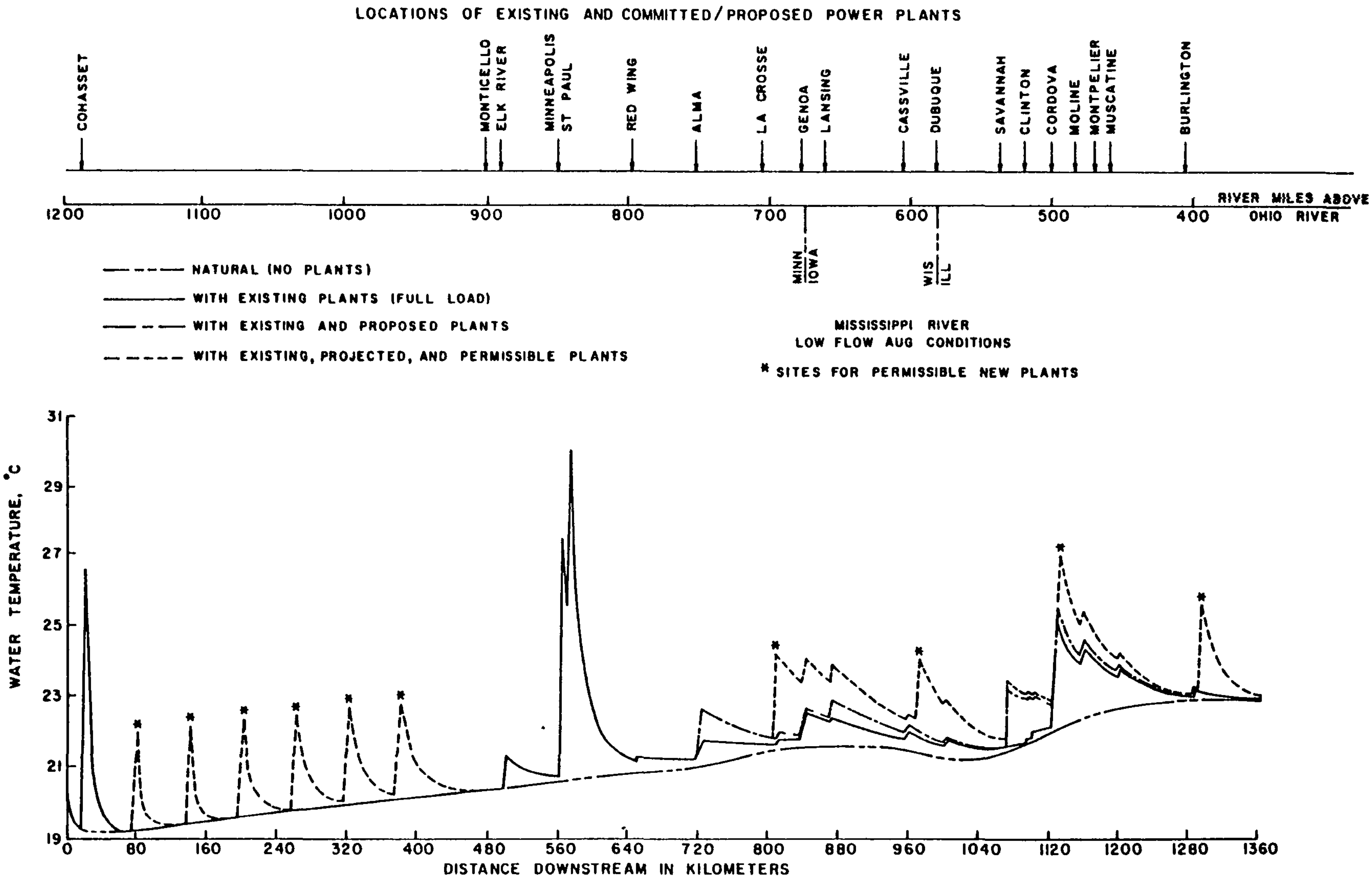

Figure 8. Temperature Distributions Along the Mississippi River for Low Flow Conditions With Full-Load Operation and Permissible New Plants Based on Temperatures With Existing Heat Loads.

