THE THERMAL REGIMES OF THE UPPER MISSISSIPPI AND MISSOURI RIVERS

PART ONE: TRANSIENT AND STEADY-STATE COMPUTATIONAL MODELS FOR THE PREDICTION OF RIVER THERMAL REGIMES

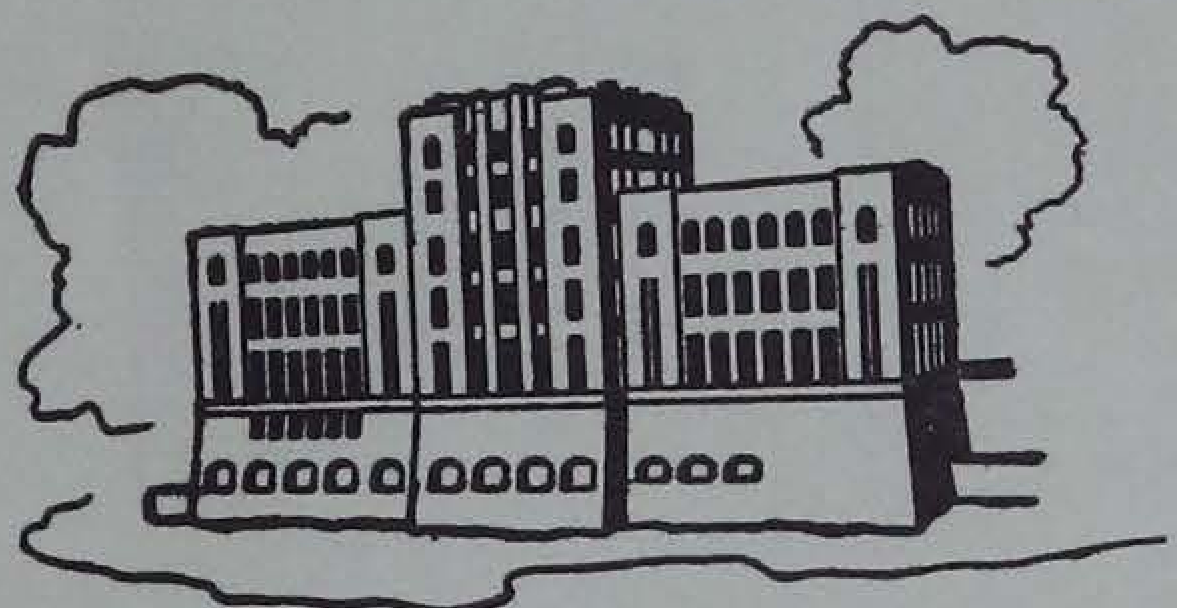
PART TWO: ANALYSIS OF THERMAL REGIMES OF THE MISSISSIPPI AND MISSOURI RIVERS IN THE MID-CONTINENT AREA POWER POOL (MAPP) GEOGRAPHICAL AREA

by

P. P. Paily, T.-Y. Su, A. R. Giaquinta, and J. F. Kennedy

Sponsored by

Mid-Continent Area Power Pool (MAPP)
Minneapolis, MN 55402



IIHR Report No. 182

Institute of Hydraulic Research
The University of Iowa
Iowa City, Iowa 52242

October, 1976

mapp
mid-continent area power pool

reply to:
Dairyland Power Cooperative
2615 East Avenue South
La Crosse, WI. 54601

mapp Environmental Committee
Thomas A. Steele, Chairman

December 21, 1976

TO MEMBERS AND FRIENDS OF MAPP:

The Environmental Committee of Mid-continent Area Power Pool (MAPP) is pleased to offer this report as a technical contribution to sound water use planning in the Upper Mississippi and Missouri River Basins of the Midwestern United States. The Committee has for several years felt a responsibility to help in the collection and analysis of planning data related to the present and projected use of these river waters for electric power, particularly the thermal component of water quality.

It was for this purpose that in January, 1974, the Environmental Committee met with Dr. John Kennedy of the Iowa Institute of Hydraulic Research to outline a plan for this very ambitious research program. The ideas and comments of the Chairman and staff members of both River Basin Commissions were also solicited at this time and throughout the conduct of this study. Verbal reports on study progress were made at the Commission meetings from time to time, and we have been encouraged by the support and interest given us by the prominent and capable people of these Commissions.

We believe that the results of this study show that, so far as cooling water requirements and thermal capacities are concerned, the electric power facilities in the Pool region can be compatible and productive neighbors along the rivers, and through wise planning create a very minimal impact in the sensitive area of water use.

But a word of caution is in order: this study, as far-reaching as it is, is not the final word. It is only an overview of the aggregate thermal profiles of these major rivers. It is a model and a tool for planning. It is not--and was never intended to be--a detailed environmental impact assessment of each power plant on each increment of the river. This type of detailed study will have to follow at appropriate times and places as new facilities are planned and as our knowledge of these waters increases. But this is a start, an important part of the foundation in long-range planning which will be of value to industry and government decision-makers alike.

Our thanks to Dr. John Kennedy, Director of the Iowa Institute of Hydraulic Research, and his staff, for the thorough and dedicated work they have done in conducting this study.

Sincerely,

Thomas A. Steele

Thomas A. Steele
Chairman
MAPP Environmental Committee

TAS/cw

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The cooperation of the MAPP-member utilities and the MAPP Coordination Center in providing data on power plants is gratefully acknowledged. Special thanks are due to members of the Environmental Committee of MAPP for working closely with us and for securing the authorizations and funding necessary to initiate and complete this major work. The Regional Offices of the Environmental Protection Agency in Chicago and Kansas City were helpful in providing information on municipal, industrial and other heat loads.

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FOREWORD

In recent years a major new burden has been placed on the large rivers of the United States: to serve as the intermediary in the transfer of waste heat from industrial sources -- principally steam-electric power plants -- to and through the atmosphere. As power plants became larger and more numerous it became evident to the Environmental Committee of the Mid-Continent Area Power Pool (MAPP)* that soon it would not suffice to examine just the individual thermal impact and water consumption of each riverside plant using once-through cooling. Instead, rational planning to make optimum use of the remaining heat assimilation capacities of rivers would require examination of the cumulative thermal impact and thermal interaction of all of the plants sited along each river, and of their total water consumption.

It was against this background that MAPP engaged the Iowa Institute of Hydraulic Research (IIHR) of the University of Iowa to undertake an investigation of the thermal characteristics of the reaches of the Mississippi and Missouri Rivers lying in the MAPP geographical area (from Fort Peck, Montana, to the Nebraska-Kansas border along the Missouri River; and the Mississippi River from its headwaters to Keokuk, Iowa); to assess the adequacy of the river flows to meet the projected cooling water needs of the MAPP-member utilities through the year 1993; and to estimate the economic benefits accruing to society from utilizing the remaining heat assimilation capacities of the streams for once-through cooling of power plants.

The investigation was conducted in the following steps, many of which were pursued simultaneously:

1. Development of a comprehensive, computer-based, numerical model for calculation of temperature distributions along rivers.

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* Mid-Continent Area Power Pool (MAPP) and Mid-Continent Area Reliability Coordination Agreement (MARCA) are two names given to voluntary electric industry organizations in the Upper Midwest, the memberships of which are identical. This study was sponsored by both organizations, but for simplicity, the term MAPP will be used throughout the report to mean both MAPP and MARCA.

2. Collection and compilation of data on the existing and proposed artificial thermal loads imposed on the Mississippi and Missouri Rivers within and immediately upstream and downstream from the MAPP region.

3. Calculation of temperature distributions along the two study rivers for sets of meteorological variables typical of different seasons of the year for the conditions of: no artifical thermal loads; existing thermal loads; and existing plus permissible thermal loads.

4. Identification of the most desirable sites along the rivers for future once-through plants and determination of the permissible once-through-cooled capacities of these plants, within the framework of existing thermal standards. No consideration was given to biological, distribution, or other constraints in the selection of plant sites.

5. Determination of the cooling water requirements of MAPP-member utilities through the year 1993, and evaluation of the adequacy of the Mississippi and Missouri River flows to meet these needs.

6. Estimation of the cost savings resulting from use of once-through cooling instead of wet cooling towers.

The investigation was conducted in two phases. The first was concerned primarily with the development of the computational model, which has come to be known as the Iowa Thermal Regime Model (ITRM), and with the collection and compilation of the necessary input data from the study reaches of the rivers. Calculation and interpretation of the temperature distributions constituted the second phase. The underlying theory and the development of the ITRM were presented in a previous report ("A Computational Model for Predicting the Thermal Regimes of Rivers," by P.P. Paily and J.F. Kennedy, IIHR Report No. 169, November 1974). The computational model has the capability of predicting time-dependent water temperatures under transient input conditions. Subsequently, a steady-state version of the ITRM was developed for the calculation of temperature distributions for time-invarient input conditions. This simplified model and a comparative review of three unsteady computational models are presented in Part One of this report. Also included in Part One is a validation of the ITRM by means of temperatures measured along the Missouri and Mississippi Rivers.

Part Two of the present report, which may be used independently of Part One, presents the results obtained from the application of the ITRM to the Upper Mississippi and Missouri Rivers and analysis of their thermal assimilation capacities. It is important to the understanding and rational application of the results presented herein to understand the limitations that were imposed on the analysis. First, the ITRM is a one-dimensional model; that is, it assumes that the heated water is completely mixed with the river flow at all stations. Therefore, the ITRM and projections based on it make no allowance for mixing-zone or zone-of-passage restrictions. Second, in this overview study of river temperatures the effects of plant load swings and of temporal variations of meteorological conditions were not considered. Finally, in selecting plant sites no consideration was given to local ecological conditions or to any of the other of the many constraints that effect plant siting. The siting and sizing recommendations are based solely on the heat assimilation capacities of the rivers.

SUMMARY AND CONCLUSIONS

A computer-based, numerical model for calculation of streamwise distributions of temperature in rivers was developed, validated, and utilized to calculate the thermal regimes of the reaches of the Mississippi and Missouri Rivers lying within the MAPP geographical area. Part One of this report describes the salient features of the computational model used and presents a comparative review of three transient models: the Iowa Thermal Regime Model (ITRM) of Paily and Kennedy; the Water Quality Model developed at MIT by Harleman, Brocard, and Najarian; and the COLHEAT River Simulation Model developed by the Hanford Engineering Development Laboratory Staff. A simplified version of ITRM is presented for computing steady-state water temperatures in rivers for cases in which the hydrological and meteorological variables are time-invariant.

The thermal regimes of the Mississippi and Missouri Rivers in the MAPP geographical area corresponding to average meteorological and hydrological conditions for the months of February, May, August, and November were determined by means of the steady-state ITRM; the results are presented and discussed in Part Two of the report. The natural thermal regimes of the rivers and the modified thermal regimes resulting from imposition of external heat loads from power plants and other heat sources were calculated. The locations along the rivers at which new plants of reasonably large size could be installed in accordance with the existing thermal standards were identified. The capacities of these plants were determined on the basis of the calculated temperature distributions with the thermal loads of the existing, proposed, and projected once-through plants imposed on the rivers.

The principal conclusions derived from the investigation may be summarized as follows:

(1) The thermal regime analysis based on average flow conditions indicates that the remaining heat assimilation capacity of the Mississippi River beyond that which will be utilized by existing and presently sited future plants ranges from approximately 5800 MW to 16000 MW fossil, or 4000 MW to 11000 MW nuclear, depending on the capacity factors of existing plants and the base (natural or existing) from which the allowable temperature rises are measured. If the thermal regime analysis is based on low flow conditions (7-day average 10-year recurrent low flows), the remaining heat assimilation

capacity ranges from about 2500 MW to 7100 MW fossil or 1700 MW to 4900 MW nuclear.

Along the Missouri River, the future presently sited capacity designed to use once-through cooling may do so without violating existing thermal standards. The remaining heat assimilation capacity beyond that which will be utilized by existing and presently sited future plants is about 7500 MW fossil or 5000 MW nuclear. This analysis was based on average flow conditions and included the assumption that all power platns will operate at rated capacity. Moreover, the thermal effects of reservoirs on the river temperatures were not considered.

(2) The total condenser cooling water requirement of the existing and future plants projected for installation through the year 1993 and employing the Mississippi and Missouri Rivers for once-through cooling amounts to about 31500 cfs (890 cu.m/s) and 19000 cfs (540 cu.m/s), respectively. The consumptive water use of these plants, which may be approximated as one percent of the cooling water requirement, will be about 315 cfs (8.9 cu.m/s) for the Mississippi River and about 190 cfs (5.4 cu.m/s) for the Missouri River. Both the Mississippi and the Missouri Rivers have adequate flow rates to meet these condenser cooling water requirements and the consumptive water uses of the plants projected for installation through the year 1993.

(3) It is important to consider the cumulative effects of all the existing plants upstream from the locations under consideration when siting and planning new once-through power plants. Certain reaches of the two rivers may not be able to accommodate any additional plants with once-through cooling when all the proposed and projected plants are put into full-load operation; these reaches include the sections of the rivers lying adjacent to and extending some distance downstream from Minneapolis-St. Paul and Omaha.

(4) Sites just downstream from the large reservoirs along the Missouri River appear to be attractive for locating new plants because the temperature of water released through the dams during the warmer months is somewhat lower than the natural river temperature, due to thermal stratification in the reservoirs. The reservoirs act, in effect, as cooling ponds which would precool the water before it would be used for once-through cooling.

(5) Mechanical draft wet cooling tower systems are the logical alternative to once-through cooling. The total capital and operating costs of these towers were calculated on the basis of current cost figures. For

the various power levels projected for installation in the MAPP area, the unit total cooling-related costs (which include all fuel costs) 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. The total unit cost of once-through cooling was also computed, and the costs penalties incurred by the use of cooling towers was found 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.

(6) Cooling systems combining once-through cooling with wet cooling towers appear to be attractive for some future riverside plants. The total cooling requirements may be shared between the two cooling systems in optimum proportions on a seasonal or even a daily basis. The supplemental cooling provided in such systems can be varied in such a way that the available heat assimilation capacity of the river is fully utilized.

PART ONE

TRANSIENT AND STEADY-STATE COMPUTATIONAL MODELS FOR THE PREDICTION OF RIVER THERMAL REGIMES

PART ONE

TRANSIENT AND STEADY-STATE COMPUTATIONAL MODELS FOR THE PREDICTION OF RIVER THERMAL REGIMES

I. INTRODUCTION

Paily and Kennedy [8]* developed a computer based numerical model of the thermal regimes of rivers, which is capable of computing transient longitudinal temperature distributions in nonuniform rivers subjected to temporally and spatially varying meteorological conditions, imposed heat loads, and tributary inflows. Calculation of the thermal response of a river to time-dependent external conditions generally requires use of an unsteady formulation. In many instances, however, it suffices to know the temperature distribution for the case of steady-state conditions corresponding to time-averaged meteorological and hydrological variables. If an unsteady formulation is used in these cases, it is necessary to introduce an initial, assumed or estimated, longitudinal temperature distribution and then let the computation proceed in time steps until steady conditions are approached. But, if one is interested in only the time-invariant situation it is much simpler and more economical in terms of computer time to use a numerical model based on a steady-state formulation.

Part of the report is given over to brief descriptions and a comparison of three computational models for prediction of the transient stages of river thermal regimes: the Iowa Thermal Regime Model (ITRM), developed at the Iowa Institute of Hydraulic Research by Paily and Kennedy [8]; the Water Quality Model developed at Massachusetts Institute of Technology by Harleman, Brocard, and Najarian [4]; and the COLHEAT River Simulation Model which was formulated by the Hanford Engineering Development Laboratory Staff [5]. The salient features of each of these models are described and discussed. A simplified steady-state version of ITRM is presented, and both the transient and steady-state versions of this model are utilized to calculate the temperature distribution of a reach of the Missouri River below Gavins Point Dam for average November conditions. The computer program for the steady-state version of ITRM also is presented.

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* Numbers in square brackets designate References listed in Appendix A.

II. TEMPERATURE PREDICTION MODELS

This section presents a brief comparative survey of the various computational methods available for predicting temperature distributions in natural rivers and in those experiencing man-made thermal loading. The details of the mathematical formulation involved in the development of each model are not given; for these the reader is referred to the references cited.

A. The One-Dimensional Formulation. The generalized differential equation that describes the conservation of heat in an elemental volume of water in a river is three-dimensional and unsteady; its solution gives the spatial and temporal distributions of temperature in the body of water. However, use of full time-dependent three-dimensional formulation is justified only if there are large temperature gradients in the transverse (width) and vertical (depth) directions. In most natural streams large temperature gradients in these directions occur only in the near-field regions of sites where thermal loads (e.g., power-plant discharges) are imposed. In considerations involving the overall thermal regime of a river, the characteristic dimensions of zones where three-dimensional effects are significant usually are small compared to the lengths of the river reaches of interest, and therefore a one-dimensional formulation, with the average temperature over the cross section treated as the dependent variable, may be employed.

The one-dimensional, unsteady, convection-diffusion equation expressing the conservation of thermal energy in a free surface flow is

$$\frac{\partial T}{\partial t} + \frac{Q}{A}\frac{\partial T}{\partial x} - \frac{1}{A}\frac{\partial}{\partial x}\left(AE\frac{\partial T}{\partial x}\right) = \frac{B}{A}\frac{\phi^*(T)}{\rho\, c_p} + \frac{1}{A}\frac{TD}{\rho c_p} + \frac{1}{A}\frac{TI}{\rho c_p} \qquad (1)$$

where T is the cross-sectional average temperature; t is time; x is the distance along the channel in the streamwise direction; Q is the river discharge; A is the cross-sectional area of flow;

E is the longitudinal dispersion coefficient; B is the top width of the river flow section; ϕ^* is the rate of surface heat-exchange between the water and the atmosphere; and TD and TI are the rates of heat input from power plants (or other artificial sources) and tributary inflows, respectively, both per unit distance along the stream. The quantities ρ and c_p are the density and specific heat of water, respectively. The quantity ϕ^* must be calculated from meteorological data; methods used in its determination are considered in the next section.

B. Heat Budget Calculations. One of the principal factors influencing the thermal regimes of natural rivers is the rate of surface heat-exchange between the water and the atmosphere. This quantity is dependent upon the current, local meteorological conditions, and therefore changes from place to place and also with time, and as a consequence so does the river temperature. Other factors which influence the water temperature include channel geometry, water discharge, and channel roughness (which influences E).

The rate of surface heat-exchange is dependent upon several climatic factors, including air temperature, wind velocity, relative humidity, and solar radiation. The principal processes of heat transfer between the water surface and the atmosphere are the net short-wave radiation entering the water, net long-wave radiation leaving the water, evaporation, conduction, and the melting of falling snow. These processes are shown schematically in Fig. 1. Each of these generally is evaluated by an empirical formula. Paily, Macagno, and Kennedy [9] present a detailed description of the various heat transfer processes and the different predictors for calculating them. Only a brief description of the various predictors used in the present study will be given here.

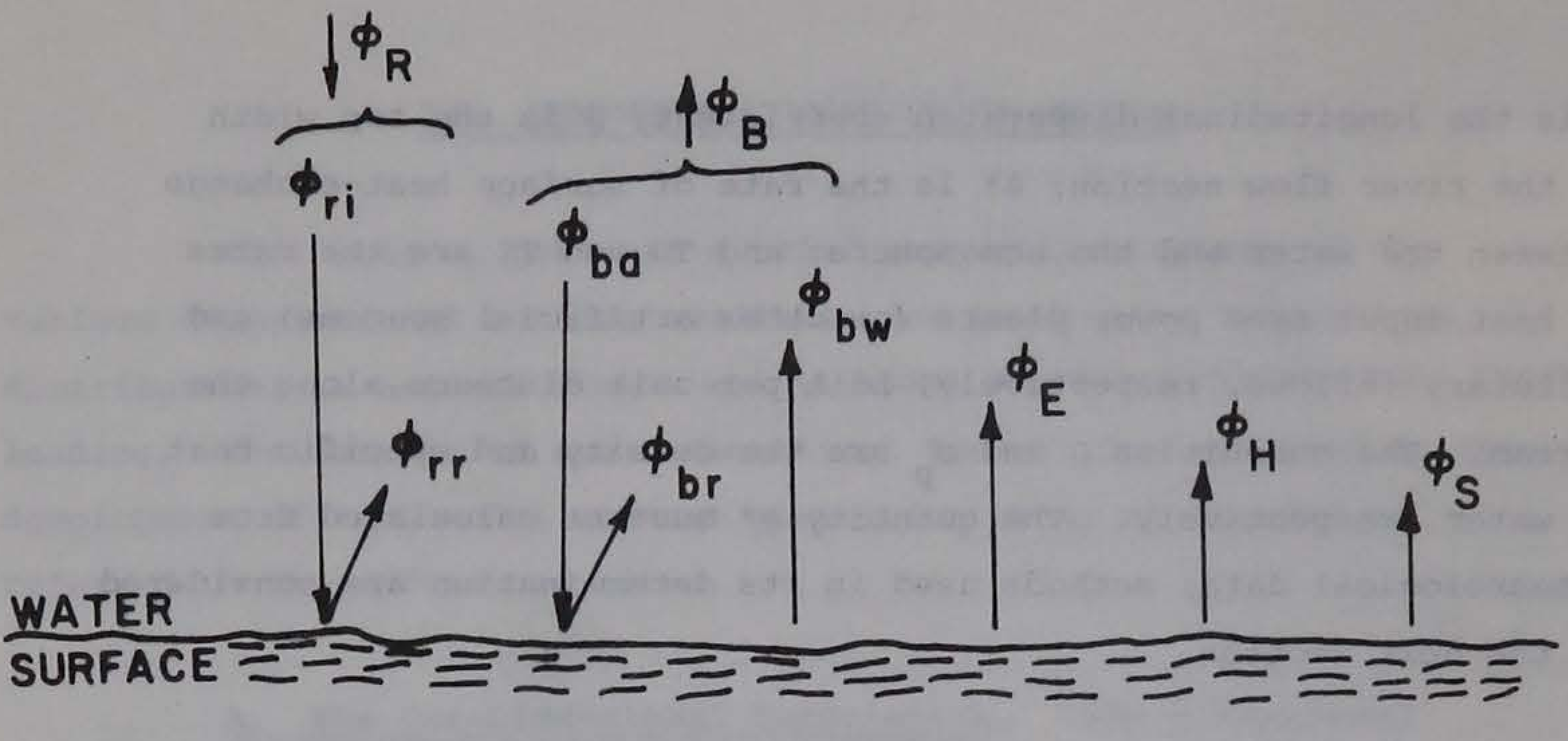

Figure 1. Surface heat-exchange components

1. Net Short-Wave Radiation, ϕ_R. The net short-wave radiation absorbed by a waterbody is the difference between the incoming solar radiation, ϕ_{ri}, and the reflected solar radiation, ϕ_{rr}:

$$\phi_R = \phi_{ri} - \phi_{rr} \tag{2}$$

where ϕ_{ri} and ϕ_{rr} are given by *

$$\phi_{ri} = \phi_{CL}\ f(C) = \phi_{CL}\ [0.35 + 0.061\ (10-C)] \tag{3}$$

$$\phi_{rr} = 0.108\ \phi_{ri} - 6.766\text{x}10^{-5}\ \phi_{ri}^{\ 2} \tag{4}$$

in which C is the cloud cover in tenths ($0 \leq C \leq 10$) and ϕ_{CL} is the clear-sky solar radiation, which generally is expressed in cal per sq cm per day. Daily average values of both can be obtained from the records of major weather stations.

2. Net Long-Wave Radiation, ϕ_B. The difference between the long-wave radiation emitted by the waterbody, ϕ_{bw}, and the net atmospheric long-wave radiation entering it, ϕ_{ba}, provides the net long-wave radiation leaving the waterbody:

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[*] For information on the sources of the empirical relations given in this section, refer to Paily, Macagno, and Kennedy [9].

$$\phi_B = \phi_{bw} - \phi_{ba} \tag{5}$$

where

$$\phi_{bw} = 0.97\ \sigma\ T_w^4 \tag{6}$$

$$\phi_{ba} = \varepsilon_a\ \sigma\ T_a^4 \tag{7}$$

with

$$\varepsilon_a = [0.937 \times 10^{-5}\ T_a^2]\ [1 + 0.0017\ C^2] \tag{8}$$

or,

$$\varepsilon_a = 0.68 + 0.036\ \sqrt{e_a},\ \text{(clear skies, C = 0)} \tag{9}$$

$$\varepsilon_a = (i + j\ e_a),\ \text{(cloudy skies, } 0 < C \leq 10) \tag{10}$$

$$i = 0.74 + 0.025\ C\ \exp(-1.92\text{x}10^{-4}\ H) \tag{11}$$

$$j = 4.9\text{x}10^{-3} - 5.4\text{x}10^{-4}\ C\ \exp\ (-1.97\text{x}10^{-4}\ H) \tag{12}$$

In the foregoing relations, σ is the Stefan-Boltzmann radiation constant (1.171×10^{-7} cal per sq. cm per day per $^{\circ}K^{-4}$); T_w is the water temperature in $^{\circ}K$; T_a is air temperature in $^{\circ}K$; e_a is air vapor pressure, in mb, corresponding to the dew-point or relative humidity; and H is the cloud height, in m.

3. Evaporation, ϕ_E. The heat flux from the water due to evaporation is given by

$$\phi_E = \rho\ L\ (NV_a)\ (e_s - e_a) \tag{13}$$

with

$$NV_a = 1.107\text{x}10^{-2}\ V_a + 9.34\text{x}10^{-3}\ (\Delta\theta_v)^{1/3},\ (\Delta\theta_v > 0) \tag{14}$$

$$= 1.360\text{x}10^{-2}\ V_a,\qquad (\Delta\theta_v \leq 0) \tag{15}$$

where

$$\Delta\theta_v = [T_w\ (1 + 0.378\ \frac{e_s}{p_a}) - T_a\ (1 + 0.378\ \frac{e_a}{p_a})] \tag{16}$$

(summer conditions)

$$NV_a = 2.09\text{x}10^{-2} + 9.107\text{x}10^{-4}\ (T_w - T_a) + 1.018\text{x}10^{-2}\ V_a \tag{17}$$

(winter conditions)

In the above, ρ is the density of water (1 gm per cu cm); L is the latent heat of vaporization (597 cal per gm); e_s is the saturation vapor pressure, in mb, corresponding to T_w; V_a is the wind velocity, in m per sec; and p_a is the atmospheric pressure, in mb.

4. Conduction, ϕ_H. The heat transfer by conduction is related to that by evaporation by Bowen's ratio, and is given by

$$\phi_H = c\left(\frac{p_a}{1000}\right)\left(\frac{T_w - T_a}{e_s - e_a}\right)[\rho\ L\ (NV_a)\ (e_s - e_a)] \tag{18}$$

in which c is Bowen's constant (0.61 mb per °C)

5. Melting of Snow, ϕ_S. The rate of heat loss from the water during snowfall in winter is related to the snow accumulation rate A_s, by

$$\phi_S = A_s\ [L_i + c_i\ (T_w - T_a]] \tag{19}$$

with

$$A_s = 7.85\ V^{-2.375} \qquad (1 \leq V \leq 10) \tag{20}$$

where V is the visibility in km; L_i is the latent heat of fusion of ice (80 cal per gm); and c_i is the specific heat of ice.

The units of the variables and coefficients in all of the above empirical relations were selected to yield the heat transfer components in units of cal per sq cm per day

The net rate of surface heat-exchange is the algebraic sum of the foregoing components:

$$\phi^* = \phi_R - \phi_B - \phi_E - \phi_H - \phi_S \tag{21}$$

Solution of (1) with ϕ^* represented by (21) gives the longitudinal distribution of temperature in a river. These solutions are considered in the following sections.

C. Closed-Form Solutions. The closed-form solutions, which can be utilized with the aid of only a slide rule or desk calculator, are based on certain simplifying assumptions. These solutions generally are developed for a channel of uniform cross-sectional area and discharge without any tributary inflows. The thermal discharge appears in the specification of the upstream boundary condition, which is given as the temperature at the upper end of the reach. A separate solution is developed for each reach between adjacent imposed heat loads. A major simplification incorporated into the formulations, leading to the closed-form solutions is the expression of the surface heat exchange rate, ϕ^*, as a linear function of the water temperature. With these approximations, closed-form solutions of (1) corresponding to different cases have been obtained by several investigators; among them, two are of interest here: those of Edinger and Geyer [3] and of Paily, Macagno, and Kennedy [10]. These two solutions are briefly summarized below.

1. Edinger and Geyer Solution. This solution applies only to steady-state conditions. The surface heat exchange rate is represented by the equilibrium temperature model:

$$\phi^* = -K(T - T_E) \tag{22}$$

where K is a surface exchange coefficient and T_E is the equilibrium temperature (i.e., the water temperature at which there is no heat exchange with the atmosphere). For these conditions (1) reduces to

$$u\frac{dT}{dx} - E\frac{d^2T}{dx^2} = -\frac{K}{\rho c_p h}(T - T_E) \tag{23}$$

in which $u = Q/A$ is the mean flow velocity, and $h = A/B$ is the mean depth of flow. The solution of (23) with the boundary conditions $T = T_i$ at $x = 0$, and $T = T_E$ at $x\to\infty$, is

$$\frac{T - T_E}{T_i - T_E} = \exp\left[\frac{ux}{2E}\left(1 - \sqrt{1 + \alpha}\right)\right] \tag{24}$$

where $\alpha = 4KE/\rho c_p h u^2$ and T_i is the fully mixed temperature of water at the thermal discharge section, $x = 0$.

2. Paily, Macagno, and Kennedy Solution. These investigators adopted a linear relation for ϕ^* given by

$$\phi^* = -(\varepsilon T + \eta) \tag{25}$$

where ε is a surface transfer coefficient, and η is a base heat-exchange rate. If the unsteady term in the heat conservation equation is retained, (1) then becomes

$$\frac{\partial T}{\partial t} + u\,\frac{\partial T}{\partial x} - E\,\frac{\partial^2 T}{\partial x^2} = -\,\frac{(\varepsilon T+\eta)}{\rho c_p h} \qquad (26)$$

The initial and boundary conditions for (26) are

$$\left.\begin{aligned} T(x,\ 0) &= T_o \\ T(0,\ t) &= T_{in} + T_r(t),\ t < t_o \\ &= T_{in} + T_F \quad ,\ t \geq t_o \\ T(\infty,\ t) &= T_r(t) \end{aligned}\right\} \qquad (27)$$

in which T_o is a constant initial temperature distribution throughout the reach; T_{in} is the input mixed temperature at the thermal discharge section (temperature *increase* of the ambient flow assuming complete mixing); T_F is the freezing point temperature; and $T_r(t)$ is the natural river temperature. This last quantity is obtained from

$$T_r(t) = T_o \exp\left(\frac{-\varepsilon t}{\rho c_p h}\right) - \frac{\eta}{\varepsilon}\left[1-\exp\left(\frac{-\varepsilon t}{\rho c_p h}\right)\right] \qquad (28)$$

The time t_o in (27) is that in which T_r drops from T_o to T_F, and is given by

$$t_o = \frac{\rho c_p h}{\varepsilon}\ \ln\left[\frac{T_o+\eta/\varepsilon}{T_F+\eta/\varepsilon}\right] \qquad (29)$$

The solutions of (26) corresponding to the two upstream conditions given in (27) are as follows:

(a) $t < t_o$; $(T_r > T_F)$:

$$\begin{aligned} \frac{T(x,\ t)}{T_{in}} = {} & \frac{T_o}{T_{in}} \exp\left(\frac{-\varepsilon t}{\rho c_p h}\right) - \frac{\eta}{\varepsilon T_{in}}\left[1 - \exp\left(\frac{-\varepsilon t}{\rho c_p h}\right)\right] \\ & + \frac{1}{2}\left[\exp\left\{\frac{ux}{2E}\left(1 + \sqrt{1+\alpha}\right)\right\} \operatorname{erfc}\left(\frac{x + ut\sqrt{1+\alpha}}{2\sqrt{Et}}\right)\right. \\ & \left. + \exp\left\{\frac{ux}{2E}\left(1 - \sqrt{1+\alpha}\right)\right\} \operatorname{erfc}\left(\frac{x - ut\sqrt{1+\alpha}}{2\sqrt{Et}}\right)\right] \end{aligned} \qquad (30)$$

(b) $t \geq t_o$; $(T_r \leq T_F)$:

$$\frac{T(x,\ t)}{T_{in}} = \frac{T_o}{T_{in}} \exp\left(\frac{-\varepsilon t}{\rho c_p h}\right) - \frac{\eta}{\varepsilon T_{in}}\left[1 - \exp\left(\frac{-\varepsilon t}{\rho c_p h}\right)\right] +$$

$$\frac{1}{2}\left[1 + \frac{T_F + \eta/\varepsilon}{T_{in}}\right]\left[\exp\left\{\frac{ux}{2E}\left(1 + \sqrt{1+\alpha}\right)\right\} \operatorname{erfc}\left(\frac{x + ut\sqrt{1+\alpha}}{2\sqrt{Et}}\right)\right.$$

$$\left. + \exp\left\{\frac{ux}{2E}\left(1 - \sqrt{1+\alpha}\right)\right\} \operatorname{erfc}\left(\frac{x - ut\sqrt{1+\alpha}}{2\sqrt{Et}}\right)\right]$$

$$- \frac{1}{2}\left[\frac{T_o + \eta/\varepsilon}{T_{in}}\right] \exp\left(\frac{-\varepsilon t}{\rho c_p h}\right)\left[\exp\left(\frac{ux}{E}\right) \operatorname{erfc}\left(\frac{x + ut}{2\sqrt{Et}}\right) + \operatorname{erfc}\left(\frac{x - ut}{2\sqrt{Et}}\right)\right] \qquad (31)$$

in which $\alpha = 4\varepsilon E/\rho c_p hu^2$, and $\operatorname{erfc}(\zeta) = 1-\operatorname{erf}(\zeta)$ is the complementary error function.

D. Computer-Based Numerical Solutions. The solutions described in the previous section and similar closed-form solutions are applicable only to uniform flows. Moreover, they include time-independent, linearized surface heat-exchange expressions, a valid representation only in the case of steady meteorological conditions. Natural rivers rarely conform to these constraints, so that the closed-form solutions can be used only for approximate estimates of the water temperature. For a more complete evaluation of the thermal regime of a river it is necessary to take into account changes in all the variables involved, including channel geometry, flow patterns, climatic conditions, and thermal input rates. Some of the variables can be treated as constant in time but varying with downstream distance, while others may change both with time and distance. When all of these variations are incorporated into (1), it is evident that its solution is possible only by means of computer-based numerical methods. This section briefly outlines the main features of three prominent computer-based numerical solutions for predicting the thermal regimes of rivers.

1. Iowa Thermal-Regime Model (ITRM). The thermal-regime model developed by Paily and Kennedy [8] at the Iowa Institute of Hydraulic Research solves (1) utilizing an implicit predictor-corrector scheme. The details of the formulation and development of the numerical scheme have been given in IIHR Report No. 169, prepared for the Mid-Continent Area Power Pool, by Paily and Kennedy [8]. The predictor and corrector schemes are represented by

$$\frac{1}{h^2}\,\delta_x^2\,T_i^{n+\frac{1}{2}} = F[ih,\ (n+\tfrac{1}{2})k,\ T_i^n,\ \frac{1}{2h}\,\delta_x\,T_i^n,\ \frac{1}{k/2}\,(T_i^{n+\frac{1}{2}} - T_i^n)] \tag{32}$$

and

$$\frac{1}{h^2}\,\delta_x^2\,(T_i^{n+1} - T_i^n) =$$

$$F[ih,\ (n+\tfrac{1}{2})k,\ T_i^{n+\frac{1}{2}},\ \frac{1}{4h}\,\delta_x\,(T_i^{n+1} + T_i^n),\ \frac{1}{k}\,(T_i^{n+1} - T_i^n)] \tag{33}$$

where n is the number of time steps; i is the number of distance steps; k is the temporal increment; h is the spatial increment, and δ_x and $\delta_x{}^2$ are the central difference operators given by

$$\left.\begin{aligned} \delta_x\,T_i^n &= T_{i+1}^n - T_{i-1}^n \\ \delta_x^2\,T_i^n &= T_{i+1}^n - 2T_i^n + T_{i-1}^n \end{aligned}\right\} \tag{34}$$

In order to apply the predictor-corrector scheme, the governing equation, (1), is written in a modified form:

$$\left.\begin{aligned} \frac{1}{s}\,\frac{\partial^2 T}{\partial \bar{x}^2} &= -[\frac{\sigma s}{u_o}\,\frac{1}{A\rho c_p}\,(B\phi^* + TD + TI)] \\ &\quad + \frac{\partial T}{\partial \bar{t}} + [\frac{Q}{u_o A} - \frac{1}{sA}\,\frac{\partial A}{\partial \bar{x}}]\,\frac{\partial T}{\partial \bar{x}} \end{aligned}\right\} \tag{35}$$

where u_o is a reference velocity, taken as the flow rate divided by the flow area at the entrance section of a reach; s is a nondimensional scale factor; and $\bar{x}$ and $\bar{t}$ are nondimensional variables given by

$$\left.\begin{aligned} \bar{x} &= \frac{x}{\sigma s} \\ \bar{t} &= \frac{u_o t}{\sigma s} \\ \sigma &= \frac{E}{u_o} \end{aligned}\right\} \tag{36}$$

The prediction of temperature distribution along a river is achieved by dividing the total river length into a convenient number of reaches, not necessarily of the same length, and solving (35) for each reach separately. Each reach is divided into a number of elements; the size of mesh spacing and the number of meshpoints are not necessarily the same for all the reaches. The solutions for adjacent reaches are linked by the common conditions at the junction or node points connecting them, as shown in Fig. 2.

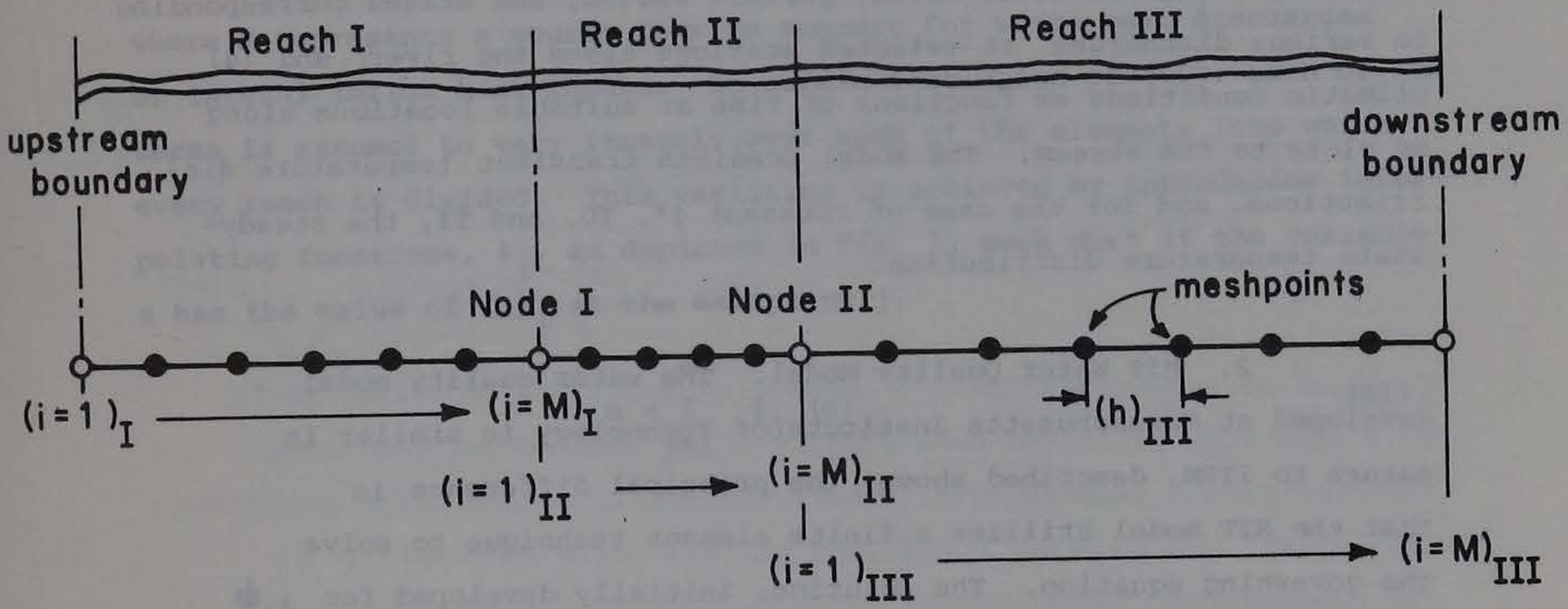

Figure 2. River reaches for Iowa thermal-regime model

To obtain a solution it is necessary to specify an initial temperature distribution along the entire river length. The conditions at the upstream and downstream ends of the river length are also initially specified in terms of temperatures, temperature gradients, or a combination of the two. The predictor-corrector scheme then is applied successively to the interior meshpoints to obtain a set of simultaneous linear algebraic equations of the form

$$[\alpha]\,[T] = [\beta] \tag{37}$$

where $[\alpha]$ is a tridiagonal matrix with known elements; $[\beta]$ is a column matrix with known elements; and $[T]$is a column matrix of unknown temperatures. Equation 37 is then solved to obtain the unknown temperatures at all meshpoints.

The input data required for the computational model include: (1) thermal discharges into the river from power plants and from industrial and municipal sources; (2) flow rates and natural water temperatures of the river at selected locations; (3) river geometry, including cross-sectional areas, surface widths, and stages corresponding to various discharges at selected stations along the river; and (4) climatic conditions as functions of time at suitable locations along or close to the stream. The model predicts transient temperature distributions, and for the case of constant ϕ^*, TD, and TI, the steady-state temperature distribution.

2. MIT Water Quality Model. The water quality model developed at Massachusetts Institute of Technology is similar in nature to ITRM, described above; the principal difference is that the MIT model utilizes a finite element technique to solve the governing equation. The solution, initially developed for estuary flows, by Daily and Harleman [2], consists of a hydraulic solution to obtain the flow characteristics, which is then used as input data for the water quality model of Harleman, Brocard, and Najarian [4]. The hydraulic solution involves the numerical solution of the open-channel continuity and momentum equations,

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} - q_L = 0 \tag{38}$$

and

$$\frac{\partial}{\partial t}(Au) + \frac{\partial}{\partial x}(Qu) = -Ag\left(\frac{\partial z}{\partial x} + \frac{u|u|}{C^2 R_h}\right) \tag{39}$$

where q_L is the lateral inflow per unit length of the channel; g is the acceleration due to gravity; C is the Chezy coefficient, and R_h is the hydraulic radius of the channel. Solution of (38) and (39) with appropriate initial and boundary conditions yields the distributions of flow rate and free surface elevation in the channel at any time.

The governing relation for the water quality (temperature) is written as

$$\frac{\partial}{\partial t}(AT) + \frac{\partial}{\partial x}(QT) = \frac{\partial}{\partial x}(AE\frac{\partial T}{\partial x}) + B\frac{\phi^*}{\rho c_p} + \frac{S}{\rho c_p} \qquad (40)$$

where S represents a source term to account for waste heat discharges or lateral inflow heat inputs. To obtain a solution of (40), each of its terms is assumed to vary linearly over each of the elements into which every reach is divided. This variation is achieved by introducing interpolating functions, ϕ_j, as depicted in Fig. 3, such that if the variable α has the value of $(\alpha)_j$ at the meshpoint j,

$$\alpha = \sum_{j=1}^{M} \phi_j (\alpha)_j \qquad (41)$$

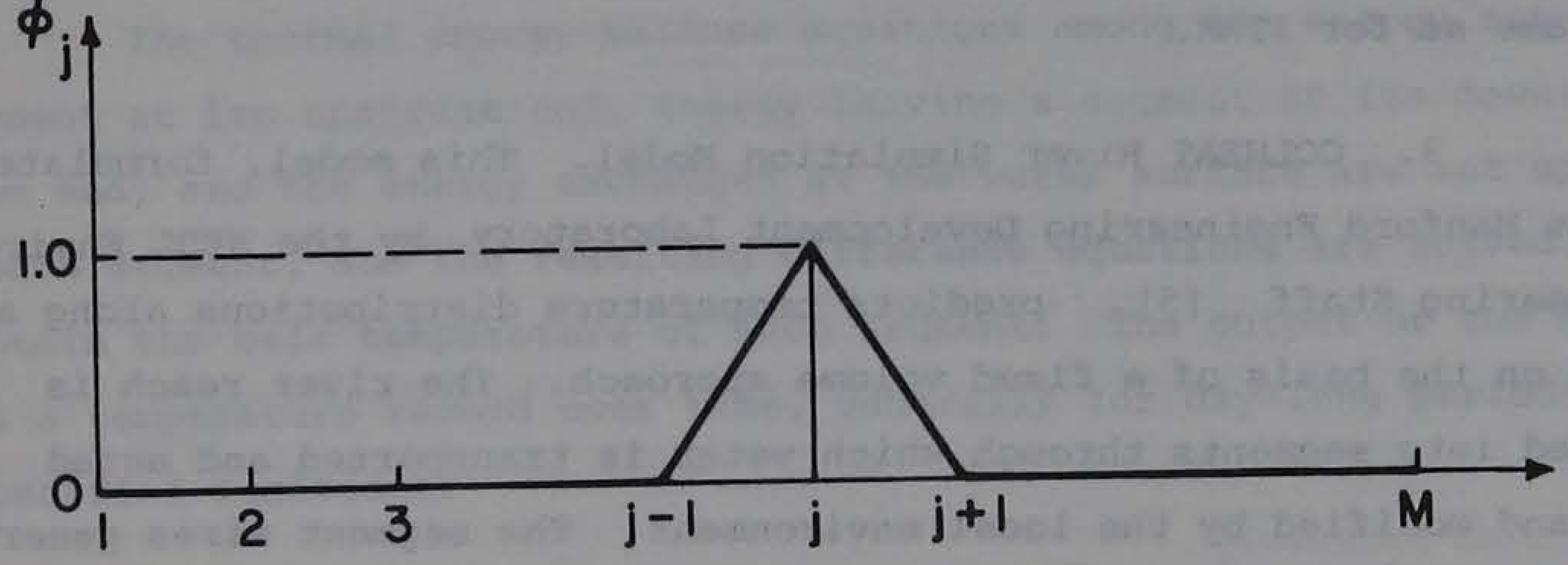

Figure 3. Interpolating function for MIT water quality model

The method of weighted residuals, in the form of the Galerkin method, is then applied to achieve the solution. The residual resulting from the above piecewise linear approximation, (41), is weighted with the interpolating functions, integrated over the length of the channel, and set equal to zero. The resulting relation is

$$\Sigma \int \phi_i \, R(x,t) \, dx = 0, \text{ for } i = 1,2,\ldots\ldots, M \tag{42}$$

where

$$R(x,t) = \frac{\partial}{\partial t} \Big[\sum_{j=1}^{M} \phi_j (AT)_j \Big] + \frac{\partial}{\partial x} \Big[\sum_{j=1}^{M} \phi_j (QT)_j \Big]$$

$$- \frac{\partial}{\partial x} \Big[\sum_{j=1}^{M} \phi_j \Big(AE \frac{\partial T}{\partial x}\Big)_j \Big] - \frac{1}{\rho c_p} \sum_{j=1}^{M} \phi_j (B\phi^*)_j$$

$$- \frac{1}{\rho c_p} \sum_{j=1}^{M} \phi_j \, (S)_j \tag{43}$$

A number of approximations are introduced into (42) to transform it to a form that is solved more readily. The form of the resulting relation is the same as (37). The requirements of the model regarding the initial and boundary conditions and the input information are the same as for ITRM.

3. COLHEAT River Simulation Model. This model, formulated at the Hanford Engineering Development Laboratory by the HEDL Environmental Engineering Staff [5], predicts temperature distributions along a river on the basis of a fixed volume approach. The river reach is divided into segments through which water is transported and acted upon and modified by the local environment. The segment sizes generally are based on a travel time of one day. The travel time, or time required for a parcel of water to traverse the segment, is determined by dividing the volume of the segment by the water discharge.

In the simulation model, the river cross section is approximated by a trapezoid with the river bottom parallel to the water surface. The section then is divided crosswise into three troughs: a central trough in which the velocity is relatively high and two identical shallower side troughs where the velocity is smaller. The division is shown in Fig. 4.

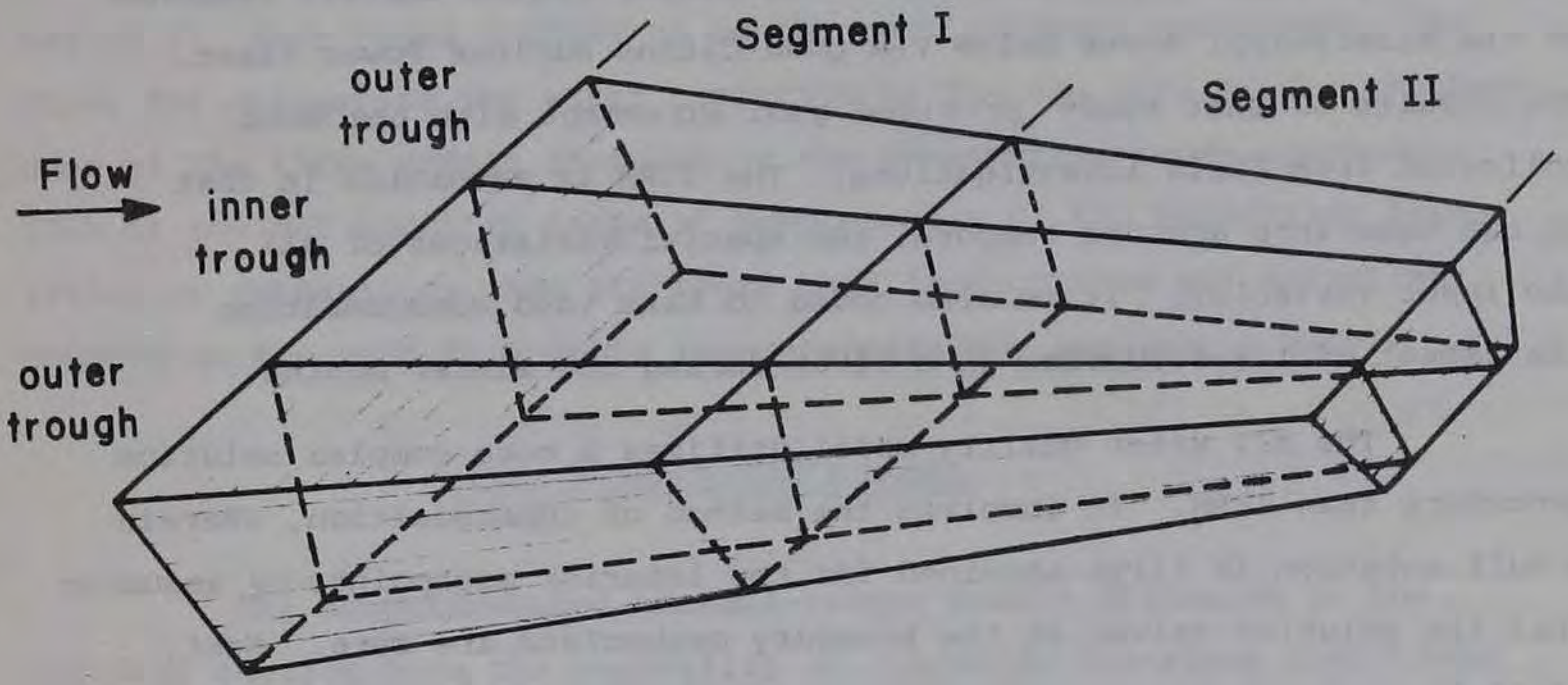

Figure 4. River configuration for COLHEAT river simulation model

The thermal energy-balance equations among the energy entering a segment at its upstream end, energy leaving a segment at its downstream end, and the energy exchanged at the water surface are set up for each segment, and the resulting difference equations are solved to obtain the bulk temperature of each segment. The output of the model gives a temperature record over time, generally for day-long periods, at specified locations.

E. Discussion of the Predictive Models. The IIHR thermal-regime model and the MIT water quality model use practically identical approaches to the determination of river themal regimes. Both solve the differential equation which expresses the conservation of thermal energy. However, the models utilize different solution techniques. Since no comparative study has been carried out using the two models, it is not easy to evaluate their relative merits. The ITRM was developed as part of the study covered by this report, and the results of its first application are presented herein. A simplified version of the model was used by Paily [7] to predict the winter-regime thermal response of the Mississippi River below the Quad-Cities Nuclear Power Plant. The results of that study provided good agreement with the data collected from field investigations. The ITRM is versatile in that it can take into account temporal and spatial variations of all the input variables. It is also coded to take into consideration the aspect of ice-formation in a river during the winter months.

The MIT water quality model utilizes a more complex solution procedure than ITRM. It involves the method of superposition, wherein a null solution is first obtained for the interior meshpoints by assuming that the solution values at the boundary meshpoints are zero. Next, using the same set of equations, and assuming unit solution values at the boundary meshpoints, influence factors at the interior meshpoints are computed. Then the set of equations, which includes the boundary conditions, is solved for values at the boundary meshpoints. The resulting solution is multiplied by the influence factors and added to the null solution to obtain the values at the interior meshpoints. The solution procedure thus involves many more computational steps than ITRM. The hydraulic solution included in the model is necessary only in situations where the flow conditions are highly transient, such as in estuaries or hydroelectric reservoirs. In the case of most rivers the flow conditions change relatively slowly, so the hydraulic solution may not be necessary.

Compared to the ITRM and the MIT model, the COLHEAT model appears to be somewhat unsophisticated because it is based on a simplified heat budget approach. It also neglects the effect of longitudinal dispersion on the temperature distributions. Recently, Argonne National Laboratory applied this model to a cooling water study of the Ohio River by Butz, Schregardus, Lewis, Policastro, and Reisa [1]. That investigation included a comparative study of the COLHEAT model, the STREAM river simulation package developed by the Ohio River Valley Water Sanitation Commission (ORSANCO) [6], and the Edinger-Geyer one-dimensional model, (24), as coded by the U.S. Environmental Protection Agency, Region V. They found COLHEAT to be the most reliable model among the three for evaluating the water temperatures for the Ohio River. However, none of the three models included in the comparative study approaches ITRM or the MIT model in terms of completeness of the underlying formulation or versatility, and therefore this finding does not establish COLHEAT as the most dependable river-temperature prediction model.

III. STEADY-STATE MODEL

The computer-based thermal-regime models discussed in the previous section have the capability of computing transient conditions of river thermal regimes when the flow rates, meteorological conditions, and thermal input rates are time-dependent or constant. However, the determination of the transient temperature distributions in a river is important only for special situations, e.g., when the weather conditions change significantly over short time periods, or a power plant is operating intermittently or at variable load.

During any period of time (e.g., a month or a calendar-year quarter), the water temperature of a river will fluctuate over a certain range. Moreover, the maximum and minimum temperatures will vary from one period to another and also from year to year during corresponding periods. However, in examining the thermal regime of a river, it frequently suffices to determine various steady-state temperature distributions corresponding to average meteorological and hydrological conditions. The use of transient computational models for predicting the steady-state conditions involves a large number of computational steps and consequently a large amount of computer time. Therefore, it is preferable to use a steady-state model when one is interested just in calculating river temperatures for average conditions.

In general, longitudinal dispersion makes only a very small contribution to the energy-balance equation, and therefore may be neglected. For steady-state conditions, (1) then becomes

$$\frac{Q}{A}\frac{dT}{dx} = \frac{B}{A}\frac{\phi^*(T)}{\rho c_p} + \frac{1}{A}\frac{TD}{\rho c_p} + \frac{1}{A}\frac{TI}{\rho c_p} \qquad (44)$$

or

$$\frac{dT}{dx} = \frac{B}{Q}\frac{\phi^*(T)}{\rho c_p} + \frac{1}{Q}\frac{TD}{\rho c_p} + \frac{1}{Q}\frac{TI}{\rho c_p} \qquad (45)$$

This relation can be solved numerically to obtain the steady-state longitudinal distribution of temperature in a river. If the temperature at any point x_i in the river is T_i, the temperature at a point x_{i+1} which is at a distance Δx downstream, is given by

$$T_{i+1} = T_i + (\Delta x)\left[\frac{(B_{i+1} + B_i)/2}{(Q_{i+1} + Q_i)/2}\right]\frac{(\phi^*)_{i+\frac{1}{2}}}{\rho c_p} + \frac{1}{(Q_{i+1} + Q_i)/2}\left[\frac{(TD)_{i+1} + (TI)_{i+1}}{\rho c_p}\right] \qquad (46)$$

where $\phi^*_{i+\frac{1}{2}}$ is the surface heat exchange rate corresponding to $T_{i+\frac{1}{2}}$, the temperature at the middle of the mesh space Δx. The temperature $T_{i+\frac{1}{2}}$ is determined by

$$T_{i+\frac{1}{2}} = T_i + \left(\frac{\Delta x}{2}\right)\left[\frac{B_{i+1} + B_i}{Q_{i+1} + Q_i}\right]\frac{(\phi^*)_i}{\rho c_p} + \frac{1}{2}\left(\frac{2}{Q_{i+1} + Q_i}\right)\left[\frac{(TD)_{i+1} + (TI)_{i+1}}{\rho c_p}\right] \qquad (47)$$

in which ϕ^*_i corresponds to the known temperature, T_i. The solution requires that the temperature at the upstream boundary (i=1) be known in order to calculate the temperatures at the downstream meshpoints, i = 2,3,....,M, where M is the total number of meshpoints for the entire length of the reach under consideration. A Fortran computer program for calculation of temperature distributions using the steady-state model is given in Appendix B.

IV. VERIFICATION

To develop an illustrative set of results, and to confirm that the unsteady and steady-state models give the same results for constant hydrological and meteorological conditions, temperature distributions were calculated by applying both models to a 400-mi reach of the Missouri River below Gavins Point Dam (South Dakota), which is shown in Fig. 5. The input data used for the computations are listed in Appendix C. The meteorological and hydrological data utilized are 20-year and 50-year averages, respectively, for the month of November. The artificial heat inputs include both existing and proposed thermal loads. The detailed results of the calculations are tabulated in Appendix D, and the computed temperature distribution is shown in Fig. 6. The results produced by the steady and unsteady models are identical except for small differences in the second decimal place. The calculation with the unsteady model utilized an initial temperature distribution along the entire length corresponding to the temperature at the upstream point. This initial distribution was assumed to exist at zero time, and the temperatures at successive time steps were determined numerically. The magnitude of the time steps varied from 0.2 hr at the beginning of computations to 0.9 hr toward the end, the increase being by 0.1 hr at suitable intervals. The results given in Appendix D were obtained after 440 time steps, which corresponds to nearly 290 hrs of prototype time. The amount of computer time required for the calculation was about 23 minutes. The calculation using the steady-state model, on the other hand, required only about 15 seconds of computer time. Clearly, when the transient conditions are not desired, the direct use of the steady-state model is advantageous in terms of savings in computer cost.

The ITRM was validated by comparing computed results with field measurements obtained along reaches of the Missouri and Mississippi Rivers. The temperature distribution in the Missouri River between Salix, Iowa (RM 733), and Brownville, Nebraska (RM 533), was determined by the predictive model for an "average" August day. The average values of flow rates and weather conditions measured at stations along the reach during August, 1974, which were used in the calculations are listed in Table 1a. The numerical model was also tested along a 100-mile reach of the Mississippi River between Becker, Minnesota (RM 906), and Lock and Dam No. 3 (RM 796). A summary of the data for this study is listed in Table 1b.

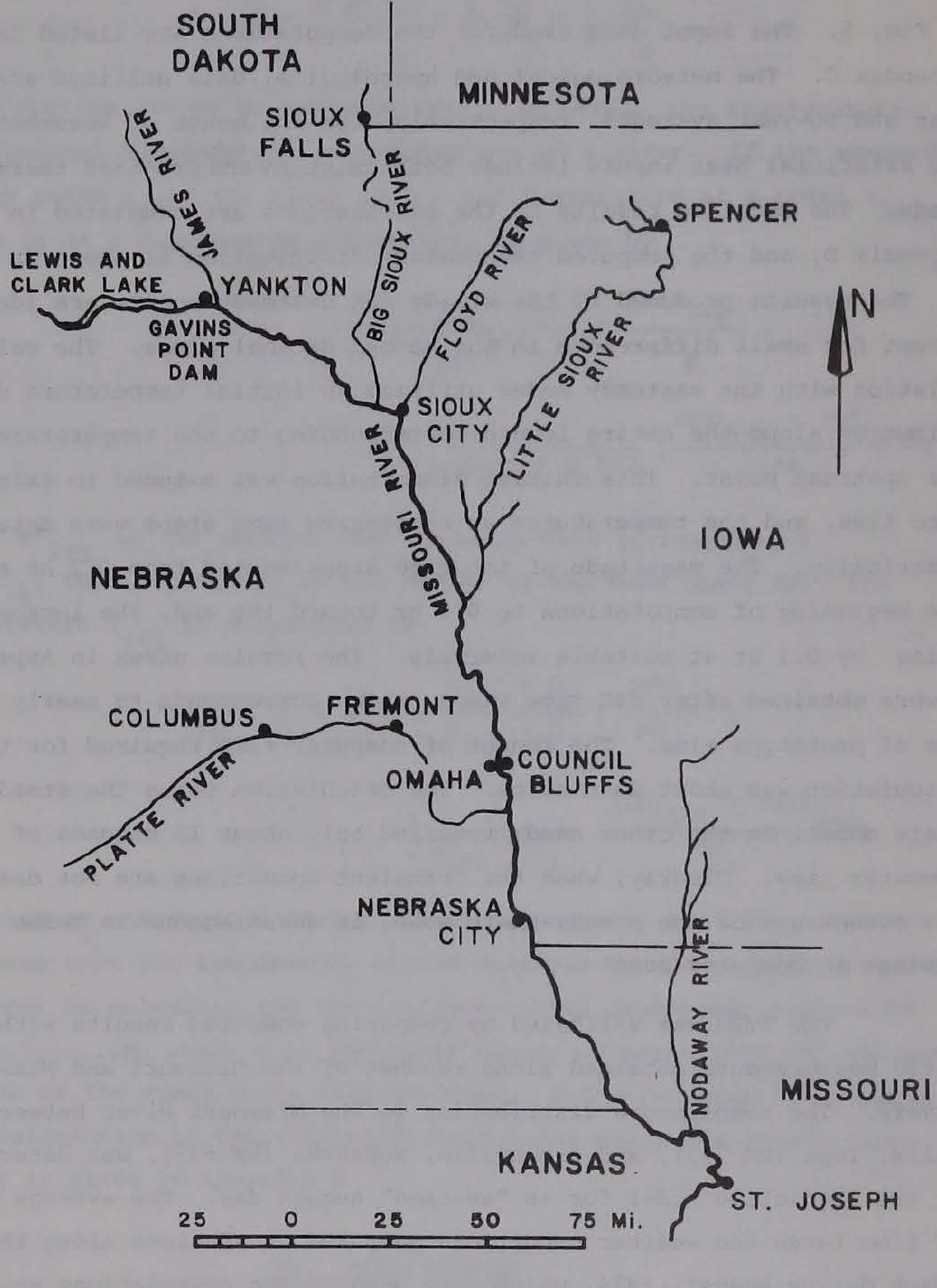

Figure 5. Missouri River between Gavins Point Dam, South Dakota, and St. Joseph, Missouri

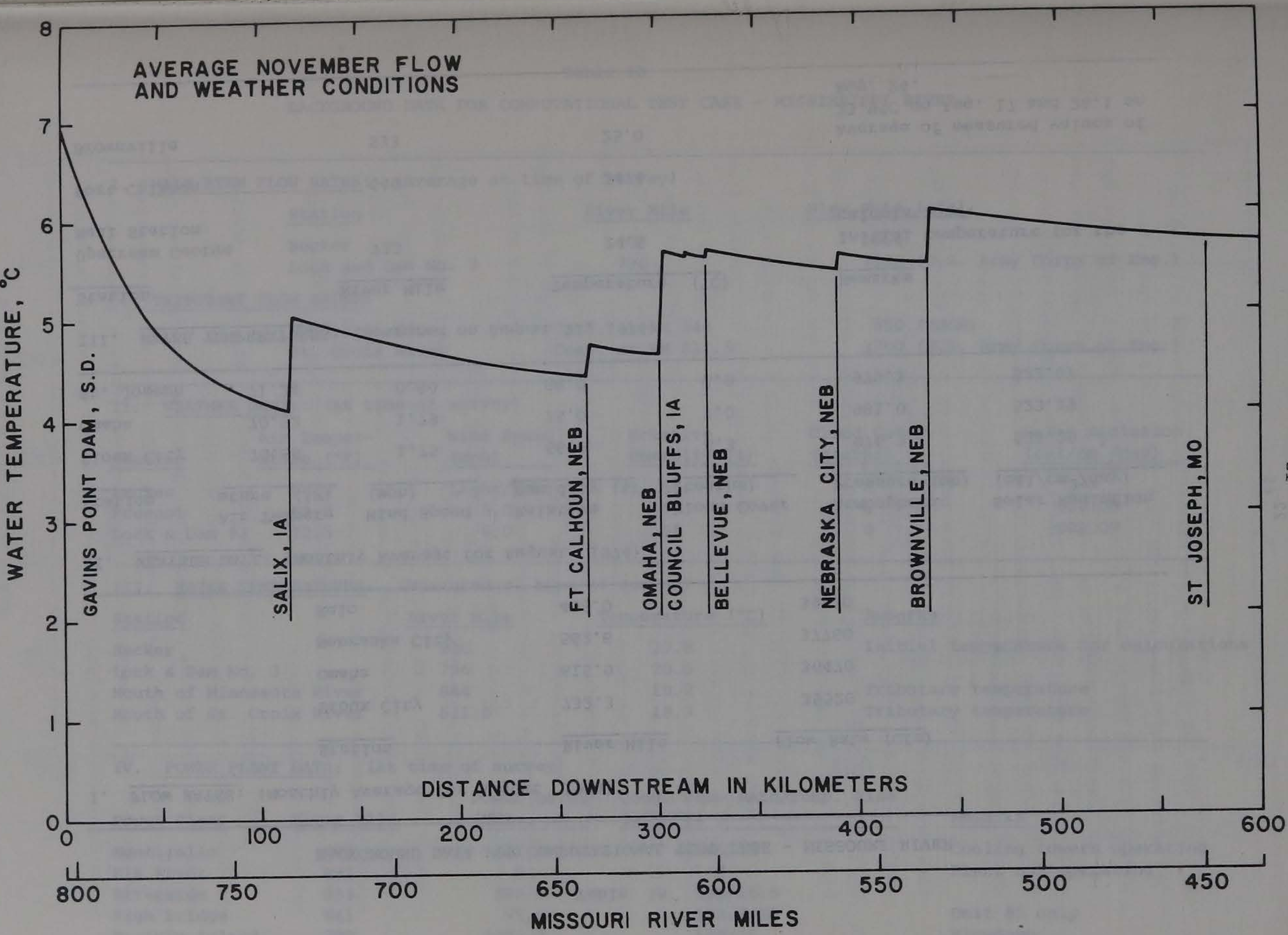

Figure 6. Predicted temperature distribution in the Missouri River between Gavins Point Dam and St. Joseph, Missouri, for average November conditions

Table 1a

BACKGROUND DATA FOR COMPUTATIONAL TEST CASE - MISSOURI RIVER

I. FLOW RATES: (Monthly Average for August 1974)

Station	River Mile	Flow Rate (cfs)
Sioux City	732.3	35520
Omaha	615.9	36470
Nebraska City	562.6	37760
Rulo	498.0	39130

II. WEATHER DATA: (Monthly Average for August 1974)

Station	Air Temperature (°F)	Wind Speed (mph)	Relative Humidity (%)	Cloud Cover (tenths)	Atmospheric Pressure (mb)	Solar Radiation (cal/cm^2/day)
Sioux City	70.88	1.75	66.0	6.3	976.3	523.29
Omaha	70.52	1.79	75.0	7.0	981.0	523.29
St. Joseph	71.24	0.90	68.0	6.9	979.3	522.67

III. WATER TEMPERATURES: (Measured on August 21, 1974)

Station	River Mile	Temperature (°C)	Remarks
Upstream George Neal Station	733	24.5	Initial temperature for the calculations.
Fort Calhoun	646	24.4	
Brownville	533	25.0	Average of measured values of 23.9°C on Aug. 17 and 26.1 on Aug. 24.

Table 1b

BACKGROUND DATA FOR COMPUTATIONAL TEST CASE - MISSISSIPPI RIVER

I. MAIN STEM FLOW RATES: (Average at time of survey)

Station	River Mile	Flow Rate (cfs)
Becker	906	1664
Lock and Dam No. 3	796	7380 (U.S. Army Corps of Eng.)

TRIBUTARY FLOW RATES:

Minnesota River	Conf. at RM 844	850 (USGS)
St. Croix River	Conf. at RM 811.5	3780 (U.S. Army Corps of Eng.)

II. WEATHER DATA: (At time of survey)

Station	Air Temperature (°F)	Wind Speed (mph)	Relative Humidity (%)	Cloud Cover (tenths)	Solar Radiation (cal/cm^2/day)
Becker	64.0	Light/Var.	56	0	--
Prescot	69.8	5.0	55	0	601.09
Lock & Dam #3	72.5	5.0	55	0	601.09

III. WATER TEMPERATURES: (Measured at time of survey)

Station	River Mile	Temperature (°C)	Remarks
Becker	906	20.8	Initial temperature for calculations
Lock & Dam No. 3	796	20.6	
Mouth of Minnesota River	844	19.2	Tributary temperature
Mouth of St. Croix River	811.5	18.3	Tributary temperature

IV. POWER PLANT DATA: (At time of survey)

Power Plant	River Mile	Power Level (MW)	Cond. Flow Rate/Temp. Rise (cfs/°F)	Remarks
Monticello	900	371.3	545/15	Cooling towers operating
Elk River	891	0	0	Plant not operating
Riverside	853	295.0	590/16.5	
High Bridge	841	95.0	133.7/18	Unit #5 only
Prairie Island	798	1002.2	150/15	Blowdown

For the Missouri River check, the temperature utilized at the upstream end of the reach (RM 733), which is about two miles upstream from the George Neal Station of the Iowa Public Service Company, is the temperature measured at that site on August 21, 1974. As seen in Fig. 7a, the predicted temperatures at two downstream stations, Fort Calhoun (RM 646) and Brownville (RM 533), are very close to the actual temperatures measured at those locations on the same date.

Along the Mississippi River reach used in the validation test there are four power plants employing once-through cooling systems (Monticello, Elk River, Riverside, and High Bridge), one power plant using closed-cycle cooling but discharging blowdown effluent (Prairie Island), and two major tributaries (Minnesota River and St. Croix River).

On June 2, 1976, at approximately 10:00 a.m., temperature surveys were made of the Mississippi River about 6 miles upstream from Monticello, near Becker, and just downstream from Lock and Dam No. 3. Simultaneously, a temperature survey of each of the tributaries was made just upstream of its confluence with the Mississippi River. The surveys, made by Northern States Power Company, consisted of measurement of vertical temperature profiles at several locations across the river. Meteorological and flow rate data were obtained by the field crews or from the U.S. Geological Survey, the U.S. Army Corps of Engineers, or National Weather Service.

To aid in the evaluation of the thermal loading imposed by each plant on the river, a record of the hourly gross power plant load was kept for the twelve hours prior to the test, and a record of the daily total gross power plant load was kept for the seven days prior to the test. On the day of the test the Elk River plant was shut down, and had been for several days.

The steady-state thermal regime model was employed to predict the temperature distribution along the 100-mile reach of the river. The average river temperature computed from the survey near Becker was used as the upstream ambient river temperature. The streamwise temperature distribution and the comparison with the average surface temperature and average cross-sectional temperature measured downstream from Lock

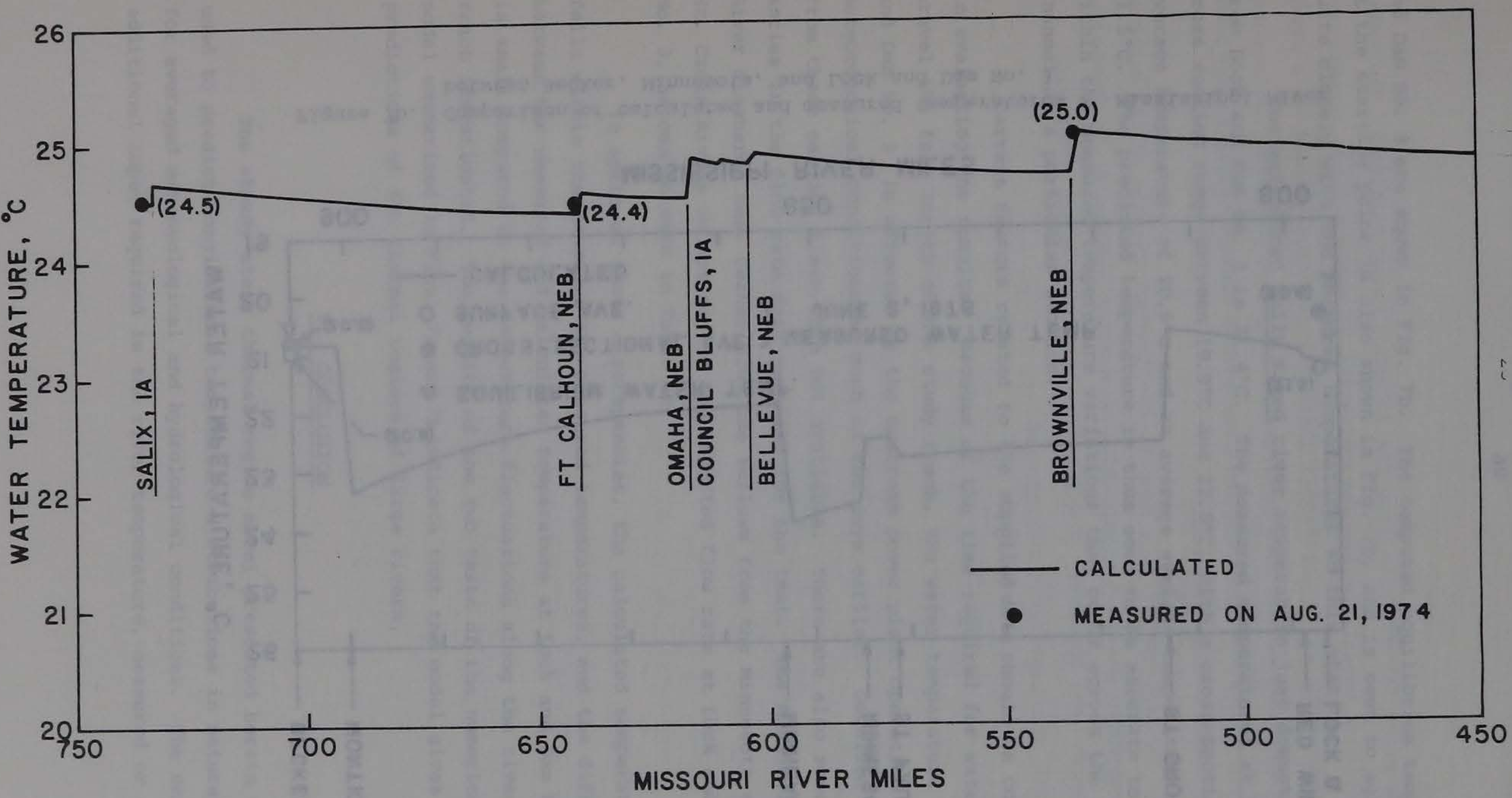

Figure 7a. Comparison of calculated and measured temperatures - Missouri River between Salix, Iowa, and Brownville, Nebraska

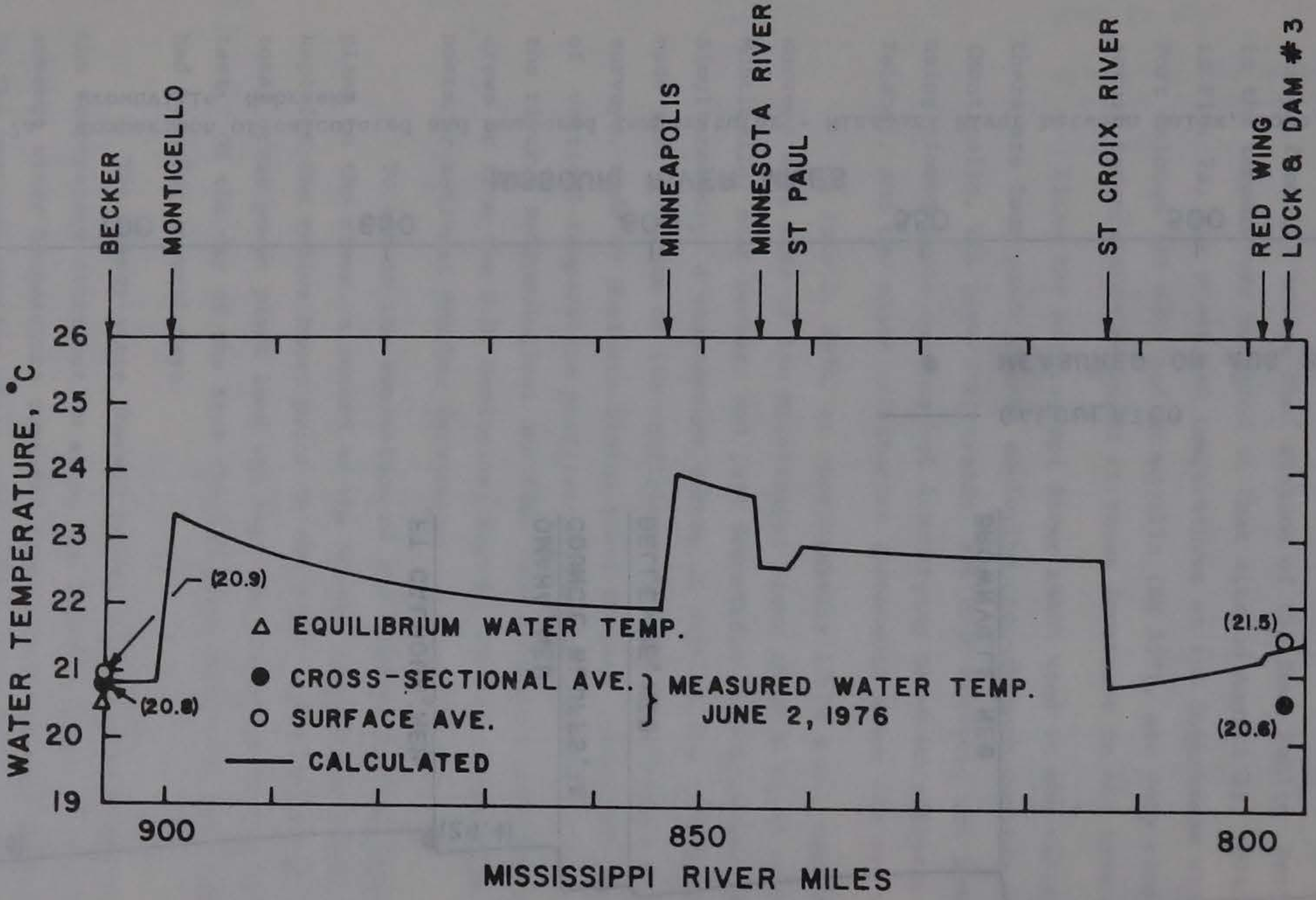

Figure 7b. Comparison of calculated and measured temperatures - Mississippi River between Becker, Minnesota, and Lock and Dam No. 3

and Dam No. 3 are shown in Fig. 7b. The computed equilibrium temperature at the starting point is also shown in Fig. 7b, and is seen to agree quite closely with the measured temperatures at this station.

The calculated fully mixed river temperature just downstream from Lock and Dam No. 3 is 21.4°C. The measured temperatures at the cross section range between 19.9°C and 22.5°C, with a cross-sectional average temperature of 20.6°C and an average surface-temperature of 21.5°C. The predicted temperature is thus seen to be accurate to within the measured temperature variations that occur across the river channel at a particular section.

Certain factors related to the supplied data should be considered in evaluating the results. Because of the time required for water to travel the full length of the study reach, the water temperature at Lock and Dam No. 3 is affected by the upstream power plant operation and meteorological conditions as much as two days earlier. Detailed data from these earlier times were not available. There are also some discrepancies in the flow rate data supplied for the test. The Mississippi River discharge near Becker plus the inflows from the Minnesota and St. Croix Rivers do not sum to the reported flow rate at Lock and Dam No. 3, as can be seen in Table 1b.

In spite of these discrepancies, the calculated temperature falls within the range of the measured temperatures, and the difference between the measured and calculated temperature at Lock and Dam No. 3 is small compared to the temperature fluctuations along the river reach investigated. The results of the two tests of the numerical model summarized in Figs. 7a and 7b indicate that the model gives reliable predictions of the thermal regimes of large rivers.

V. CONCLUSION

The steady-state thermal regime model presented herein can be used to predict longitudinal temperature distributions in natural rivers for averaged meteorological and hydrological conditions. The only additional input required is the river temperature, measured or calculated, at some point far upstream from the location being examined. The model is especially useful for the determination of ambient river temperatures that would exist if no artificial thermal loads were imposed on a river. The verification of the ITRM obtained by comparing computed and measured temperatures for the Missouri and Mississippi Rivers validates the model as a reliable predictive tool.

In Part Two of this report, the thermal regimes of the Missouri and Mississippi Rivers corresponding to average conditions in February, May, August, and November, predicted by the steady-state ITRM are presented, discussed, and interpreted.

APPENDICES (PART ONE)

APPENDIX A (PART ONE)

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APPENDIX B (PART ONE)

LISTING OF COMPUTER PROGRAM, IN FORTRAN LANGUAGE, FOR PREDICTING THE STEADY-STATE THERMAL REGIMES OF RIVERS

Pages 32 through 56
Available separately upon request from the
Iowa Institute of Hydraulic Research

APPENDIX C (PART ONE)

INPUT DATA FOR SAMPLE RUN-
MISSOURI RIVER BELOW GAVINS POINT DAM-
AVERAGE NOVEMBER CONDITIONS

Pages 58 through 62
Available separately upon request from the
Iowa Institute of Hydraulic Research

APPENDIX D (PART ONE)

RESULTS OF SAMPLE RUN-
THERMAL REGIME OF MISSOURI RIVER
BELOW GAVINS POINT DAM-
AVERAGE NOVEMBER CONDITIONS

Pages 64 through 75
Available separately upon request from the
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PART TWO

ANALYSIS OF THERMAL REGIMES OF THE MISSISSIPPI AND MISSOURI RIVERS IN THE MID-CONTINENT AREA POWER POOL (MAPP) GEOGRAPHICAL AREA

PART TWO

ANALYSIS OF THERMAL REGIMES OF THE MISSISSIPPI AND MISSOURI RIVERS IN THE MID-CONTINENT AREA POWER POOL (MAPP) GEOGRAPHICAL AREA

I. INTRODUCTION

The demand for electrical energy in the United States has been increasing at an annual rate of about 7 percent in recent years, and by the year 2000 the nation's annual electrical energy demand is expected to approach seven billion megawatt-hours [5]*. In order to meet this increasing energy requirement, fossil and nuclear power plants of large capacity presently are being planned or installed by many utilities. The low thermal efficiencies of these plants necessitate the rejection of large amounts of waste heat from their generating units to the surroundings. The heat rejection is achieved by transferring the waste heat in the condensers from the low pressure steam to the cooling water, as illustrated in the schematic representations of fossil and nuclear plants in Figs. 8 and 9, respectively. The heat eventually is transferred from the cooling water to the atmosphere, either directly by means of a cooling tower or spray canal, or indirectly through a cooling pond, river, or large body of water.

The availability of cooling water is of central importance in determining the locations of steam-electric power plants. These plants also require water for boiler make-up, and in some installations, for sluicing ashes; however, these requirements are relatively minor compared to the water needs for condenser cooling. The cooling water system of a plant can be either the recirculating type (closed-cycle cooling) or the once-through type (open-cycle cooling). In recirculating systems, heated water from the condensers is circulated through a cooling tower, cooling pond, or spray canal where its excess heat is transferred, and then the water is returned to the condensers. In once-through systems, cooler water is

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* Numbers in square brackets designate References listed in Appendix A.

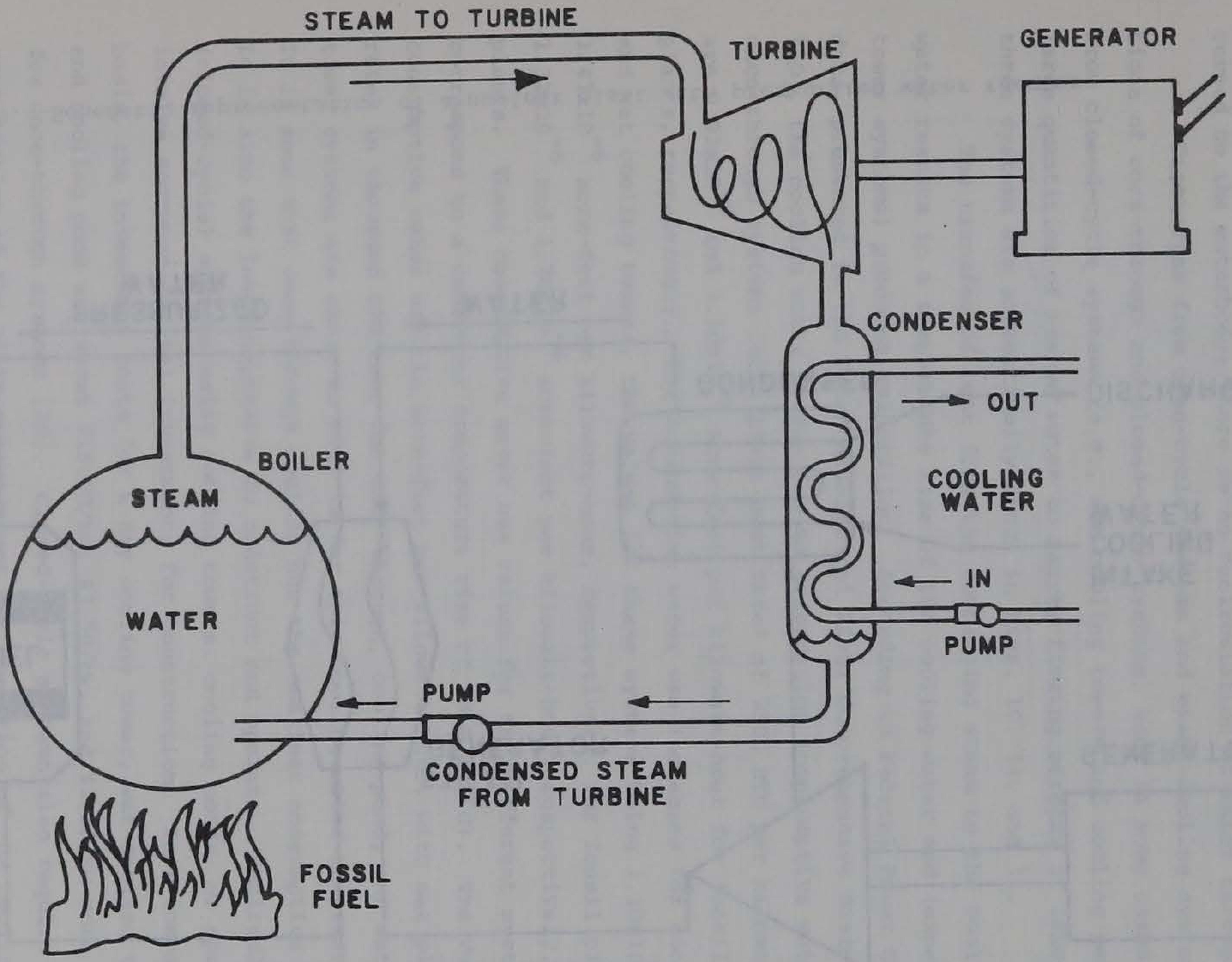

Figure 8. Schematic representation of a fossil plant

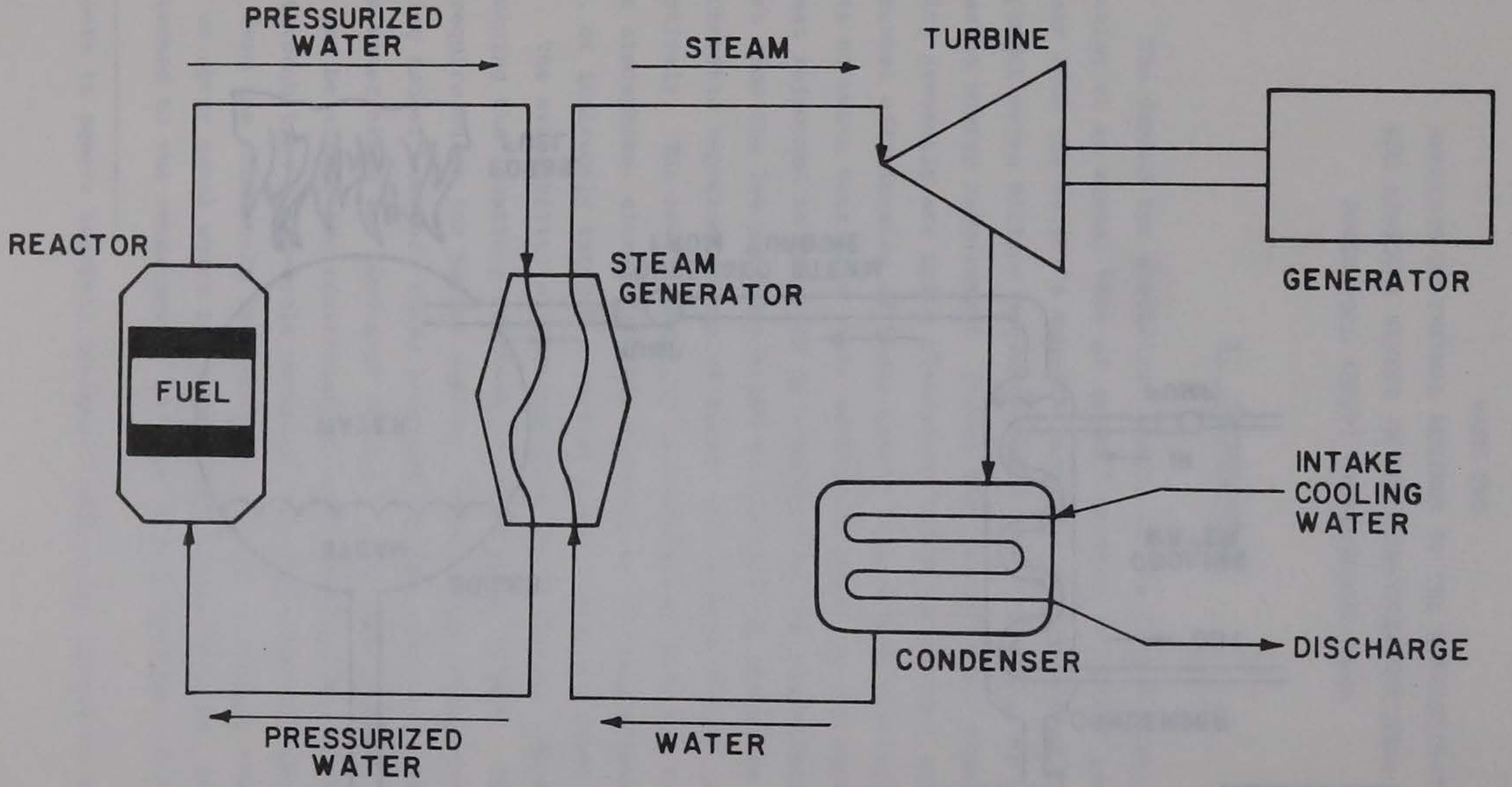

Figure 9. Schematic representation of a nuclear plant with pressurized water reactor

withdrawn from a nearby natural source of water, and the heated water is returned to the waterbody; there is no recirculation of water through the plant.

Discharges from open-cycle systems and mixed-cooling systems (combinations of once-through and closed-cycle systems) and, in some cases, blowdown from closed-cycle systems (e.g., wet cooling towers and cooling ponds) add large quantities of heated water to nearby flowing streams or lakes. These three systems are schematically shown in Figs. 10, 11, and 12.

The transfer of heat from the condensing steam to the cooling water results in a temperature rise of the cooling water and (except in dry tower systems) produces evaporation. According to Federal Power Commission data, presented in the Upper Mississippi River Comprehensive Basin Study [10], the cooling water losses due to evaporation (consumptive water use) in once-through systems for a plant heat rate* of 9500 BTU per kilowatt-hour are 0.92×10^{-6} and 1.10×10^{-6} acre-feet per kilowatt-hour for fossil and nuclear plants, respectively. The consumptive water use increases for cooling ponds and wet cooling towers, the values for these systems being 1.10×10^{-6} and 1.47×10^{-6} acre-feet per kilowatt-hour, respectively, for fossil plants, and 1.32×10^{-6} and 1.76×10^{-6} acre-feet per kilowatt-hour, respectively, for nuclear plants. These consumptive water use values for the different systems correspond to a condenser temperature rise of $18^{\circ}F$ ($10^{\circ}C$). The variation of consumptive water use, in acre-feet per kilowatt-hour, with net plant heat rate, in thousand BTU/kwh, for once-through, cooling pond, and wet cooling tower systems are shown in Fig. 13 for this cooling water temperature rise. It is seen that once-through cooling has the smallest consumptive water losses. It is also the least expensive to construct and operate. Recirculating (closed-cycle) systems using cooling towers, cooling ponds, or spray canals involve enormous capital investments for construction. On a comparative basis, the investment costs for a dry cooling tower, wet cooling tower, and cooling pond are about \$15.00/kw, \$3.50/kw, and \$2.50/kw more than that for once-through systems [10]. Closed-cycle systems also require a significant portion of the plant output power for operation of the cooling systems,

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* The net plant heat rate is the ratio of the total heat content of the fuel consumed (or of the heat released from a nuclear reactor) to the net electrical energy generated; it is a measure of the thermal efficiency of the plant.

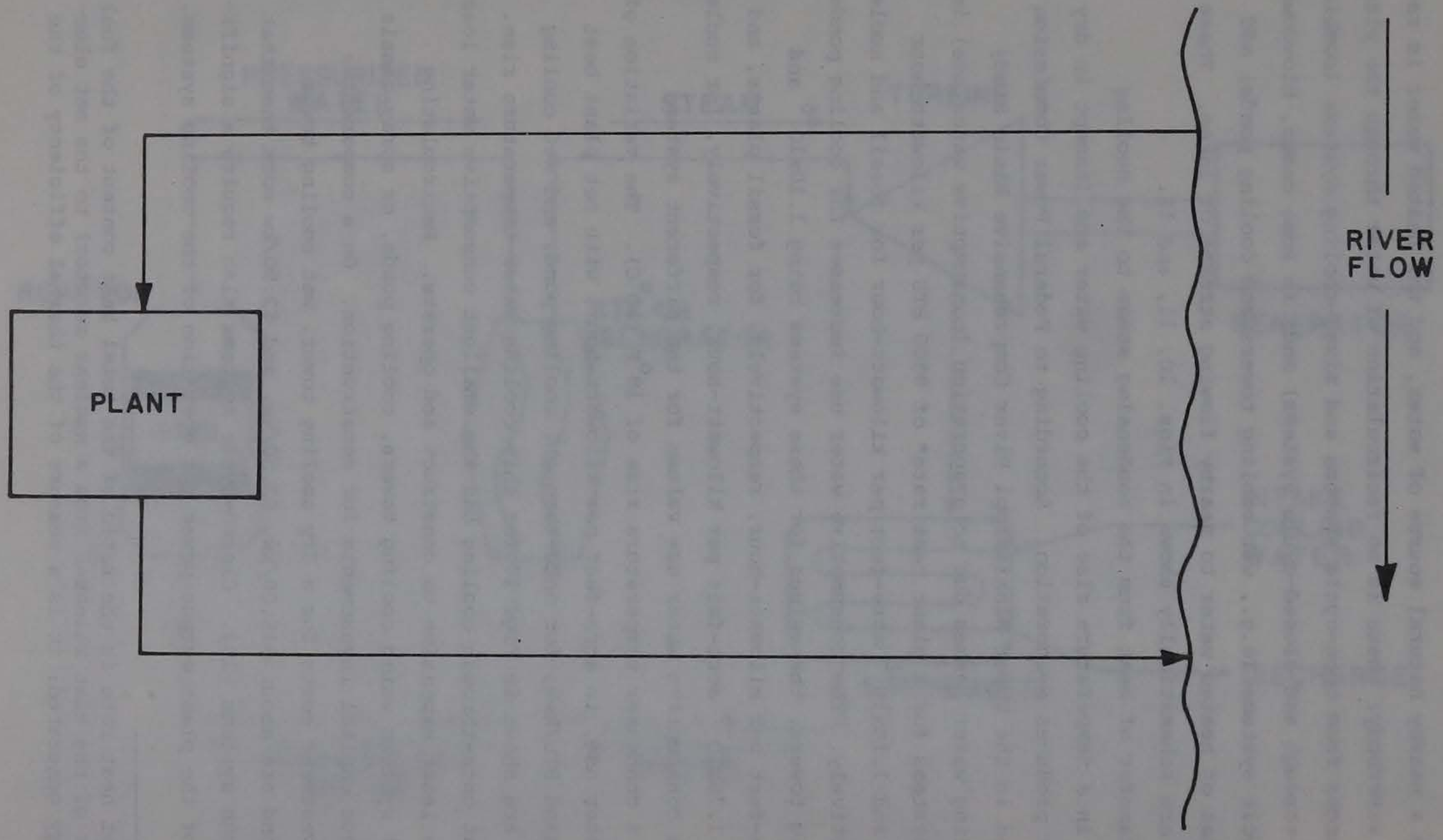

Figure 10. Open-cycle cooling system

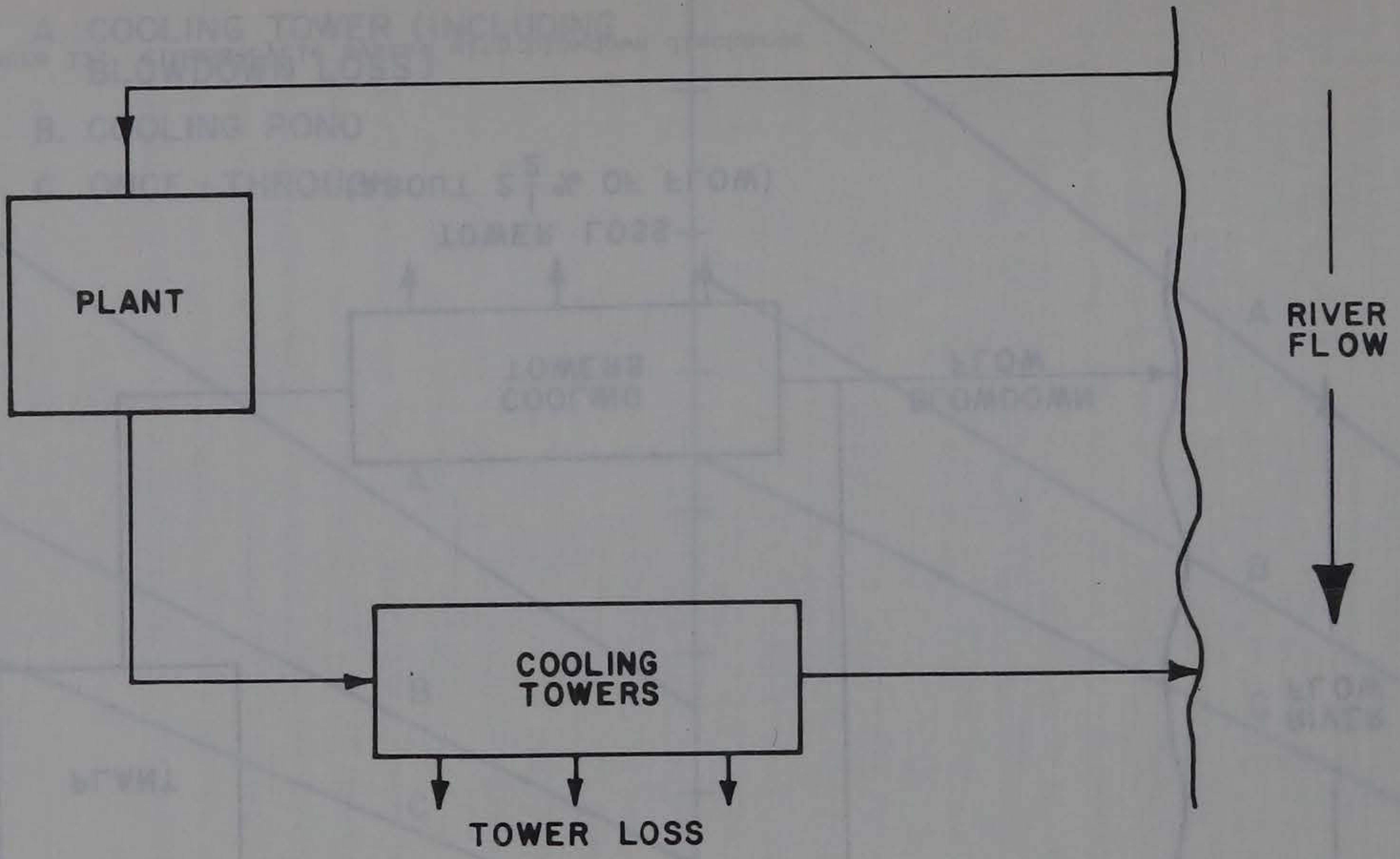

Figure 11. Hybrid system consisting of once-through cooling with a helper tower

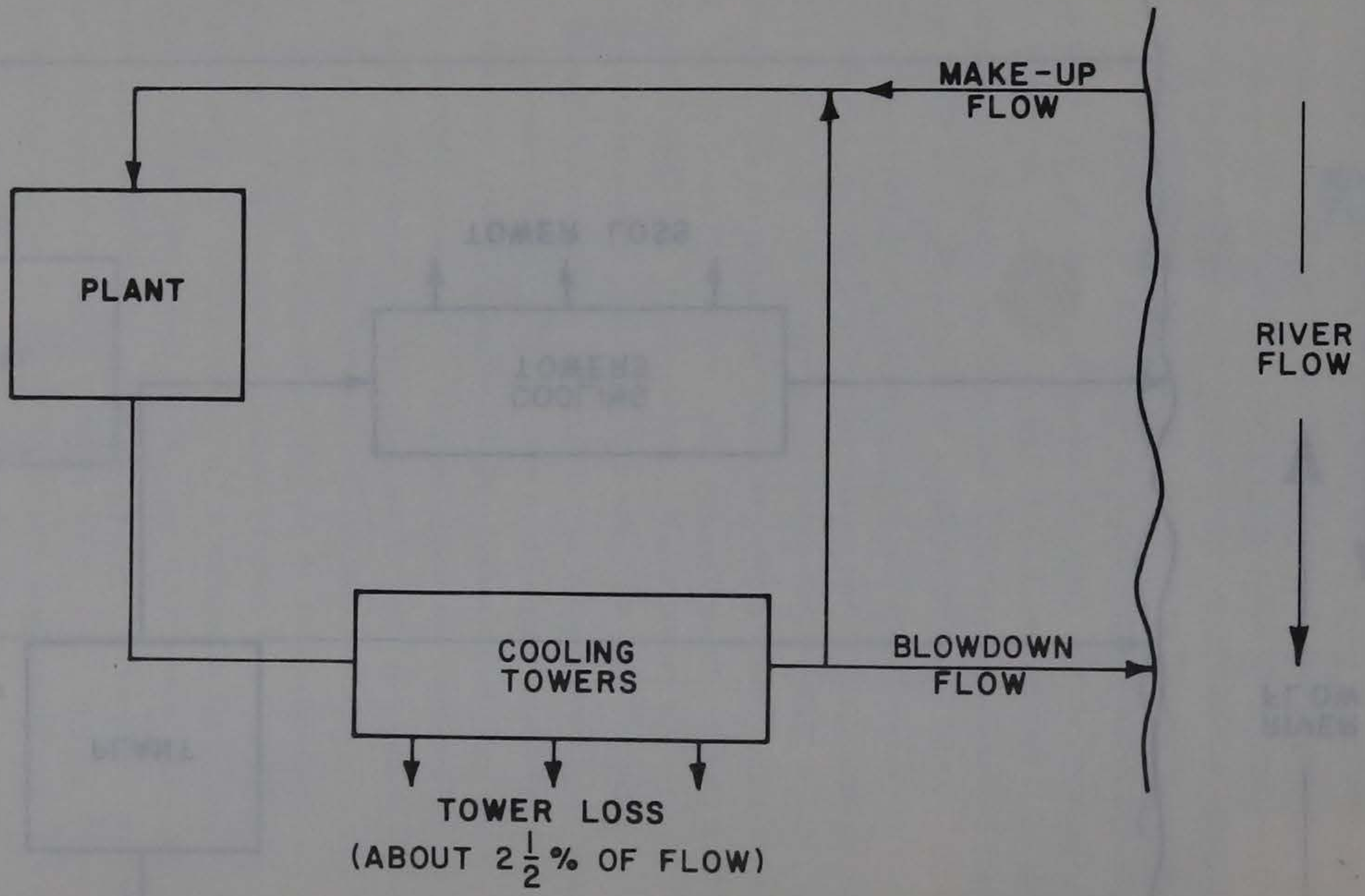

Figure 12. Closed-cycle system with blowdown discharge

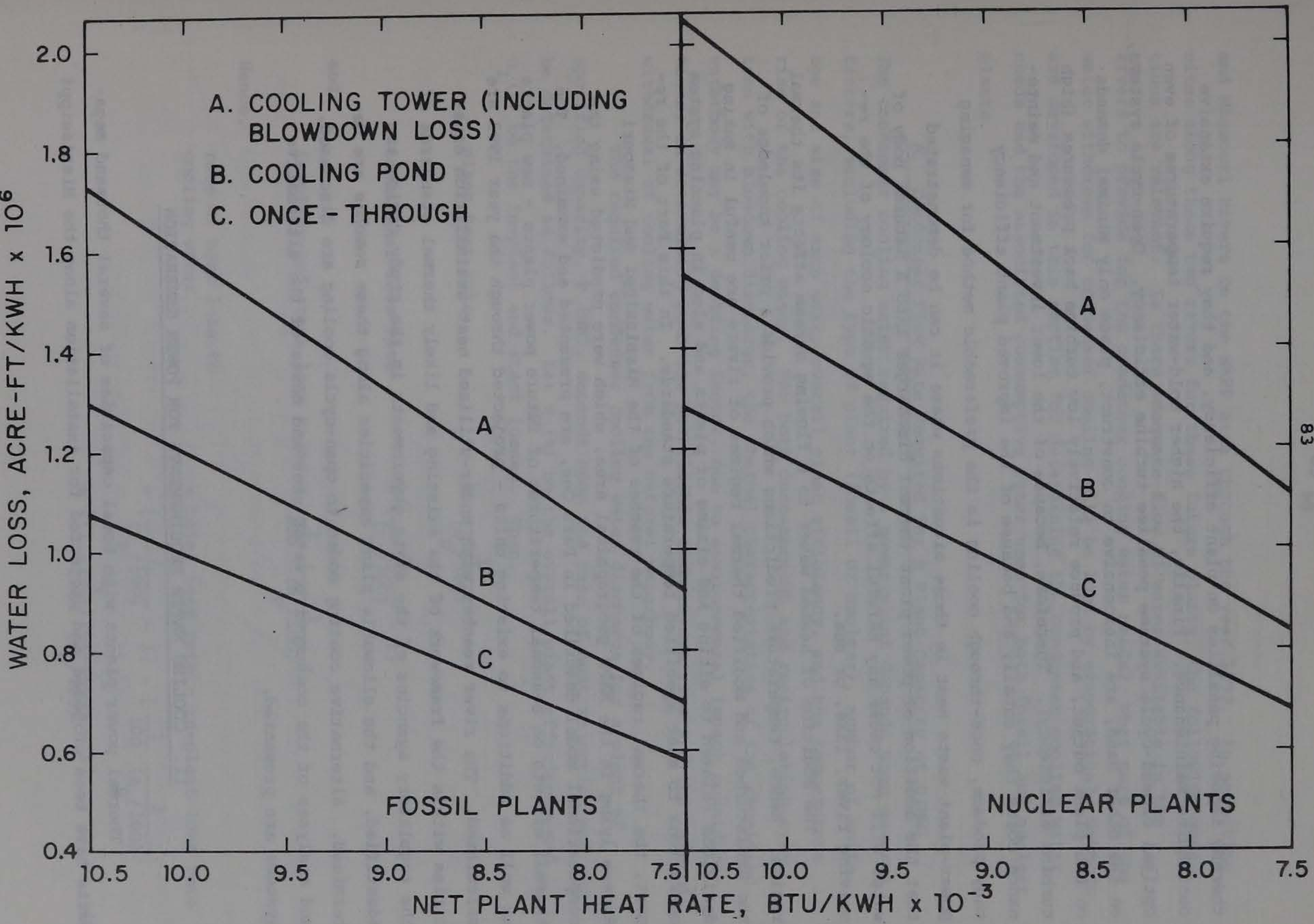

Figure 13. Variation of consumptive water use with net plant heat rate [10]

thereby imposing penalties on plant efficiency, and they require extensive continuing maintenance. Finally, the higher cold-water temperatures of even optimal closed-cycle systems penalize turbine efficiency. Open-cycle systems, on the other hand, are inexpensive to construct, place only minimal demands on the plant output, and produce relatively low turbine back pressures (high turbine efficiency). Therefore, because of the lower investment and maintenance costs they entail, and because of the improved plant efficiency they produce, once-through cooling is the prefereable method for managing power-plant waste heat in those situations where it can be demonstrated that the addition of power plant thermal discharges into a natural body of water will not cause any harmful effects on the aquatic ecology of the receiving river, lake, or sea.