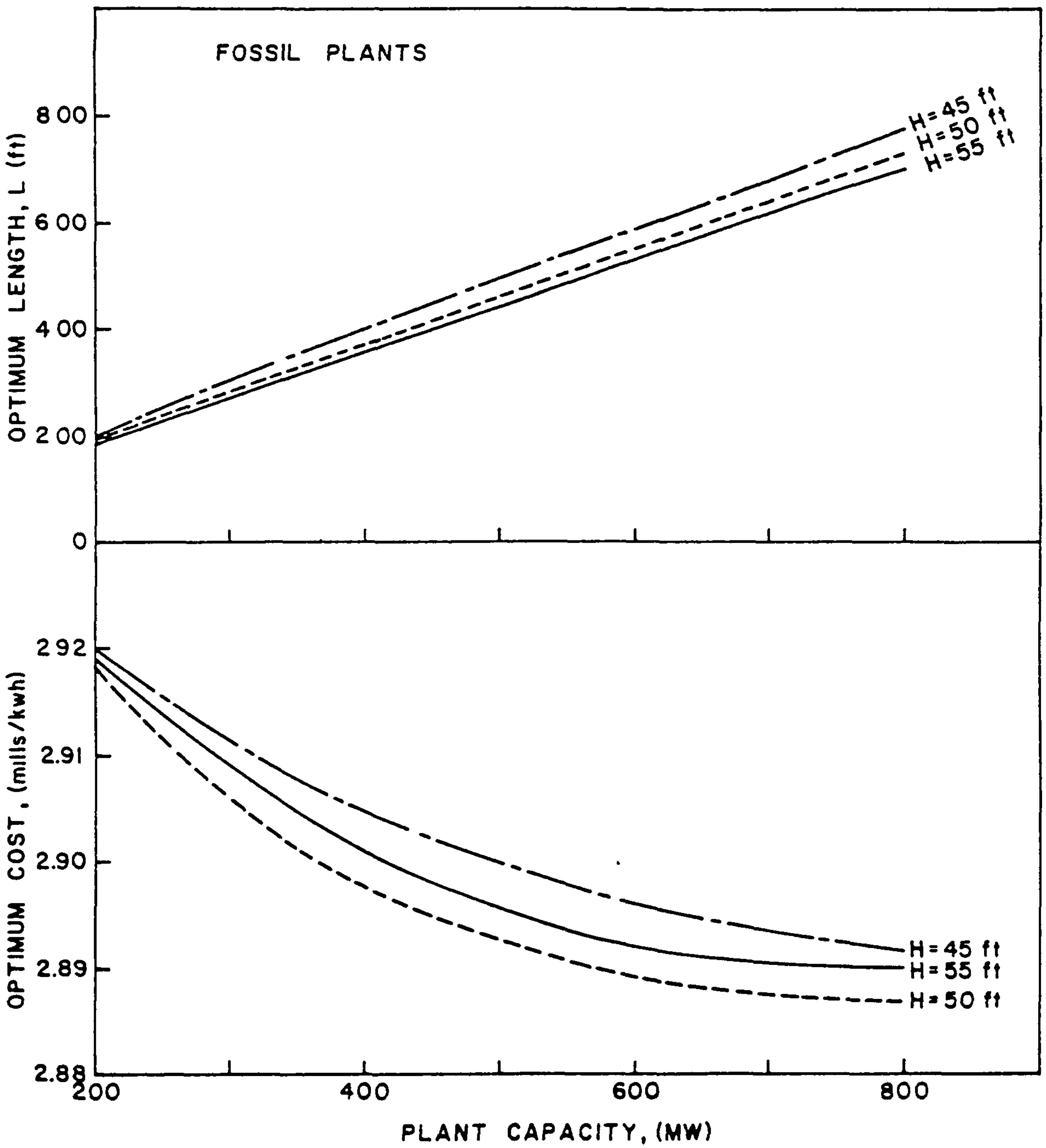

Figure 9. Optimum Sizes and Total Unit Costs of Wet Cooling Towers -- Fossil Plants