The addition of heated water to a flowing stream affects its thermal regime. Hence, temperature predictions which provide a prior knowledge of the undisturbed and modified thermal regimes of rivers are useful in making decisions related to siting and sizing of plants and also in planning system operations to meet specified temperature standards. In this Part of the report, the thermal regimes of the reaches of the Mississippi and Missouri Rivers lying in the MAPP geographical area, which were predicted using the computational model described in Part One, are presented and examined. The thermal effects on seasonal temperatures of future power plants - new plants as well as additions to existing units - projected through the year 1993 are calculated. The river reaches with under-utilized heat assimilation capacities within the framework of the existing and likely thermal standards of the regulatory agencies of the state governments in the study region are identified, and the allowable plant capacities along these reaches are determined. Alternative cooling modes to open-cycle cooling are discussed, and analyses of the consumptive water uses and costs of the alternative systems are presented.

II. COOLING WATER REQUIREMENTS FOR POWER GENERATION

Thermal power plants with total capacities of several thousand megawatts have been proposed and projected for installation along the Mississippi and Missouri Rivers in the MAPP area through the year 1993. In selecting sites along these two rivers for these future plants, the following questions are relevant: Is there adequate flow of water available in the rivers to provide for the condenser cooling water needs? What part of the water withdrawn for condenser cooling will be lost by evaporation? Methods are developed in this section for determining the condenser cooling water needs and the associated consumptive water uses for both fossil and nuclear plants.

A. Condenser Flow Rate Required for a Plant Capacity of P(MW).

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 for a plant of specified capacity, P (MW), depends upon the rate of heat rejection and can be determined as follows. Let $\eta_p(\%)$ be the overall plant efficiency and $\eta_I(\%)$ be the in-plant and stack losses. Then,

$$\text{plant heat rate} = \frac{1}{(\eta_p/100)}$$

$$\text{total heat-loss rate} = \left[\frac{1}{(\eta_p/100)} - 1\right]$$

and

$$\text{in-plant and stack loss rate} = \frac{\eta_I}{100}\left[\frac{1}{(\eta_p/100)}\right].$$

Hence,

$$\begin{aligned}\text{rate of heat loss to cooling water} &= \text{total loss rate - in-plant loss rate}\\ &= \left[\frac{1}{(\eta_p/100)} - 1\right] - \left[\frac{\eta_I}{100}\,\frac{1}{(\eta_p/100)}\right]\\ &= \left[\left(1 - \frac{\eta_I}{100}\right)\frac{1}{(\eta_p/100)} - 1\right] \qquad (48)\end{aligned}$$

or,

$$\text{unit rate of heat rejected to cooling water} = \left[\left(1 - \frac{\eta_I}{100}\right) \frac{1}{(\eta_p/100)} - 1\right] \times (K) \tag{49}$$

where

$K = 0.86\text{x}10^6$, calories/kwh, or

$K = 3.413\text{x}10^3$, BTU/kwh, or

$K = 3.6\text{x}10^6$, Joules/kwh

Therefore, for a plant of capacity P (MW), the heat rejection rate is

$$[HR] = \left[\left(1 - \frac{\eta_I}{100}\right) \frac{1}{(\eta_p/100)} - 1\right] \times (K) \times (10^3 P) \tag{50}$$

in heat units per hr.

Also,

$$[HR] = (\rho c_p)(Q_e)(\Delta T_e) \tag{51}$$

where

$\rho c_p = 1.0$ cal/cm^3-$^\circ$C, for [HR] in cal/kwh, (ΔT_e) in $^\circ$C,

$\rho c_p = 62.4$ BTU/ft^3-$^\circ$F, for [HR] in BTU/kwh, (ΔT_e) in $^\circ$F, and

$\rho c_p = 4.186$ Joules/cm^3 - $^\circ$C, for [HR] in Joules/kwh, (ΔT_e) in $^\circ$C

Thus, for a specified temperature rise of ΔT_e, the required condenser cooling water flow rate is

$$\begin{aligned} Q_e &= \left(\frac{K}{\rho c_p}\right)\left(\frac{10^3 P}{\Delta T_e}\right) \left[\left(1 - \frac{\eta_I}{100}\right) \frac{1}{(\eta_p/100)} - 1\right] \\ &= K_1\left(\frac{P}{\Delta T_e}\right)\left[\left(1 - \frac{\eta_I}{100}\right) \frac{1}{(\eta_p/100)} - 1\right], \end{aligned} \tag{52}$$

where $K_1 = 0.86\text{x}10^9$, for Q_e in cm^3/hr, with (ΔT_e) in $^\circ$C, or

$K_1 = 0.547\text{x}10^5$, for Q_e in ft^3/hr, with (ΔT_e) in $^\circ$F

The condenser-water discharge required by a plant of specified capacity, P(MW), can be determined, from (52) if allowable temperature rise is specified and the in-plant losses and the overall plant efficiency are known. Figure 14 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 (52) are as follows.

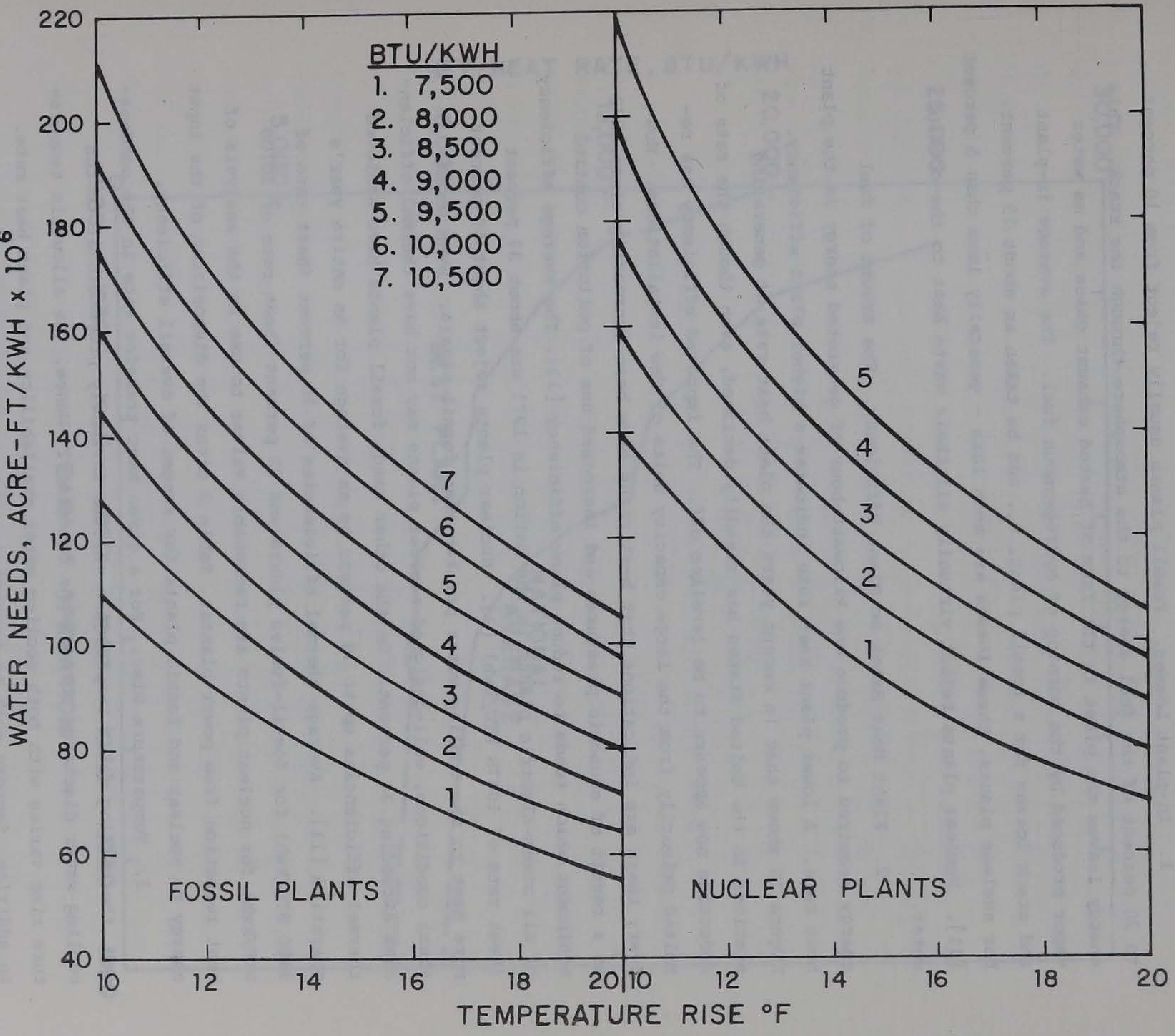

Figure 14. Cooling water requirements of fossil and nuclear plants [10]

1. In-plant Losses. Fossil plants usually reject from 10 percent to 20 percent of the fuel energy to the atmosphere through the stack. This energy leaves the plant in the form of heated exhaust gases and as water vapor produced by the burning of hydrogeneous fuel. The average in-plant and stack losses for a fossil plant, η_I, can be taken as about 15 percent. For nuclear plants, these losses are much less - generally less than 5 percent [11]. Nuclear plants reject virtually all their waste heat to the cooling water.

2. Plant Heat Rates or Plant Efficiency. The amount of fuel energy required to produce one kilowatt-hour of generated energy is the plant heat rate. A lower plant heat rate indicates a higher plant efficiency. Figure 15 shows that in recent years the plant heat rate of generating stations in the United States has steadily declined, even though the rate of reduction now appears to be leveling off. The improved efficiency has resulted primarily from the large capacity units of new installations. However, there are indications that heat rates have been increasing since 1972 as a result of economic pressures and increased use of pollution control equipment which tends to reduce plant efficiency [11]. The average efficiency of all steam-electric plants in the nation in 1971 was about 33 percent (heat rate of 10478 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 [11]. Average thermal efficiencies of 36 percent (heat rate of 9480 BTU/kwh) for fossil-fueled plants and 32 percent (heat rate of 10700 BTU/kwh) for nuclear plants are reasonable values to use in the analysis of heat rejection from power plants. Table 2 gives the disposition of the input energy to nuclear and fossil plants for ranges of overall efficiency.

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

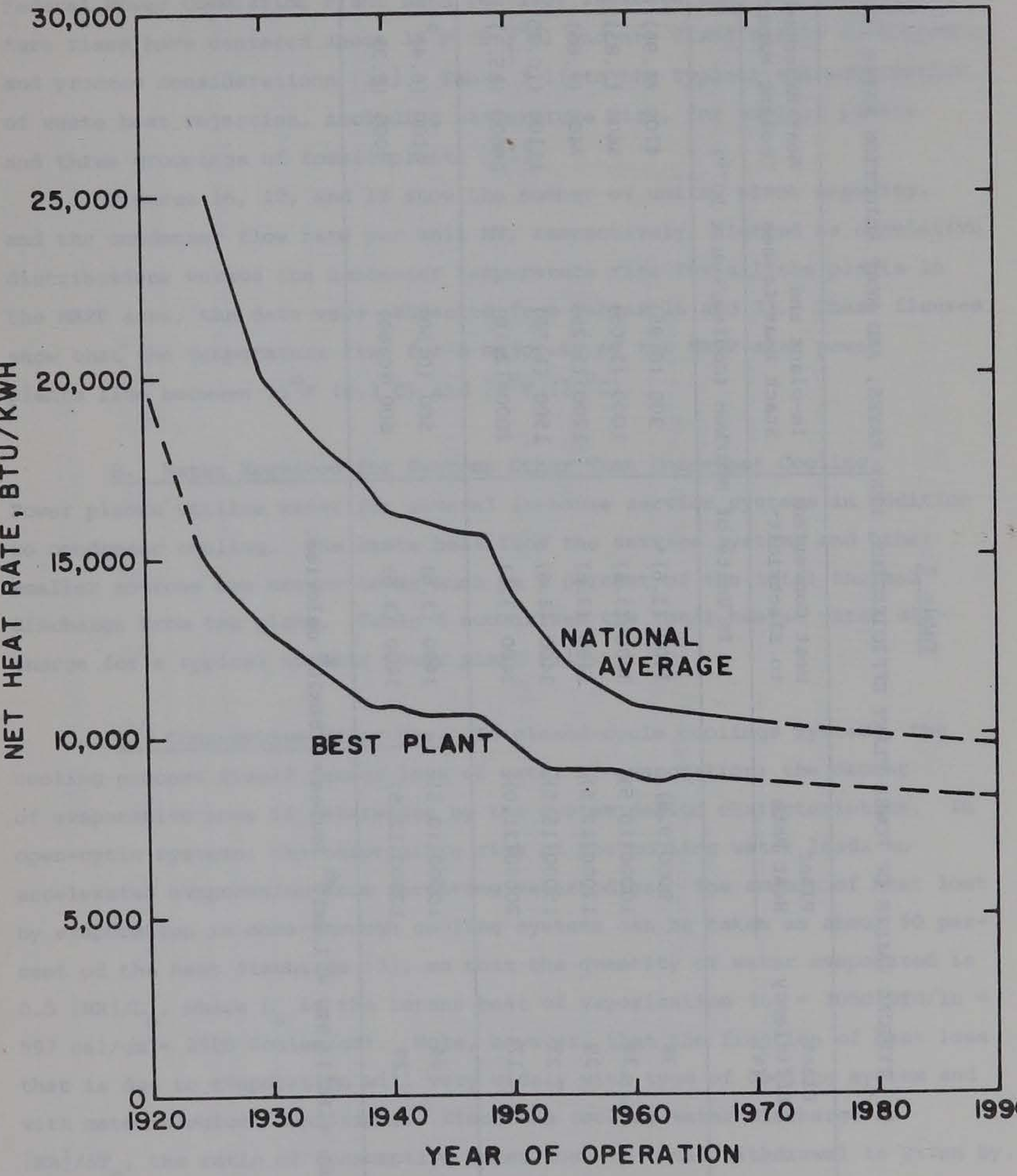

Figure 15. Heat rates of fossil plants [11]

Table 2

TYPICAL VALUES OF POWER PLANT EFFICIENCIES, HEAT RATES, AND HEAT REJECTION RATES [11]

Type	Plant Efficiency (%)	Plant Heat Rate	Heat Converted to Electricity	In-plant and Stack Heat Losses	Heat Rejected to Cooling Water
		In Units of BTU/kwh (Joules/kwh x 10^{-6})			
Fossil Plant	38	9000(9.5)	3400 (3.6)*	900 (0.95)	4700 (4.95)
	34	10000(10.5)	3400 (3.6)	1000 (1.05)	5600 (5.85)
	29	12000(12.5)	3400 (3.6)	1200 (1.25)	7400 (7.65)
	23	15000(15.5)	3400 (3.6)	1500 (1.55)	11100 (10.35)
	17	20000(21.0)	3400 (3.6)	2000 (2.10)	14600 (15.3)
Nuclear Plant	34	10000(10.5)	3400 (3.6)	500 (0.50)	6100 (6.4)
	29	12000(12.5)	3400 (3.6)	600 (0.60)	8000 (8.3)

* 1 kwh = 3413 BTU = 3.6×10^6 Joules = 0.86×10^6 calories.

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 [11]. Table 3 lists the typical characteristics of waste heat rejection, including temperature rise, for nuclear plants and three groupings of fossil plants [11].

Figures 16, 17, and 18 show the number of units, plant capacity, and the condenser flow rate per unit MW, respectively, plotted as cumulative distributions versus the condenser temperature rise for all the plants in the MAPP area; the data were extracted from Tables 16 and 31. These figures show that the temperature rise for a majority of the MAPP-area power plants lies between 15°F (8.3°C) and 18°F (10°C).

B. Water Required for Systems Other Than Condenser Cooling. Power plants utilize water for several in-house service systems in addition to condenser cooling. The waste heat from the service systems and other smaller sources can amount to as much as 1 percent of the total thermal discharge from the plant. Table 4 summarizes the total heated water discharge for a typical nuclear power plant [11].

C. Consumptive Water Use. In closed-cycle coolings systems, the 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 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,

$$\frac{\text{consumptive water loss}}{\text{total withdrawal}} = \frac{\Delta T_e}{2L_o} \text{ (for once-through cooling)} \qquad (53)$$

Table 3

TYPICAL CHARACTERISTICS OF WASTE HEAT REJECTION [11]

Type	Heat Rate, in BTU/kwh (Joules/kwh x 10^{-6})		Heat Rejection to Cooling Water, in BTU/kwh (Joules/kwh x 10^{-6})		Temperature Rise, in °F (°C)	
Fossil Plants:						
(i) National Average	10500	(11.1)	5500	(5.8)	15.5	(8.6)
(ii) High Utilization*	8700-12500	(9.2-13.2)	4000 - 7600	(4.2-8.0)	8.1-23.4	(4.5-13.0)
(iii) Intermediate Utilization	10000-16000	(10.5-16.9)	5000-10100	(5.3-10.7)	8.1-23.4	(4.5-13.0)
(iv) Low Utilization	10000-20000	(10.5-21.0)	5000-13600	(5.3-14.3)	8.1-19.8	(4.5-11.0)
Nuclear Plants	9700-11000	(10.2-11.6)	6800 - 7600	(7.2-8.0)	18.0-28.8	(10.0-16.0)

* High Utilization: Plant operated more than 6000 hrs per year; Intermediate Utilization: Between 2000 and 6000 hrs per year; Low Utilization: Less than 2000 hrs per year.

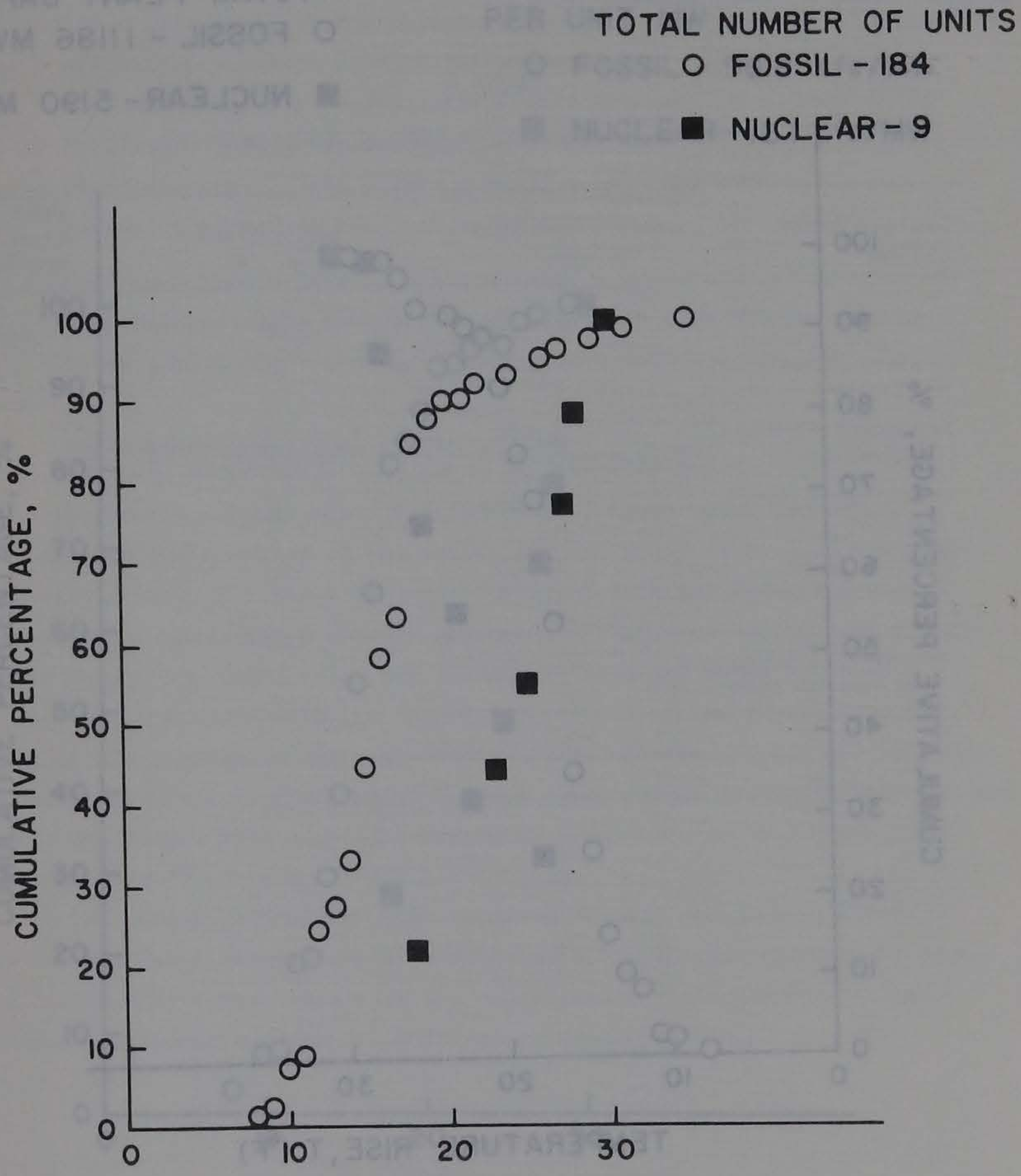

Figure 16. Cumulative distribution of number of units in the MAPP region with condenser temperature rise less than T

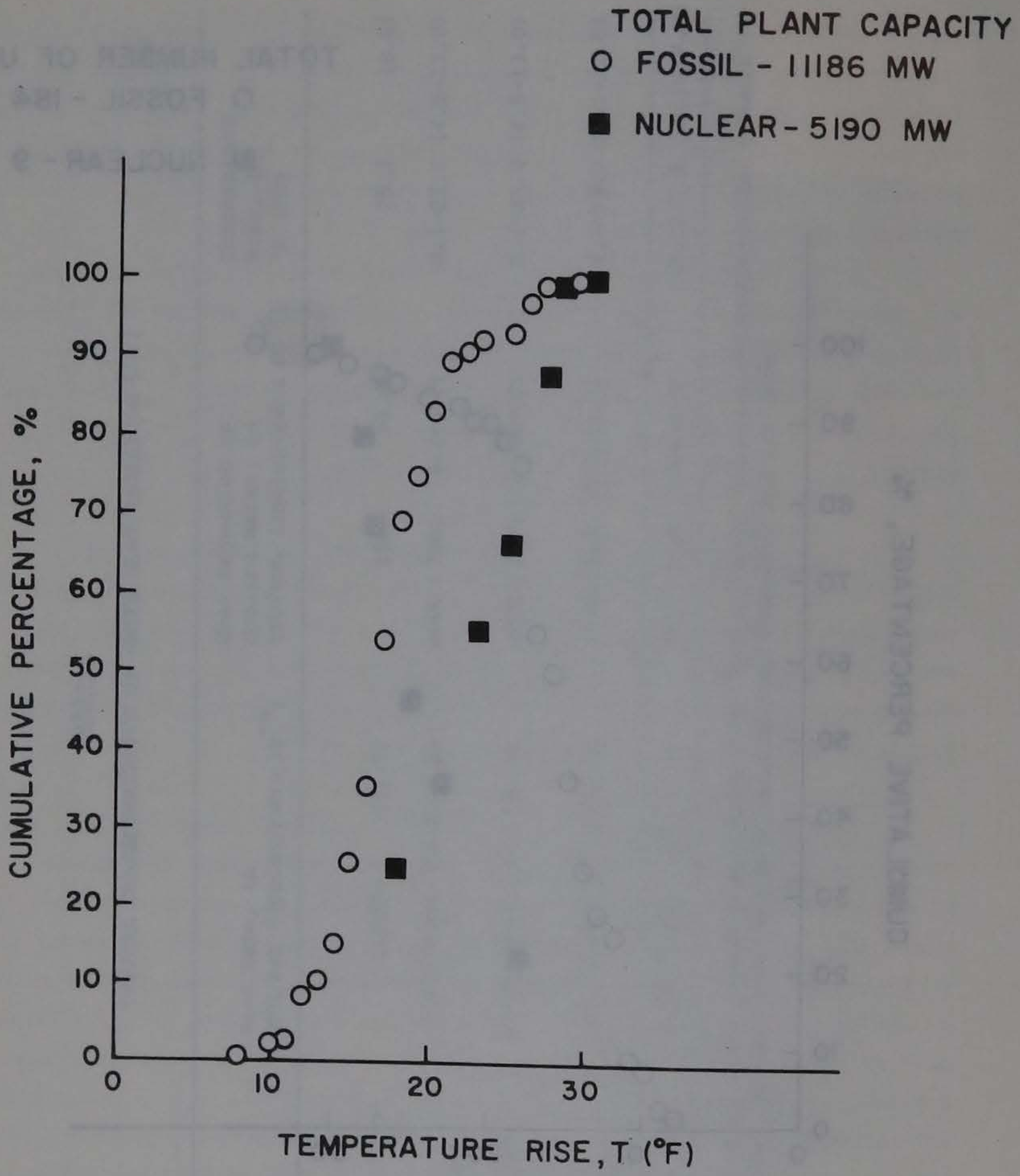

Figure 17. Cumulative distribution of power generation in the MAPP region with condenser temperature rise less than T

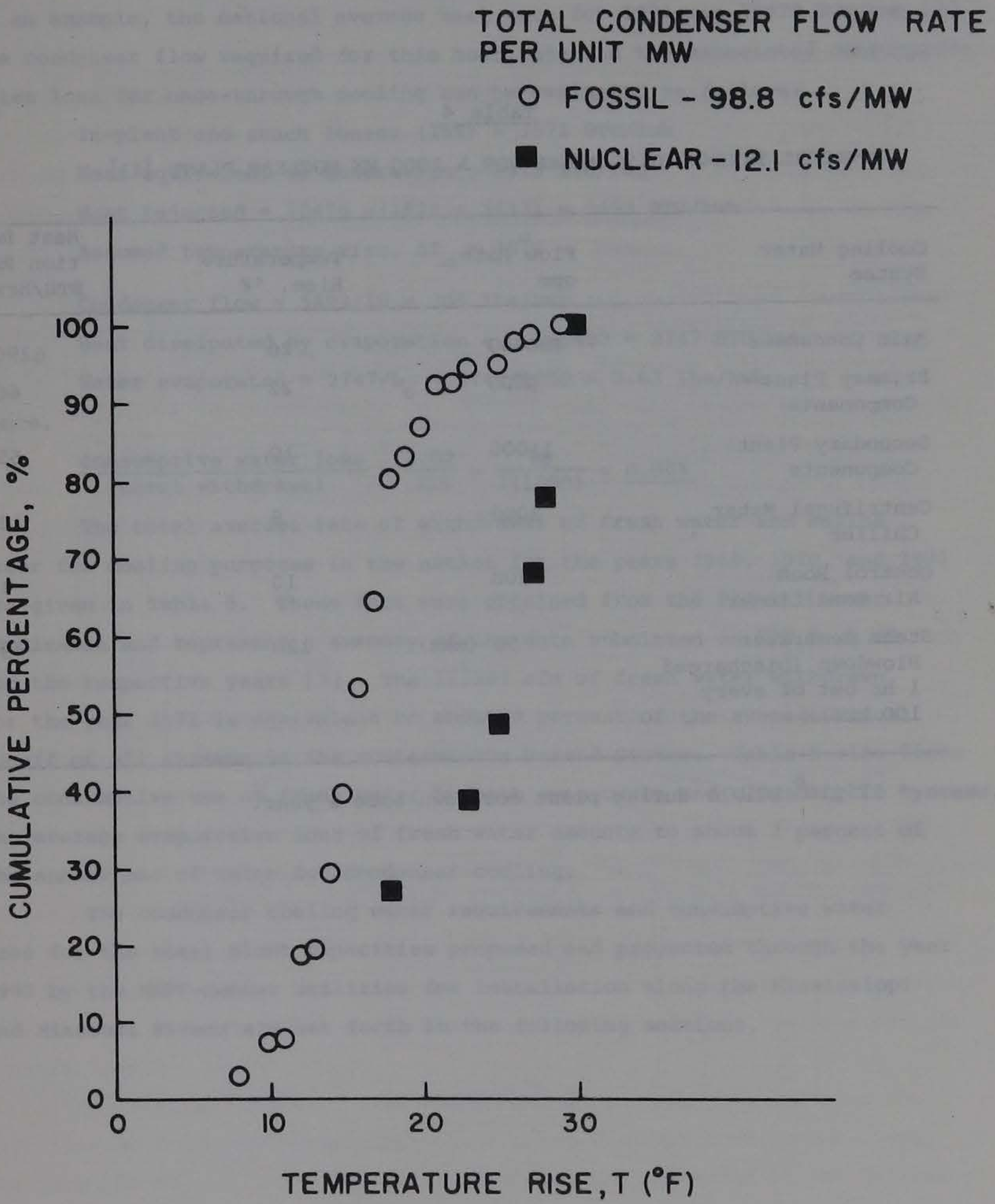

Figure 18. Cumulative distribution of condenser flow rate per MW in MAPP region with condenser temperature rise less than T

Table 4

TYPICAL THERMAL DISCHARGES FOR A 1000 MW NUCLEAR PLANT [11]

Cooling Water System	Flow Rate, gpm	Temperature Rise, °F	Heat Rejection Rate BTU/hrx10^{-6}
Main Condenser	480400	26	6290
Primary Plant Components	5800	22	66*
Secondary Plant Components	11000	10	55
Centrifugal Water Chiller	3000	9	13
Control Room Air Conditioner	200	10	1
Steam Generator Blowdown (Discharged 1 hr out of every 100 hrs)	50 (max)	120	3 (max)

* 175x10^{6} BTU/hr during plant cooldown once a year.

As an example, the national average heat rate for 1971 was 10478 BTU/kwh [3]. The condenser flow required for this heat rate and the associated consumptive water loss for once-through cooling can be evaluated as follows:

In-plant and stack losses (15%) = 1572 BTU/kwh

Heat equivalent of generation = 3413 BTU/kwh

Heat rejected = 10478 -(1572 + 3413) = 5493 BTU/kwh

Assumed temperature rise, $\Delta T_e = 18^{\circ}F$

Condenser flow = 5493/18 = 305 lbs/kwh

Heat dissipated by evaporation = 0.5x5493 = 2747 BTU/kwh

Water evaporated = $2747/L_o$ = 2747/1050 = 2.62 lbs/kwh

Hence,

$$\frac{\text{consumptive water loss}}{\text{total withdrawal}} = \frac{2.62}{305} = \frac{18}{2(1050)} = \underline{0.86\%}$$

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 5. 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 172392 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 5 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.

The condenser cooling water requirements and consumptive water uses for the total plant capacities proposed and projected through the year 1993 by the MAPP-member utilities for installation along the Mississippi and Missouri Rivers are set forth in the following sections.

Table 5

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

	Quantity of Water, (cfs)		
year	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.

III. THERMAL ANALYSIS OF THE MISSISSIPPI RIVER

A. The Upper Mississippi River System. The Mississippi River rises in the lake and forest country of north-central Minnesota near the village of Bemidji and in the vicinity of Lake Itasca. The river follows a roughly circular course for the first 375 miles and then flows in a general southerly direction about 2100 miles farther to the Gulf of Mexico. The reach of the river extending about 1370 miles between its source and its junction with the Ohio River at Cairo, Illinois, is referred to as the Upper Mississippi River. Locations along this reach are identified by their distance in miles, measured along the channel, from the intersection of the thalwegs of the Mississippi and Ohio Rivers. The Missouri River merges with the Upper Mississippi at Mile 196 between Alton, Illinois, and St. Louis, Missouri. There are eight major tributaries that enter the Upper Mississippi River: the Minnesota River (at Mile 844), St. Croix River (at Mile 811), Chippewa River (at Mile 763), Wisconsin River (at Mile 631) Rock River (at Mile 479), Cedar-Iowa River (at Mile 434), Des Moines River (at Mile 362), and Illinois River (at Mile 218). A map of the river system is shown in Fig. 19.

The waterway of the Upper Mississippi River contains 26 pools formed by navigation dams which lie between St. Anthony Falls Dam (Mile 853.7) at Minneapolis, Minnesota, and Lock and Dam No. 26 (Mile 202.7) at Alton, Illinois, as shown in Fig. 20. The locations of the locks and dams that separate the pools are listed in Table 6. Pool No. 1 lies between River Miles 847.6 and 853.7, and the St. Anthony Pool extends above it to Mile 857.6. The Mississippi River waterway has been improved to provide a minimum navigation-channel depth of 9 ft for long-haul common-carrier service. The channel width normally available for navigation during ice-free periods ranges from 200 ft to 400 ft.

The Mid-Continent Area Power Pool geographic area contains the portions of the Upper Mississippi River lying upstream from Keokuk, Iowa, as shown in Fig. 21. The thermal regime analysis presented in the following sections covers the approximately 840-mile long stretch of the river between Cohasset, Minnesota (Mile 1200), and Keokuk, Iowa (Mile 364).

B. Cooling Water Uses and Needs. The total installed thermal plant capacity along the Mississippi River in the MAPP area as of 1975 was about

Figure 19. Upper Mississippi River system

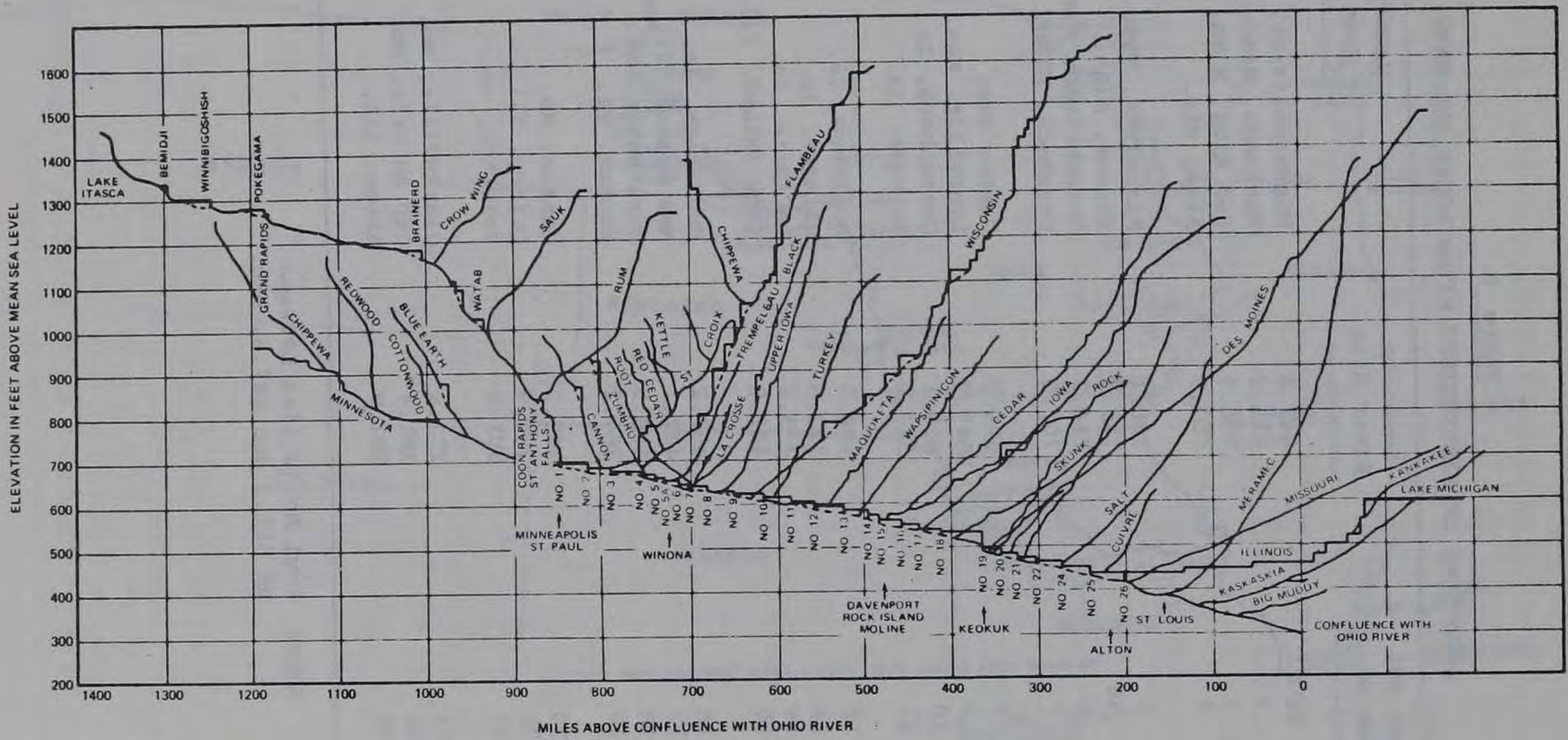

Figure 20. Locations of Mississippi River locks and dams

Table 6

LOCATIONS OF MISSISSIPPI RIVER LOCKS AND DAMS

Lock and Dam No.	Location River Mile	Nearest Town
1	847.6	Minneapolis-St. Paul, Minn.
2	815.2	Hastings, Minn.
3	796.9	Red Wing, Minn.
4	752.8	Alma, Wis.
5	738.1	Minneiska, Minn.
5A	728.5	Winona, Minn.
6	714.3	Trempealean, Wis.
7	702.5	Dresbach, Minn.
8	679.2	Genoa, Wis.
9	647.9	Lynxville, Wis.
10	615.1	Guttenberg, Ia.
11	583.0	Dubuque, Ia.
12	556.7	Bellevue, Ia.
13	522.5	Clinton, Ia.
14	493.3	LeClaire, Ia.
15	482.9	Rock Island, Ill.
16	457.2	Muscatine, Ia.
17	437.1	New Boston, Ill.
18	410.5	Burlington, Ia.
19	364.2	Keokuk, Ia.
20	343.2	Canton, Mo.
21	324.9	Quincy, Ill.
22	301.2	Severton, Mo.
24	273.4	Clarksville, Mo.
25	241.4	Cap Au Gris, Mo.
26	202.9	Alton, Ill.

Note: Pool No. 2 lies between RM 815.2 and 847.6, etc.

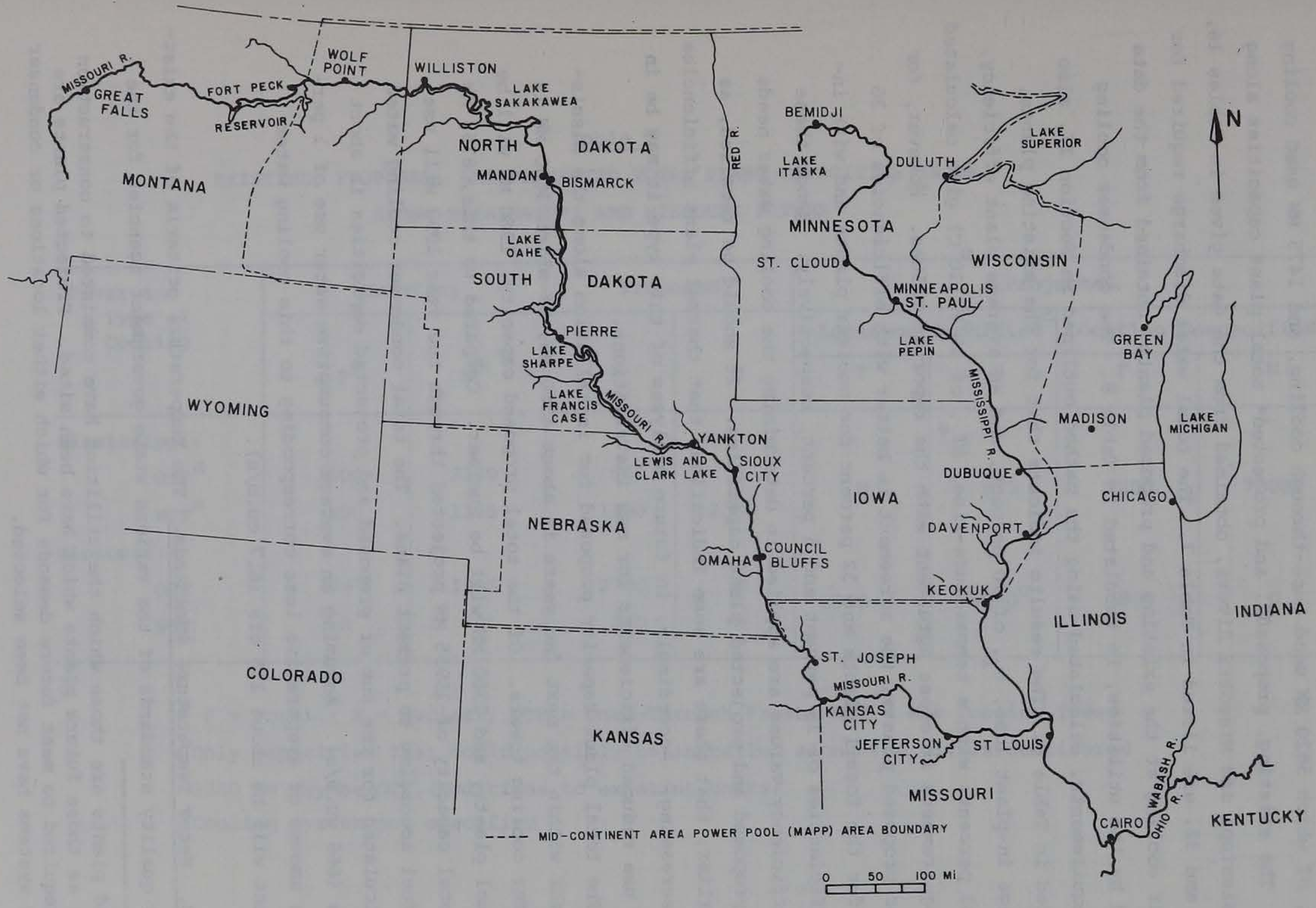

Figure 21. Mississippi and Missouri Rivers and the MAPP geographical area

7295 MW, of which 5820 MW used once-through cooling, and 1475 MW used cooling towers. The existing, proposed*, and projected* total plant capacities along the Mississippi and Missouri Rivers, obtained from the data given in Tables 16, 17, 31, and 32, are listed in Table 7. 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 8. The condenser cooling water requirements, calculated using the method outlined in Section II, also are listed in Table 8. The results indicate that for the existing plants, an average in-plant loss, η_I, of 10 percent, and an average plant efficiency, η_p, of 33 percent, with a temperature-rise, ΔT_e, 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 are applied in determining the cooling water needs for the proposed and projected plant capacities. It should be recalled, as noted earlier, that there are some indications that thermal plant efficiencies may be decreasing. Accordingly, in future analyses of this type it may be in order to use reduced efficiencies for new installations.

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. 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 15955 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 23510 cfs (666 cu.m/s). Assuming an average consumptive water use of 1 percent, the amount of evaporative loss corresponding to this cooling water requirement will be about 235 cfs (6.7 cu.m/s).

C. Water Temperature Standards. The temperature criteria of the existing water quality standards of the various state government agencies for the

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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 have not been selected.

Table 7

EXISTING, PROPOSED, AND PROJECTED TOTAL PLANT CAPACITIES IN MW ALONG MISSISSIPPI AND MISSOURI RIVERS

River and Type of Cooling	Existing		Proposed		Projected			
					Location Specified[d]		Location Unspecified[b]	
	F[a]	N[a]	F	N	F	N	F	N
Mississippi:								
OTF[a]	3600	2220	600	0	0	955	7200	7800
WCT[a]	350	1125	1360	2300				
Missouri:								
OTF	2140	1295	2760	0	2920	4200[c]	800	0
WCT	0	0	840	0				

---

[a] F = Fossil; N = Nuclear; OTF = Once-Through Fresh; WCT = Wet Cooling Tower

[b] Only capacities that could possibly be installed along the rivers considered

[c] 2300 MW may be OTF (additions to existing units)

[d] Cooling system not specified

Table 8

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. 52)		Reported, (Table 16)
		η_I = 15%(F), 5%(N); η_p = 36%(F), 32%(N)	η_I = 10%(F,N); η_p = 33%(F,N)	
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

Mississippi and Missouri Rivers are given in Appendix B. A summary of the existing thermal standards of the States of Minnesota, Wisconsin, Iowa, Illinois, and Missouri applicable to the Mississippi River is given in Tables 9 and 10. The maximum allowable temperature excess produced by thermal discharges to the river is $5^{o}F$ ($2.78^{o}C$) at the edge of the mixing zone along the entire study reach of the Mississippi River. The maximum allowable water temperatures change from reach to reach and also from month to month, as shown in Table 10. During January and February the maximum allowable temperatures range from $40^{o}F$ to $50^{o}F$, while during July and August, the range is $83^{o}F$ to $89^{o}F$.

D. Climatic Conditions. The climate of the Upper Mississippi River region is generally continental, but varies somewhat from the northern to the southern extremities of the basin. The climate of the northern part is characterized by cold humid winters and hot summers. The average monthly temperatures vary from $10^{o}F$ to $86^{o}F$ in the northern regions and from $28^{o}F$ to $92^{o}F$ in the south. The frost-free growing season increases from 160 days in the north to 210 days in the south.

Monthly mean values of daily weather data for the 20-year period from 1953 to 1974, determined from data from seventeen first-order weather stations in the MAPP and adjacent areas, are tabulated in Appendix C. These weather stations are located along or close to the course of the Mississippi and Missouri Rivers, as shown in Fig. 22, so that the data reported from them closely represent the climatic conditions along the two rivers. A summary of the average values of the important meteorological factors, which include air temperature, wind speed, relative humidity, atmospheric pressure, cloud cover, and solar radiation for the different weather stations, is given in Tables 11, 12, 13, and 14. The data listed in Appendix C and Tables 11 through 14 correspond to the months of February, May, August, and November, which were selected to represent conditions during the four seasons of a year.

E. River Flow Rates. The surface-water runoff from the Upper Mississippi basin via the Mississippi River averages about 67.1 billion gallons per

Table 9

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 10

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

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* 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.

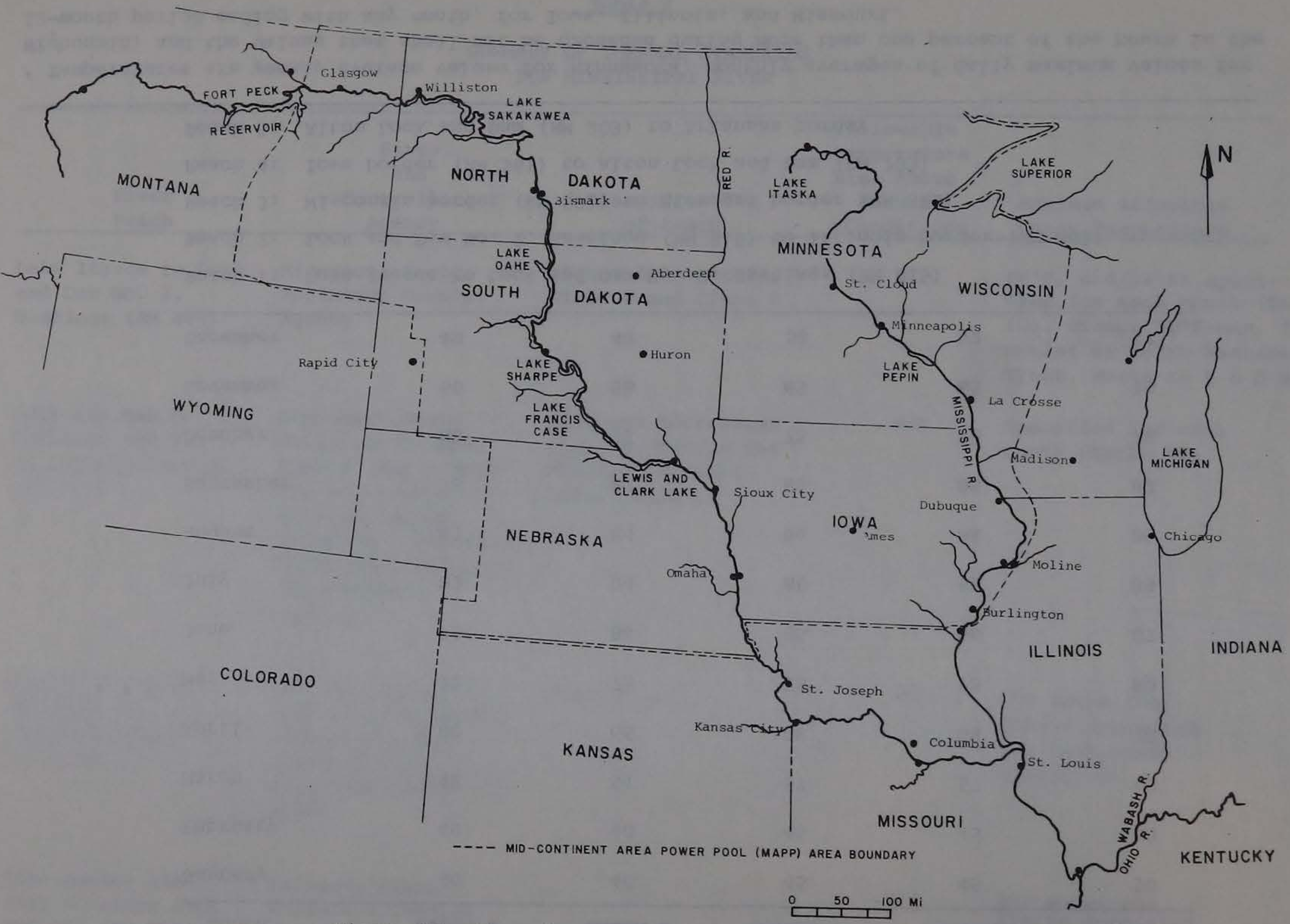


Figure 22. Locations of Class A weather stations in the Mississippi and Missouri River basins

Table 11

SUMMARY OF MONTHLY MEAN VALUES
OF DAILY WEATHER CONDITIONS--
FEBRUARY

Weather Station	Averaging Period	Air Temperature (°F)	Wind Speed (mph)	Relative Humidity (%)	Atmospheric Pressure (mb)	Cloud Cover (tenths)	Solar Radiation (cal/cm^2/day)
Glasgow, Mont.	1954-73	15.57	5.35	78.64	938.41	7.19	242.50
Williston, N.D.	1954-73	14.83	5.56	73.43	948.01	6.79	--
Huron, S.D.	1954-73	17.65	7.66	76.30	970.79	6.71	246.44[a]
Aberdeen, S.D.	1965-73	14.50	3.10	72.78	971.04	6.53	--
Bismark, N.D.	1954-73	14.01	6.97	72.85	956.79	6.90	251.50
Sioux City, Ia.	1954-73	23.01	6.85	71.95	977.53	6.35	--
Omaha, Neb.	1954-73	26.96	7.92	70.00	980.70	6.11	281.77
St. Joseph, Mo.	1954-73	31.41	6.87	64.33	982.20	5.94	--
Kansas City, Mo.	1954-73	34.13	7.00	65.10	986.36	6.24	--
Columbia, Mo.	1954-73	33.10	7.14	70.16	989.04	6.36	263.39
St. Louis, Mo.	1954-73	34.88	7.49	69.25	998.14	6.52	--
Burlington, Ia.	1954-73	26.88	7.91	71.40	992.29	6.21	258.31[b]
Moline, Ill.	1954-73	25.25	7.65	71.55	996.03	6.24	230.23[c]
Dubuque, Ia.	1954-73	21.47	--	73.63	986.03	6.35	--
La Crosse, Wis.	1954-73	19.82	6.37	69.70	993.41	5.99	255.50[d]
Minneapolis, Mn.	1954-73	16.92	7.35	69.90	985.39	6.07	--
St. Cloud, Mn.	1954-73	13.31	7.40	70.27	979.65	5.96	264.06

[a] from Rapid City, South Dakota

[b] from Ames, Iowa

[c] from Argonne National Laboratory, Illinois

[d] from Madison, Wisconsin

Table 12

SUMMARY OF MONTHLY MEAN VALUES OF DAILY WEATHER CONDITIONS-- MAY

Weather Station	Averaging Period	Air Temperature (°F)	Wind Speed (mph)	Relative Humidity (%)	Atmospheric Pressure (mb)	Cloud Cover (tenths)	Solar Radiation (cal/cm^2/day)
Glasgow, Mont.	1954-73	54.83	6.33	55.08	937.66	6.66	518.65
Williston, N.D.	1954-73	54.57	6.76	55.73	946.66	6.47	--
Huron, S.D.	1954-73	57.09	8.08	65.55	966.67	6.29	518.61[a]
Aberdeen, S.D.	1965-73	55.79	2.64	63.22	967.20	6.28	--
Bismark, N.D.	1954-73	54.63	8.10	59.55	952.46	6.56	540.50
Sioux City, Ia.	1954-73	61.69	8.32	61.20	973.29	6.21	--
Omaha, Neb.	1954-73	63.20	7.70	62.55	976.01	6.27	518.39
St. Joseph, Mo.	1954-73	65.42	7.48	58.60	979.34	5.97	--
Kansas City, Mo.	1954-73	66.49	7.06	62.05	982.82	6.19	--
Columbia, Mo.	1954-73	63.87	7.28	66.21	985.68	6.10	533.41
St. Louis, Mo.	1954-73	65.33	6.60	65.70	995.04	6.13	--
Burlington, Ia.	1954-73	61.94	7.48	65.58	989.98	6.12	468.36[b]
Moline, Ill.	1954-73	61.09	7.02	65.30	992.85	6.15	491.83[c]
Dubuque, Ia.	1954-73	58.12	--	62.13	982.48	6.45	--
La Crosse, Wis.	1954-73	58.93	7.04	63.90	989.74	6.37	506.86[d]
Minneapolis, Mn.	1954-73	57.51	7.70	61.40	981.99	6.33	--
St. Cloud, Mn.	1954-73	55.31	9.13	62.40	975.99	6.47	479.77

[a] from Rapid City, South Dakota

[b] from Ames, Iowa

[c] from Argonne National Laboratory, Illinois

[d] from Madison, Wisconsin

Table 13

SUMMARY OF MONTHLY MEAN VALUES OF DAILY WEATHER CONDITIONS-- AUGUST

Weather Station	Averaging Period	Air Temperature (°F)	Wind Speed (mph)	Relative Humidity (%)	Atmospheric Pressure (mb)	Cloud Cover (tenths)	Solar Radiation (cal/cm^2/day)
Glasgow, Mont.	1954-73	69.72	3.83	47.71	937.27	4.50	534.06
Williston, N.D.	1954-73	69.55	5.80	53.33	946.12	4.79	--
Huron, S.D.	1954-73	72.47	8.21	65.25	968.90	4.53	520.44[a]
Aberdeen, S.D.	1965-73	70.86	2.38	60.78	967.60	4.23	--
Bismark, N.D.	1954-73	69.61	6.42	58.55	954.41	4.72	531.00
Sioux City, Ia.	1954-73	73.12	6.93	71.10	974.67	4.73	--
Omaha, Neb.	1954-73	75.16	6.78	70.00	977.54	4.66	523.29
St. Joseph, Mo.	1954-73	76.24	5.55	72.20	980.63	4.24	--
Kansas City, Mo.	1954-73	78.78	6.60	63.05	983.91	4.68	--
Columbia, Mo.	1954-73	76.67	5.92	67.90	986.98	4.97	522.67
St. Louis, Mo.	1954-73	77.03	4.91	68.90	995.96	5.25	--
Burlington, Ia.	1954-73	73.49	5.50	72.45	991.66	5.26	487.36[b]
Moline, Ill.	1954-73	73.03	4.93	72.85	994.69	5.23	471.07[c]
Dubuque, Ia.	1954-73	70.16	--	70.13	984.65	5.56	--
La Crosse, Wis.	1954-73	71.06	5.27	72.80	991.15	5.49	488.93[d]
Minneapolis, Mn.	1954-73	69.86	6.12	68.75	983.54	5.22	--
St. Cloud, Mn.	1954-73	68.45	5.90	72.46	977.34	5.12	486.50

[a] from Rapid City, South Dakota

[b] from Ames, Iowa

[c] from Argonne National Laboratory, Illinois

[d] from Madison, Wisconsin

Table 14

SUMMARY OF MONTHLY MEAN VALUES OF DAILY WEATHER CONDITIONS-- NOVEMBER

Weather Station	Averaging Period	Air Temperature (°F)	Wind Speed (mph)	Relative Humidity (%)	Atmospheric Pressure (mb)	Cloud Cover (tenths)	Solar Radiation (cal/cm^2/day)
Glasgow, Mont.	1954-73	29.23	3.86	72.53	938.64	7.19	150.69
Williston, N.D.	1954-73	28.14	6.01	74.14	947.19	7.23	--
Huron, S.D.	1954-73	32.30	7.89	70.80	969.35	6.70	211.78[a]
Aberdeen, S.D.	1965-73	30.23	2.49	77.00	969.44	7.11	--
Bismark, N.D.	1954-73	28.53	7.33	68.05	955.79	7.12	157.88
Sioux City, Ia.	1954-73	36.82	8.00	69.40	978.44	6.42	--
Omaha, Neb.	1954-73	39.67	7.38	68.60	979.31	6.14	201.24
St. Joseph, Mo.	1954-73	42.67	6.85	69.17	982.92	5.72	--
Kansas City, Mo.	1954-73	43.36	6.41	64.40	985.39	5.83	--
Columbia, Mo.	1954-73	44.19	7.61	68.37	988.42	6.01	207.24
St. Louis, Mo.	1954-73	44.66	6.76	69.60	997.95	6.31	--
Burlington, Ia.	1954-73	39.95	7.68	72.75	992.14	6.48	182.42[b]
Moline, Ill.	1954-73	39.20	7.00	71.80	995.25	6.89	153.33[c]
Dubuque, Ia.	1954-73	36.10	--	70.63	985.67	7.16	--
La Crosse, Wis.	1954-73	35.34	6.99	75.10	991.66	7.21	149.57[d]
Minneapolis, Mn.	1954-73	33.02	7.48	74.55	983.84	7.36	--
St. Cloud, Mn.	1954-73	30.45	8.47	73.86	977.68	7.43	143.47

[a] from Rapid City, South Dakota

[b] from Ames, Iowa

[c] from Argonne National Laboratory, Illinois

[d] from Madison, Wisconsin

day (103800 cfs or 2940 cu.m/s). The runoff is subjected to seasonal variations of temperature and precipitation. The highest flows generally occur during March through June, roughly paralleling the monthly precipitation pattern. The average monthly flows then generally decrease and reach their minimum values during the winter months or in late summer or early fall. Monthly flows during winter months in the southern reaches are relatively high compared to the northern regions, due to the more evenly distributed annual precipitation and moderate temperatures prevailing over the larger watershed.

Monthly average values of daily flow rates at sixteen gaging stations along the Mississippi River, obtained from U.S. Geological Survey Water Supply publications, are given in Appendix D for the months of February, May, August, and November. The locations of the gaging stations are shown in Fig. 23. The discharge data given in Appendix D are 36-year averages for the period from 1939 to 1974. (The system of locks and dams in the Upper Mississippi River was completed in 1938, and the river regulation for navigation needs became fully effective at that time.) A summary of the mean daily flow rates at all the gaging stations is given in Table 15, which also includes the 7-day, 10-year low flow values. The 7-day, 10-year low flow is the 7-day average discharge for which there is a 10 percent probability of a smaller discharge occurring one or more times in any year. The 7-day, 10-year low flow is used as a "worst case" criterion in the application of thermal standards by several regulatory agencies, as described in Appendix B.

F. Thermal Regimes of the Mississippi River. The temperature distributions along the Mississippi River corresponding to the average weather and flow conditions during the months of February, May, August, and November were determined using the steady-state computational model outlined in Part One of this report. River cross-section charts and corresponding flow profiles furnished by the U.S. Army Corps of Engineers were used to obtain the necessary geometric parameters of the river. The top widths and flow cross-sectional areas were adjusted according to the flow rates, using the stage-discharge relationships for the gaging stations. The details of the stage variations with discharge at each gaging station were obtained from the records of the U.S. Geological Survey. The predicted temperature profiles for each month include the following:

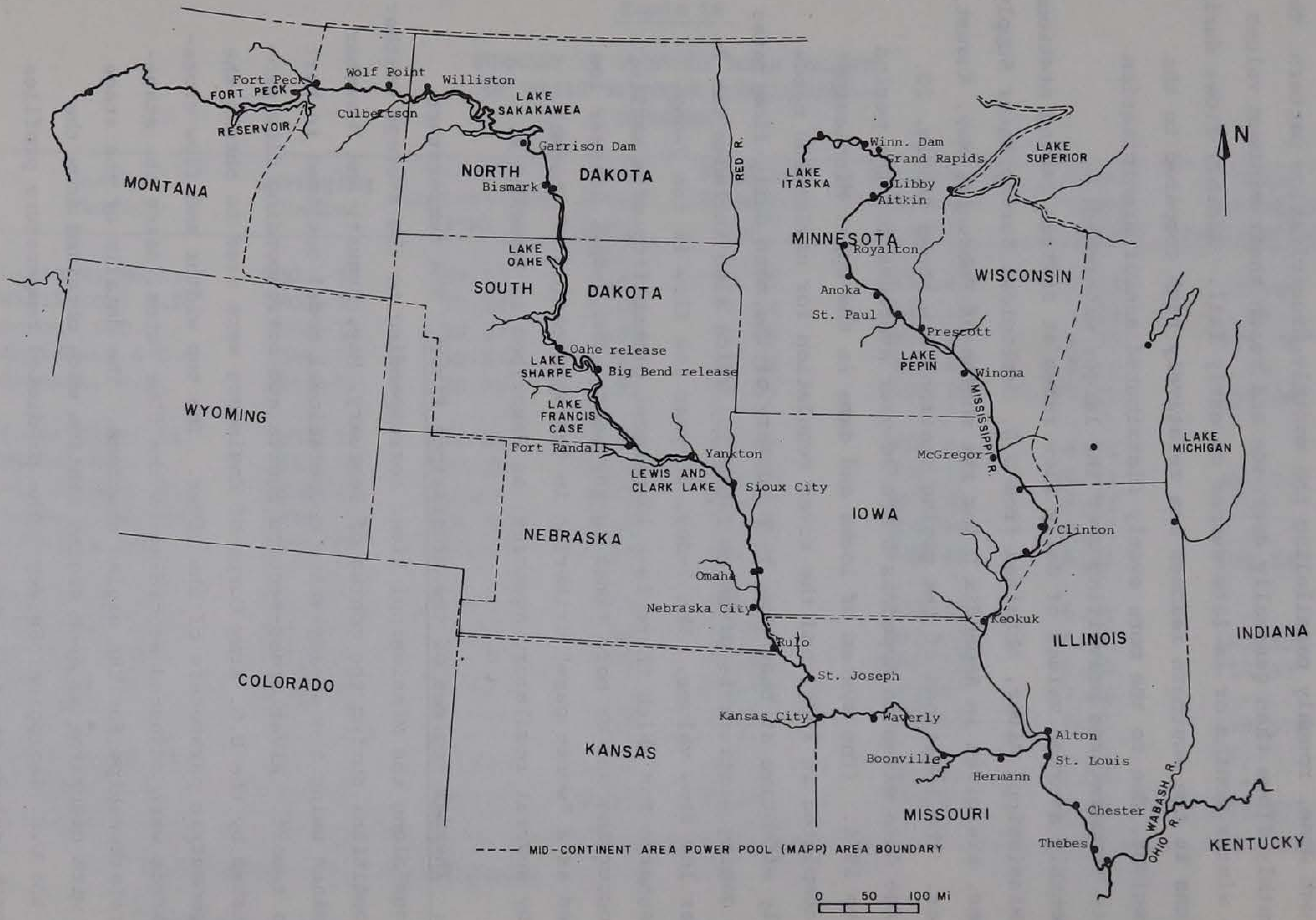


Figure 23. Locations of U.S. Geological Survey flow gaging stations along the Mississippi and Missouri Rivers

Table 15

SUMMARY OF MONTHLY MEAN VALUES
OF DAILY FLOW RATES --
MISSISSIPPI RIVER

Gaging Station	River Mile	Mean Daily Flow Rates in cfs					7-day, 10-year Low Flow	
		Averaging Period	February	May	August	November	Period	Flow Rate (cfs)
Winnibigo-Shish Dam	1248.0	1939-74	790	219	627	692	--	--
Grand Rapids	1182.0	1939-74	1714	1248	1204	1420	--	--
near Libby	1106.0	1949-74	1709	3799	1893	2059	1932-68	192
Aitkin	1056.0	1945-74	1809	5224	2399	2371	1946-68	476
Royalton	956.0	1939-74	2789	9552	4198	4095	1925-68	606
Anoka	864.8	1940-74	4130	15241	6707	6293	1933-68	951
St. Paul	839.3	1939-74	5107	22903	9035	8135	1907-68	1350
Prescott	811.4	1939-74	8003	32603	13801	13149	1930-68	3110
Winona	725.7	1939-74	14439	48499	20987	21546	1930-68	5570
McGregor	633.4	1939-74	17662	57467	25369	25665	1938-69	8604
Clinton	511.8	1939-74	27294	73032	34063	36401	1940-68	9800
Keokuk	364.2	1939-74	44412	105697	45294	48219	1880-73	10950
Alton	202.7	1939-74	77808	164240	66895	70105	1934-67	20860
St. Louis	180.0	1939-74	132988	281165	129750	128893	1934-69	37800
Chester	109.9	1939-74	143913	302677	156623	134435	1934-67	41800
Thebes	43.7	1939-74	150290	305577	135493	138947	1934-67	43800

- 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 conditions for the months of August and November. Permissible new power plants based on low and on average flow conditions are indicated.

1. Natural Thermal Regime. In order to identify the effects of power-plant effluents on the natural conditions of a river, it is necessary to know its natural thermal regime. The natural thermal regime represents the temperature distributions that would exist if all the man-made heat sources were absent. Since there were no available data representing the natural conditions in the Mississippi River, its natural thermal regime was calculated, assuming that the temperature at the upstream point (Mile 1200) was at the equilibrium state. This calculated natural temperature distribution is included in all the results discussed later in this section.

2. Existing Heat Loads. There are 19 power plants, with a total of 59 units, in the MAPP area which utilize the Mississippi River water for once-through cooling. The locations of these plants are listed in Appendix E and shown in Fig. 24; the characteristics of each plant are tabulated in Table 16. Besides the power plants, industries and municipalities located along the river impose additional thermal loads on the river. The sources and quantities of the industrial and municipal discharges are listed in Appendices F and G, respectively. The industrial and municipal effluents are small compared to those of power plants, and generally are not large enough to produce any significant effect on the temperature profiles.

3. Proposed and Projected Power Plants. Those power plants proposed for installation in the near future for which the type of cooling system already has been specified are described in Appendix E and Table 16. The remaining plant capacities, projected through the year 1993, are listed in Table 17. The locations of the future plants are shown in Fig. 25. The types of cooling systems that will be used for some of the projected plants

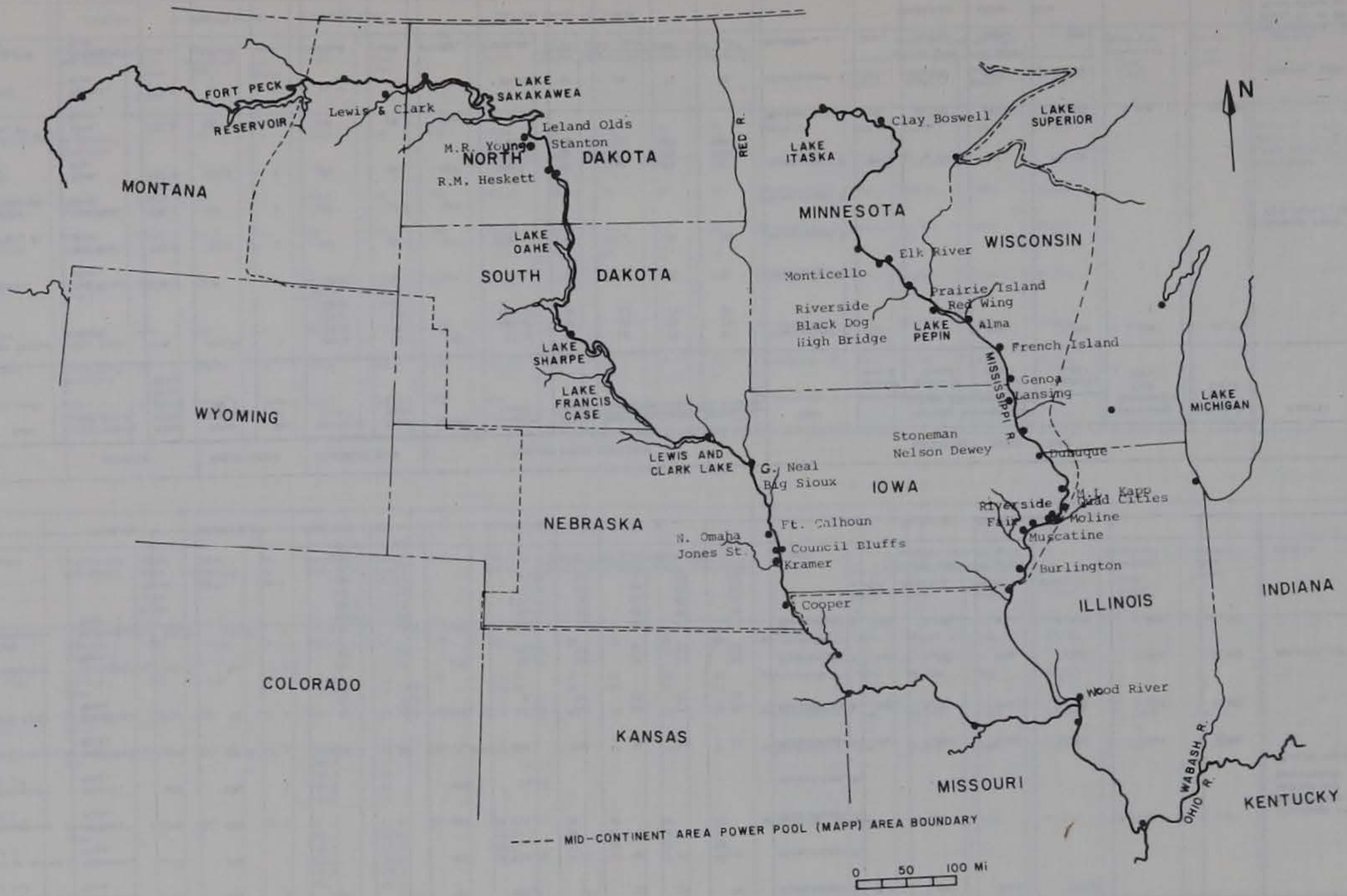


Figure 24. Locations of existing thermal power plants along the Mississippi and Missouri Rivers in the MAPP area

Table 16

SUMMARY OF EXISTING AND PROPOSED POWER PLANTS IN BASINS OF THE UPPER MISSISSIPPI RIVER AND ITS MAJOR TRIBUTARIES LOCATED IN THE MAPP REGION

PLANT		LOCATION		INSTALLATION		CONDENSER FLOW		COOLING WATER DISCHARGE						RECEIVING WATER BODY							
Utility	Name	City/County and State	River Mile above Ohio River	Total Capacity (MW_e)	No. of Units	Quantity (cfs)	Temp. Rise (°F)	Nature	Quantity (cfs)	Winter Temp.(°F)		Summer Temp.(°F)		Name	Monthly Average Flow During Peak Load Month				Seven-day Dependable Flow (cfs)	Average Flow (cfs)	Remarks
										Intake	Discharge	Intake	Discharge		Winter Month	Quantity (cfs)	Summer Month	Quantity (cfs)			
MPL	Clay Boswell # 1,2	Cohasset, Minn.	1187	150	2	234	13.5	OTF	256.4	38	55	74	86	Mississippi R.	Nov.	2,205	Sept.	292.6			
MPL	Clay Boswell # 3	Cohasset, Minn.	1187	350	1			WCT	2.23	38	64	74	100	Mississippi R.							
NSP	Sherburne # 1*	Becker, Minn.	906	680	1			WCT	14.13					Mississippi R.							Discharge temp. corresponds to ambient air temperature *Future Unit
NSP	Sherburne # 2*	Becker, Minn.	906	680	1			WCT	14.13					Mississippi R.							
NSP	Monticello	Monticello, Minn.	900	568.8	1	645	28	OTF,WCT	645	32	35	72	75	Mississippi R.	Dec.	8,600	Sept.	1,500	600	3,300	
UPA	Elk River	Elk River, Minn.	891	48	3	31 31 50	11.5 11.5 15.9	OTF	47.94 0.77	42 42	59 53	75 75	84 81	Mississippi R.	Dec.	5,370	Oct.	7,560	800	4,000	
NSP	Southeast	Minneapolis, Minn.	851.7	40	2	66 42	15 15	OTF	31.97 26.06	42 42	52 52	71 71	80 80	Mississippi R.	Jan.	6,597	Aug.	7,303	1,470	10,050	Retired, 1974
NSP	Riverside	Minneapolis, Minn.	851.7	455.85	8	236 93.4 93.5 110 109 60.5 104.5 104.5	18.4 18 18 15 15 15 15 15	OTF	158.97 54.12 157.73 0.08 0.28	40 39 36 50 40	49 62 71 99 41	67 66 68 60 67	75 80 84 75 68	Mississippi R.	Jan	6,597	Aug.	7,303	1,470	11,320	

PLANT		LOCATION		INSTALLATION		CONDENSER FLOW		COOLING WATER DISCHARGE						RECEIVING WATER BODY							
Utility	Name	City/County and State	River Mile above Ohio River	Total Capacity (MW_e)	No. of Units	Quantity (cfs)	Temp. Rise (°F)	Nature	Quantity (cfs)	Winter Temp.(°F)		Summer Temp.(°F)		Name	Monthly Average Flow During Peak Load Month				Seven-day Dependable Flow (cfs)	Average Flow (cfs)	Remarks
										Intake	Discharge	Intake	Discharge		Winter Month	Quantity (cfs)	Summer Month	Quantity (cfs)			
NSP	High Bridge	St. Paul, Minn.	841	463.84	6	182.8 178.2 133.7 168.2	20 18 18 18	OTF	70.33 127.79 253.70	33 34 36	38 55 66	75 53 75	85 74 95	Mississippi R.	Jan.	8,210	Aug.	7,741	1,900	21,720	
NSP	Red Wing	Red Wing, Minn.	796.9	27	2	32.62	26	OTF	32.63	32	55	76	85	Mississippi R.							
NSP	Prairie Island, #1	Red Wing, Minn.	796.9	593.1	1	680	27.4	WCT	668	32	50	74	79	Mississippi R.							Make-up water from river, 188 cfs
NSP	Prairie Island, #2	Red Wing, Minn.	796.9	530	1	680	27.4	WCT						Mississippi R.							
DPC	Alma #1-5	Alma, Wis.	752.8	205.3	5	280	18	OTF	260.7 0.16 0.28	34 34 34	50 84 50	72 72 72	87 86 87	Mississippi R.	Jan.	12,700	Aug.	27,200			
DPC	Alma, #6 *	Alma, Wis.	752.8	350	1	446	18	OTF						Mississippi R.	Jan.	12,700	July	27,200	5,700	25,260	
NSP	Winona	Winona, Minn.	728.5	26	3	86.7	2.7	OTF	30.46	32	48	72	85	Mississippi R.	Dec.	28,400	Sept.	.24,000			Retired, 1974
NSP	Black Dog #1-4	Minneapolis, Minn.	-	486.66	4	574.9	18	OTF, CP	174.90					Minnesota R.	Dec.	2,200	Sept.	660			Minnesota R. joins Miss. R. at RM 844. Plant close to confluence

(Table 16 continued)

PLANT		LOCATION		INSTALLATION		CONDENSER FLOW		COOLING WATER DISCHARGE						RECEIVING WATER BODY							
Utility	Name	City/County and State	River Mile above Ohio River	Total Capacity (MW_e)	No. of Units	Quantity (cfs)	Temp. Rise (°F)	Nature	Quantity (cfs)	Winter Temp. (°F)		Summer Temp.(°F)		Name	Monthly Average Flow During Peak Load Month				Seven-day Dependable Flow (cfs)	Average Flow (cfs)	Remarks
										Intake	Discharge	Intake	Discharge		Winter Month	Quantity (cfs)	Summer Month	Quantity (cfs)			
NSP	French Island	La Crosse, Wisconsin	-	27	2	82.2	18	OTF	22.1 25.8 0.22 0.19	34 34 34 34	45 45 54 54	79 79 79 79	85 85 99 99	Black R.	Dec.	1,270	Sept.	605			Black R. joins Miss. R. at RM [illegible]. Plant close to confluence
DPC	Genoa Nuclear (LACBWR)	Genoa, Wisconsin	679.2	50	1	133.6	30	OTF	93.59	38	60	73	82	Mississippi R.	Jan.	12,700	Aug.	27,200			
DPC	Genoa #3	Genoa, Wisconsin	679.2	345.6	1	362	17.3	OTF	395.56 4.95 0.16	38 38 38	67 67 67	73 73	90 90	Mississippi R.	Jan.	12,700	Aug.	27,200			
ISP	Lansing #1-3	Lansing, Iowa	660	64	3	44.53 29.84 55.67	12.5 12.5 16	OTF	55.05	36	49	79	87	Mississippi R.	Nov.	34,730	Aug.	27,813			
ISP	Lansing #4 *	Lansing, Iowa	660	250	1	311.75	20	OTF						Mississippi R.	Nov.	34,730	Aug.	27,813			
DPC	Stoneman	Cassville, Wisconsin	607	51.75	2	85.9	16.5	OTF	53.4 2.0	33 33	44 44	75	83	Mississippi R.	Jan.	25,700	Aug.	35,000			
WPLC	Nelson Dewey	Grant Co., Wisconsin	605	227.2	2	223.2	15	OTF	209					Mississippi R.	Dec.	37,500	June	37,500			

PLANT		LOCATION		INSTALLATION		CONDENSER FLOW		COOLING WATER DISCHARGE						RECEIVING WATER BODY							
Utility	Name	City/County and State	River Mile above Ohio River	Total Capacity (MW_e)	No. of Units	Quantity (cfs)	Temp. Rise (°F)	Nature	Quantity (cfs)	Winter Temp.(°F)		Summer Temp.(°F)		Name	Monthly Average Flow During Peak Load Month				Seven-day Dependable Flow (cfs)	Average Flow (cfs)	Remarks
										Intake	Discharge	Intake	Discharge		Winter Month	Quantity (cfs)	Summer Month	Quantity (cfs)			
ISP	Dubuque	Dubuque, Iowa	580	91.25	1	211.54	17	OTF	67	33	52	80	98	Mississippi R.	Nov.	46,187	Aug.	39,461			
ISP	M.L. Kapp	Clinton, Iowa	518	237.2	2	44.53 218.2	13 12	OTF	14.06 142.35	36 36	49 50	78 78	88 90	Mississippi R.	Nov.	49,080	Aug	41,703			
IIGE	Quad Cities	Cordova, Ill.	502	1600	2	2270	23	OTF	2270	36	59	75	98	Mississippi R.	Dec.	19,500	June	28,500	13,400	47,000	
IIGE	Moline	Moline, Ill.	483	99	5	62.4 66.8 42.3 52.1 52.1	24 17 19 12 14	OTF	116.91	39	55	78	94	Mississippi R.	Dec.	19,500	June	28,500	13,400	47,000	
IIGE	Riverside	Bettendorf, Iowa	482	222	6	71.2 61.0 16.6 89.0 144.0 61.0	11.5 13.0 13.2 14.9 18.5 18.5	OTF	146.6 17.8 90.5 19.64	39 39 39 39	59 51 59 54	78 78 78 78	98 90 98 93	Mississippi R.	Dec.	41,787	Aug.	43,535	13,400	47,000	
EILP	Fair	Montpelier, Iowa	468	62.5	2	45.5 63.5	12.2 26.9	OTF	0.24 74.2	33 33	42 42	84 84	70 75	Mississippi R.		44,000		30,000	10,000	44,000	

(Table 16 continued)

Table 16 (continued)

PLANT		LOCATION		INSTALLATION		CONDENSER FLOW		COOLING WATER DISCHARGE						RECEIVING WATER BODY							
Utility	Name	City/County and State	River Mile above Ohio River	Total Capacity (MW_e)	No. of Units	Quantity (cfs)	Temp. Rise (°F)	Nature	Quantity (cfs)	Winter Temp. (°F)		Summer Temp. (°F)		Name	Monthly Average Flow During Peak Load Month				Seven-day Dependable Flow (cfs)	Average Flow (cfs)	Remarks
										Intake	Discharge	Intake	Discharge		Winter Month	Quantity (cfs)	Summer Month	Quantity (cfs)			
City of Muscatine	Municipal Elec. Plant	Muscatine, Iowa	457.2	124	4	167.1	15	OTF	99 0.16 44.8 0.35 18.56	35 53 35 53 35		78 57 78 57 78	90 72 90 90 90	Mississippi R.							
ISU	Burlington	Burlington, Iowa	404	212	1	180	22	OTF	176.75	36	58	76	98	Mississippi R.	Dec.	72,000	July	40,000	15,500	60,970	
IPC	Wood River	Wood River, Ill.	198	650.1	5	912	14.5	OTF	771.3					Mississippi R.	Dec.	67,900	July	263,500			
OTPC	Hoot Lake	Fergus Falls, Minn.	-	136.9	3	38.8 60 81	12 19 22	OTF or WCT	107.81					Otter Tail R.	Dec.	459	Aug.	227			Plant at approx. 400 mi. from Miss.R.
NSP	A.S. King	Stillwater, Minn.	-	598.4	1	619.5	16.9	OTF, WCT	519.58	33	54	76	83	St. Croix R.	Dec.	4,000	Sept.	2,460	1,570	5,969	St. Croix R. joins Miss. R. at RM 811. Plant at approx. 20 mi. from confluence
NSP	Minnesota Valley	Granite Falls, Minn.	-	46	3	14.9 14.9 62.6	16 16 16	OTF	64.85	34	53	78	90	Minnesota R.	Jan.	573	Aug.	107		1,809	Minnesota R. joins Miss. R. at RM 844. Plant at approx. 250 mi. from confluence
NSP	Wilmarth	Mankato, Minn.	-	28	2	25.6 25.6	18 18	OTF	22.98 0.07	35 56	55 65	77 56	93 73	Minnesota R.	Jan.	1,468	Aug.	408	145	8,673	Plant at approx. 100 mi. from confluence
RDPU	Silver Lake	Rochester, Minn.	-	98.4	4	22 32 47 89	11 12 15 17	OTF, CP	98.97	32	44	80	77	Zumbro R.		83		86			Zumbro R. joins Miss. R. at RM 750. Plant at approx. 80 mi. from confluence
MPL	Hibbard #1-4	Duluth, Minn.	-	124	1	356.4	20.5	OTF	364					St. Louis R.	Nov.	10,395	Sept.	1,040			Plant located close to Lake Superior
MPL	Aurora #1,2	Aurora, Minn.	-	116	2	186	14	OTF	210					Colby Lake	Nov.	279.3	Sept.	18.3			
WPLC	Blackhawk	Rock Co., Wis.	-	50	2	152	12	OTF	91.2					Rock R.	Dec.	1,205	June	1,409			Rock R. joins Miss. R. at RM 479. Plant at approx. 180 mi. from confluence
WPLC	Rock River	Rock Co., Wis.	-	150	2	214	12	OTF	159.7					Rock R.	Dec.	1,205	June	1,409			
WPSC	Pulliam	Brown Co., Wis.	-	392.50	8	837.9	11.2	OTF	609					Fox R.	Dec.		July				Plant close to Lake Winnebago
IELP	Prairie Creek #1-3	Cedar Rapids Iowa	-	96	3	107.94	18	OTF	108.8 0.51	38 38	56 45	74 74	86 74	Cedar R.	Dec.	1,475	July	3,059			Cedar R. joins Miss. R. at RM 434. Plant at approx. 110 mi. from confluence

(Table 16 continued)

Table 16 (continued)

PLANT		LOCATION		INSTALLATION		CONDENSER FLOW		COOLING WATER DISCHARGE						RECEIVING WATER BODY							
										Winter Temp.(°F)		Summer Temp.(°F)			Monthly Average Flow During Peak Load Month						
Utility	Name	City/County and State	River Mile above Ohio River	Total Capacity (MW_e)	No. of Units	Quantity (cfs)	Temp. Rise (°F)	Nature	Quantity (cfs)	Intake	Discharge	Intake	Discharge	Name	Winter Month	Quantity (cfs)	Summer Month	Quantity (cfs)	Seven-day Dependable Flow (cfs)	Average Flow (cfs)	Remarks
IELP	Prairie Creek #4	Cedar Rapids Iowa	-	148.7	1	113.72	18	OTF	114.1 1.22	38 38	53 45	74 74	89 74	Cedar River	Dec.	1,475	July	3,059			Plant at approx. 110 mi. from confluence
IELP	D. Arnold	Palo, Iowa	-	553	1	661.8	25	WCT						Cedar River							Plant at approx. 122 mi. from confluence. Blow-down from cold side of tower only
IPS	Maynard	Waterloo, Iowa	-	100	6	15.6 33.4 33.4 49 7.5	10 10 10 10 10	OTF	147.0					Cedar River	Dec.	1,730	Aug.	19,270	1,050	2,614	Plant at approx 190 mi. from confluence
IPL	Des Moines	Des Moines, Iowa	-	325	7	56 78 13 100 110 144 155	12 12 15 15 15 18 18	WCT, CP	265 10.24 1.11	38 38 38	58 32 40	78 78 85	104 85 85	Des Moines River	Jan	3,000	Aug.	77,000	200	3,849	Des Moines R. Joins Miss. R. at RM 361. Plant at approx. 200 mi. from confluence
CBPC	Humboldt	Humboldt, Iowa	-	43.8	4	6.95 6.95 6.2 6.2	11 11 8.25 12.1	OTF	39.9	33	50	89	77	Des Moines River						1,358	Des Moines R. Joins Miss. R. at RM 361. Plant at approx. 340 mi. from confluence

PLANT		LOCATION		INSTALLATION		CONDENSER FLOW		COOLING WATER DISCHARGE						RECEIVING WATER BODY							
										Winter Temp.(°F)		Summer Temp.(°F)			Monthly Average Flow During Peak Load Month						
Utility	Name	City/County And State	River Mile above Ohio River	Total Capacity (MW_e)	No. of Units	Quantity (cfs)	Temp. Rise (°F)	Nature	Quantity (cfs)	Intake	Discharge	Intake	Discharge	Name	Winter Month	Quantity (cfs)	Summer Month	Quantity (cfs)	Seven-day Dependable Flow (cfs)	Average Flow (cfs)	Remarks
PMPL	Municipal Power & Light	Pella, Iowa	-	43.5	4	4.4 11.1 24.4 53.3	14 14 15.5 14	WCT						S. Skunk R. /Des Moines R.							Plant at approx. 140 mi. from confluence
ISU	Bridgeport	Eddyville, Iowa	-	71	3	41 41 42	17.5 17.5 17.5	WCT	2.01					Miller's Creek /Des Moines R.							Plant at approx. [illegible] mi. from confluence.
ISU	Streeter	Cedar Falls,	-		4	6.68 6.68 12.4 63.5	31 31 13 16	OTF	8.35	51	85	51	85	Dry Run Creek /Cedar R.							Plant at approx. 190 mi. from confluence
IELP	Sixth Street #1-8	Cedar Rapids, Iowa	-	102	8	31.9	16	CP	5.5					Local Run-off							
IELP	Sutherland #1-3	Marshalltown, Iowa	-	156.6	3	220	16	WCT	3.6					Well							
City of Ames	Municipal Power Plant	Ames, Iowa	-	89.15	3	22.27 28.95 57.90	13.6 13.5 19	DCT													

Table 17

ADDITIONAL PROPOSED AND PROJECTED PLANTS ALONG MISSISSIPPI RIVER (FROM MAPP R-362 DATA)

Utility	Plant and Unit	Location	Capacity (MW)	Type	Remarks
IIGE[a]	Carroll Co., #1	Savannah, Ill.	478	Nuclear	New Plant (5-1-83)[c]
IIGE[a]	Carroll Co., #2	Savannah, Ill.	478	Nuclear	(5-1-84)[c]
b	Tyrone Energy Park, #1	Durand, Wis.	1150	Nuclear	New Plant (5-1-82)
b	Tyrone Energy Park, #2	Durand, Wis.	1150	Nuclear	(5-1-84)
MPL	-	-	800	Fossil, Coal	(11-1-82)
-	-	Minnesota	800	Fossil, Coal	(Through 88)
-	-	Minnesota	1100	Nuclear	(Through 88)
-	-	Minnesota	1100	Nuclear	(Through 88)
-	-	Minnesota	800	Fossil, Coal	(Through 88)
-	-	Minnesota	800	Fossil, Coal	(1989-93)
-	-	Minnesota	1500	Nuclear	(1989-93)
-	-	Minnesota	1500	Nuclear	(1989-93)
-	-	Minnesota	800	Fossil, Coal	(1989-93)
-	-	Minnesota	800	Fossil, Coal	(1989-93)
-	-	Wisconsin	1500	Nuclear	(1989-93)
IELP[a]	Central Iowa	N.E. Iowa	1100	Nuclear	(5-1-83)
IIGE[a]	1985 Fossil	S.E. Iowa	600	Fossil, Coal	(5-1-85)
		S.E. Iowa	600	Fossil	(5-1-86)
		S.E. Iowa	600	Fossil	(5-1-91)
		S.E. Iowa	600	Fossil	(5-1-93)

[a] Shared with other utilities

[b] Shared by several utilities

[c] Projected in-service date

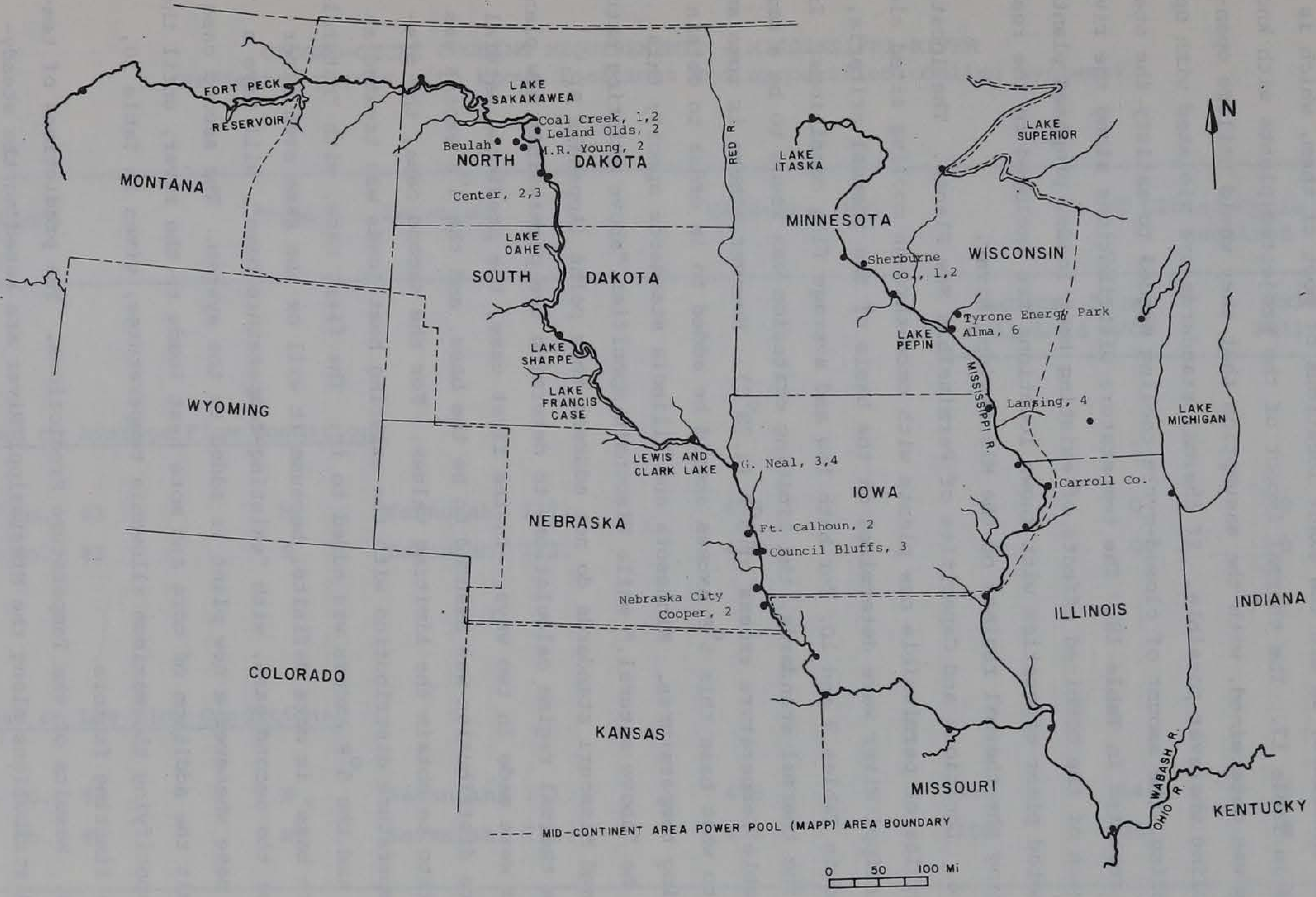


Figure 25. Locations of proposed and projected thermal power plants along the Mississippi and Missouri Rivers in the MAPP area

are as yet undecided, as are the exact locations of most of them, which is reflected in Table 17. The thermal impact of the projected plants with known locations was determined, with the assumption that they would utilize open-cycle cooling wherever possible. If thermal standards are violated with open-cycle cooling, the amount of closed-cycle cooling needed to satisfy the standards is reported in Table 18. The temperature distributions along the river for the case of the combined effects of existing heat loads, proposed plants, and projected plant capacities with known locations are included in the results representing the thermal regimes of the Mississippi River.

4. Locations and Capacities of Permissible New Plants. 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 Tables 9 and 10, for both low and average flow conditions. In applying the thermal standards, the limiting criterion was found to be a maximum allowable temperature excess of $5^{o}F$ ($2.78^{o}C$). However, there is some ambiguity as to what base this $5^{o}F$ excess should be added to in order to obtain the limiting temperatures. Minnesota and Illinois standards specify this excess to be "above natural," while Wisconsin specifies "above existing natural," and Iowa and Missouri standards do not address this point (Appendix B). Hence, the thermal regime calculations to determine the permissible new plant capacities were made in two ways. In the first case, the predicted natural temperature distribution was assumed to be the base, and the $5^{o}F$ 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 $5^{o}F$ 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 10, become the limiting factors.

5. Results of the Temperature Predictions. The predictions of temperature distributions along the Mississippi River are based on the steady-state version of the ITRM. In addition, several assumptions were made related to the use and interpretation of the available data. These assumptions are as follows:

Table 18

CLOSED-CYCLE COOLING REQUIREMENTS - MISSISSIPPI RIVER
(Projected plants with known locations and unspecified cooling systems)

Plant	Type	Location	Capacity (MW)	% of Closed-Cycle Cooling Required			
				Natural Base		Existing Base	
				Full Load	w/CF	Full Load	w/CF
A. Based on Average Flow Conditions							
Carroll Co., #1	N	Savannah, Ill.	478	0	0	0	0
Carroll Co., #2	N	Savannah, Ill.	478	0	0	0	0
B. Based on Low Flow Conditions							
Carroll Co., #1	N	Savannah, Ill.	478	100	14	0	0
Carroll Co., #2	N	Savannah, Ill.	478	100	100	0	0

a. The information on plant capacities and locations used in this study was obtained from "Supplement to MAPP Long Range G & T Plan 1974-1993," December 1974, which reflects available data as of July 1974.

b. The thermal discharges included were those from steam-electric power plants of rated capacity greater than 25 MW, industries, and municipalities located either on the main-stem of the river or on major tributaries within 25 miles of their mouths.

c. The natural thermal impacts of tributary streams were not considered, and effluent discharges located along a tributary, within the 25-mile limit, were assumed to be located at the confluence of the main stream and the tributary.

d. Those plants described as employing some form of closed-cycle cooling system in combination with once-through (open-cycle) cooling were assumed to use 100 percent once-through cooling unless specific contrary information was given. This assumption relates particularly to the Monticello and Black Dog plants in Minnesota.

e. Channel cross-sectional geometrical parameters were assumed to vary linearly between surveyed sections. River discharge and climatological variables also were assumed to vary linearly between any two adjacent gaging and weather stations.

f. The upstream initial river temperature, where the river enters the MAPP geographical area, was assumed to be the equilibrium value for each set of conditions.

g. Future proposed and projected plants were assumed to be operating at full load during the study months: February, May, August, and November.

h. The minimum plant capacity considered in estimating permissible future utilization of the Mississippi River for once-through cooling was about 200 MW for predictions based on average flow conditions. For predictions based on low flow conditions, the minimum plant capacity considered was about 30 MW.

i. For the analysis of mechanical-draft wet cooling towers, the meteorological conditions in the MAPP/MARCA area were assumed to be the same as those used by Giaquinta et al. [4] for Chicago, Illinois.

The predicted temperature distributions in the Mississippi River corresponding to average flow and weather conditions for the months of February, May, August, and November are shown in Figs. 26. These results are based on the assumption that all the existing, proposed, and projected power plants are operating at their full-load capacities. Figures 26 indicate that the temperature excess above the calculated natural temperature due to the existing plants in the vicinity of Minneapolis-St. Paul is more than 5°F during some periods. However, the probability that all the existing power plants would operate at full-load capacity simultaneously likely is small. Therefore, the temperature distributions due to the existing plants were determined in another way, utilizing their capacity factors based on 1974 operational data; these capacity factors for the existing power plants along the Mississippi River, determined from the MAPP R-362 data for the year 1974, are tabulated in Table 19. The predicted temperature distributions, including the capacity factors for the existing plants, are shown in Figs. 27. Based on existing thermal standards some of the proposed and projected plants will have to use at least partial closed-cycle cooling. The affected plants and the amount of closed-cycle cooling required are listed in Table 18.