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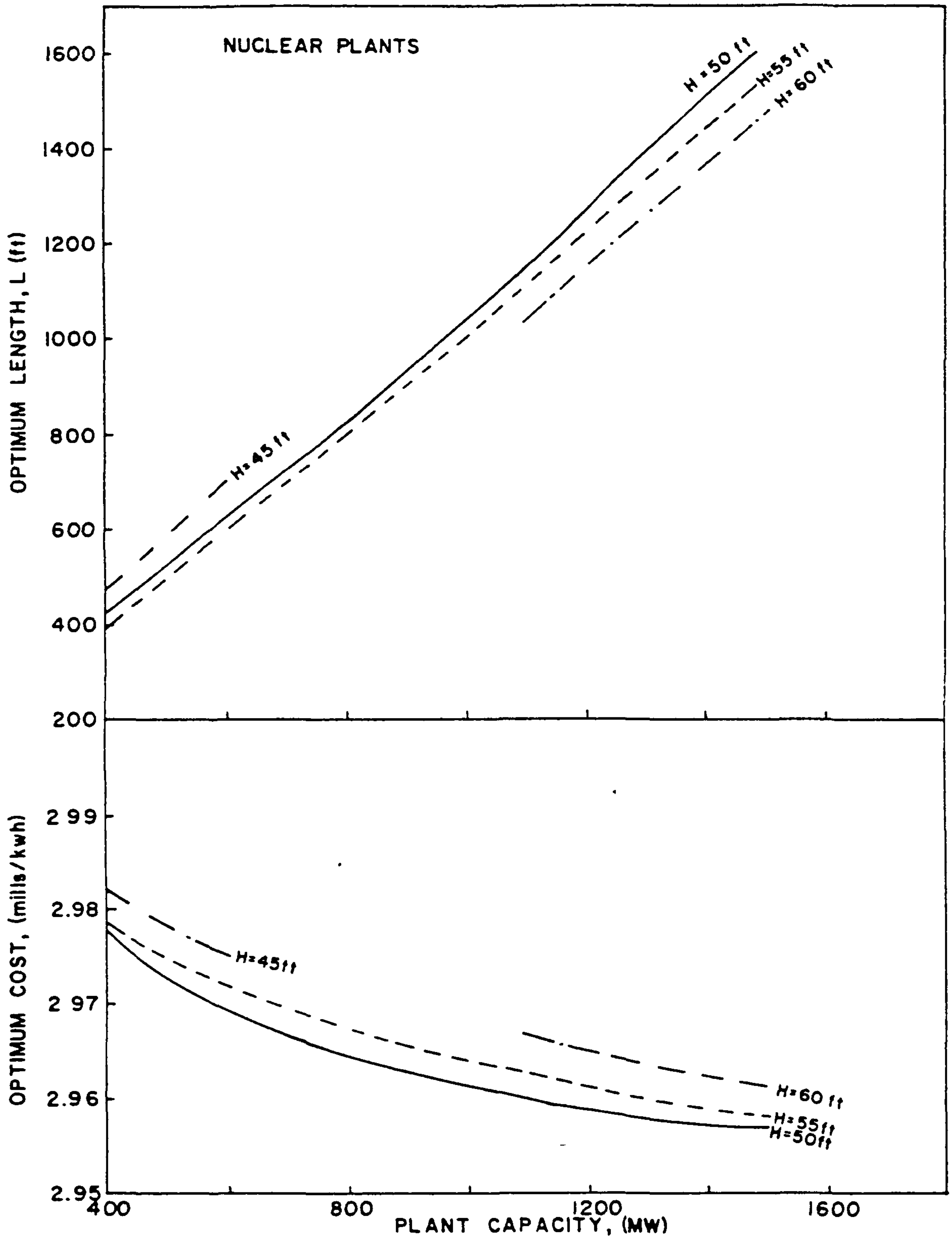

Figure 10. Optimum Sizes and Total Unit Costs of Wet Cooling Towers -- Nuclear Plants