The locations of the permissible new plants and the resulting temperature distributions also are shown in Figs. 26 and 27. 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 are tabulated in Tables 20 and 21 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 the 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 20. However, Table 21 shows that when the capacity factors of the

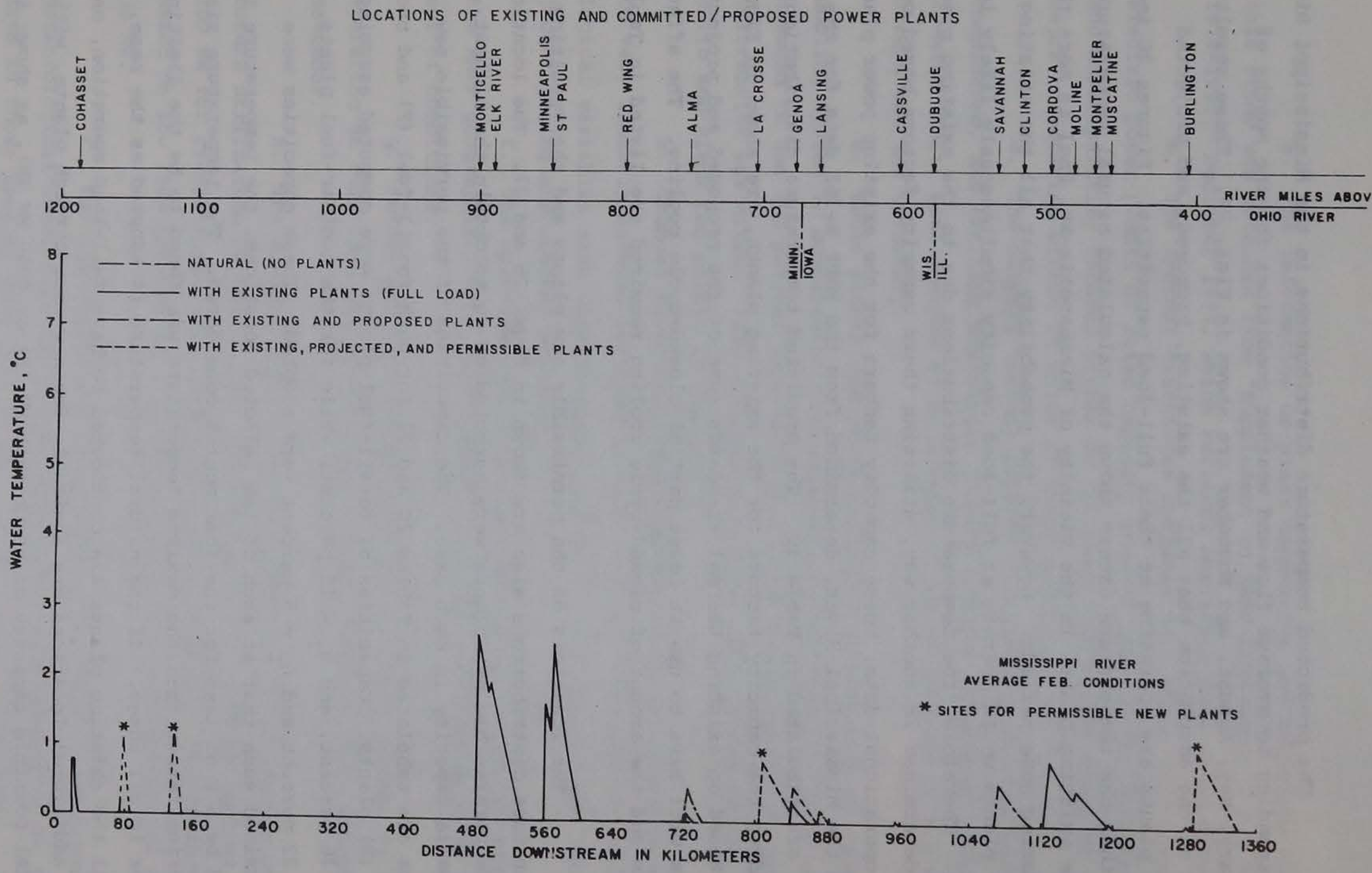


Figure 26. Temperature distributions along the Mississippi River for average conditions with full-load operation and permissible new plants based on predicted natural temperatures

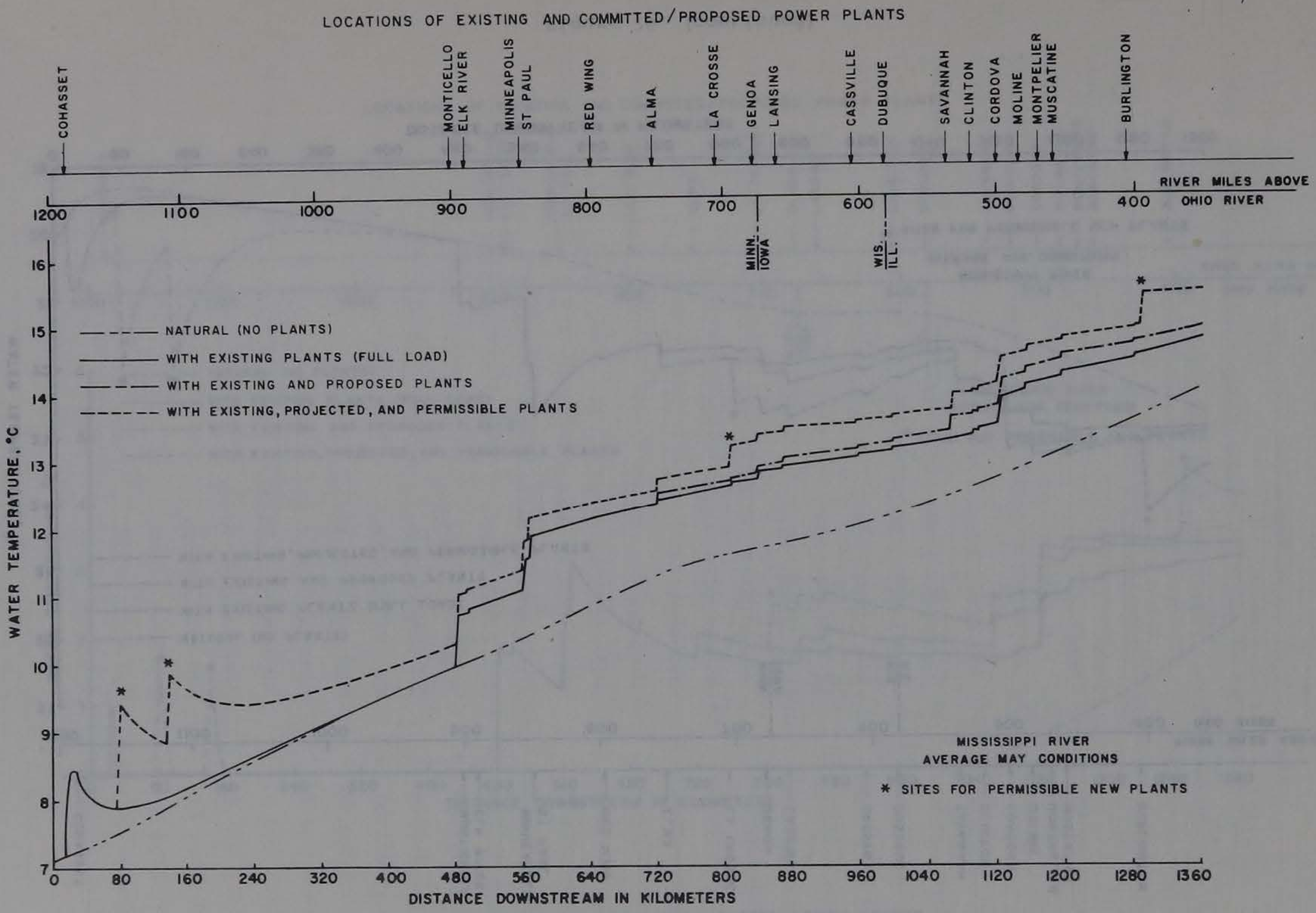


Figure 26. (continued)

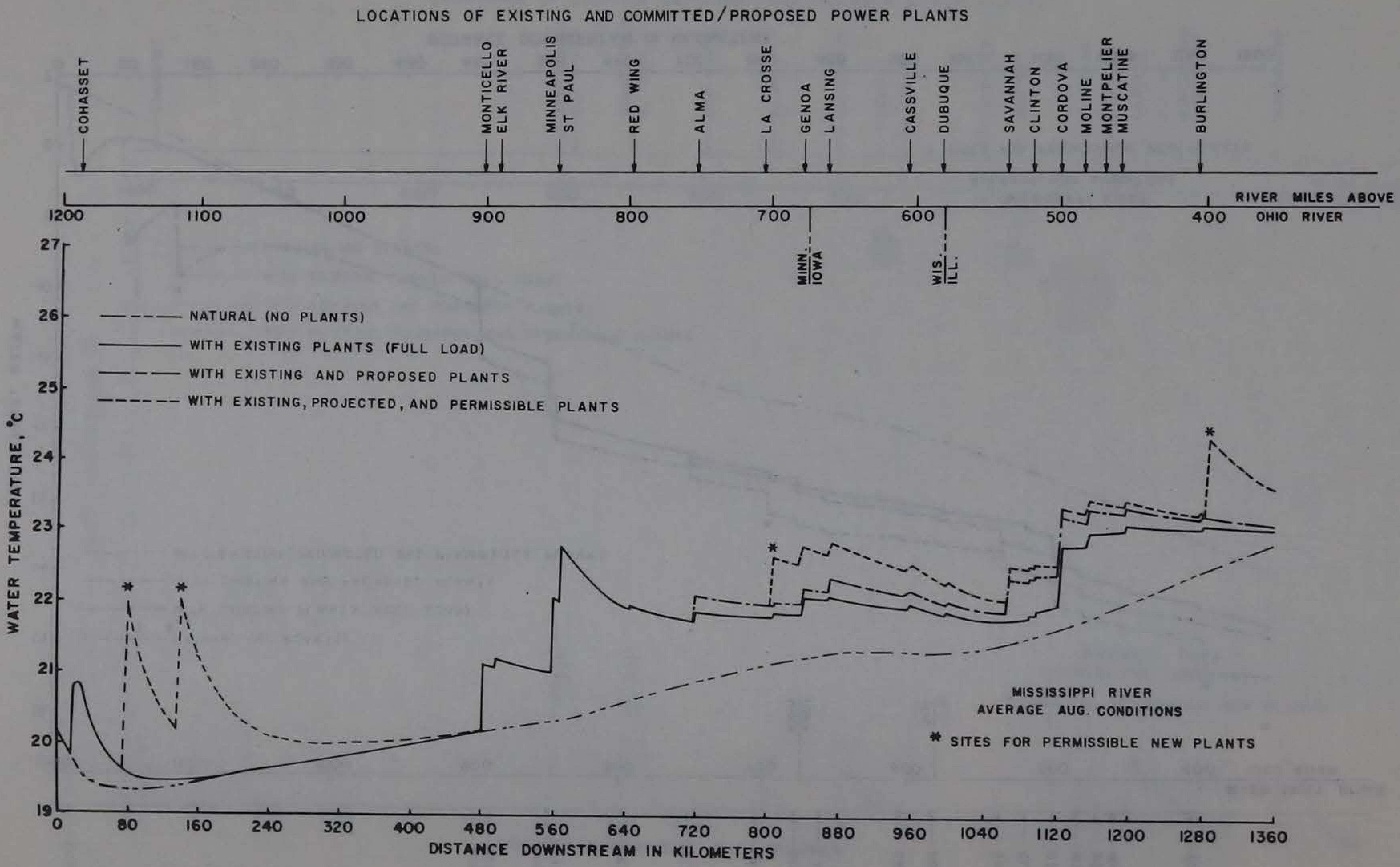


Figure 26. (continued)

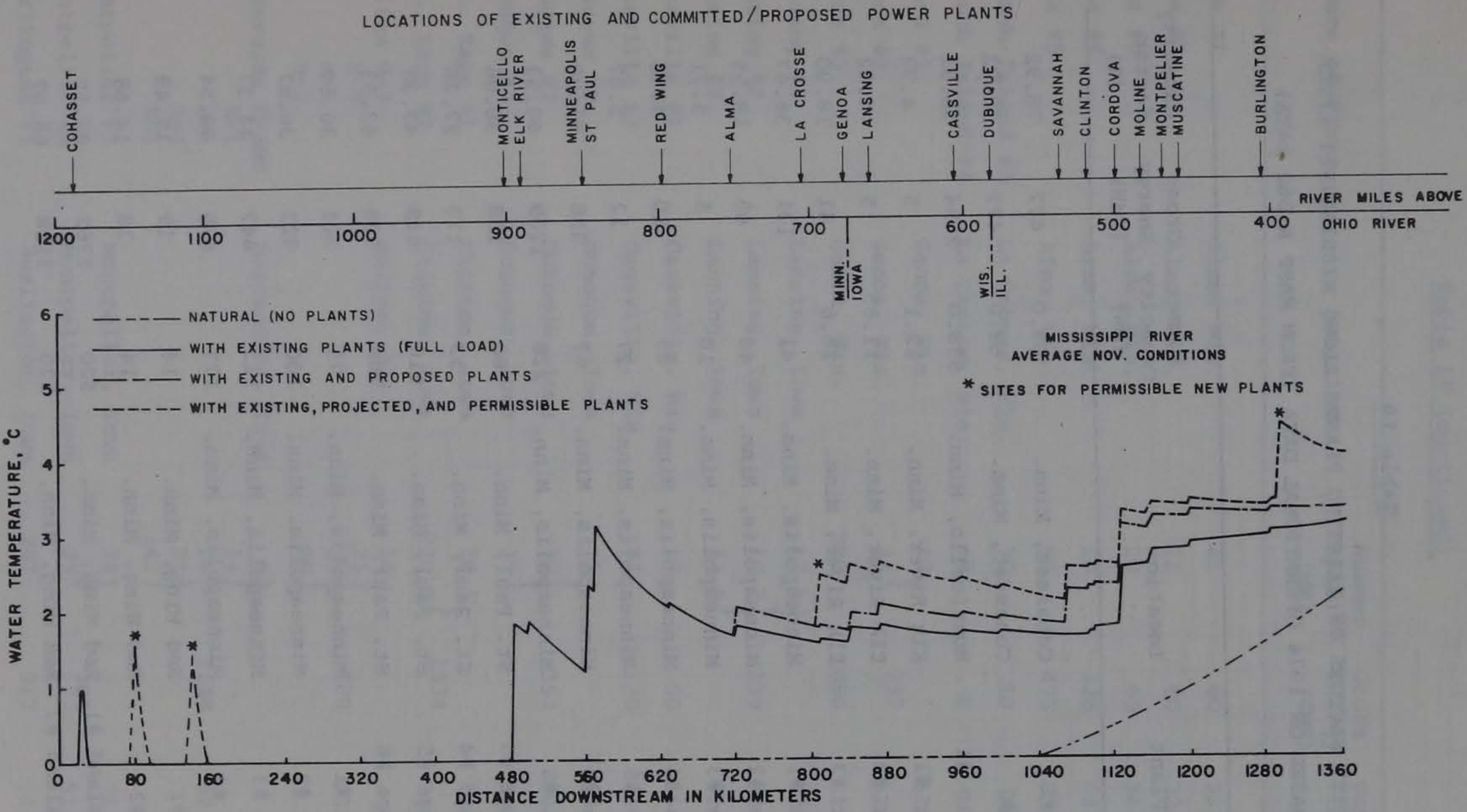


Figure 26. (continued)

Table 19

CAPACITY FACTORS OF EXISTING PLANTS ALONG MISSISSIPPI RIVER BASED ON 1974 OPERATIONAL DATA (FROM MAPP R-362 DATA)

Name of Plant	Location	Summer Capacity (MW)	Gross Energy (GWH)	Capacity factor (%)
Boswell #1	Cohasset, Minn.	69.0	477	78.92
Boswell #2	Cohasset, Minn.	69.0	477	78.92
Monticello #1	Monticello, Minn.	538.0	2654	56.31
Elk River #1	Elk River, Minn.	12.1	5	4.72
Elk River #2	Elk River, Minn.	11.85	5	4.82
Elk River #3	Elk River, Minn.	26.0	41	18.00
Riverside #1	Minneapolis, Minn.	41	131	36.47
Riverside #2	Minneapolis, Minn.	40	65	18.55
Riverside #3	Minneapolis, Minn.	10	5	5.71
Riverside #4	Minneapolis, Minn.	23	10	4.96
Riverside #5	Minneapolis, Minn.	27	12	5.07
Riverside #6	Minneapolis, Minn.	67	358	61.00
Riverside #8	Minneapolis, Minn.	228	1209	60.53
High Bridge #3	St. Paul, Minn.	60	158	30.06
High Bridge #4	St. Paul, Minn.	53	173	27.26
High Bridge #5	St. Paul, Minn.	110	418	43.38
High Bridge #6	St. Paul, Minn.	168	935	63.53
Black Dog #1	Minneapolis, Minn.	75	201	30.59
Black Dog #2	Minneapolis, Minn.	100	323	36.87
Black Dog #3	Minneapolis, Minn.	115	447	44.37
Black Dog #4	Minneapolis, Minn.	173	675	44.54
Red Wing #1	Red Wing, Minn.	14	19	15.49
Red Wing #2	Red Wing, Minn.	14	18	14.68
Prairie Island #1	Red Wing, Minn.	520	3762	82.59
Prairie Island #2	Red Wing, Minn.	520	3128	68.67

(Table 19 continued)

Table 19 (continued)

Name of Plant	Location	Summer Capacity (MW)	Gross Energy (GWH)	Capacity factor (%)
Alma #1	Alma, Wis.	21	60	32.62
Alma #2	Alma, Wis.	21	60	32.62
Alma #3	Alma, Wis.	20	60	34.25
Alma #4	Alma, Wis.	59	326	63.08
Alma #5	Alma, Wis.	83	475	65.33
French Island #3	La Crosse, Wis.	70	10	1.63
French Island #4	La Crosse, Wis.	69	8	1.32
Genoa #1	Genoa, Wis.	12	337	61.73
Genoa #2	Genoa, Wis.	48		61.73
Genoa #3	Genoa, Wis.	350	1880	61.73
Lansing #1	Lansing, Iowa	17.5	339	62.42
Lansing #2	Lansing, Iowa	10.7		62.42
Lansing #3	Lansing, Iowa	33.8		62.42
Cassville #1	Cassville, Wis.	19	60	36.05
Cassville #2	Cassville, Wis.	33	120	41.51
Dubuque #2	Dubuque, Iowa	15	353	50.37
Dubuque #3	Dubuque, Iowa	30		50.37
Dubuque #4	Dubuque, Iowa	35		50.37
M.L. Kapp #1	Clinton, Iowa	18.5	1534	73.42
M.L. Kapp #2	Clinton, Iowa	220.0		73.42
Moline M-3	Moline, Ill.	14	189	23.97
M-5		21		
M-6		27		
M-7		28		
Riverside R-3HS	Bettendorf, Iowa	6	1148	52.63
R-1		24		
R-3		26		
R-4		51		
R-5		142		
Montpelier #1	Montpelier, Iowa	24	285	51.64
Montpelier #2	Montpelier, Iowa	39		51.64
Burlington #1	Burlington, Iowa	207	917	50.57

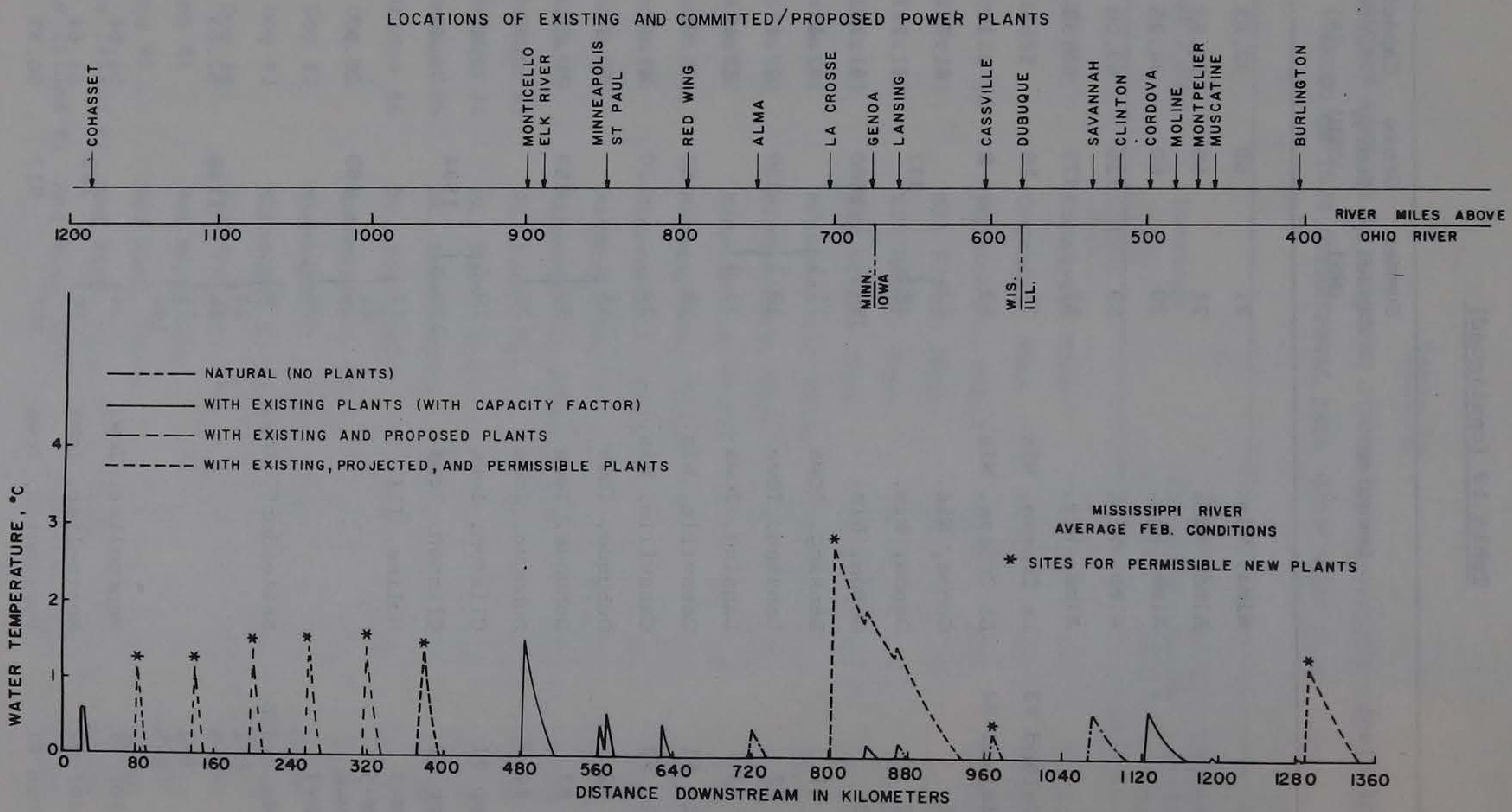


Figure 27. Temperature distributions along the Mississippi River for average conditions with 1974 capacity factors and permissible new plants based on predicted natural temperatures

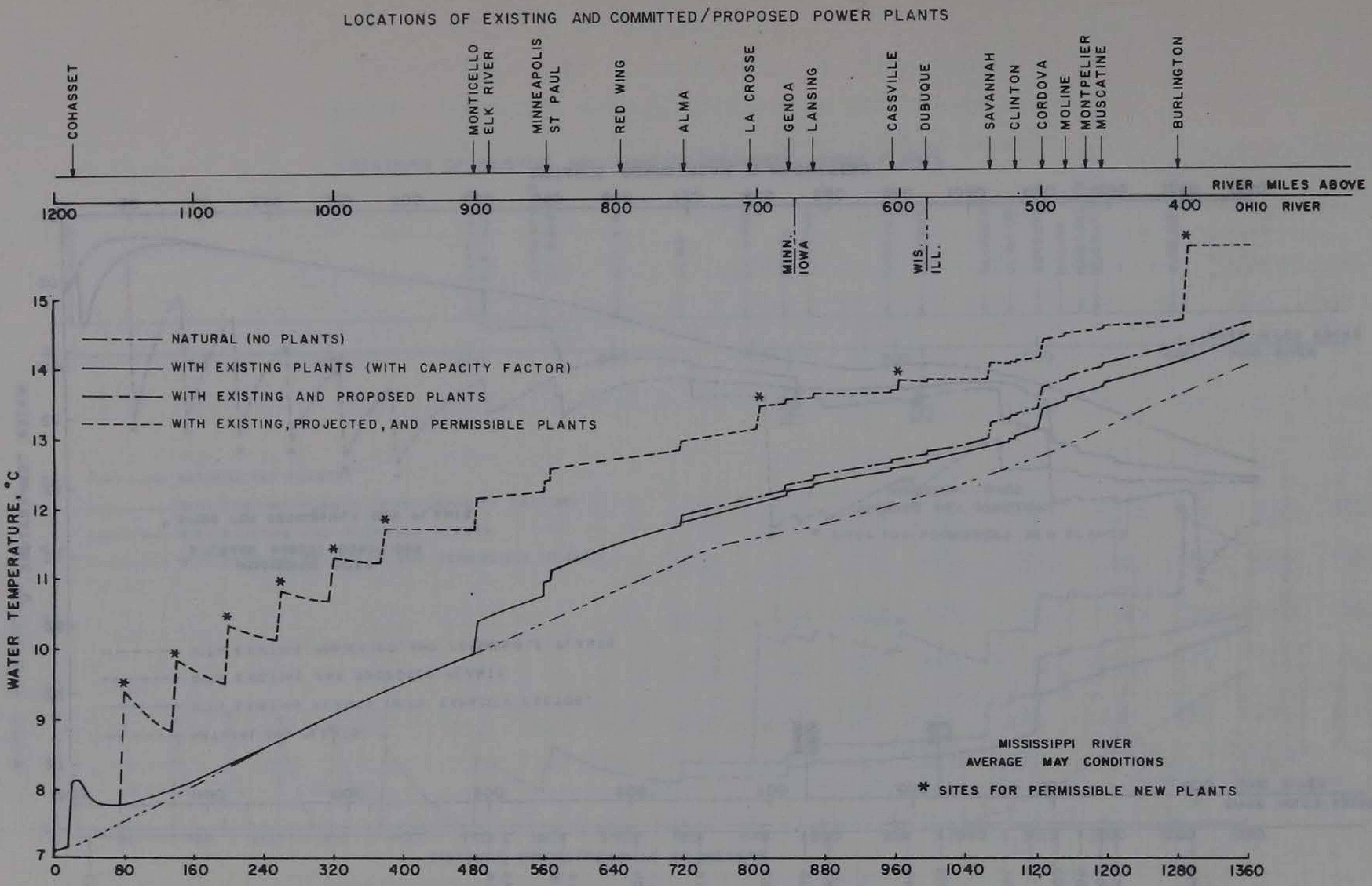


Figure 27. (continued)

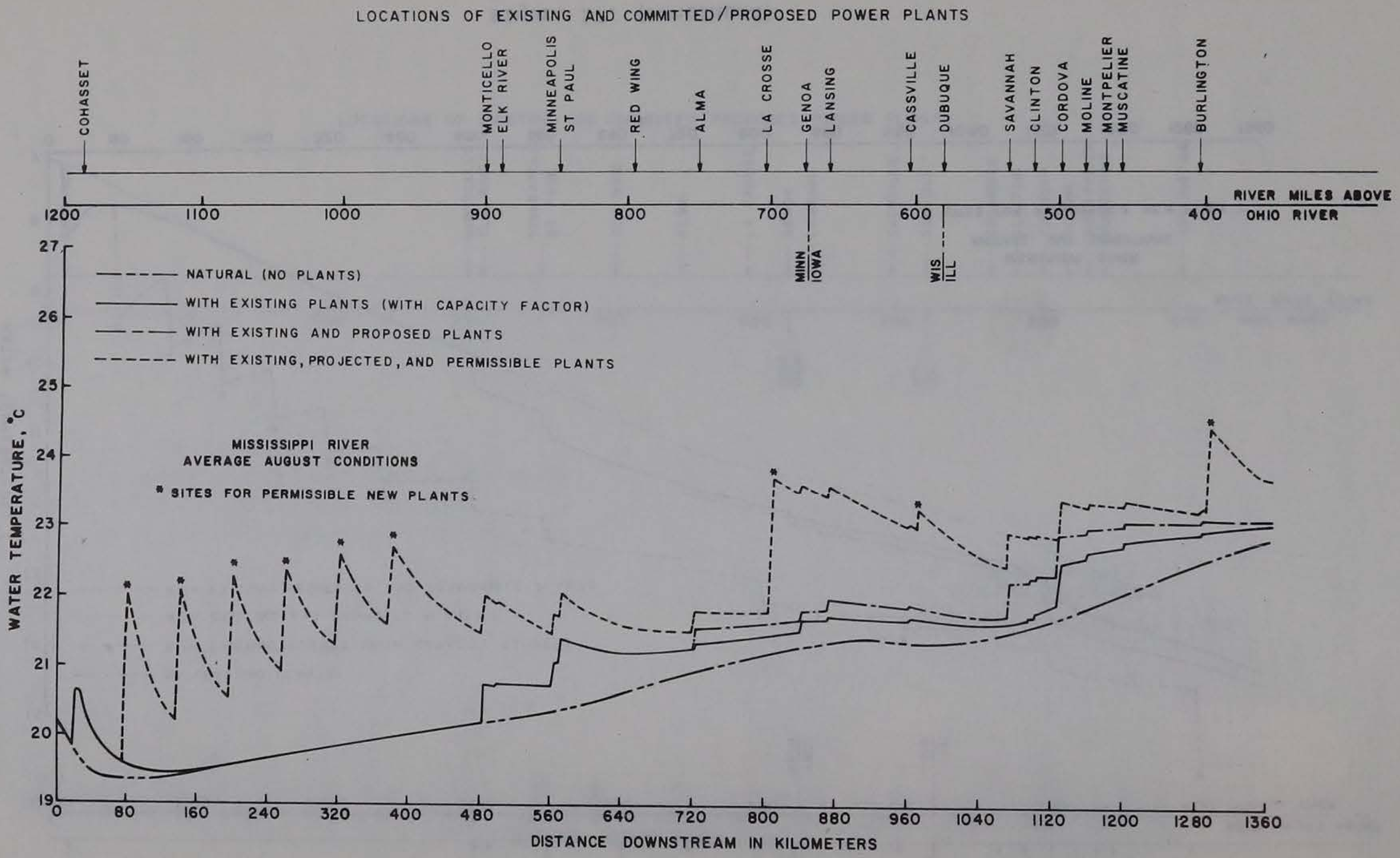


Figure 27. (continued)

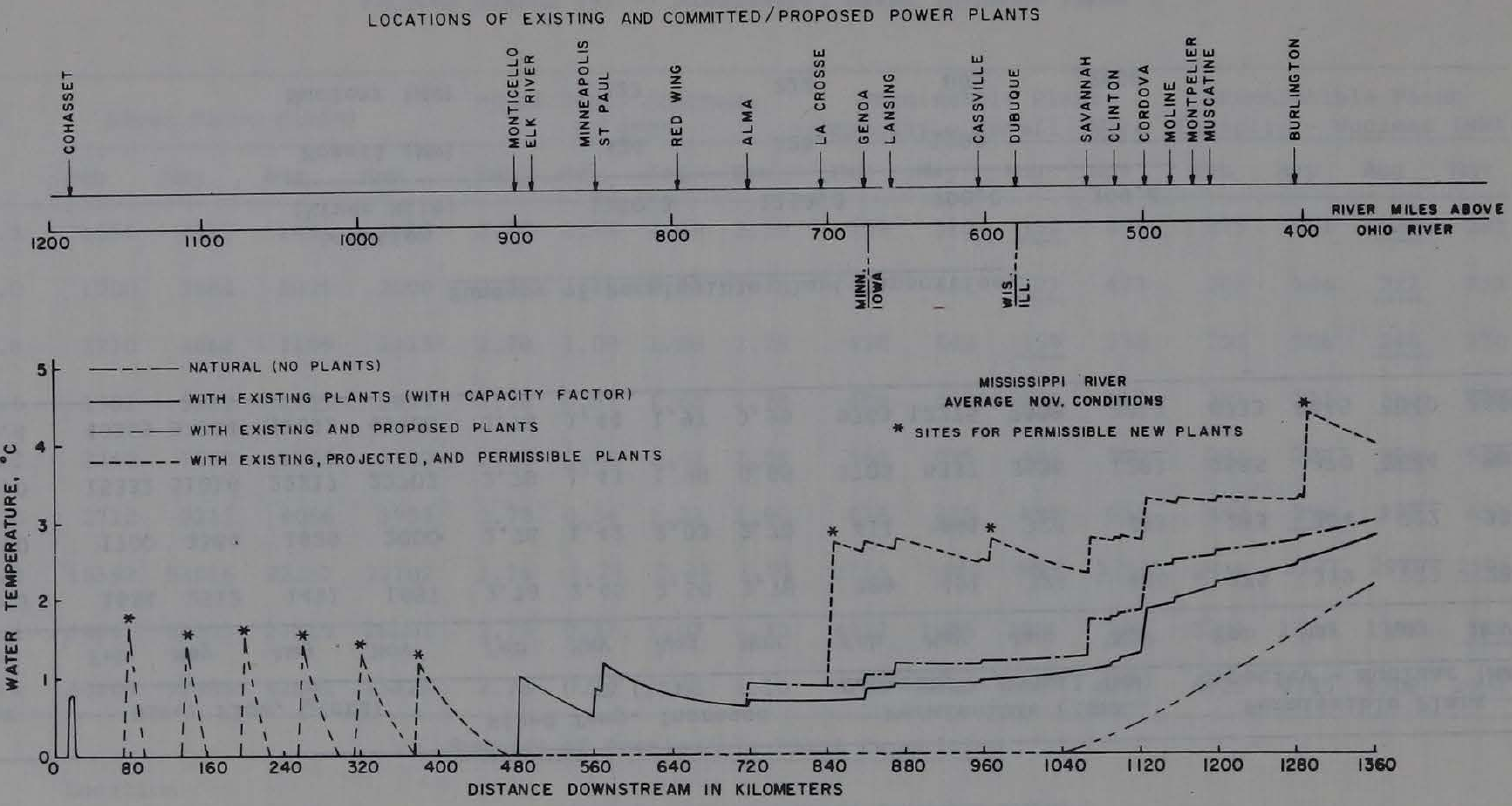


Figure 27. (continued)

Table 20

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 21

LOCATIONS AND CAPACITIES OF PERMISSIBLE POWER PLANTS BASED ON PREDICTED NATURAL TEMPERATURES AND 1974 CAPACITY FACTORS (TABLE 19) -- 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	2.54	2.56	2.78	399	510	332	408	275	351	229	281
1113.0	1700	3564	1829	2000	2.78	1.42	2.03	2.78	411	441	323	483	283	304	222	333
1075.8	1770	4662	2199	2215	2.78	1.09	1.88	2.78	428	442	359	536	295	306	248	370
1038.5	1981	5984	2715	2629	2.78	0.87	1.63	2.78	479	452	386	635	331	311	266	438
1001.2	2346	7598	3385	3292	2.78	0.66	1.43	2.58	568	435	423	739	391	300	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	1.24	2.24	1.91	3705	5492	4320	3764	2555	3787	2979	2595
599.4	20347	61853	27819	28691	2.78	0.37	1.07	0.30	4917	1966	2601	743	3391	1356	1793	512
399.4	40369	97984	42642	45428	2.78	0.74	1.68	1.10	9755	6300	6247	4341	6728	4345	4308	2994

Summary of Permissible Plant Capacities

Location (River Mile)	1150.3	1113.0	1075.8	1038.5	1001.2	964.0	700.0	599.4	399.4
Fossil (MW)	332	323	359	386	423	429	3764	743	4341
Nuclear (MW)	229	222	248	266	291	296	2595	512	2994

existing plants are taken into account, nine locations, with a total permissible once-through-cooled capacity of 11100 MW (F) or 7650 MW (N), can accommodate new plants.

The temperature distributions that would result with the permissible new plants on-line for the case of the existing-temperature base are shown in Figs. 28 and 29. In this case, it is allowable to site plants at ten locations. Figures 28 correspond to the full-load operation, and Figs. 29 to operation with 1974 capacity factors. The locations of the permissible new plants in these figures are the same as those in Figs. 27 plus the addition of a capacity increase at river mile 500. The permissible capacities of the new plants at these locations for this case with the existing-temperature base are tabulated in Tables 22 and 23. For the full-load operation of existing plants, the permissible new plant capacities total about 15900 MW (F) or 10970 MW (N). In this case the capacity factors of the existing plants do not have very much influence on the capacities of the new plants, since the allowable temperature excess is always added to the existing temperature, whatever it may be. Of course, the maximum temperature limitation cannot be exceeded. Hence the capacities of the permissible new plants listed in Table 23 are almost the same as those in Table 22.

The thermal regimes of the Mississippi River for the "worst case" conditions - 7 day, 10-year low flows, combined with average weather conditions for August and November - are presented in Figs. 30 through 33. These four figures show the temperature distributions along the river during low flow conditions and operation of existing, proposed, projected, and permissible future power plants based on average flow conditions as listed in Tables 20 through 23. Figures 30 correspond to the full-load operation of all the existing plants while the results shown in Figs. 31 include the 1974 capacity factors of the existing plants. Future plants were assumed to be operating at rated capacity. Both figures show that temperature excesses above natural due to the existing plants are more than 5°F in the vicinity of Minneapolis-St. Paul. Figures 30 also indicate that if all the existing plants operate at full load, temperature excesses in the river reach starting at Cordova, Illinois, and extending about 30 miles downstream will also be greater than 5°F. However, if 1974 capacity factors are used to estimate the existing plant loads, the temperature excess in this reach

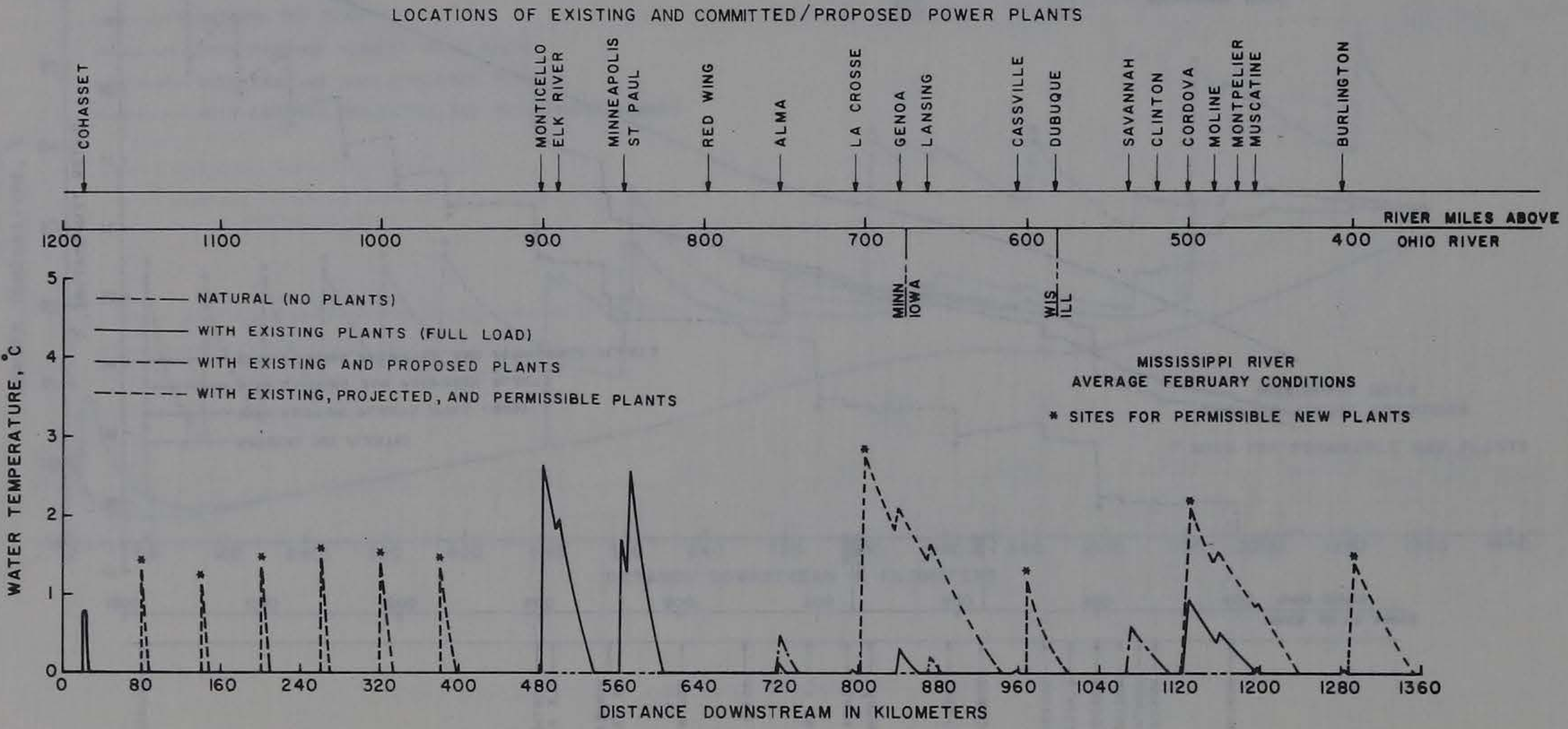


Figure 28. Temperature distributions along the Mississippi River for average conditions with full-load operation and permissible new plants based on temperatures with existing heat loads

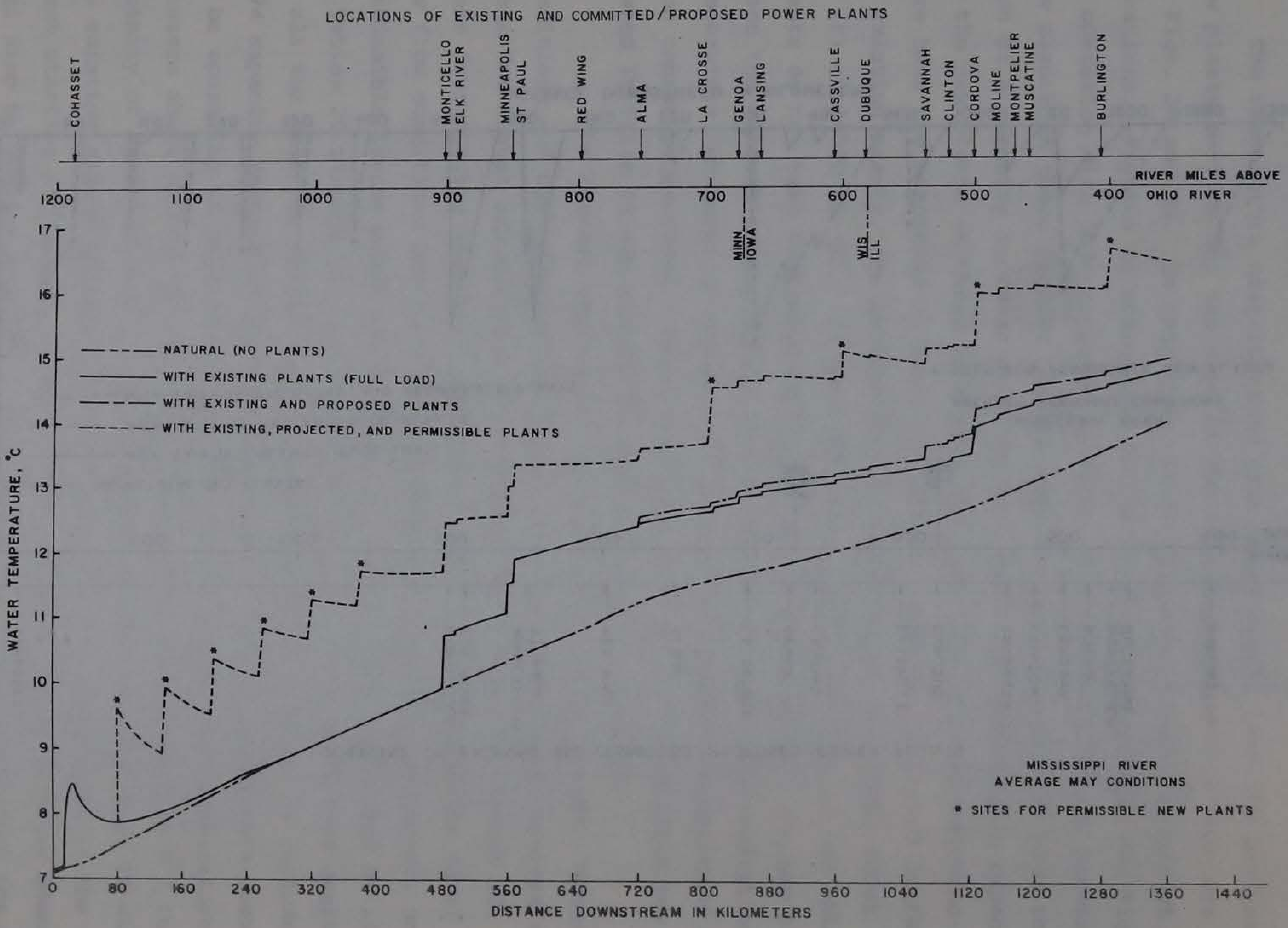


Figure 28. (continued)

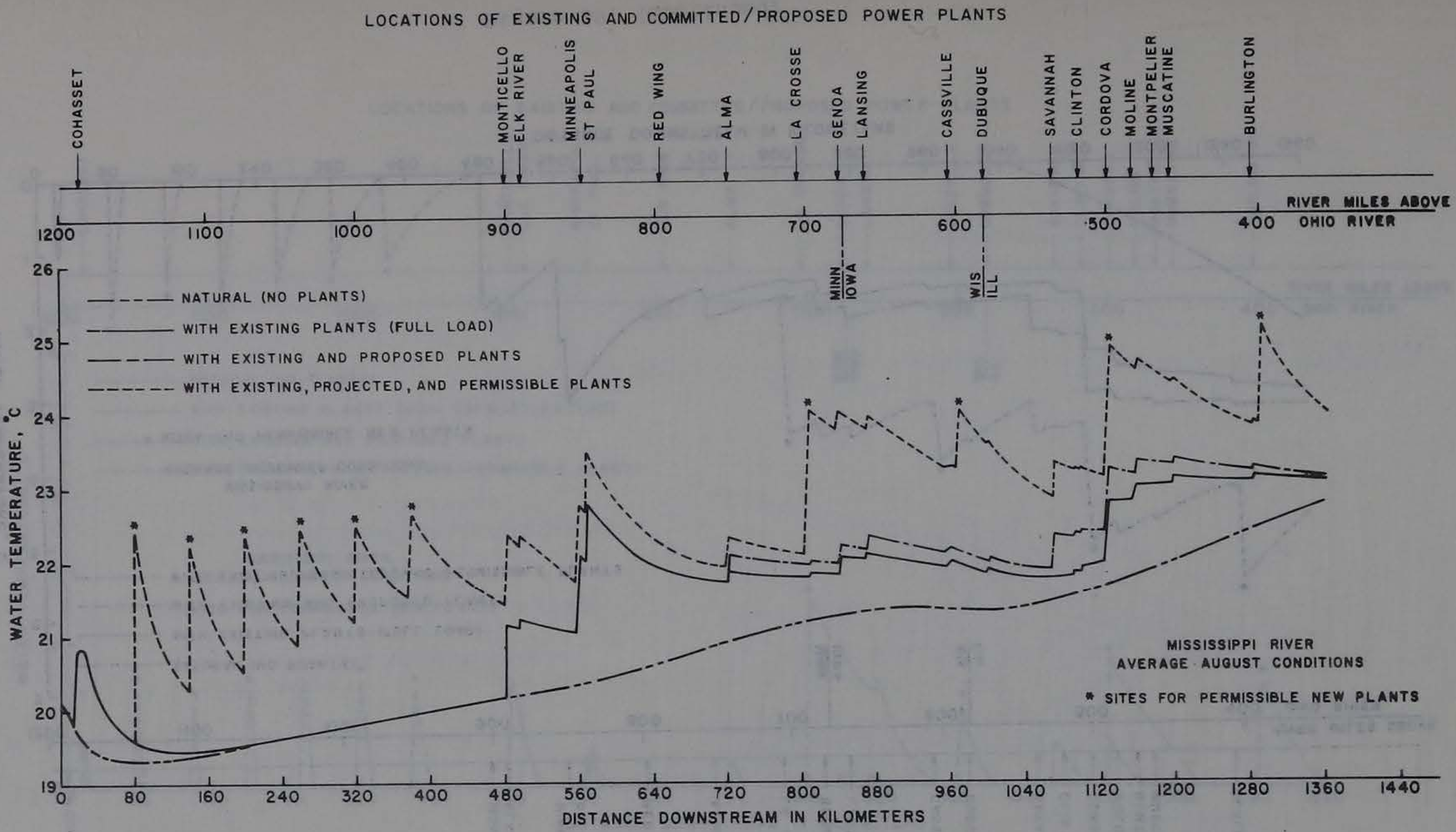


Figure 28. (continued)

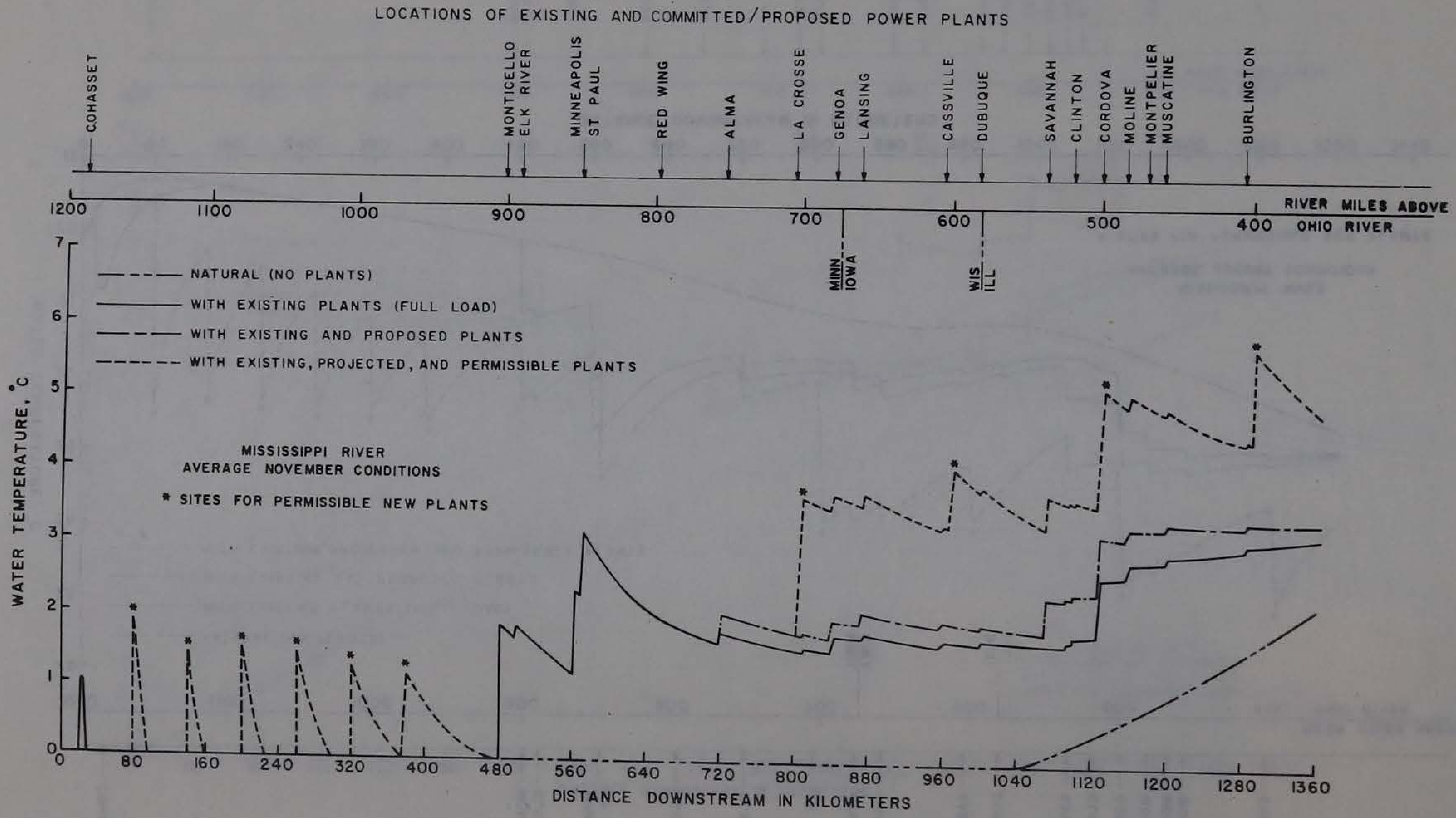


Figure 28. (continued)

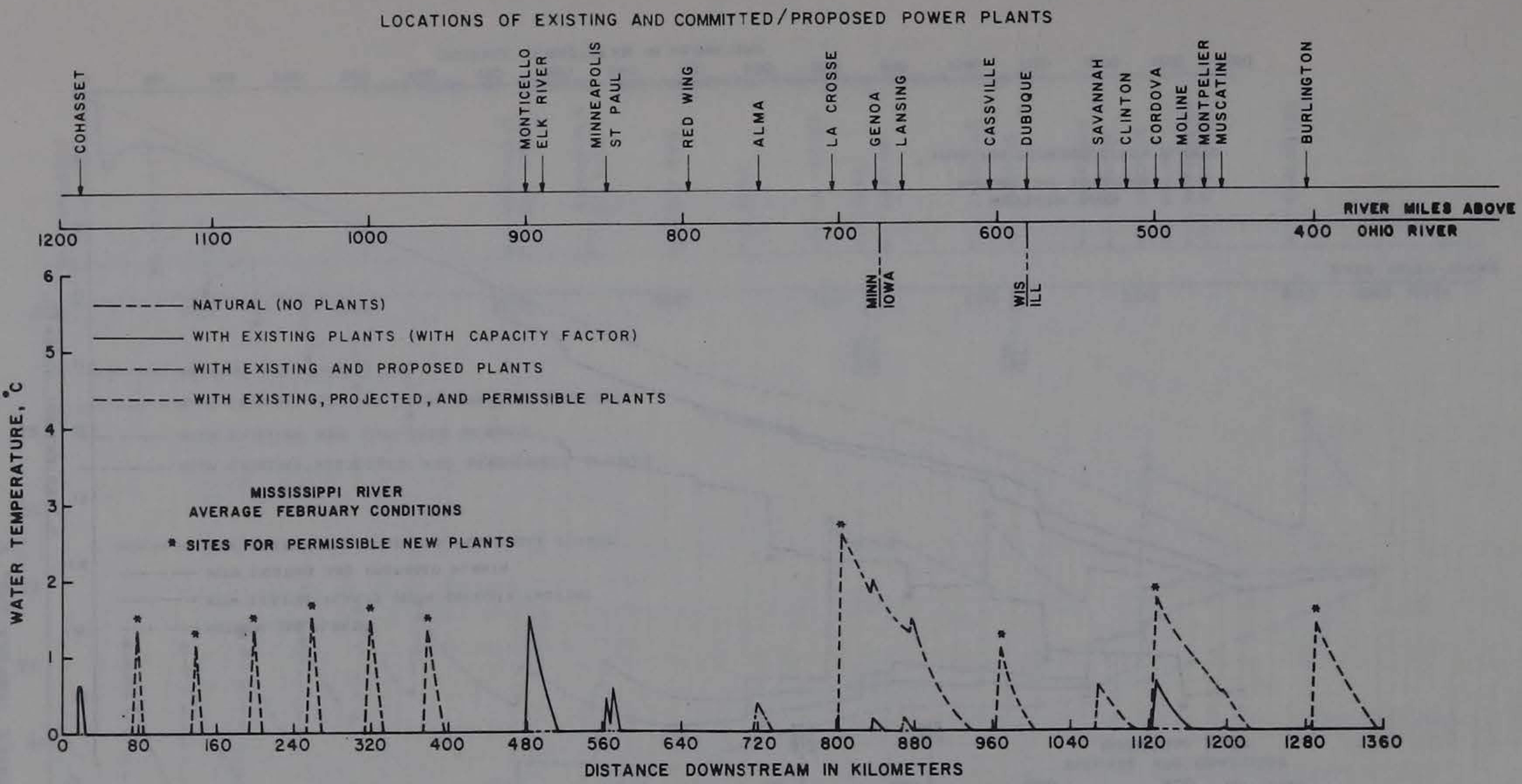


Figure 29. Temperature distributions along the Mississippi River for average conditions with 1974 capacity factors and permissible new plants based on temperatures with existing heat loads

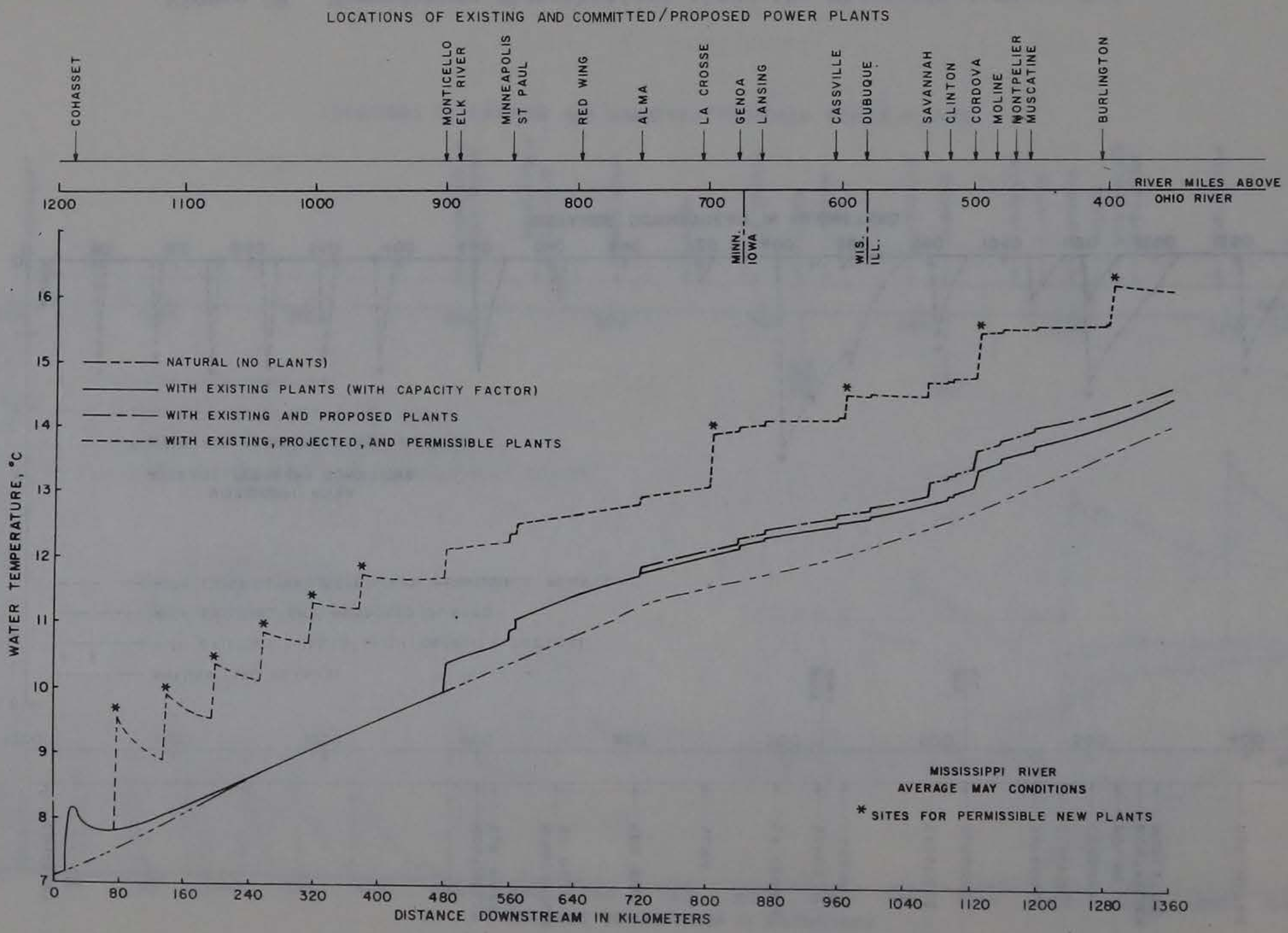


Figure 29. (continued)

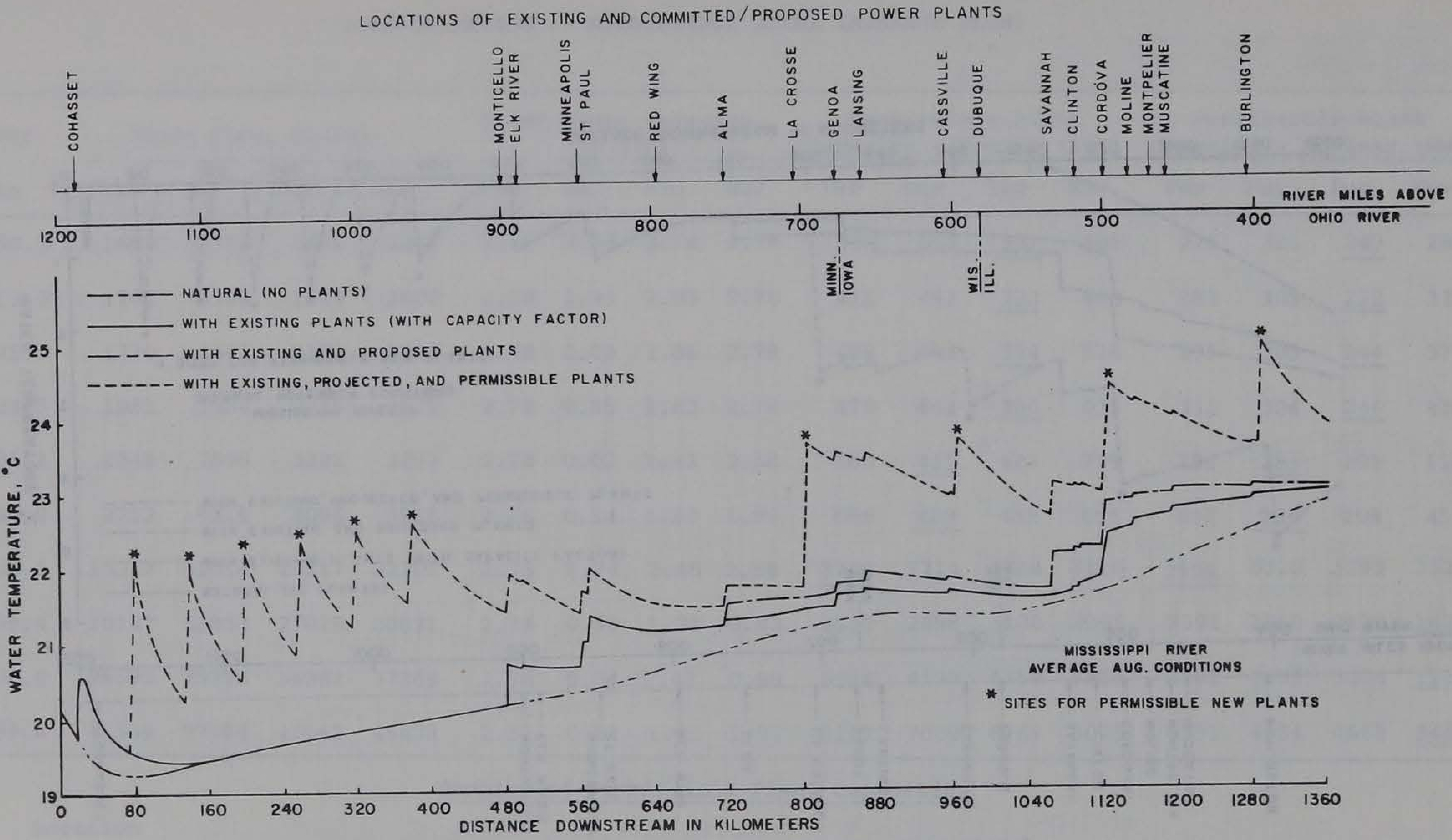


Figure 29. (continued)

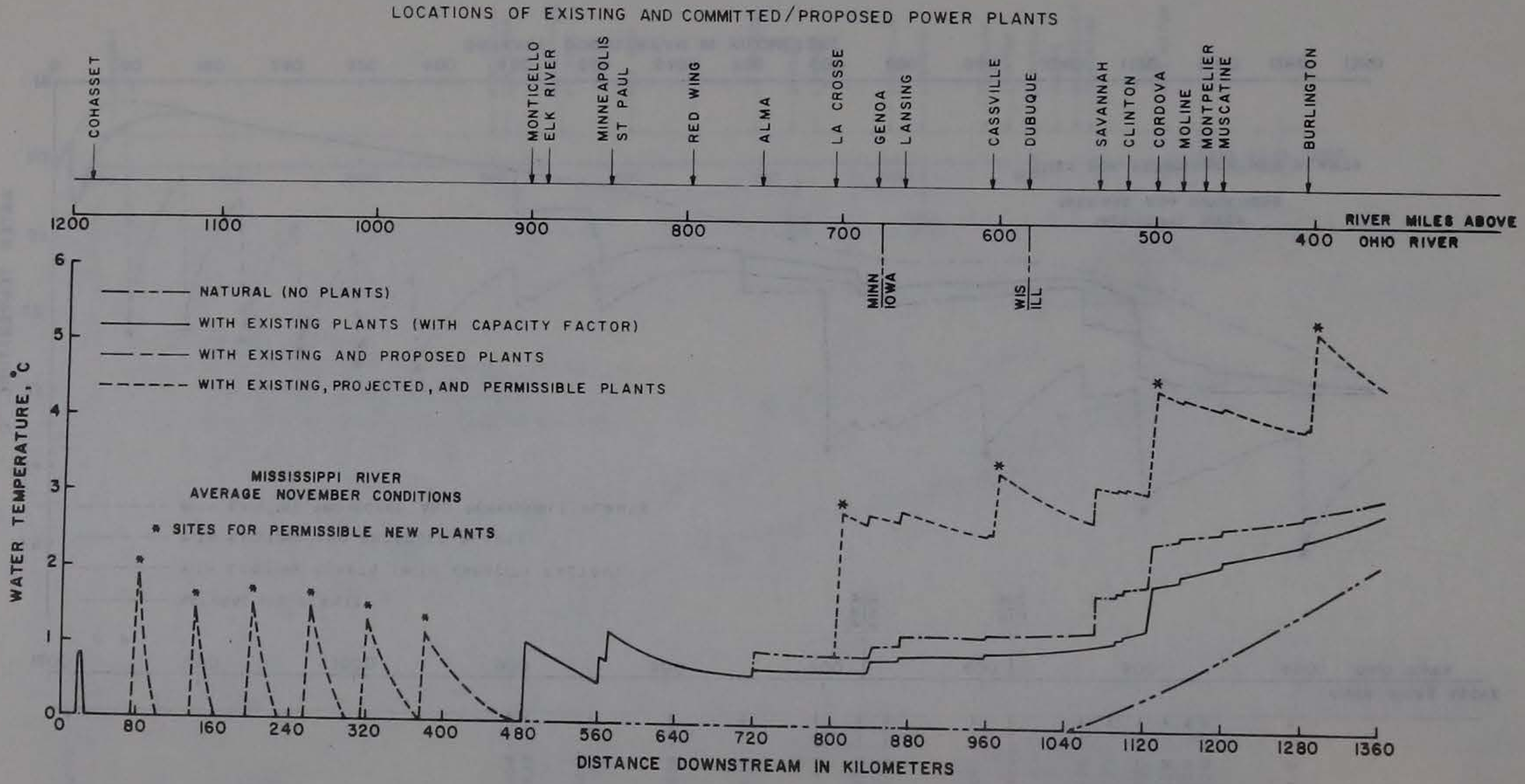


Figure 29. (continued)

Table 22

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 23

LOCATIONS AND CAPACITIES OF PERMISSIBLE POWER PLANTS BASED ON TEMPERATURES WITH EXISTING PLANTS AND 1974 CAPACITY FACTORS (TABLE 19) -- 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	1.45	2.05	2.78	411	450	325	483	283	311	224	333
1075.8	1770	4662	2199	2215	2.78	1.09	1.85	2.78	428	441	353	536	295	304	243	370
1038.5	1981	5984	2715	2629	2.78	0.87	1.66	2.78	479	453	391	635	331	312	270	438
1001.2	2346	7598	3385	3292	2.78	0.66	1.43	2.58	568	433	420	739	391	299	290	510
964.0	2712	9211	4056	3955	2.78	0.53	1.25	1.90	656	424	440	655	452	292	303	451
700.0	15332	51016	22217	22702	2.78	1.73	2.48	2.59	3705	7680	4786	5106	2555	5297	3300	3522
599.4	20347	61853	27819	28691	2.78	0.47	1.27	0.80	4917	2516	3063	1993	3391	1735	2112	1374
500.0	28695	75706	34982	37369	2.78	0.58	1.43	0.84	6934	3841	4357	2745	4782	2649	3005	1893
399.4	40369	97984	42642	45428	2.55	0.77	1.82	1.25	8962	6549	6753	4939	6180	4517	4657	3406

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	325	353	391	420	424	3705	1993	2745	4939
Nuclear (MW)	249	224	243	270	290	292	2555	1374	1893	3406

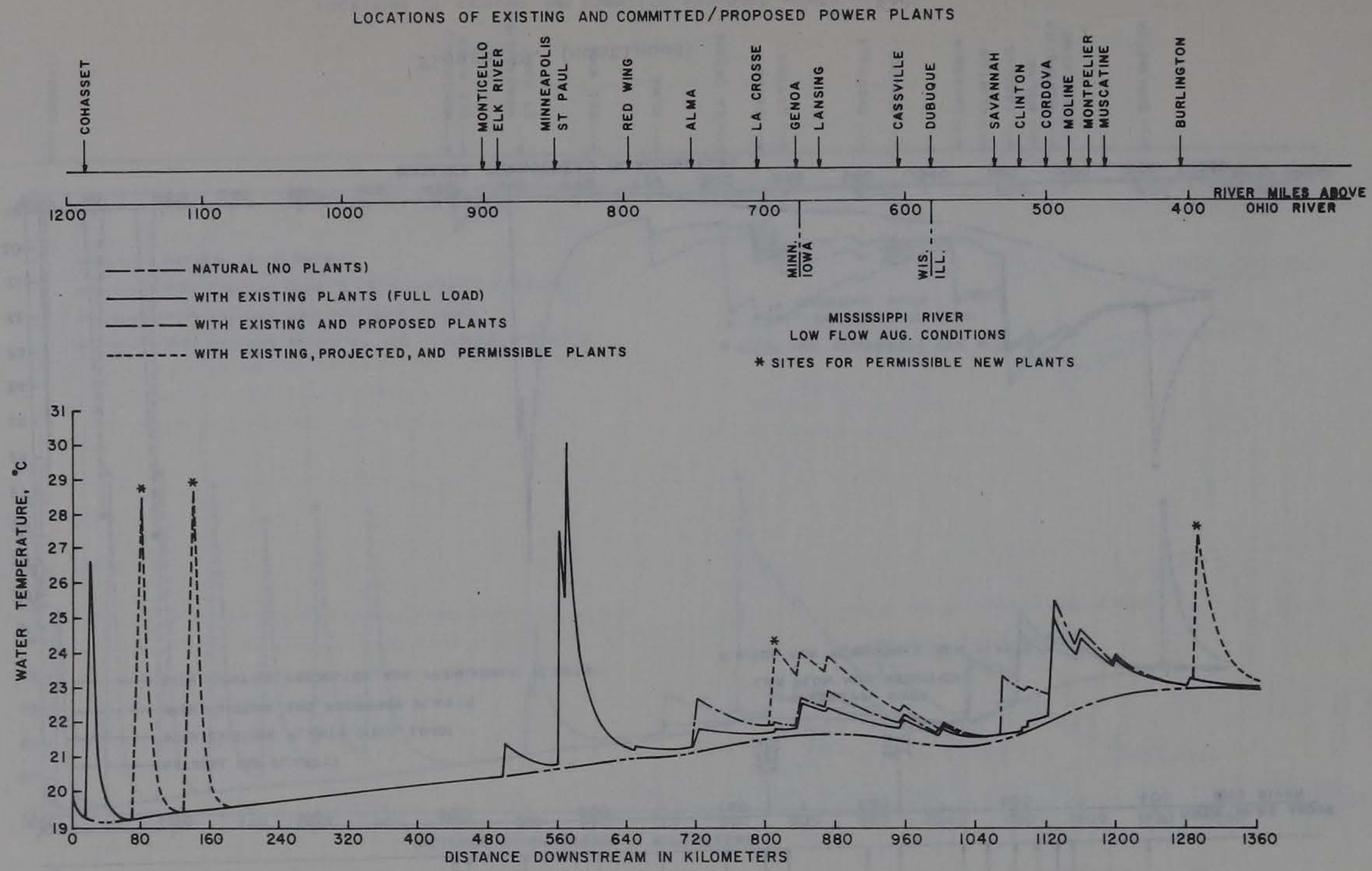


Figure 30. Temperature distributions along the Mississippi River for low flow conditions with full-load operation and permissible new plants based on predicted natural temperatures and average flow conditions

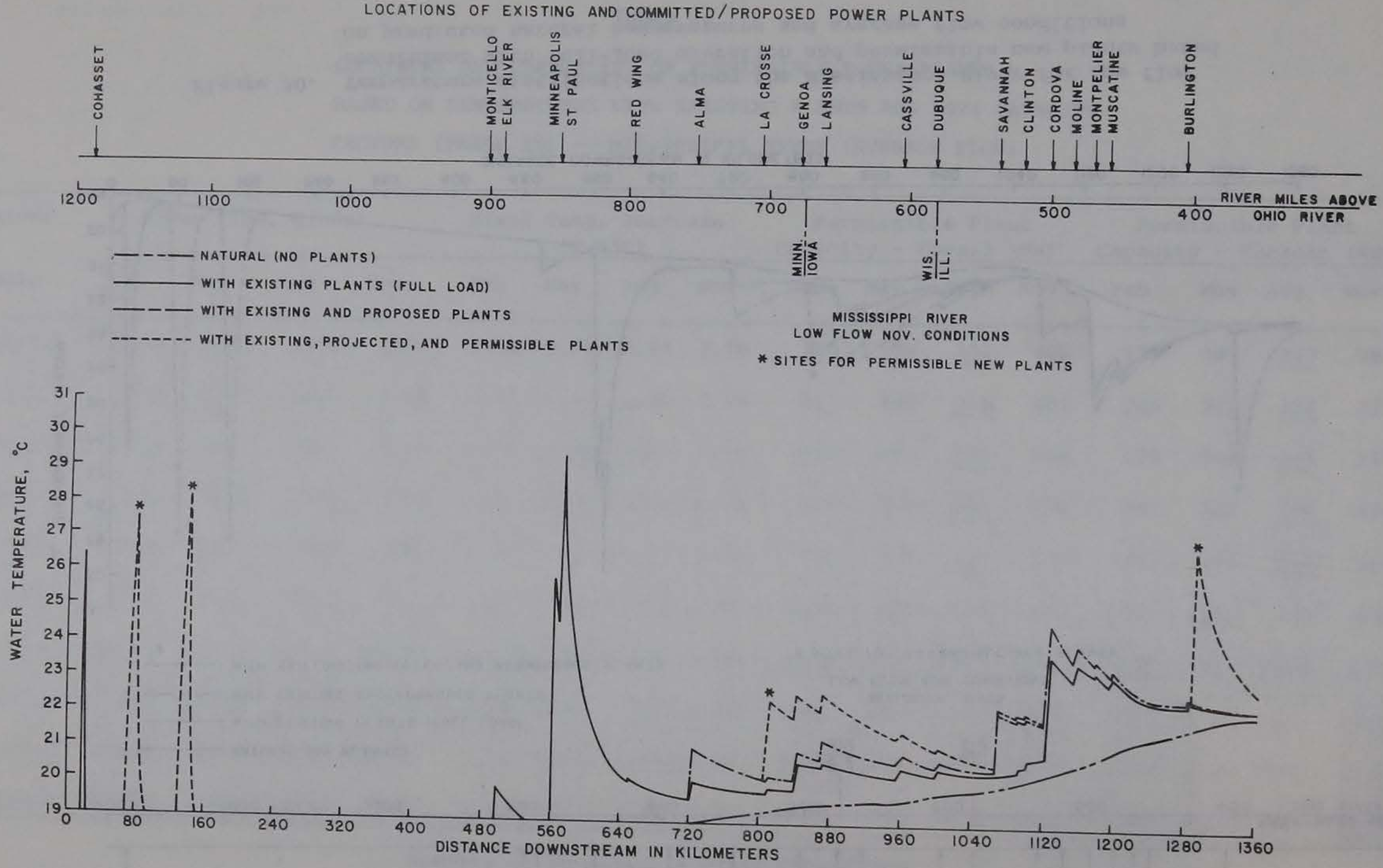


Figure 30. (continued)

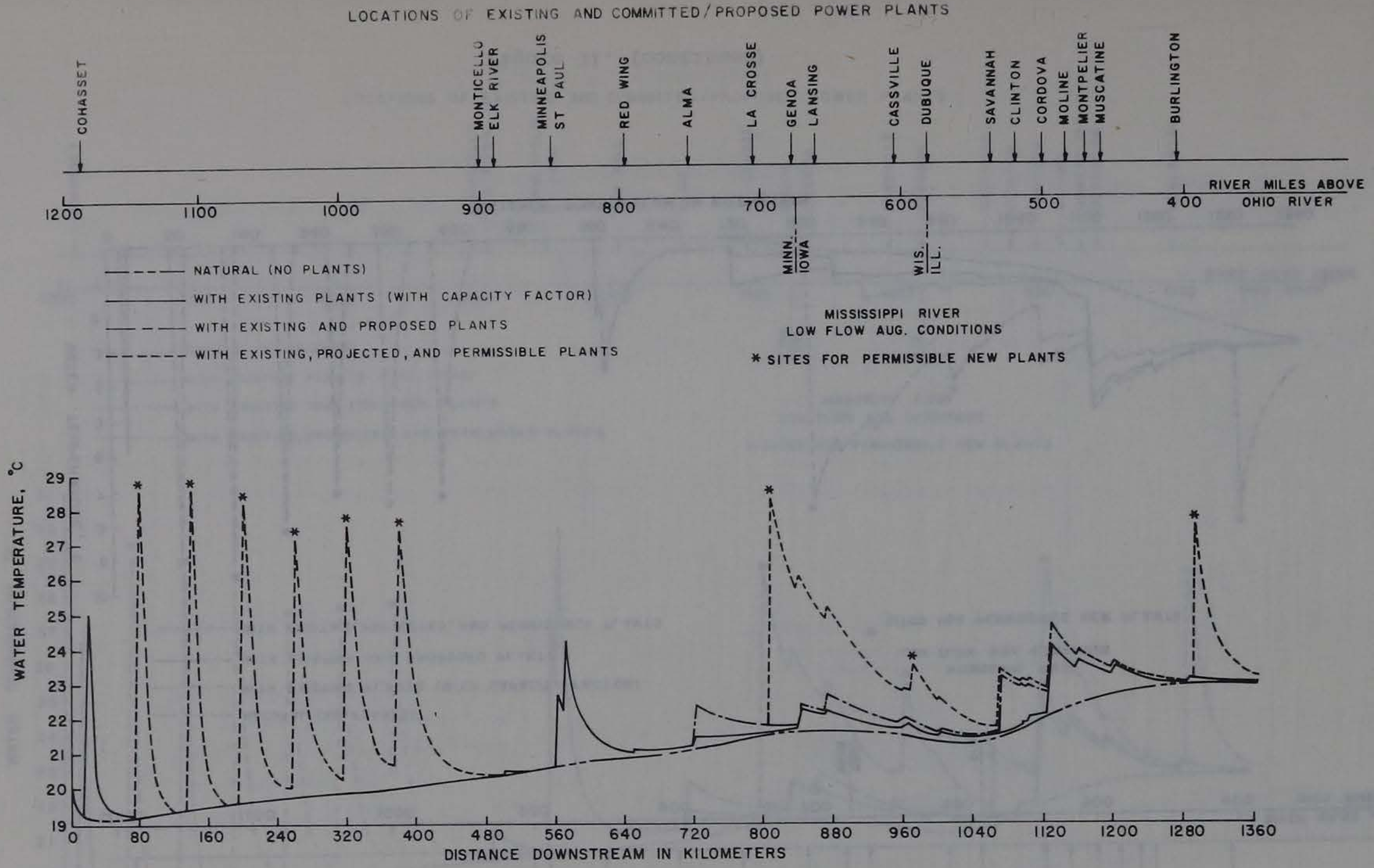


Figure 31. Temperature distributions along the Mississippi River for low flow conditions with 1974 capacity factors and permissible new plants based on predicted natural temperatures and average flow conditions

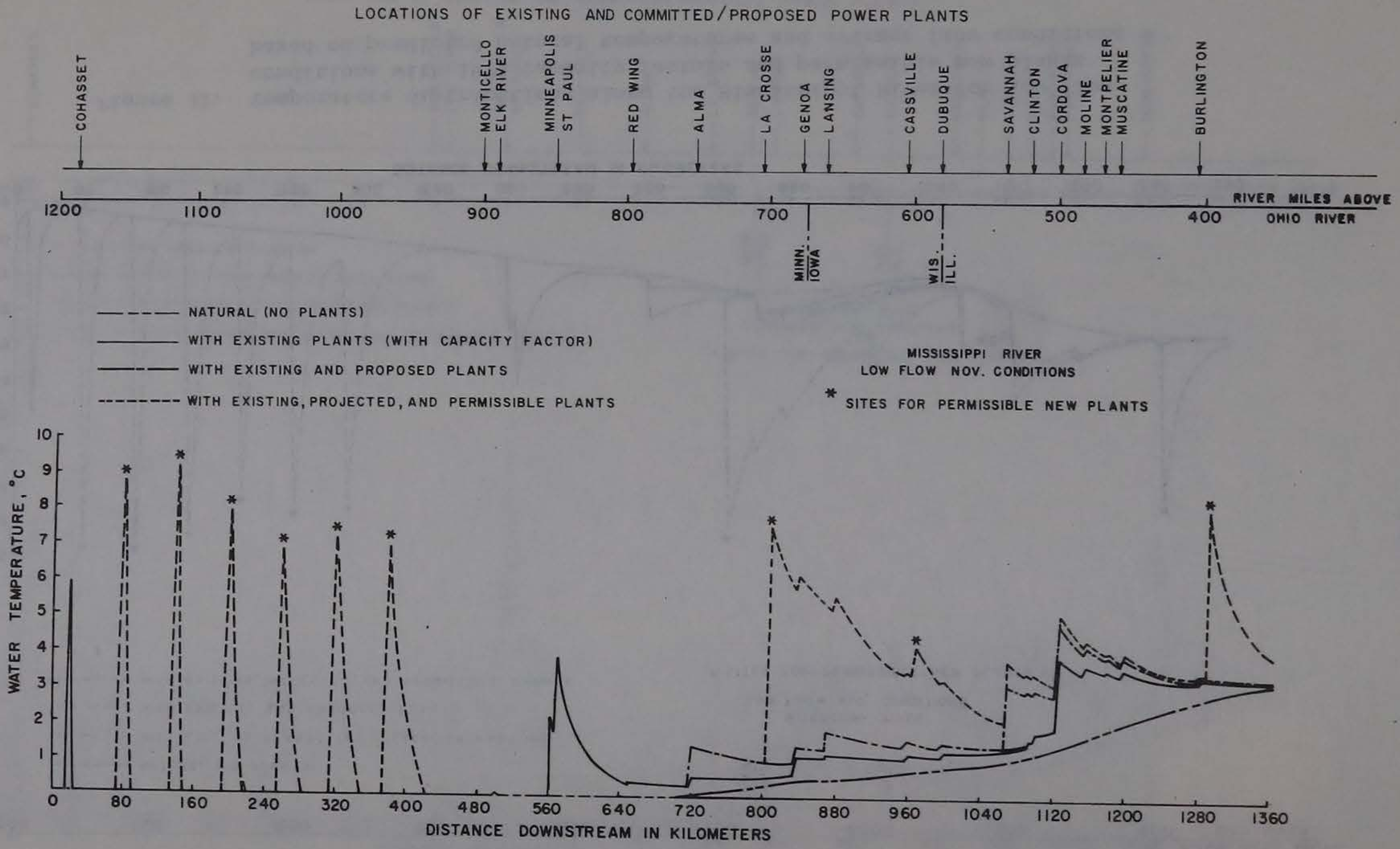


Figure 31. (continued)

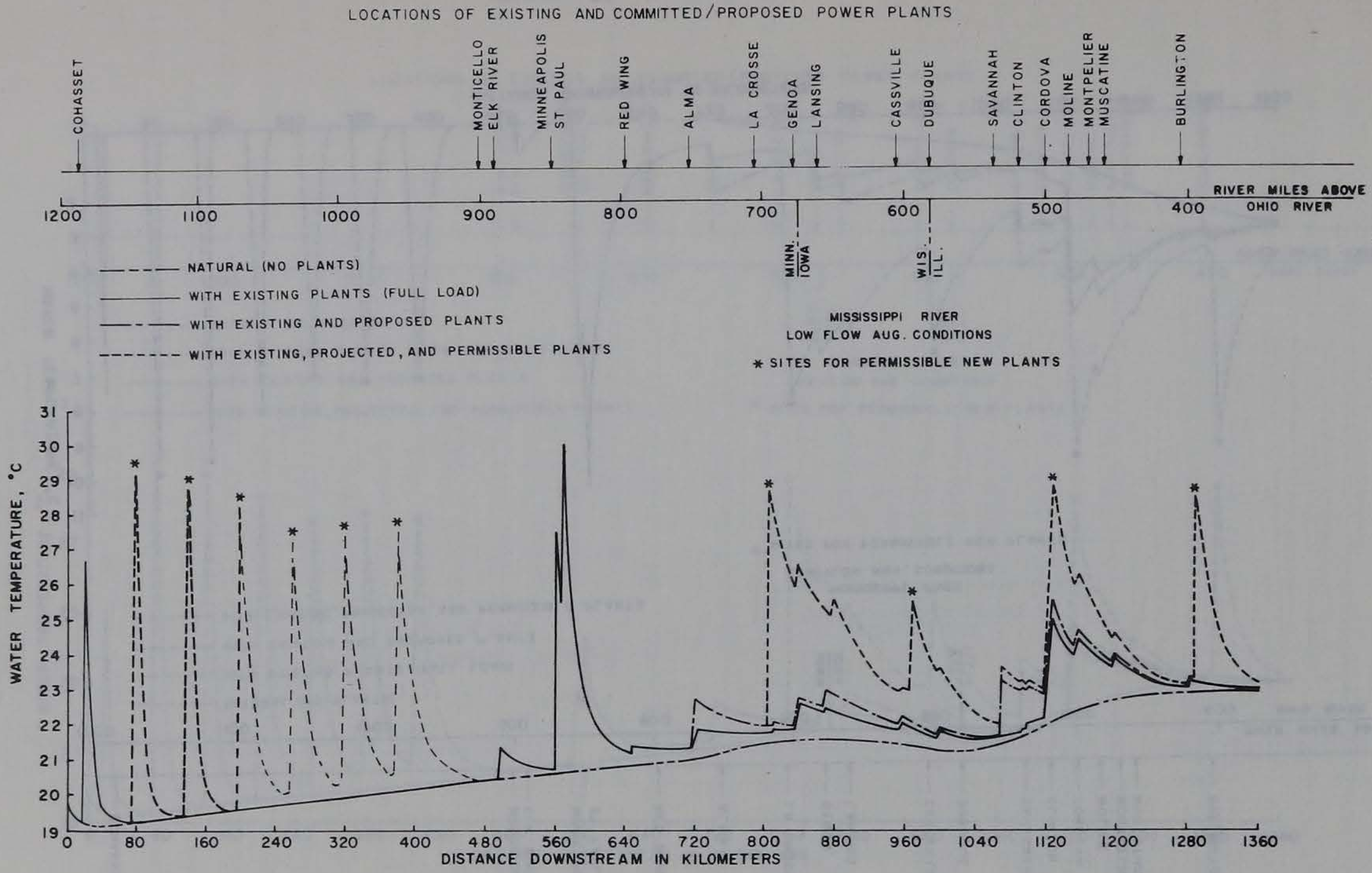


Figure 32. Temperature distributions along the Mississippi River for low flow conditions with full-load operation and permissible new plants based on temperatures with existing heat loads and average flow conditions

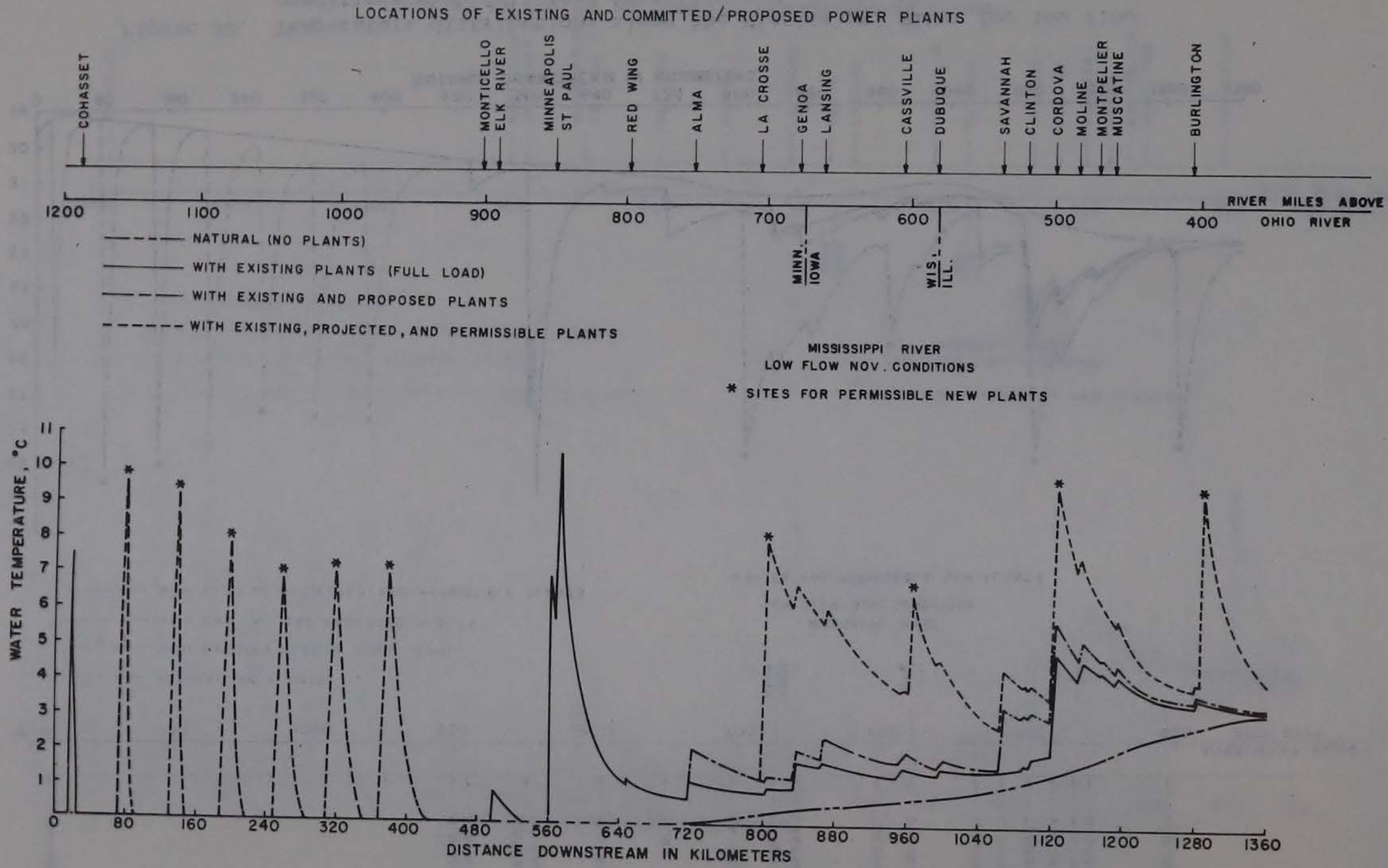


Figure 32. (continued)

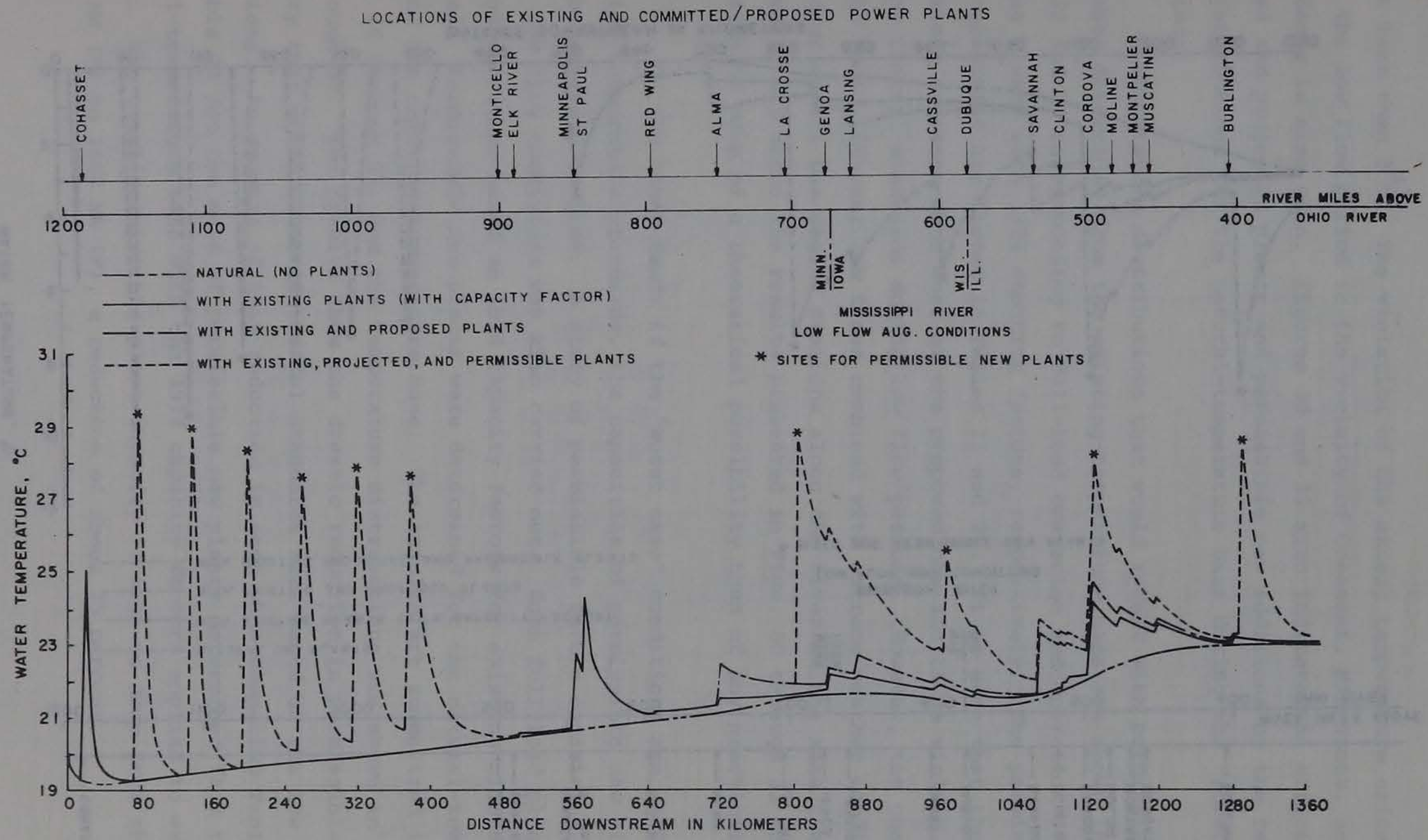


Figure 33. Temperature distributions along the Mississippi River for low flow conditions with 1974 capacity factors and permissible new plants based on temperatures with existing heat loads and average flow conditions

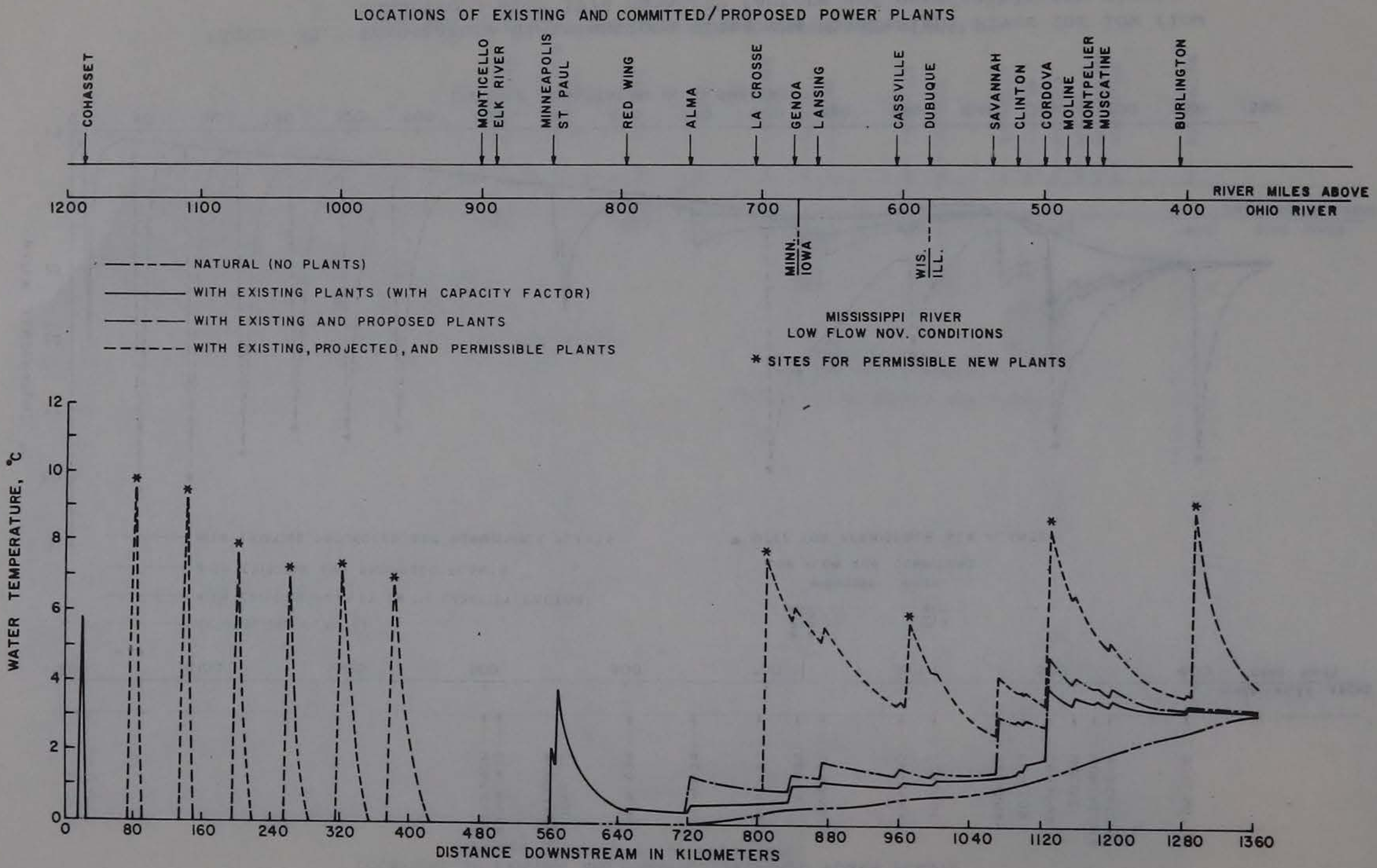


Figure 33. (continued)

will be less than $5^{\circ}F$. The violation of the excess temperature criterion during the low flow period in the vicinity of Cohasset, Minnesota, and its rapid decay is also seen. Figures 30 and 31 also indicate the effects of proposed and projected plants and permissible new additions on the temperature distributions for the natural-temperature base during the "worst case" conditions.

Temperature distributions that would result with permissible new plants determined from the existing-temperature base are shown in Figs. 32 and 33 corresponding to full-load operation and operation of existing plants with 1974 capacity factors, respectively. The permissible plant capacities are listed in Tables 22 and 23. It is seen that the temperature excesses with most of the proposed new additions violate the existing thermal standards during low flow periods. However, the chance that the 7-day, 10-year low flows combined with extreme weather conditions will occur at all the gaging stations along the river at the same time is very small, and hence the results presented in Figs. 30 through 33 should be considered more of a theoretical possibility than of any practical importance.

On the other hand, if the "worst case" conditions are used to establish temperature standards, the capacities of permissible new plants would be severaly limited. A study of permissible future capacities based on the low flow conditions was also carried out. Both full-load plant operation and operation based on 1974 capacity factors for existing plants were examined. Permissible new plants were determined for the natural-temperature base and the existing-temperature base. The results are summarized in Tables 24 through 27, and the temperature distributions are shown in Figs. 34 through 37. The results show the drastic reduction in permissible plant capacity that would occur if thermal standards were based on the low flow conditions. An example of this reduction is seen when comparing Table 25 and Table 21 for the case of permissible new plants determined from the natural-temperature base with the 1974 capacity factors applied to existing plants. The total permissible plant capacity is seen to drop from about 11100 MW (F) to 2660 MW (F), a reduction of about 75 percent.

Table 24

LOCATIONS AND CAPACITIES OF PERMISSIBLE POWER PLANTS BASED ON PREDICTED NATURAL TEMPERATURES 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
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 25

LOCATIONS AND CAPACITIES OF PERMISSIBLE POWER PLANTS BASED ON PREDICTED NATURAL TEMPERATURES AND 1974 CAPACITY FACTORS (TABLE 19) -- 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
399.4	10678	10678	2.62	2.26	2434	2100	1678	1448

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	2100
Nuclear (MW)	32	32	60	83	88	94	1448

Table 26

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 27

LOCATIONS AND CAPACITIES OF PERMISSIBLE POWER PLANTS BASED ON TEMPERATURES WITH EXISTING PLANTS AND 1974 CAPACITY FACTORS (TABLE 19)-- 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
700.0	6421	6421	2.57	2.39	1437	1337	991	922
599.4	8941	8941	2.30	1.78	1790	1382	1235	953
500.0	9894	9894	2.17	1.60	1864	1381	1286	952
399.4	10678	10678	2.73	2.54	2536	2332	1749	1629

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	1337	1382	1381	2362
Nuclear (MW)	32	32	60	83	88	94	922	953	952	1629

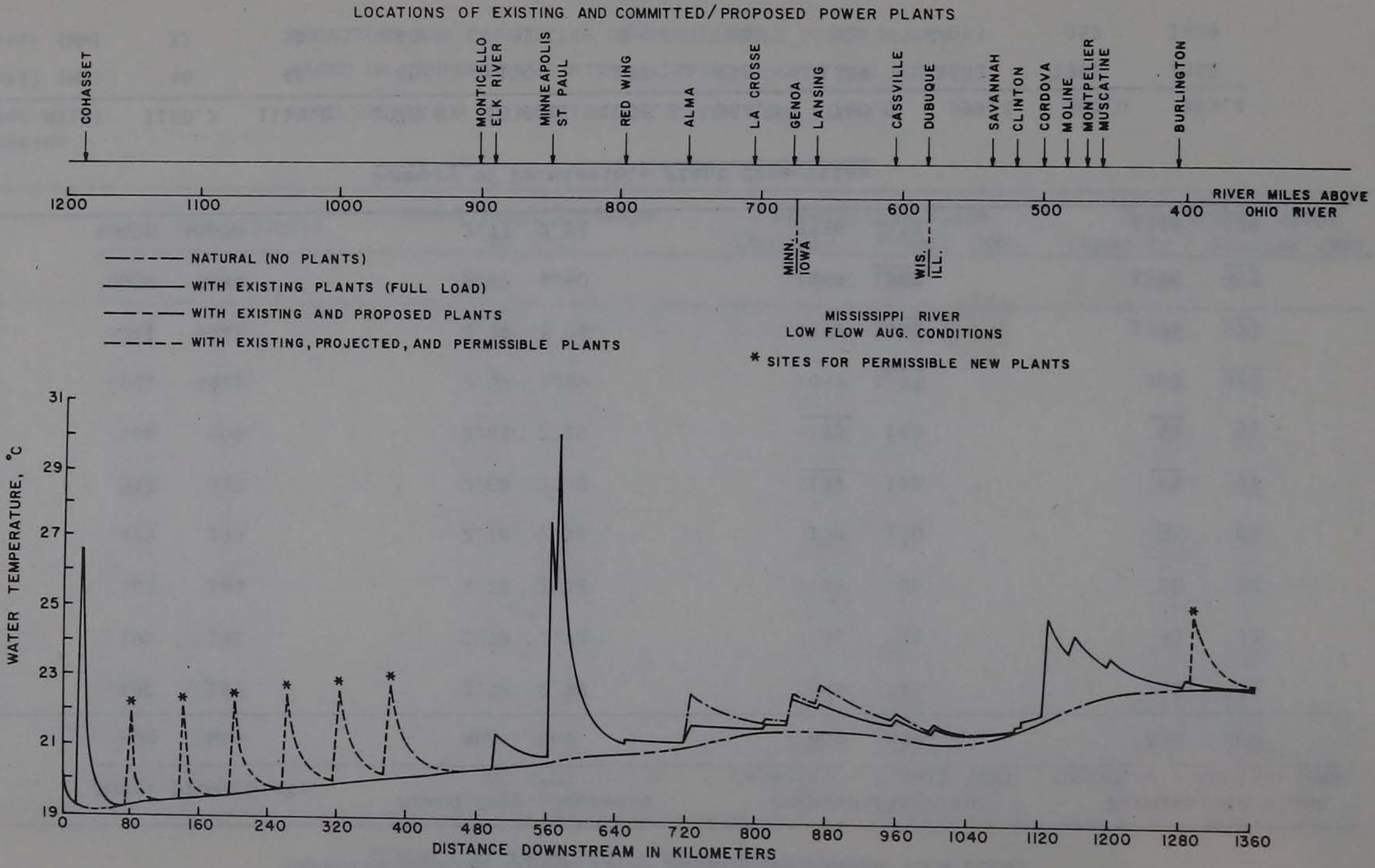


Figure 34. Temperature distributions along the Mississippi River for low flow conditions with full-load operation and permissible new plants based on predicted natural temperatures and low flow conditions

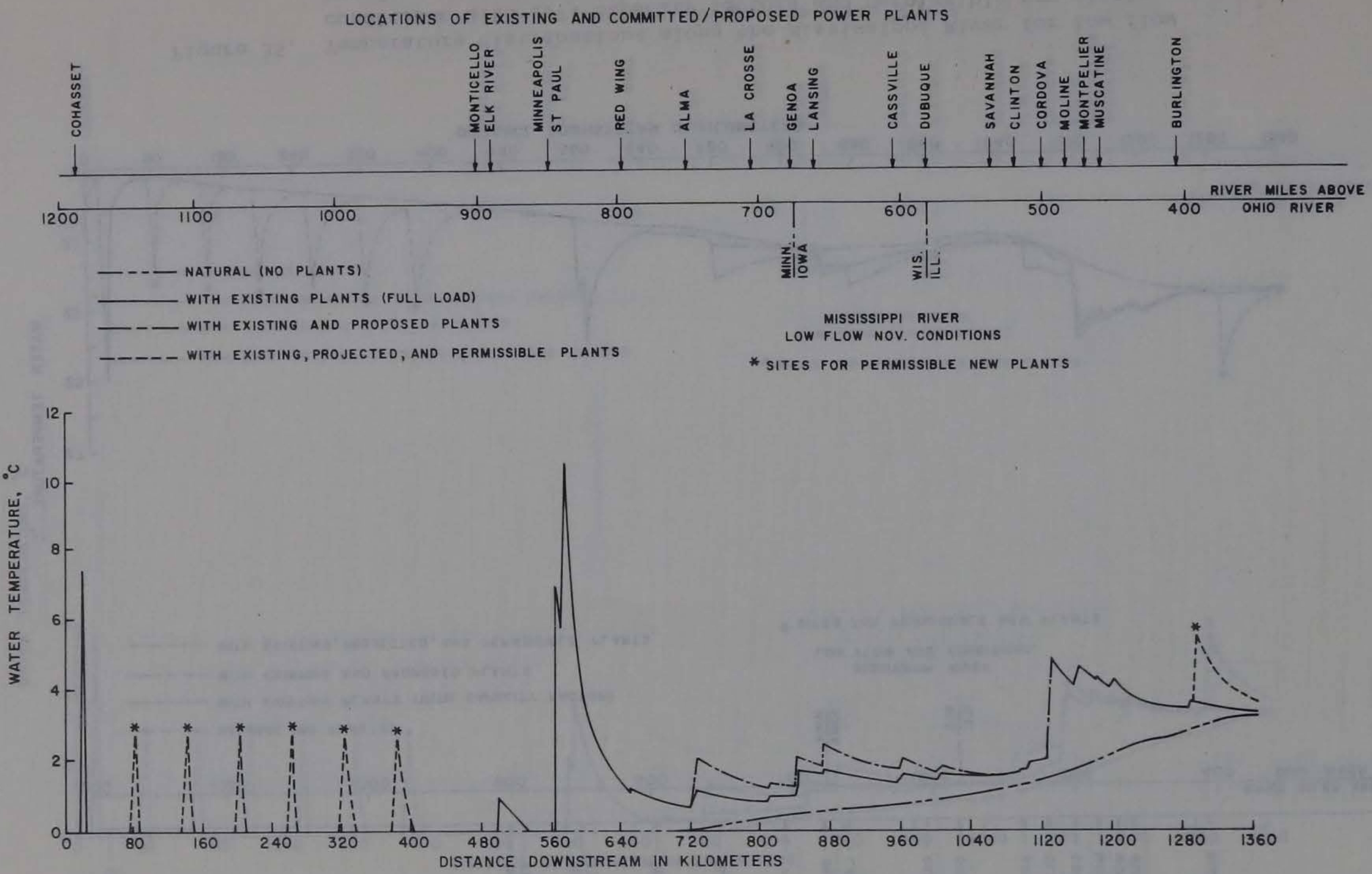


Figure 34. (continued)

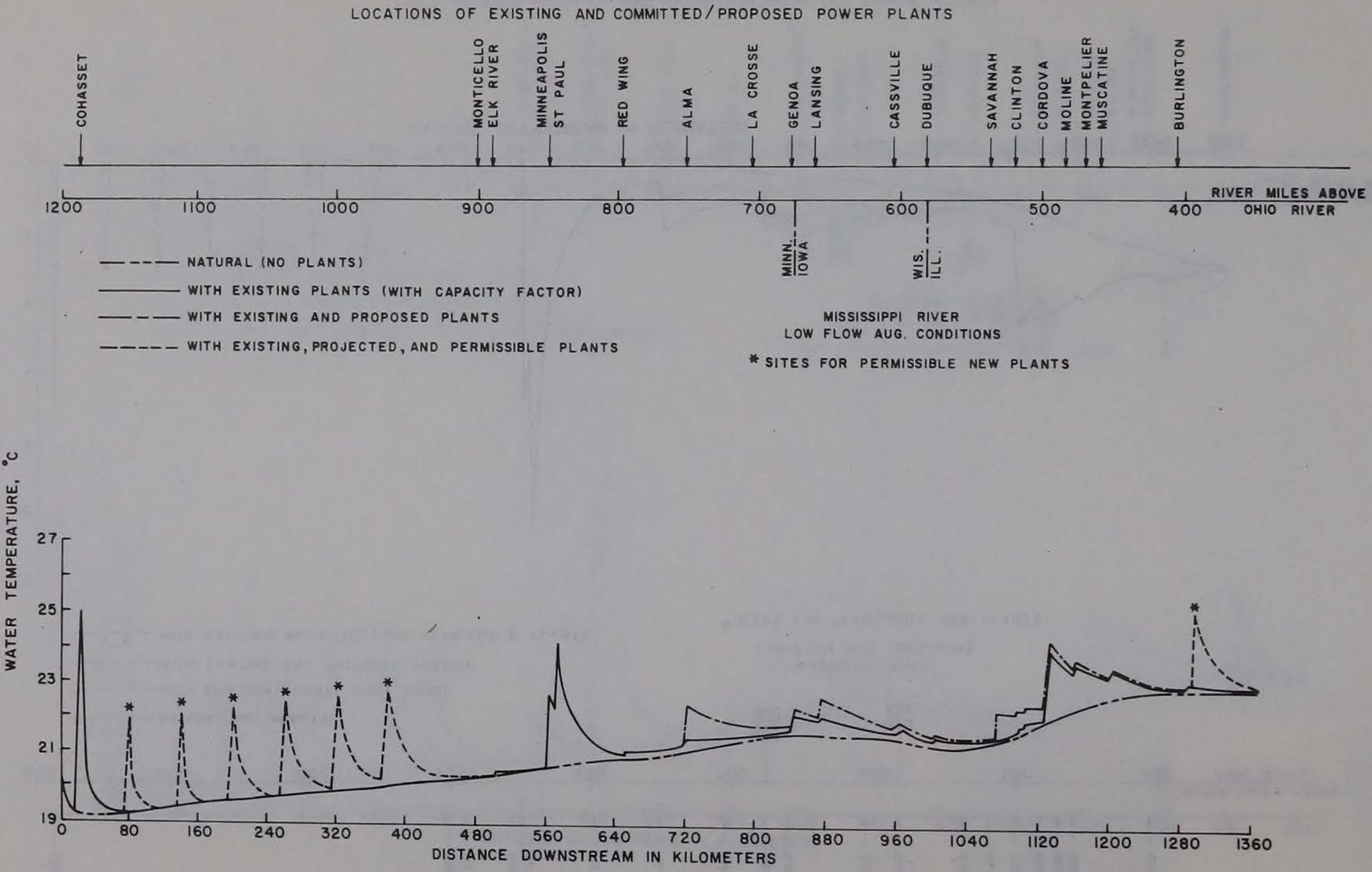


Figure 35. Temperature distributions along the Mississippi River for low flow conditions with 1974 capacity factors and permissible new plants based on predicted natural temperatures and low flow conditions

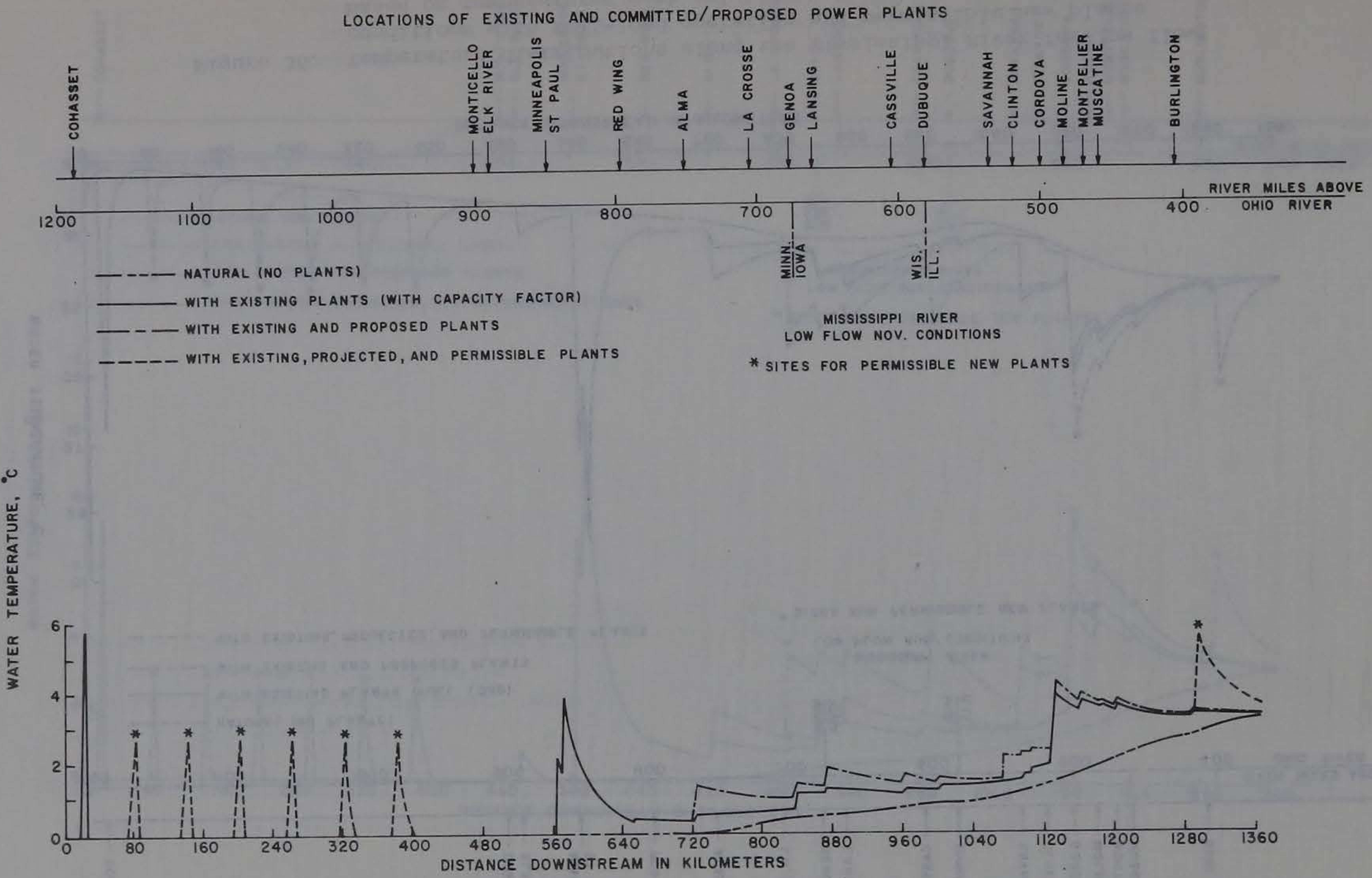


Figure 35. (continued)

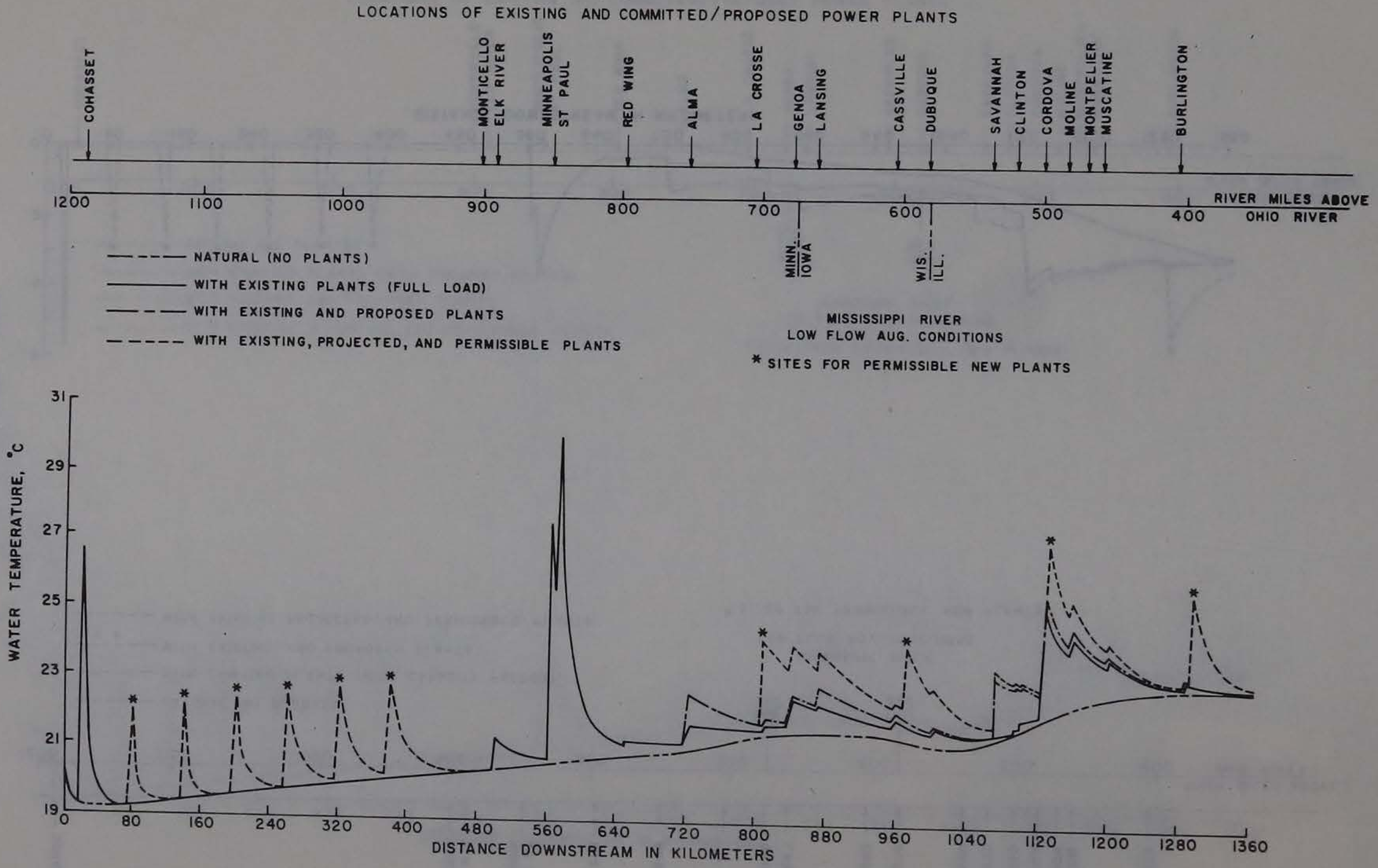


Figure 36. Temperature distributions along the Mississippi River for low flow conditions with full-load operation and permissible new plants based on temperatures with existing heat loads and low flow conditions

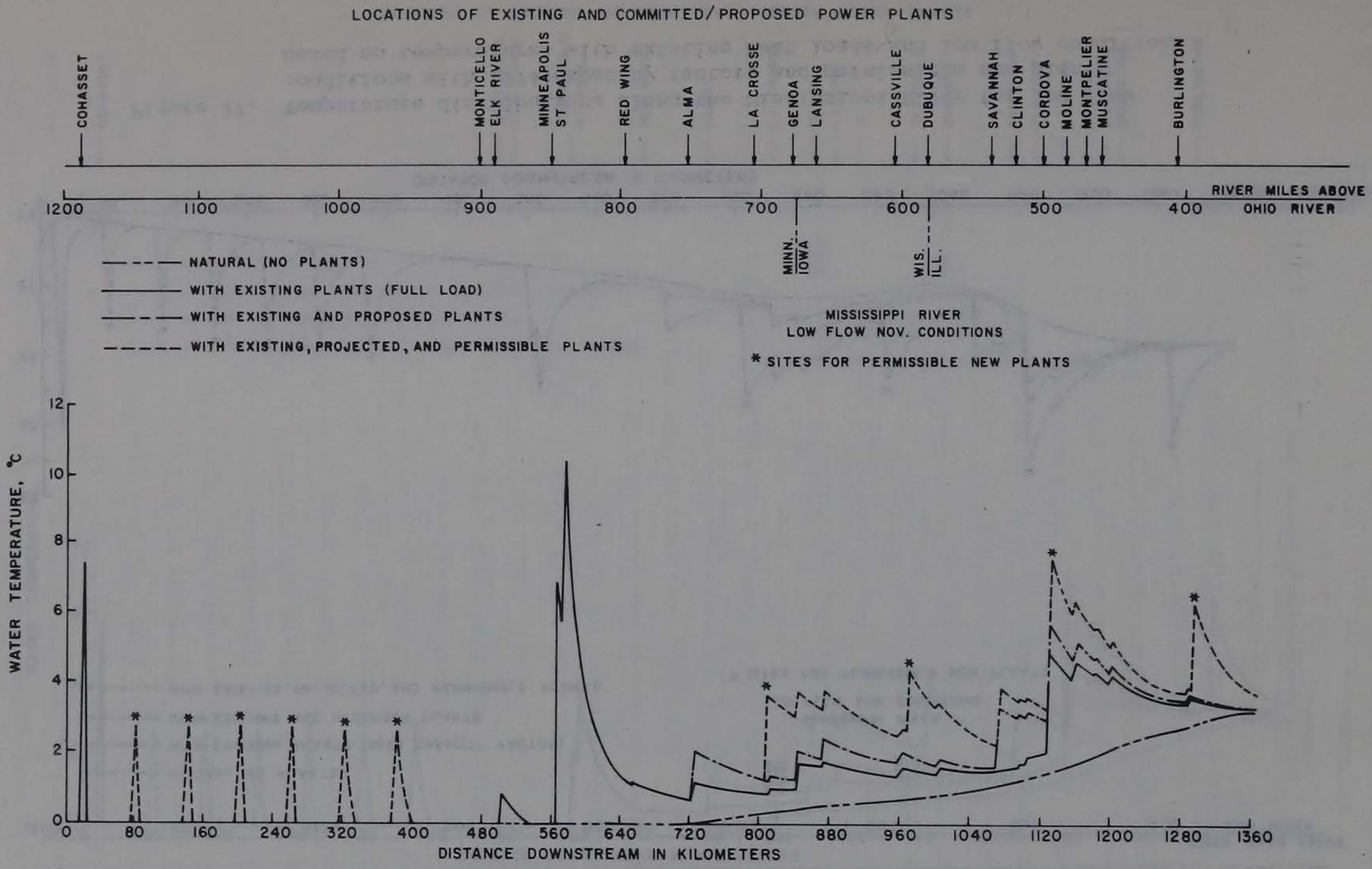


Figure 36. (continued)

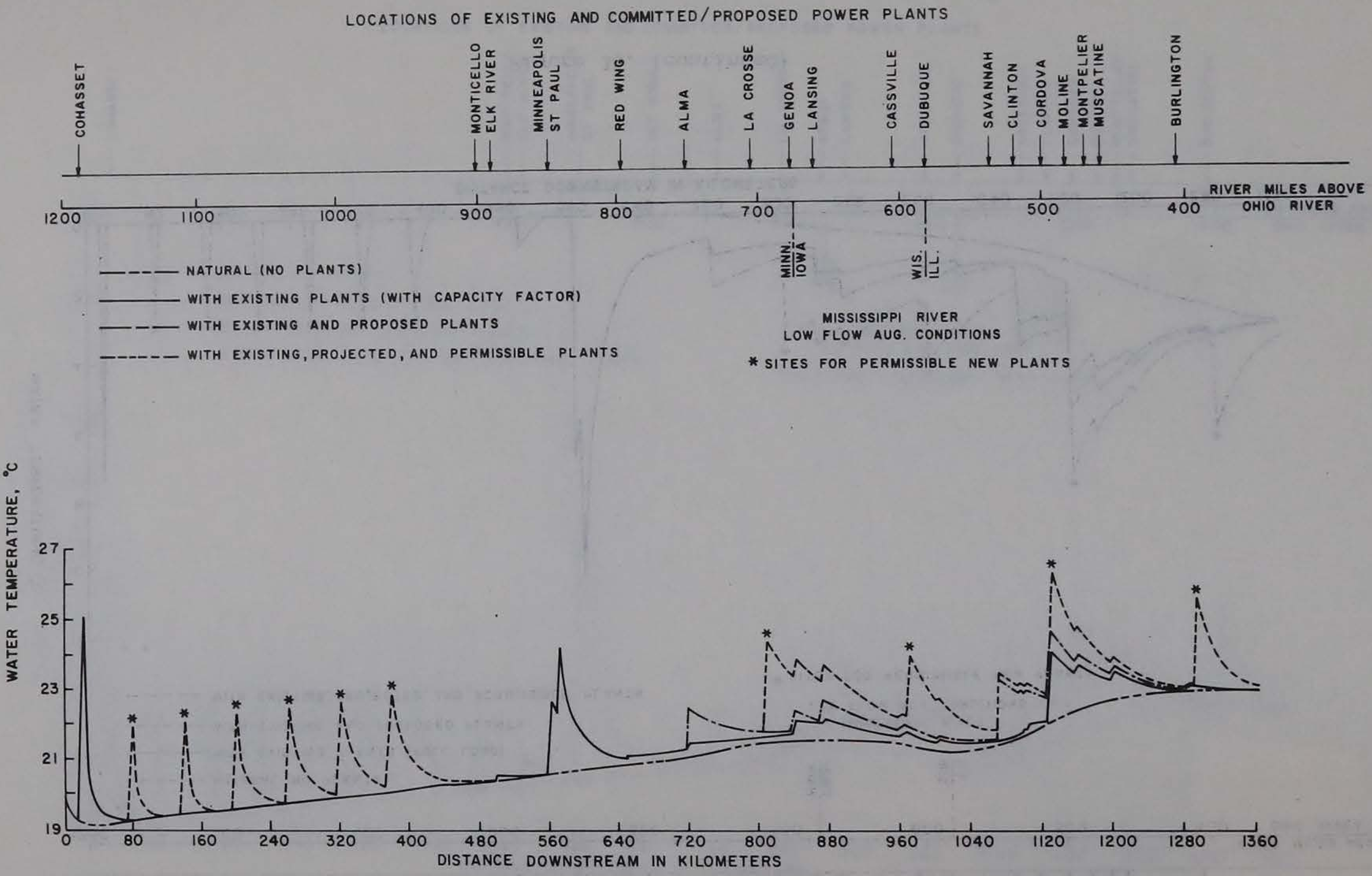


Figure 37. Temperature distributions along the Mississippi River for low flow conditions with 1974 capacity factors and permissible new plants based on temperatures with existing heat loads and low flow conditions

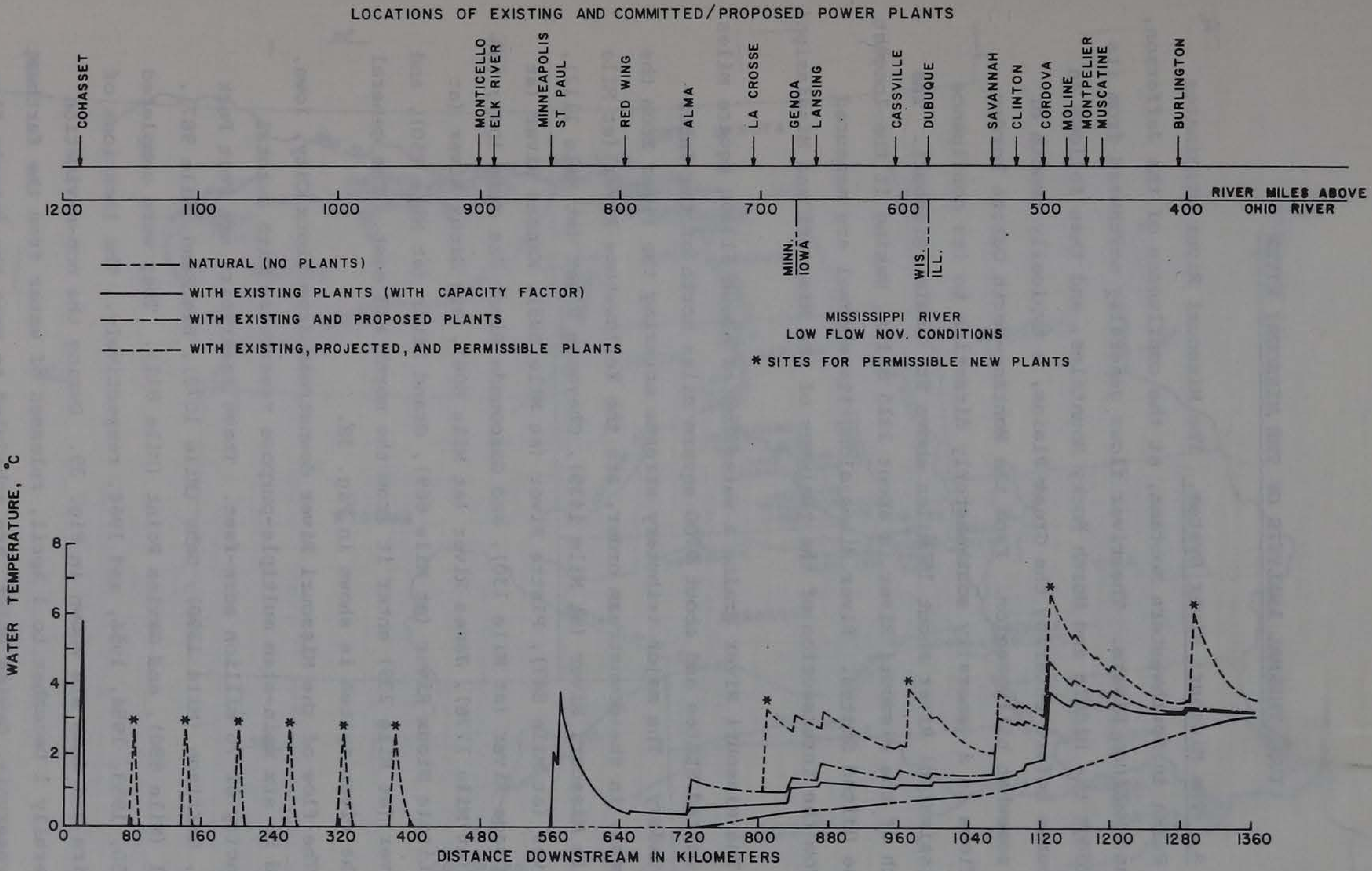


Figure 37. (continued)

IV. THERMAL ANALYSIS OF THE MISSOURI RIVER

A. The Missouri River System.

The Missouri River originates near Three Forks in Southwestern Montana, at the confluence of the Jefferson, Gallatin, and Madison Rivers. The river flows generally northward from its origin, through the Middle and North Rocky Mountains, and then follows an easterly course before entering the Great Plains, a typically smooth or rolling to somewhat hilly region. From the Montana-North Dakota border the river flows in a generally southeasterly direction to its confluence with the Mississippi River about 15 miles above St. Louis, Missouri. The total length of the Missouri River is about 2315 miles, making it the longest river in the United States. River Miles along its channel are measured upstream from the intersection of the thalwegs of the Missouri and Mississippi Rivers.

The Missouri River drains a watershed of about 513300 square miles within the United States and about 9700 square miles north of the International Boundary. The major tributary streams entering the river from the south and west, in the downstream order, are the Yellowstone River (at Mile 1584), Little Missouri River (at Mile 1439), Cheyenne River (at Mile 1112), Niobrara River (at Mile 847), Platte River (at Mile 595), Kansas River (at Mile 367), Osage River (at Mile 130), and Gasconade River (at Mile 104); the Milk River (at Mile 1776), James River (at Mile 806), Big Sioux River (at Mile 734), Little Sioux River (at Mile 669), Grand River (at Mile 250), and Chariton River (at Mile 239) enter it from the north and east. The general layout of the river system is shown in Fig. 38.

The flow of the Missouri River downstream from Sioux City, Iowa, is regulated by six main-stem multiple-purpose reservoirs with a total storage capacity of 76 million acre-feet. These reservoirs are Fort Peck (Mile 1775), Garrison (Mile 1390), Oahe (Mile 1072), Big Bend (Mile 987), Fort Randall (Mile 880), and Gavins Point (Mile 811). They were completed in 1943, 1950, 1953, 1954, 1956, and 1964, respectively. The locations of the reservoirs and dams are shown in Fig. 39. During the non-navigation season, generally 1 December to 1 April, releases of water from the farthest downstream reservoir, Gavins Point, are scheduled to meet the interim flow requirement for stream sanitation and supplemental power needs. During the

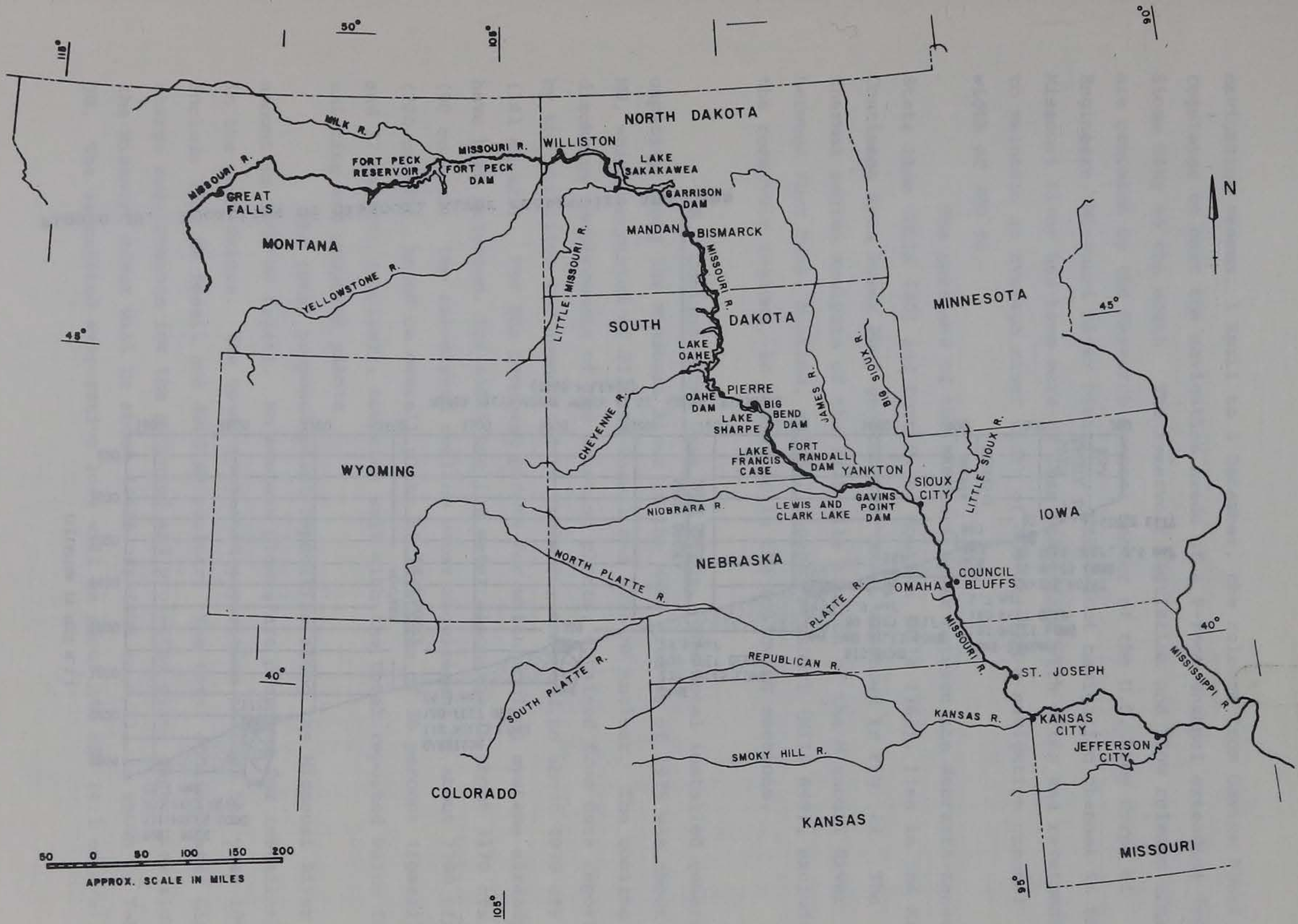


Figure 38. Missouri River system

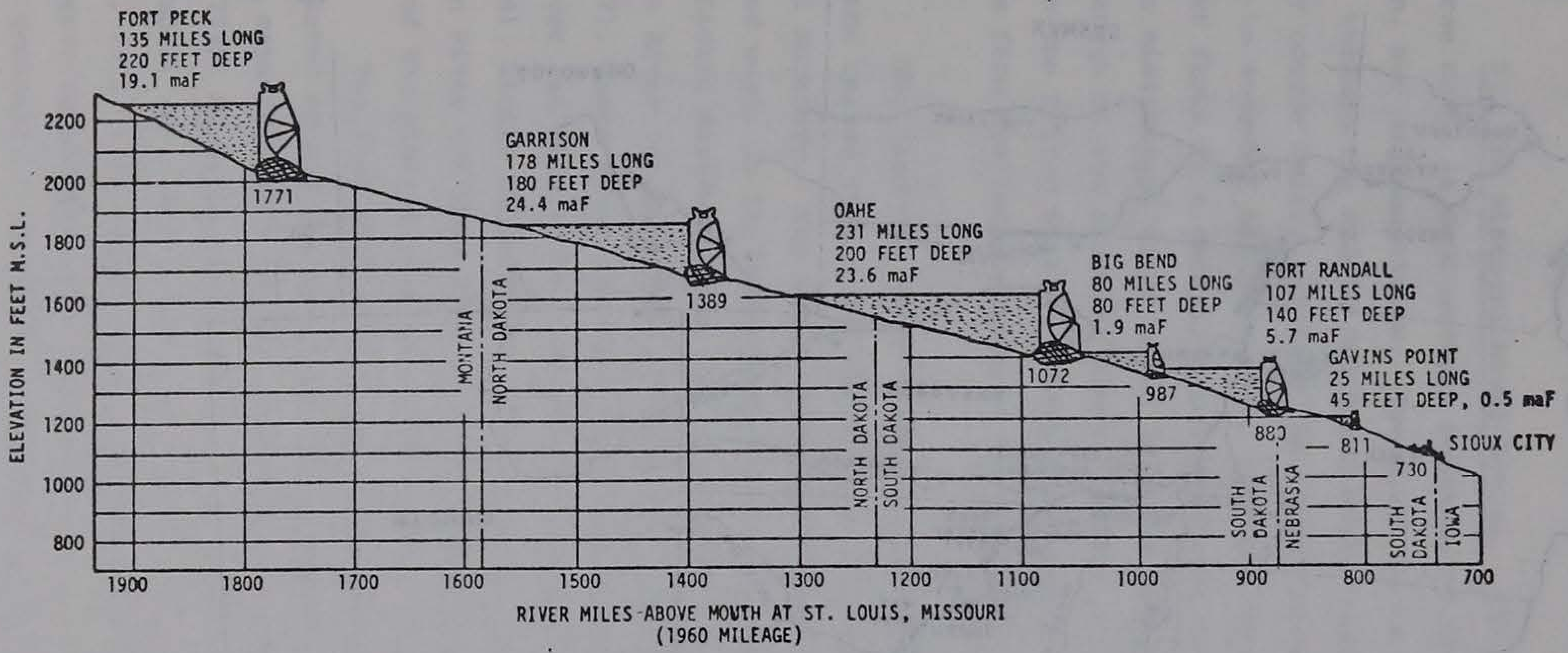


Figure 39. Locations of Missouri River reservoirs and dams

navigation season, 1 April to 1 December, the release from Gavins Point is regulated to meet the navigation needs of a 9-foot channel extending from Sioux City to the mouth. The reservoir regulation and flow release schedules are prepared by the Research Control Center of the U.S. Army Corps of Engineers, Missouri River Division. The 9-foot navigation channel in the Missouri River has been more or less stabilized with dikes and revetments to maintain an average river width of 800 ft. and a navigation channel width of 300 ft.

The portions of the Missouri River between the Nebraska-Kansas State line (Mile 490) and Fort Peck, Montana (Mile 1763), lies in the Mid-Continent Area Power Pool geographical area, as shown in Fig. 21. The thermal regime analysis of the 1315-mile stretch of the Missouri River between Fort Peck, Montana, and St. Joseph, Missouri (Mile 448), excluding the reservoir regions, is presented in the following sections.

B. Cooling Water Uses and Needs. The total installed generating capacity along the Missouri River in the MAPP area as of 1975 was about 3435 MW, which consisted of 2140 MW fossil and 1295 MW nuclear. The cooling water discharge requirements of the existing plants, obtained from data reported by the utilities and summarized in Table 28, amounted to about 4970 cfs (141 cu.m/s). For the proposed plants for which cooling systems already have been selected, the total cooling water discharge is about 3170 cfs (90 cu.m/s). The calculated cooling water requirement of about 7780 cfs (220 cu.m/s), based on overall plant efficiencies of 36 percent (fossil) and 32 percent (nuclear), compares well with the total reported value for existing and proposed plants.

The total proposed plant capacities along the Missouri River amount to 3600 MW fossil. No nuclear plants are proposed for installation in the near future. The total projected capacities through the year 1993 include 3720 MW fossil and 4200 MW nuclear. The total cooling water discharge requirements for the proposed and projected plant capacities along the Missouri River will be about 14425 cfs (408 cu.m/s), as shown in Table 28. The associated evaporative loss will be about 144 cfs (4.1 cu.m/s).

Table 28

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

Category		Plant Capacity, (MW) F = Fossil N = Nuclear	Cooling Water Required in cfs (cu·m/s)		
			Calculated, (Eq. 52)		Reported, (Table 31)
			η_I = 15%(F), 5%(N); η_p = 36%(F), 32%(N)	η_I = 10% (F,N); η_p = 33% (F,N)	
Existing Plants		2140 (F)	2458.5 (69.6)	3119.6 (88.3)	2809.5 (79.6)
		1295 (N)	2152.4 (60.9)	1887.8 (53.5)	2156.8 (61.1)
	sum:	3435	4610.9 (130.5)	5007.4 (141.8)	4966.3 (140.7)
Proposed Plants		840* (F)	--	--	--
		2760 (F)	3170.8 (89.8)	4023.5 (113.9)	3168.6 (89.7)
		0 (N)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
	sum:	3600	3170.8 (89.8)	4023.5 (113.9)	3168.6 (89.7)
Projected Plants		3720 (F)	4273.7 (121.0)	5423.0 (153.6)	--
		4200 (N)	6980.6 (197.6)	6122.6 (173.4)	--
	sum:	7920	11254.3 (318.7)	11545.6 (327.0)	--

* Cooling water data not available

C. Water Temperature Standards. The temperature criteria set forth in the water quality standards of the state government agencies for the Mississippi and Missouri Rivers are given in Appendix B. A summary of the existing thermal standards of the States of Montana, North Dakota, South Dakota, Nebraska, Iowa, Kansas, and Missouri applicable to the Missouri River is given in Table 29. The allowable temperature rises are 5°F for the Missouri River reaches within North Dakota and downstream from Sioux City, Iowa, and 4°F for other portions of the river except for reaches inside Montana. Montana state regulations allow a temperature rise of 1°F when the water temperature is between 32°F and 66°F, with the maximum limited to 67°F for water temperatures between 66°F and 66.5°F. For water temperatures above 66.5°F, the allowable excess is only 0.5°F. The maximum allowable water temperature is 90°F downstream from Sioux City, Iowa, and varies from 65°F to 85°F in other reaches, as shown in Table 29.

D. Climatic Conditions. The climate within the Missouri River basin is determined largely by the interaction of the three great air masses which originate over the Gulf of Mexico, the North Pacific, and the northern polar regions. The Gulf air dominates the summer weather, while the polar air has the dominant influence on the winter weather. Due to the mid-continental location of the Missouri River basin, which is remote from the source areas of the air masses, the weather in the basin fluctuates between extremes. Winters are long and cold, while summers are sunny and hot. Spring is cool, moist, and windy; autumn is cool, dry, and sunny. Temperature extremes range from winter lows of -60°F in Montana to summer highs of up to 120°F in Nebraska, Kansas, and Missouri. The average frost-free periods for the nonmountainous areas of the basin range from 90 to 180 days.

Monthly mean values of daily weather conditions determined from data from seventeen first order weather stations in the MAPP and adjacent areas are tabulated in Appendix C. Summaries of the weather data for the stations are given in Tables 11 through 14, and the locations of the weather stations are shown in Fig. 22. Average weather data for the 20-year period from 1953 to 1974 were used in the thermal regime analysis of the Missouri River.

Table 29

SUMMARY OF THERMAL STANDARDS FOR MISSOURI RIVER

River Reach	State, and Controlling Agency	Classification of Reach	Allowable Temperature Rise Above Natural Conditions	Maximum Allowable Water Temperature	Other
Upstream of Mile 1600, inside Montana	Montana State Health and Environmental Sciences	Category B-D_2	1°F in range 32°-66°F; 0.5°F, above 66.5°F.	67°F, for natural temperature of 66.5°F, or less.	Rate of decrease, 2°F/hour, up to 32°F.
Montana border (RM 1600) to South Dakota border (RM 1245)	North Dakota State Department of Health	Class I	5°F	85°F	
North Dakota border (RM 1245) to Big Bend Dam (RM 987)	South Dakota State Department of Environmental Protection	Cold Water Permanent Fish Life Propagation Waters	4°F	65°F	Maximum rate of increase, 2°F/hour.
Big Bend Dam (RM 987) to Nebraska border (RM 873)	South Dakota State Department of Environmental Protection	Warm Water Permanent Fish Life Propagation Waters	4°F	80°F	Maximum rate of increase, 2°F/hour.
South Dakota border (RM 873) to Sioux City, Iowa (RM 732)	Nebraska State Department of Environmental Control	Class A	4°F	85°F	Maximum rate of change, 2°F/hour.

(Table 29 continued)

Table 29 (continued)

SUMMARY OF THERMAL STANDARDS
FOR MISSOURI RIVER

River Reach	State, and Controlling Agency	Classification of Reach	Allowable Temperature Rise Above Natural Conditions	Maximum Allowable Water Temperature	Other
Sioux City, Iowa (RM 732) to Missouri border (RM 553)	Nebraska State Department of Environmental Control; and Iowa State Department of Environmental Quality	Class A	5°F	90°F	Maximum rate of change, 2°F/hour.
Iowa border (RM 553) to Kansas border (RM 490)	Nebraska State Department of Environmental Control; and Missouri State Clean Water Commission	Class A; --	5°F	90°F	
Nebraska border (RM 490) to Kansas City, Missouri (RM 366)	Missouri State Clean Water Commission; and Kansas State Board of Health	--; Class B	5°F	90°F	
Kansas City, Missouri (RM 366) to Confluence with Mississippi River (Mile 0)	Missouri State Clean Water Commission	--	5°F	90°F	

E. River Flow Rates. The average annual discharge quantity of the Missouri River is about 53.6 million acre-feet under the 1970 level of water control and utilization. The six main-stem reservoirs on the Missouri River have a total storage capacity amounting to approximately three times the average annual runoff at Sioux City, Iowa. Therefore, the reservoir regulation has a major influence on the river flow. The reservoir release varies from a minimum of 8000 cfs in the non-navigation season to more than 30000 cfs during the navigation season. Water requirements for navigation, for the season extending from 1 April to 1 December, are 25000 cfs to 31000 cfs at Sioux City, Iowa, and Omaha, Nebraska; 31000 cfs to 37000 cfs at Nebraska City, Nebraska; and 35000 cfs to 41000 cfs at Kansas City, Missouri. For locations below Kansas City, no discharge requirements have been established for navigation needs.

Monthly average values of daily discharges at nineteen gaging stations along the Missouri River, obtained from U.S. Geological Survey Water Supply Papers and U.S. Army Corps of Engineers reservoir release records, are given in Appendix D. The data represent the averages for the 19-year period 1956 to 1974. The locations of the gaging stations are shown in Fig. 23, and a summary of the mean daily flow rates is given in Table 30, which also includes the 7-day, 10-year low flows at the gaging stations.

F. Thermal Regimes of the Missouri River. The temperature distributions in the Missouri River corresponding to average flow and weather conditions for the months of February, May, August, and November were determined using the steady-state IRTM described in Part One. The geometric parameters of the river channel were obtained from the river cross-section tables and charts and corresponding water surface profiles furnished by the U.S. Army Corps of Engineers. The stage-discharge relationships for the various gaging stations were obtained from the U.S. Geological Survey. The top widths and flow cross-sectional areas were adjusted according to the flow rates, using the stage-discharge relationships for the gaging stations. The details of the stage variations with discharge at each gaging station were obtained from records of the U.S. Geological Survey. The predicted temperature profiles for each month include the following:

Table 30

SUMMARY OF MONTHLY MEAN VALUES OF DAILY FLOW RATES -- MISSOURI RIVER

Gaging Station	River Mile	Mean of Daily Flow Rates in cfs					7-day, 10-year Low Flow	
		Averaging Period	February	May	August	November	Period	Flow Rate (cfs)
Fort Peck	1763.5	1956-64	10775	8351	9028	8454	1935-72	639
Wolf Point	1701.4	1956-74	10890	9457	9160	8435	1930-72	936
Culbertson	1620.8	1958-74	12015	10188	9169	8754	1962-72	2358
Williston	1552.7	1956-65	15127	23165	13295	13694	1930-65	2824
Garrison Dam	1389.9	1956-74	23959	21288	20617	21069	1955-68	5025
Bismark	1314.5	1956-74	24269	22152	21522	21722	1929-66	3420
Oahe Res. Rel.	1073.2	1968-74	22157	27057	39683	33533	--	--
Big Bend Res.Rel.	987.4	1968-74	22357	27086	39000	23600	--	--
Fort Randall	873.0	1956-74	9631	25673	33844	23420	--	--
Yankton	805.8	1956-74	12282	28368	34538	26065	1932-72	3920
Sioux City	732.3	1956-74	13668	31440	25129	27197	1940-68	4082
Omaha	615.9	1956-74	15160	34492	35728	25600	1930-67	3624
Nebraska City	562.6	1956-74	22272	42101	39494	34033	1931-68	4156
Rulo	498.0	1956-74	23910	45184	40843	35733	1957-71	5956
St. Joseph	448.2	1956-74	25209	47544	42459	36486	1930-67	4044
Kansas City	366.1	1956-74	31696	59134	49047	42935	1930-67	4342
Waverly	294.4	1956-74	32040	59884	49108	43506	1930-67	5302
Boonville	196.6	1956-74	39613	71237	53546	50576	--	--
Hermann	97.9	1956-74	53621	99149	61151	63073	1930-67	9254

- 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, the temperature distributions for the 7-day, 10-year low flows and August and November weather conditions were also determined.

1. Natural Thermal Regime. The natural thermal regime of a river corresponds to the temperature distributions that would exist in the absence of man-made heat loads. Surface heat exchange with the atmosphere and the convective transport of heat are the main factors that control the natural thermal regime. For the Missouri River, the natural temperature distributions were calculated under the assumption that the temperature at the upstream boundary of the study reach (Mile 1763) was at its equilibrium value for each set of meteorological and hydrological conditions. The natural thermal regime was determined for two cases. In the first case, the existence of the six main-stem reservoirs was not taken into account in calculating the natural temperatures. The river reach occupied by each reservoir was assumed to have the average dimensions of the river channels at the upstream and downstream ends of the reservoir. In other words, the reservoirs were replaced by uniform channel sections. Hence, this calculated thermal regime corresponds to the temperature distribution that would be expected in the river if all the man-made structures (dams) and heat loads were absent.

In the second case, the natural thermal regime was determined including the effects of the reservoir releases. The temperature pattern within a river reach between two reservoirs is strongly influenced by the temperature of the release water from the upstream reservoir. The daily reservoir-release temperatures for each dam for the period 1971-72 were obtained from the U.S. Army Corps of Engineers and averaged for each month. These monthly-average release temperatures were used as the upstream boundary condition in the calculation of the natural temperatures in the river reaches downstream from the reservoirs. No artificial heat loads were included in these calculations.

Later in this section, in conjunction with the discussion of predicted temperature profiles, the natural temperatures in the Missouri River reaches between the reservoirs, calculated including the effects of the release temperatures, are compared with the natural temperatures calculated without the reservoir effects.

2. Existing Heat Loads. In the MAPP area, 10 power plants with a total of 24 units utilize the Missouri River water for once-through cooling. The details of the cooling systems of these plants are listed in Appendix E and Table 31, and their locations are shown in Fig. 24. The sources and locations of industrial and municipal discharges that impose heat loads on the river are listed in Appendix F and G, respectively. The heat loads from the industrial and municipal sources generally are very small compared to the power plant loads.

3. Proposed and Projected Power Plants. Table 31 and Appendix E include the proposed power plants along the Missouri River for which the type of cooling system already has been selected. The remaining plant capacities, projected through the year 1993, are listed in Table 32. The locations of the proposed and projected plants are shown in Fig. 25. The sites of most of the projected plants already have been chosen, as can be seen in Tables 7 and 32. The effects of the proposed and projected plant capacities with known locations on the river thermal regimes were determined assuming that they would be operating at full-load capacity and that they would be using open-cycle cooling wherever permissible. For those cases in which the thermal standards are violated with full open-cycle cooling, the fraction of closed-cycle cooling needed to satisfy the standards is reported in Table 33.

4. Locations and Capacities of Permissible New Plants. The locations and capacities of permissible new plants with once-through cooling were determined on the basis of the existing thermal criteria applicable to the Missouri River, summarized in Table 29. Except for the river reach in South Dakota, between the North Dakota border (Mile 1245) and Big Bend Dam (Mile 987), the limiting criterion in the determination of the capacities of permissible new plants was the allowable temperature excess. For the aforementioned reach of river, the limiting criterion was the maximum allowable water temperature, $65^{\circ}F$. The allowable temperature excess, which is $5^{\circ}F$ or $4^{\circ}F$ except for the reach within Montana, is above "naturally occurring water temperatures" for Montana; above "natural background conditions" for North Dakota; above "natural"

SUMMARY OF EXISTING AND PROPOSED POWER PLANTS IN BASINS OF THE MISSOURI RIVER AND ITS MAJOR TRIBUTARIES LOCATED IN THE MAPP REGION

PLANT		LOCATION		INSTALLATION		CONDENSER FLOW		COOLING WATER DISCHARGE						RECEIVING WATER BODY							
Utility	Name	City/County and State	River Mile	Total Capacity (MW$_e$)	No. of Units	Quantity (cfs)	Temp. Rise (°F)	Nature	Quantity (cfs)	Winter Temp.(°F)		Summer Temp.(°F)		Name	Monthly Average Flow During Peak Load Month				Seven-day Dependable Flow (cfs)	Average Flow (cfs)	Remarks
										Intake	Discharge	Intake	Discharge		Winter Month	Quantity (cfs)	Summer Month	Quantity (cfs)			
MDU	Lewis & Clark	Sidney, Montana	1679	50	1	49	25	OTF	48.55 0.45	34 34	59 50	65 65	90 90	Yellowstone R.	Jan.	9,330	Aug.	8,270	4,570	13,330	Yellowstone R. joins Missouri R. at R M 1579. Plant at approx. 30 miles from confluence
BEPC	Leland Olds # 1	Stanton, N.D.	1380	216	1	162.64	27	OTF	167	44	77	61	91	Missouri R.	Dec.	25,000	Sept.	23,000	6,000	27,800	*Future unit
BEPC	Leland Olds #2*	Stanton, N.D.	1380	438	1	369.6	25	OTF						Missouri R.							
UPA	Stanton	Stanton, N.D.	1380	172	1	220	16	OTF	223.9	41	52	58	69	Missouri R.	Dec.	24,200	July	36,900	4,940	29,300	
CPA	Coal Creek #1*, 2*	Underwood, N.D.		839	2			WCT						Missouri R.							
MPC	Milton R. Young, #1	Center, N.D.		256.5	1	250	20	CP	244.3	50	68	78	86	Nelson Lake on Square Butte Creek	Feb.	1.0	May	0.5			Square Butte Creek joins Missouri R. at R M 1326. Plant at approx. 25 miles from confluence
MPC	Milton R. Young, #2*	Center, N.D.		408	1			CP													
MDU	R.M.Heskett #1	Mandan, N.D.	1320	25	1	31.0	25.4	OTF	60.5	33	72	65	85	Missouri R.	Jan.	28,300	Aug.	28,910	5,580	27,500	
MDU	R.M.Heskett #2	Mandan, N.D.	1320	75	1	67.7	28.3	OTF	60.50	33	72	65	85	Missouri R.	Jan.	28,300	Aug.	28,910	5,580	27,500	

PLANT		LOCATION		INSTALLATION		CONDENSER FLOW		COOLING WATER DISCHARGE						RECEIVING WATER BODY							
Utility	Name	City/County and State	River Mile	Total Capacity (MW$_e$)	No. of Units	Quantity (cfs)	Temp. Rise (°F)	Nature	Quantity (cfs)	Winter Temp.(°F)		Summer Temp.(°F)		Name	Monthly Average Flow During Peak Load Month				Seven-day Dependable Flow (cfs)	Average Flow (cfs)	Remarks
										Intake	Discharge	Intake	Discharge		Winter Month	Quatity (cfs)	Summer Month	Quatity (cfs)			
IPS	George Neal #1,2	Salix, Ia.	731	496.25	2	158.9 266.5	18 22	OTF	159	40	65	67	84	Missouri R.	Dec.	21,600	June	38,600	17,000	31,670	
IPS	George Neal # 3*	Salix, Ia.	731	520	1	636	17.8	OTF						Missouri R.							
IPS	George Neal # 4*	Salix, Ia.	731	576	1	723	18	OTF						Missouri R.							
IPS	Big Sioux, # 1-4	Salix, Ia.		40	4	164.3	12	OTF	34.5					Big Sioux R.	Dec.	213	June	3,239			Big Sioux R. joins Mo R. at RM 734. Plant close to Mo R.
OPPD	Fort Calhoun	Washington, Neb.	639	475	1	701.8	18	OTF	800.9	35	53	65	83	Missouri R.	Jan.	26,020	Aug.	33,170	8,174	31,260	
OPPD	North Omaha # 1-5	Omaha, Neb.	616	646	5	109.3 133.7 133.7 167.1 254.0	16.0 16.68 16.67 16.91 17.5	OTF	684.9	35	53	65.4	83.4	Missouri R.	Jan.	26,020	Aug.	33,170	4,300	31,000	
IPL	Council Bluffs #1,2	Council Bluffs, Ia.	616	130.6	2	73.4 100	15.7 17.4	OTF	161.8	35	51	77	90	Missouri R.	Dec.	20,680	Aug.	33,170	4,531	27,000	
IPL	Council Bluffs # 3*	Council Bluffs, Ia.	616	650	1	957	18.2	OTF						Missouri R.							
NPPD	Kramer # 1-3	Bellevue, Neb.	602	113	3	306	10	OTF	160.11	36	46	78	87	Missouri R.	Jan.	14,560	Aug.	48,530			

(Table 31 continued)

Table 31 (continued)

PLANT		LOCATION		INSTALLATION		CONDENSER FLOW		COOLING WATER DISCHARGE						RECEIVING WATER BODY							Remarks
Utility	Name	City/County and State	River Mile	Total Capacity (MW_e)	No. of Units	Quantity (cfs)	Temp. Rise (°F)	Nature	Quantity (cfs)	Winter Temp. (°F)		Summer Temp. (°F)		Name	Monthly Average Flow During Peak Load Month				Seven-day Dependable Flow (cfs)	Average Flow (cfs)	
										Intake	Discharge	Intake	Discharge		Winter Month	Quantity (cfs)	Summer Month	Quantity (cfs)			
OPPD	Jones Street #6,7,8,9,11,12	Omaha, Neb.	616	173.5	6	62.4 80.2 64.6 66.8 63.4 74.9	12 12 12 12 15.4 15.4	OTF	57.68	35	53	65	83	Missouri R.	Jan.	26,020	Aug.	33,170	4,300	31,000	
OPPD	Nebraska City *	Nebraska City, Neb.	561	575	1	483	16	OTF						Missouri R.							
NPPD	Cooper	Brownville, Neb.	533	820	1	1455	18	OTF	1455	34	52	72	90	Missouri R.							
NSP	Lawrence	Sioux Falls, S.D.	-	48	3	29.0 29.0 42.3	15.4 15.4 14.5	WCT	0.31	39	69	70	84	Big Sioux R.	Jan.	102	Aug.	40	16	847	Big Sioux R. joins Missouri R. at R.M. 734-plant at approx. 80 miles from confluence.
NSP	Pathfinder	Sioux Falls, S.D.		75	1	133.1	16	WCT	0.90	36	36	70	80	Big Sioux R.	Jan.	102	Aug.	40	16	847	
NPPD	Canaday	Holdredge, Neb.		700	1	704	20	OTF						Phelps Canal/ Platte R.		1,369		270			Platte R. joins Mo. R. at R.M. 611.5. Plant at approx. 215 miles from confluence
City of Grand Island	C.W. Burdick	Grand Island, Neb.		120	3	18.8 27.5 100	35 35 17	OTF,W						Wood R./Platte R.							Plant at approx. 160 miles from confluence.
NPPD	Ogallala	Ogallala, Neb.						OTF	0.053 0.036	52 52	62 62	54 54	64 64	S. Platte R.							Plant at approx. 360 miles from confluence.

PLANT		LOCATION		INSTALLATION		CONDENSER FLOW		COOLING WATER DISCHARGE						RECEIVING WATER BODY							Remarks
Utility	Name	City/County and State	River Mile	Total Capacity (MW_e)	No. of Units	Quantity (cfs)	Temp. Rise (°F)	Nature	Quantity (cfs)	Winter Temp. (°F)		Summer Temp. (°F)		Name	Monthly Average Flow During Peak Load Month				Seven-day Dependable Flow (cfs)	Average Flow (cfs)	
										Intake	Discharge	Intake	Discharge		Winter Month	Quantity (cfs)	Summer Month	Quantity (cfs)			
NPPD	Bluff	Scottsbluff, Neb.						OTF	38.23	52	76	54	78	N. Platte R.							Plant at approx. 465 miles from confluence.
CBPC	Wisdom	Clay, Ia.		37.5				WCT	0.05	54	76	54	85	Ocheyedon Creek/Little Sioux R.							Little Sioux R. joins Mo. R. at R.M. 673. Plant at approx. 130 miles from confluence
OTPC	Big Stone	Big Stone City, S.D.		430	1	229	25.9							Big Stone Lake							
Dept. of Utilities	Lon D. Wright Memorial	Fremont, Neb.		47	2	18.93 28.50		OTF	36.74 22.3 0.39	56 56 56	76 80 70	56 56 56	76 80 70	Drainage Ditch		10,000		15,000			
NPPD	Lincoln 'K' Street	Lincoln, Neb.		30	3	89	8.0	WCT													
NPPD	Sheldon # 1-3	Hallem, Neb.		228.6	3	267.4	18	DCT	3.38					Well	Jan.		Aug.				
City of Hastings	Hastings	Hastings, Neb.		39				WCT	11.4-18.3 52.6			56 73	80 94	Storm Sewer							

Table 32

ADDITIONAL PROPOSED AND PROJECTED PLANTS ALONG MISSOURI RIVER (FROM MAPP R-362 DATA)

Utility	Plant and Unit	Location	Capacity (MW)	Type	Remarks
OPPD[a]	Fort Calhoun, #2	Fort Calhoun, Neb.	1150	Nuclear	Addition (5-1-83)[b]
NPPD[a]	Cooper, #2	Brownville, Neb.	1150	Nuclear	Addition (1985-86)
-	-	Brownville, Neb.	1300	Nuclear	New Plant (5-1-89)
OPPD	Nebraska City	Neb. City, Neb.	600	Fossil, Coal	(5-1-92)
Lincoln Electric System[a]	-	Neb. City, Neb.	600	Nuclear	New Plant (5-1-92)
BEPC	Beulah, #1	Bismark, N.D.	840	Fossil	New Plant (1983)
BEPC[a]	Beulah, #2	Bismark, N.D.	1040	Fossil	(1988)
MPC	Center, #3	Center/Bismark, N.D.	440	Fossil	(1988)
OTP[a]	1981	N.D. or S.D.	200	Fossil, Lignite	(5-1-81)
-	-	N.W. Iowa	600	Fossil	(5-1-91)

[a] Shared with other utilities

[b] Projected In-service date

Table 33

CLOSED-CYCLE COOLING REQUIREMENTS - MISSOURI RIVER

(Projected plants with known locations and unspecified cooling systems)

Plant	Type	Location	Capacity (MW)	% of Closed-Cycle Cooling Required	
				Natural Base	Existing Base
Beulah, #1	F	Bismark, N.D.	840	0	0
Beulah, #2	F	Bismark, N.D.	1040	0	0
Center, #3	F	Bismark, N.D.	440	0	0
Fort Calhoun, #2	N	Fort Calhoun, Neb.	1150	4	0
Nebraska City	F	Neb. City, Neb.	600	67	0
--	N	Neb. City, Neb.	600	100	0
Cooper, #2	N	Brownville, Neb.	1150	99	35
--	N	Brownville, Neb.	1300	100	100

for Nebraska; and above "natural conditions" for Kansas. South Dakota, Iowa, and Missouri regulations do not specify a base (Appendix B). Thus there is some ambiguity concerning the base to which the allowable temperature excess should be added to obtain limiting temperatures. Moreover, it is not clear whether the modifications of the natural thermal regime due to the artificial temperature controls produced by the reservoir releases should be included in defining the natural-temperature base for the river reaches downstream from reservoirs. Therefore, the capacities of the permissible new plants were determined in two ways, following the procedure used for the Mississippi River. For the first case, the natural-temperature base was used, and for the second, the existing-temperature base was utilized; in both cases, temperature effects of the reservoirs were not considered. Natural temperatures in river reaches between reservoirs were determined separately, including the control effects of the reservoir-release temperatures, and the temperature increments resulting from the existing, proposed and projected, and the permissible new plant capacities were added thereto in order to obtain the modified thermal regime of the river.

5. Results of the Temperature Predictions. The prediction of temperature distributions in the Missouri River followed the same basic procedure as the Mississippi River analysis. The same assumptions related to the use and interpretation of the available data were made (see page 126); additional assumptions and restrictions unique to the Missouri River study were as follows:

a. The natural thermal regime of the river was determined both with and without the reservoirs present as discussed above.

b. The initial water temperature for each individual reach was obtained either from calculated natural conditions (i.e., the equilibrium temperature) or was taken from data supplied by the U.S.G.S. and the U.S. Army Corps of Engineers.

c. Locations and capacities of permissible future plants were based on natural conditions without considering thermal effects of reservoir releases, except for the state of Montana as discussed below.

d. An investigation of the future plant capacity which is permissible when capacity factors are applied to existing plants was not made.

However, temperature distributions during low flow conditions are shown with existing plant loads adjusted by 1974 capacity factors as well as with full-load operation.

e. Predictions of permissible future plant capacities based on low flow conditions were not made.

f. The minimum plant capacity considered for estimating permissible future use of the Missouri River for once-through cooling is about 140 MW for predictions based on average flow conditions. Selection of this limit was influenced by the strict temperature standards of the state of Montana.

The predicted temperature distributions in the Missouri River, excluding reservoir-release effects, are shown in Figs. 40, 41, and 42. Figures 40 correspond to the average flow and weather conditions for full-load operation during the months of February, May, August, and November. Figures 40 also include the locations of permissible new plants and the resulting temperature distributions for both the cases of natural-temperature base and existing-temperature base. The permissible capacities of new plants are tabulated in Tables 34 and 35. In the reach between Fort Peck and Garrison reservoirs, where the thermal standards of Montana apply, only three plants of small capacities, about 200 MW fossil or 140 MW nuclear each, can be sited. However, as seen in Figs. 40, the thermal criterion of the state of Montana regarding the maximum allowable water temperature is violated even by the natural-temperature base during the month of August if the effects of reservoir release are not considered. For siting plants in Montana, therefore, it is more practical to consider the natural – temperature base including reservoir-release effects as shown later. The reach between the Garrison and Oahe Reservoirs has adequate cooling capacity for two new plants totalling about 4200 MW fossil or 2900 MW nuclear. For the reach between the Oahe and Big Bend Reservoirs, the maximum allowable water temperature is 65°F. However, the measured water temperature data available in U.S. Geological Survey Water Supply publications for this reach, where there are no power plants, indicate that during the summer months the existing water temperature is above 65°F at times. Hence, any addition of power plants in this reach would only worsen the existing situation, and, therefore, no new plants

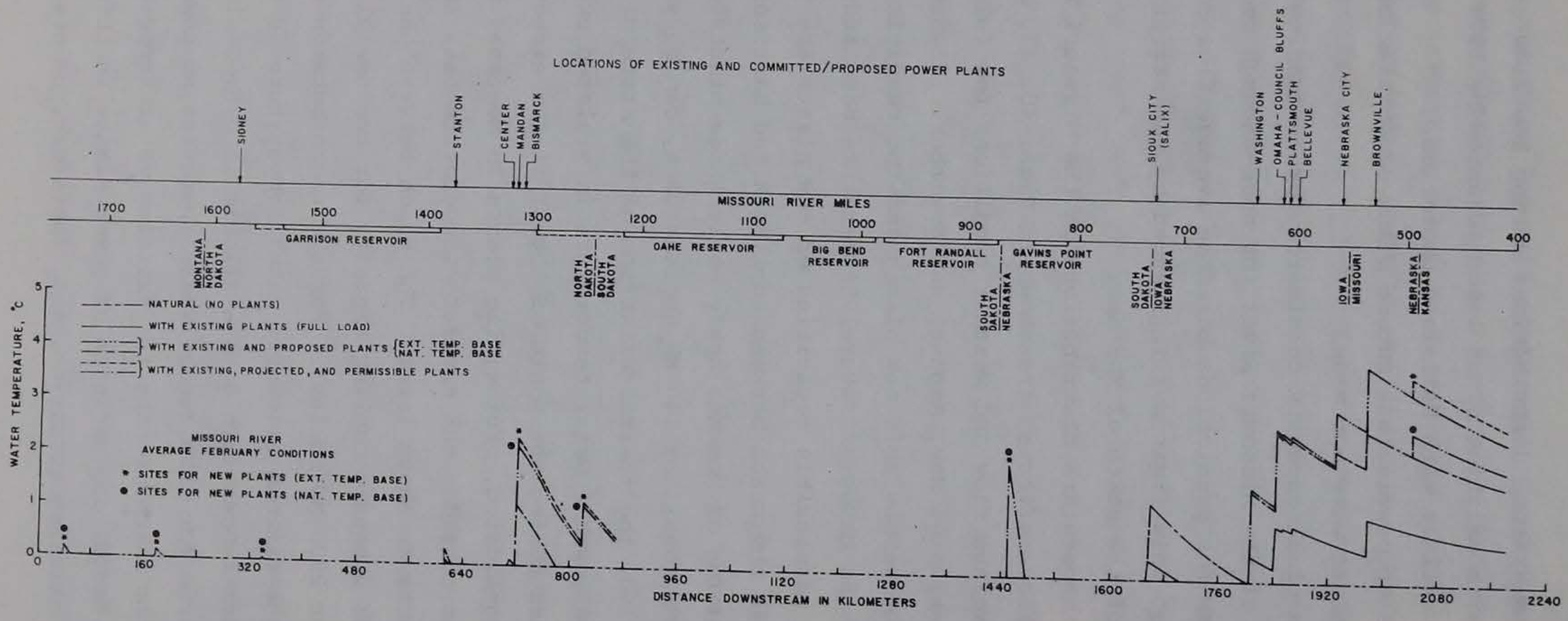


Figure 40. Temperature distributions along the Missouri River for average conditions with full-load operation

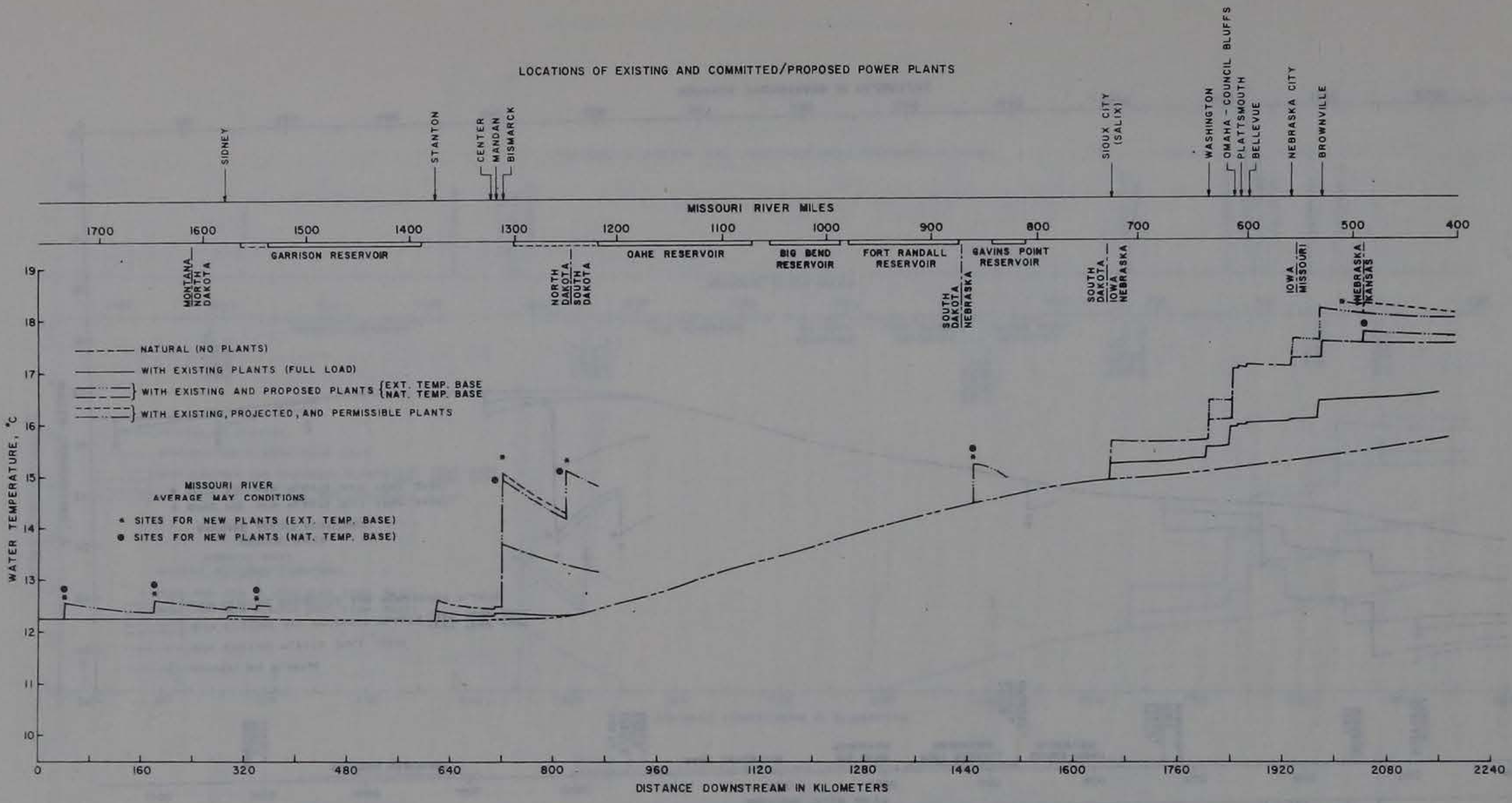


Figure 40. (continued)

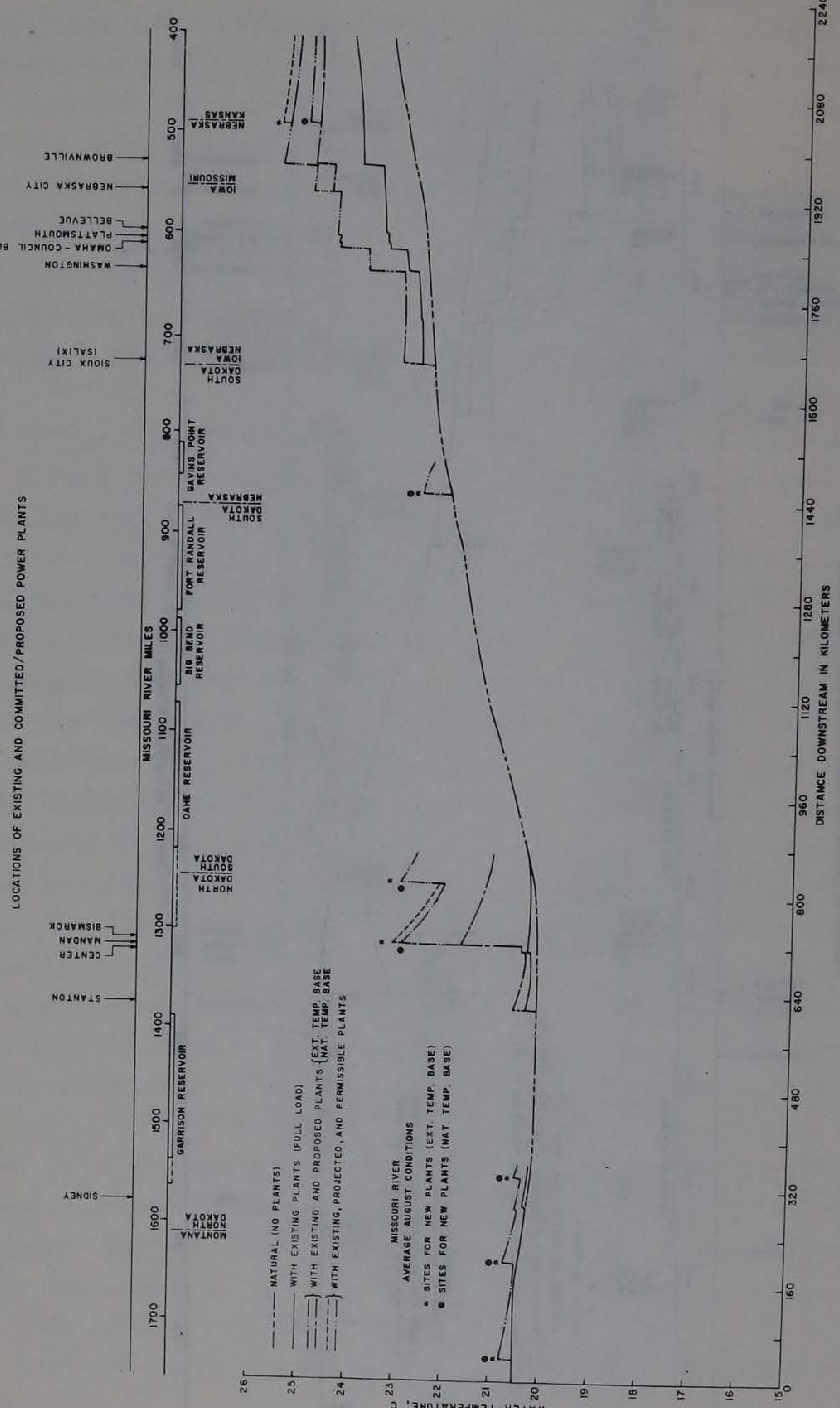


Figure 40. (continued)

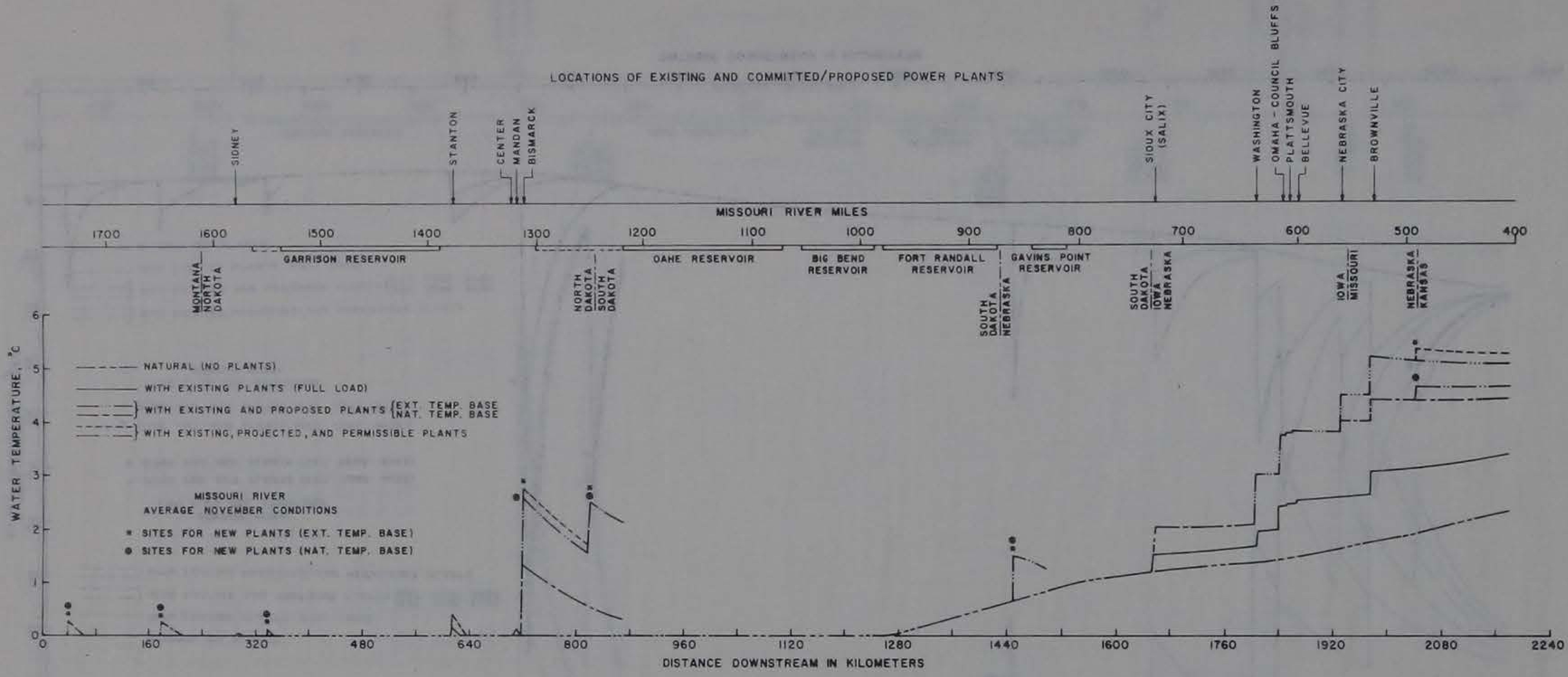


Figure 40. (continued)

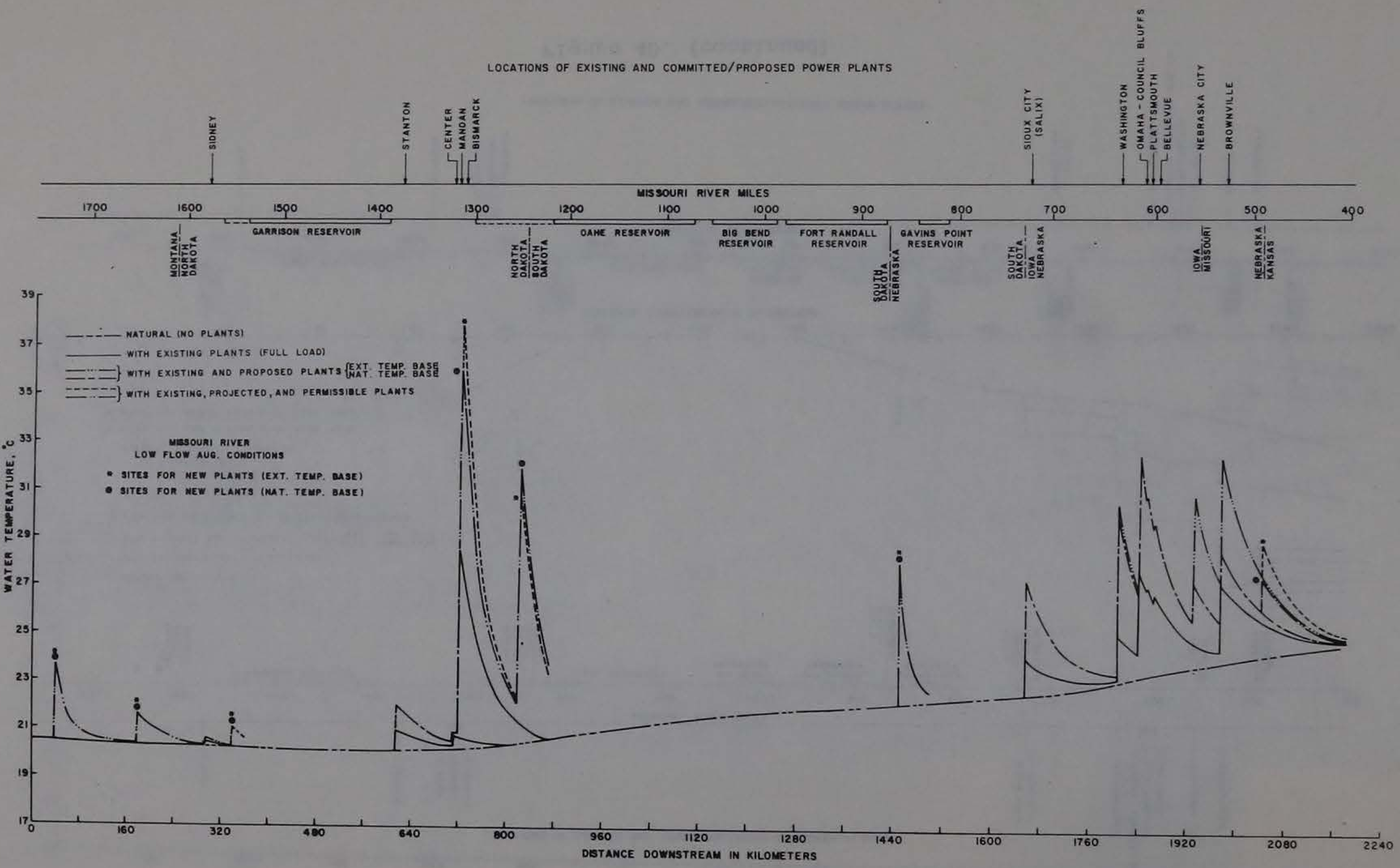


Figure 41. Temperature distributions along the Missouri River for low flow conditions with full-load operation

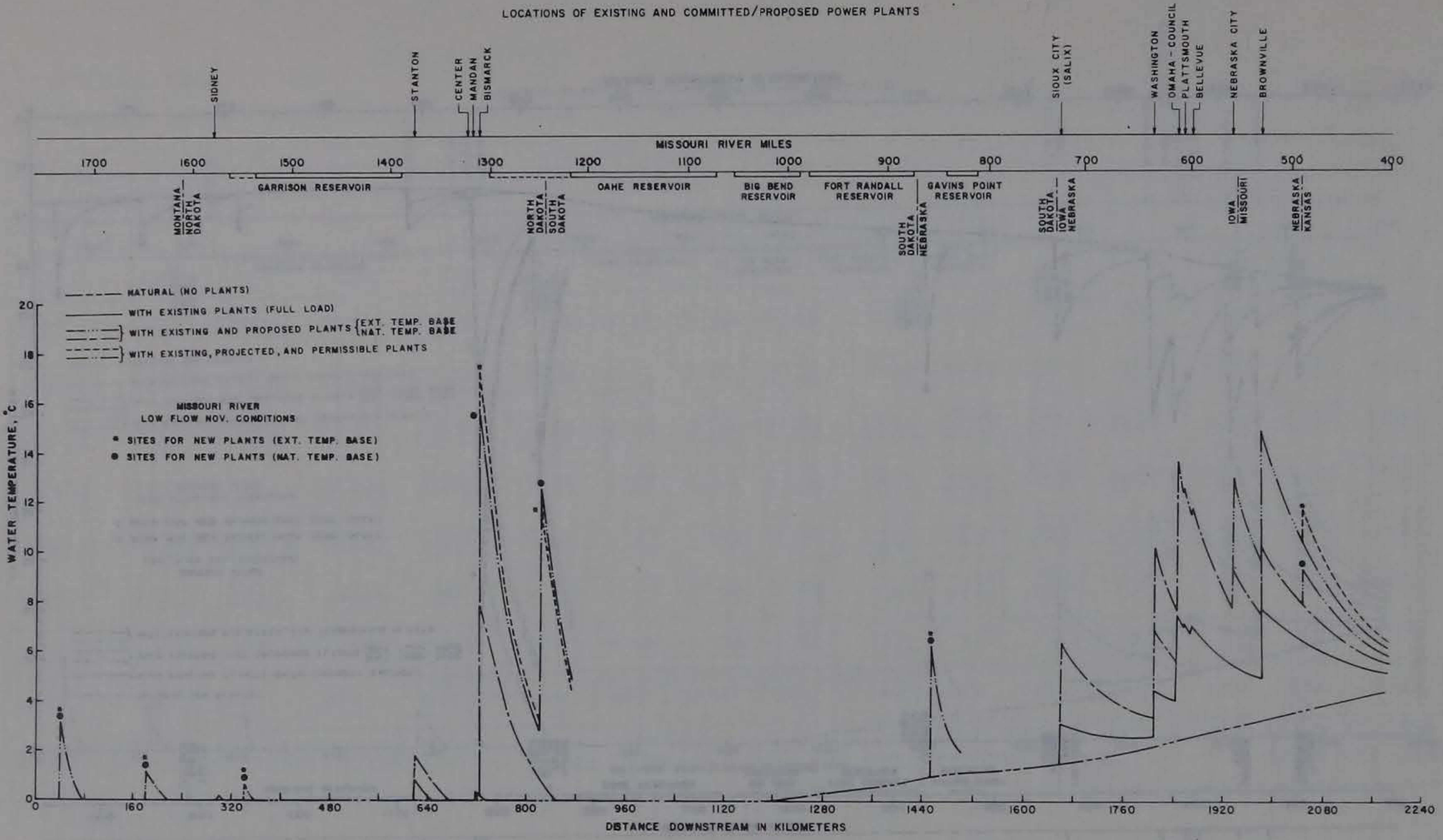


Figure 41. (continued)

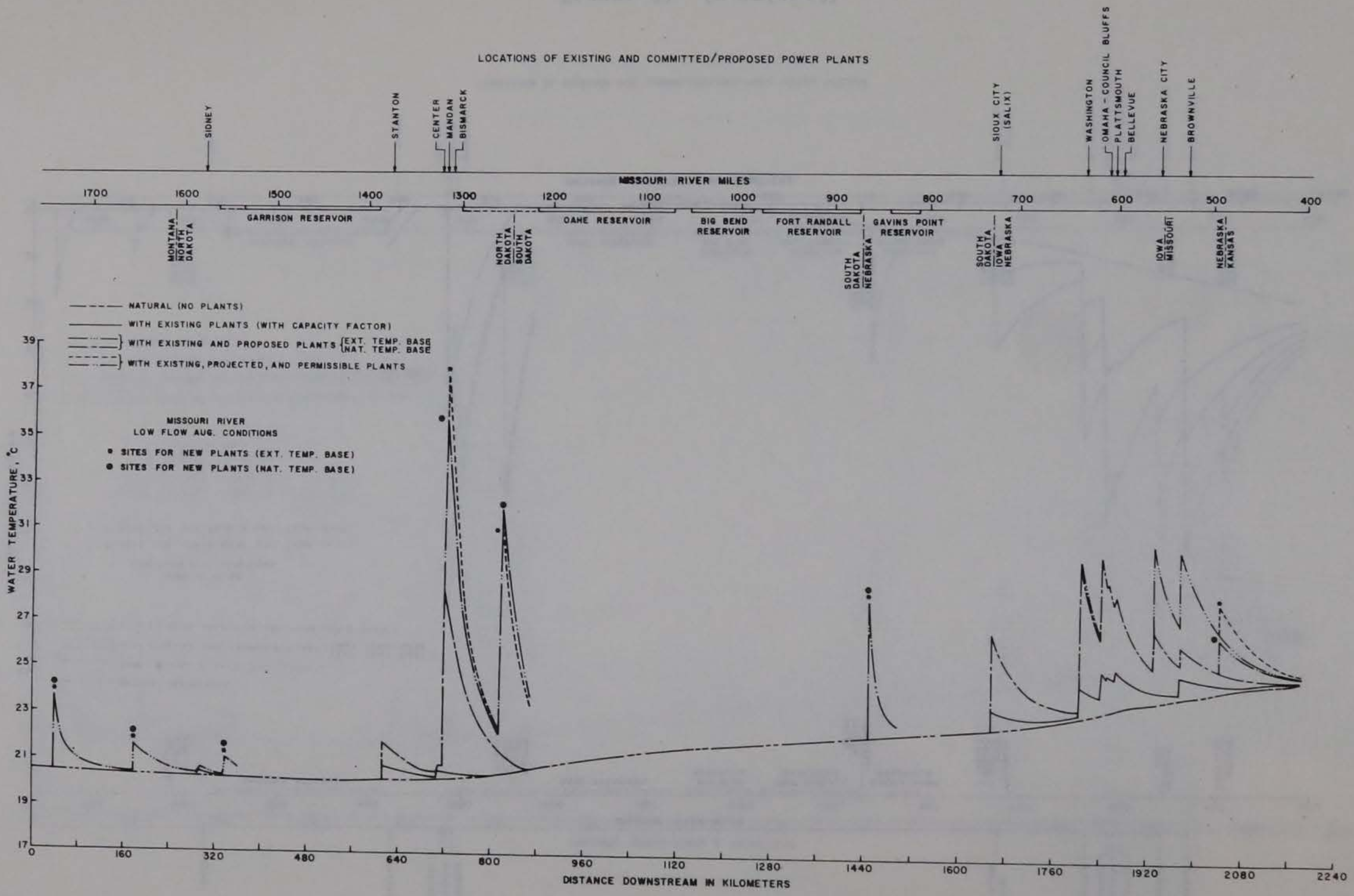


Figure 42. Temperature distributions along the Missouri River for low flow conditions with 1974 capacity factors

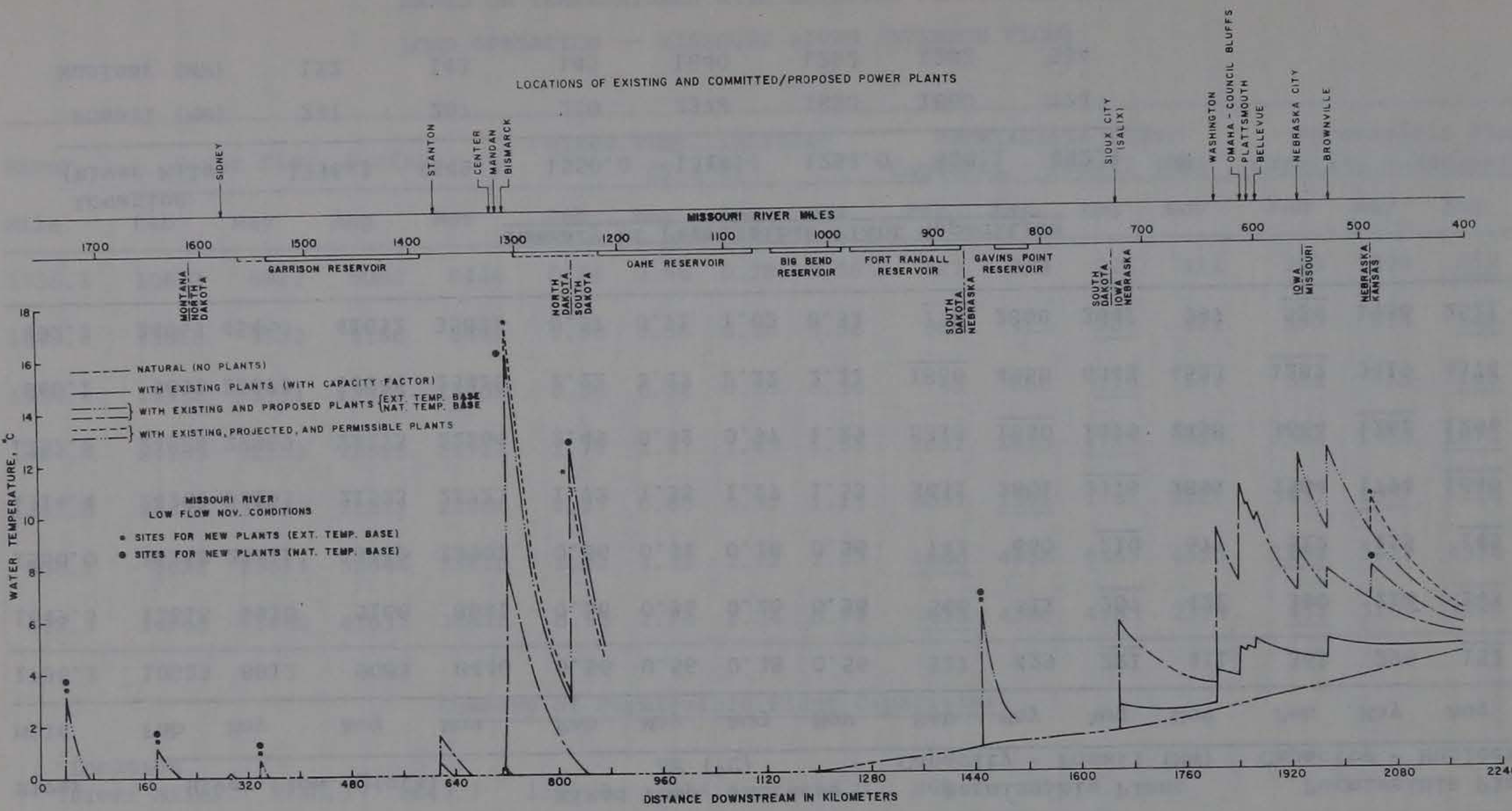


Figure 42. (continued)

Table 34

LOCATIONS AND CAPACITIES OF PERMISSIBLE POWER PLANTS BASED ON PREDICTED NATURAL TEMPERATURES AND FULL-LOAD OPERATION -- MISSOURI 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
1736.3	10823	8812	9083	8446	0.56	0.56	0.28	0.56	527	429	221	411	363	296	152	283
1649.3	11618	9930	9166	8641	0.56	0.36	0.26	0.56	566	311	207	421	390	214	143	290
1550.0	15258	23711	13469	13902	0.56	0.32	0.18	0.56	743	660	210	677	512	455	145	467
1314.4	24269	22153	21523	21723	1.72	1.35	1.27	1.53	3631	2601	2378	2891	2504	1794	1640	1994
1252.0	24526	22869	22273	22264	2.49	0.92	0.97	1.29	5313	1830	1879	2498	3664	1262	1296	1723
860.1	9631	25673	32844	23420	2.22	2.22	2.22	2.22	1860	4958	6343	4523	1282	3419	4374	3119
492.3	24063	45460	41032	35821	0.37	0.71	1.02	0.32	774	2808	3641	997	534	1936	2511	687

Summary of Permissible Plant Capacities

Location (River Mile)	1736.3	1649.3	1550.0	1314.4	1252.0	860.1	492.3
Fossil (MW)	221	207	210	2378	1830	1860	774
Nuclear (MW)	152	143	145	1640	1262	1282	534

Table 35

LOCATIONS AND CAPACITIES OF PERMISSIBLE POWER PLANTS BASED ON TEMPERATURES WITH EXISTING PLANTS AND FULL-LOAD OPERATION -- MISSOURI 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
1736.3	10823	8812	9083	8446	0.56	0.56	0.28	0.56	527	429	221	411	363	296	152	283
1649.3	11618	9930	9166	8641	0.56	0.36	0.26	0.56	566	311	207	421	390	214	143	290
1550.0	15258	23711	13469	13902	0.56	0.32	0.18	0.56	743	660	210	677	512	455	145	467
1314.4	24269	22153	21523	21723	1.72	1.47	1.45	1.55	3631	2833	2715	2929	2504	1953	1872	2020
1252.0	24526	22869	22273	22264	2.37	0.80	0.91	1.15	5057	1591	1763	2227	3487	1097	1216	1536
860.1	9631	25673	32844	23420	2.22	2.22	2.22	2.22	1860	4958	6343	4523	1282	3419	4374	3119
492.3	24063	45460	41032	35821	0.30	1.14	1.34	0.77	628	4508	4783	2399	433	3109	3298	1654

Summary of Permissible Plant Capacities

Location (River Mile)	1736.3	1649.3	1550.0	1314.4	1252.0	860.1	492.3
Fossil (MW)	221	207	210	2715	1591	1860	628
Nuclear (MW)	152	143	145	1872	1097	1282	433

with open-cycle cooling were considered permissible. The reach between the Big Bend and Fort Randall Reservoirs is very short, and no analysis was performed for this section, which was considered to be part of the reservoirs. A new plant with capacity of 1860 MW fossil or 1280 MW nuclear could be installed along the reach between the Fort Randall and Gavins Point Reservoirs. The results given in Figs. 40 show that when all the proposed and projected plant capacities are installed and operating at full load, the water temperatures in the Omaha and Brownville regions of the Missouri River will be very close to $5^{\circ}F$ above the predicted natural temperatures. Hence, no new plant capacity is permissible along this section of the river. A new plant with capacity of about 770 MW fossil or 530 MW nuclear could be installed at Mile 492, close to the downstream boundary of the MAPP area. However, as shown in Table 35, if the existing-temperature base is considered, the permissible new plant capacity will be reduced to about 630 MW fossil or 430 MW nuclear along this reach of the river.

The temperature distributions in the Missouri River for "worst case" conditions - the 7-day, 10-year low flows combined with average weather conditions for August and November - are presented in Figs. 41 for full-load operation of existing plants. These figures show that temperature excesses more than $5^{\circ}F$ would occur during the low-flow periods in the river reach adjacent to and downstream from Omaha. However, if the capacity factors of existing plants, based on the 1974 operational data given in Table 36, are considered, the temperature rises due to the existing plants would be within $5^{\circ}F$, as shown in Figs. 42. If the effects of the proposed and projected plants are added, the $5^{\circ}F$-excess criterion would not be satisfied during low-flow periods if these plants are operating at rated loads. The effects of the permissible new plants, the locations and capacities of which were determined based on the average flow conditions, on the temperature distributions during low-flow periods are also shown in Figs. 41 and 42.

The effects of the reservoir releases, which provide temperature controls at the upstream ends of river reaches between reservoirs, on the temperature distributions are shown in Figs. 43 for average flow conditions and in Figs. 44 and 45 for 7-day, 10-year low flows. These figures should be compared with Figs. 40, 41, and 42. The temperature of water released from a reservoir depends upon the temperature profile in the reservoir

Table 36

CAPACITY FACTORS OF EXISTING PLANTS ALONG MISSOURI RIVER BASED ON 1974 OPERATIONAL DATA (FROM MAPP R-362 DATA)

Name of Plant	Location	Summer Capacity (MW)	Gross Energy (GWH)	Capacity Factor (%)
Lewis & Clark	Sidney, Montana	43.5	366	96.05
Leland Olds #1	Stanton, N.D.	316	1664.6	60.13
Stanton	Stanton, N.D.	166.7	1171	80.19
Milton R. Young #1	Center, N.D.	240	1847	87.85
Heskett #1	Mandan, N.D.	28.0	171.0	69.72
Heskett #2	Mandan, N.D.	73.0	479.0	74.91
Neal #1	Salix, Iowa	147	900	69.89
Neal #2	Salix, Iowa	330	1960	67.80
Big Sioux, #1-4	Salix, Iowa	47	15	3.64
Fort Calhoun #1	Washington, Neb.	455.0	2722.1	68.30
North Omaha #1-5	Omaha, Neb.	646.0	2087.4	36.89
Council Bluffs #1	Council Bluffs, Iowa	48.0	230	54.70
Council Bluffs #2	Council Bluffs, Iowa	90.6	510	64.26
Kramer #1-3	Bellevue, Neb.	113	565	57.08
Jones Street #11,12	Omaha, Neb.	83	11.1	1.63
Jones Street #1,2	Omaha, Neb.	113.4	6.0	0.60
Cooper	Brownville, Neb.	778	1827	26.81

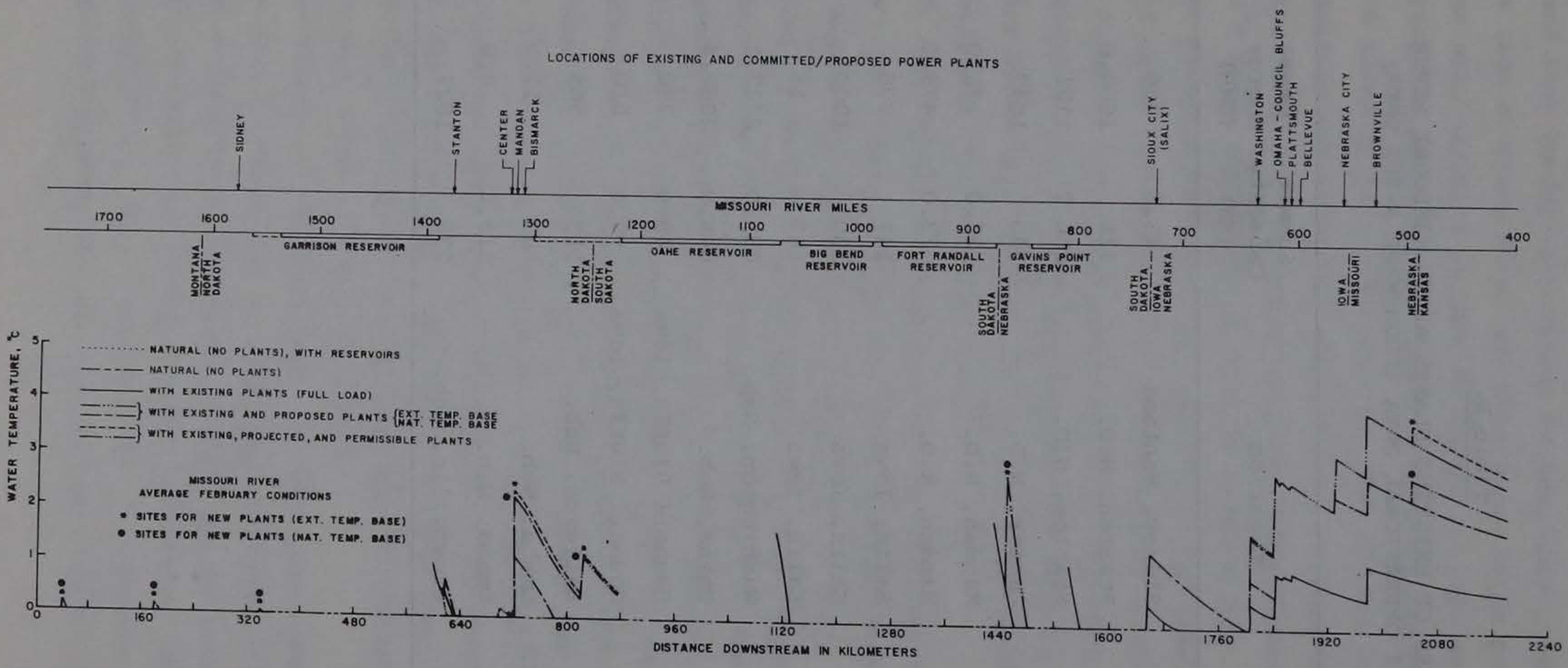
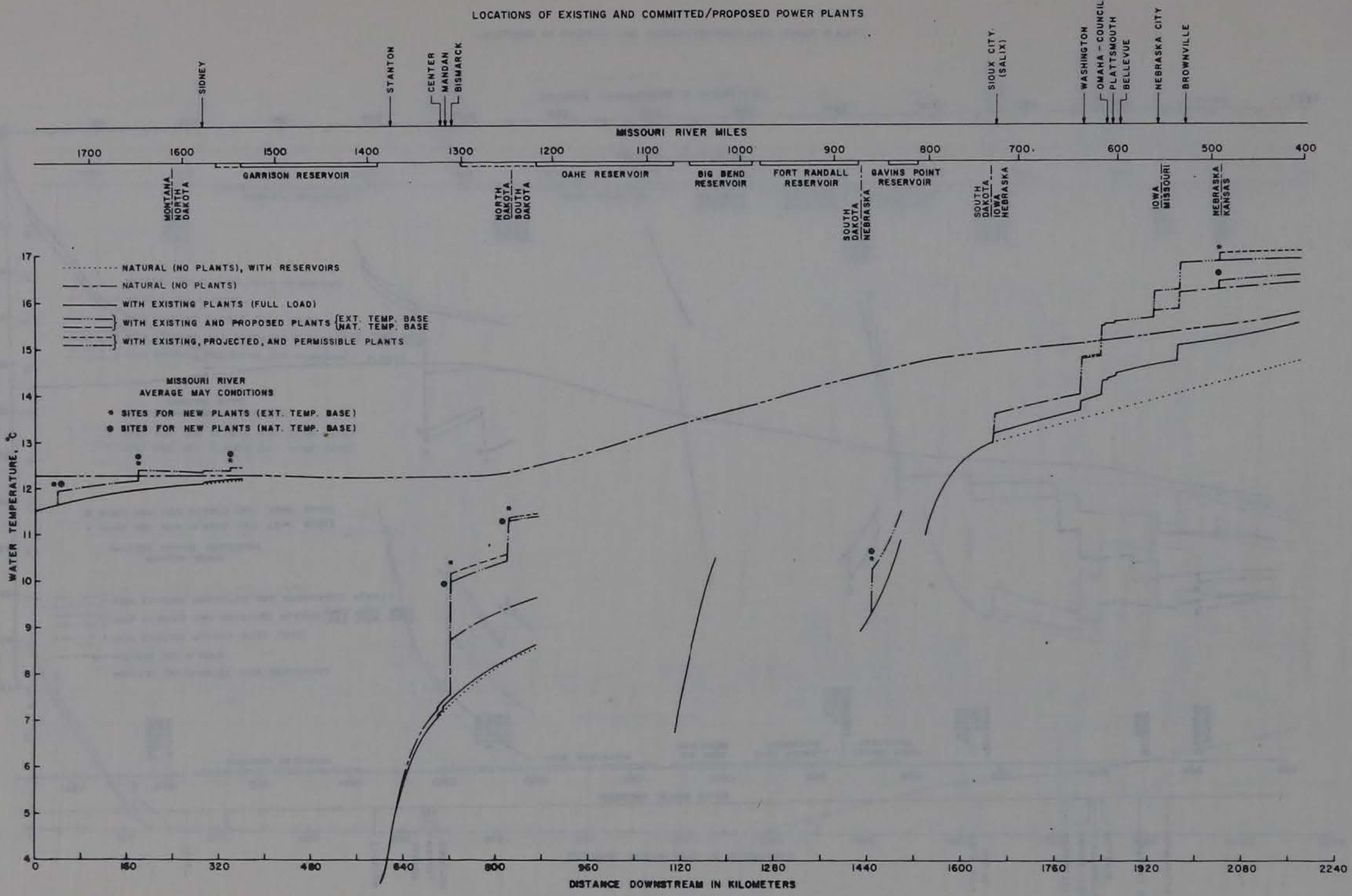


Figure 43. Temperature distributions along the Missouri River for average conditions with full-load operation and reservoir release effects



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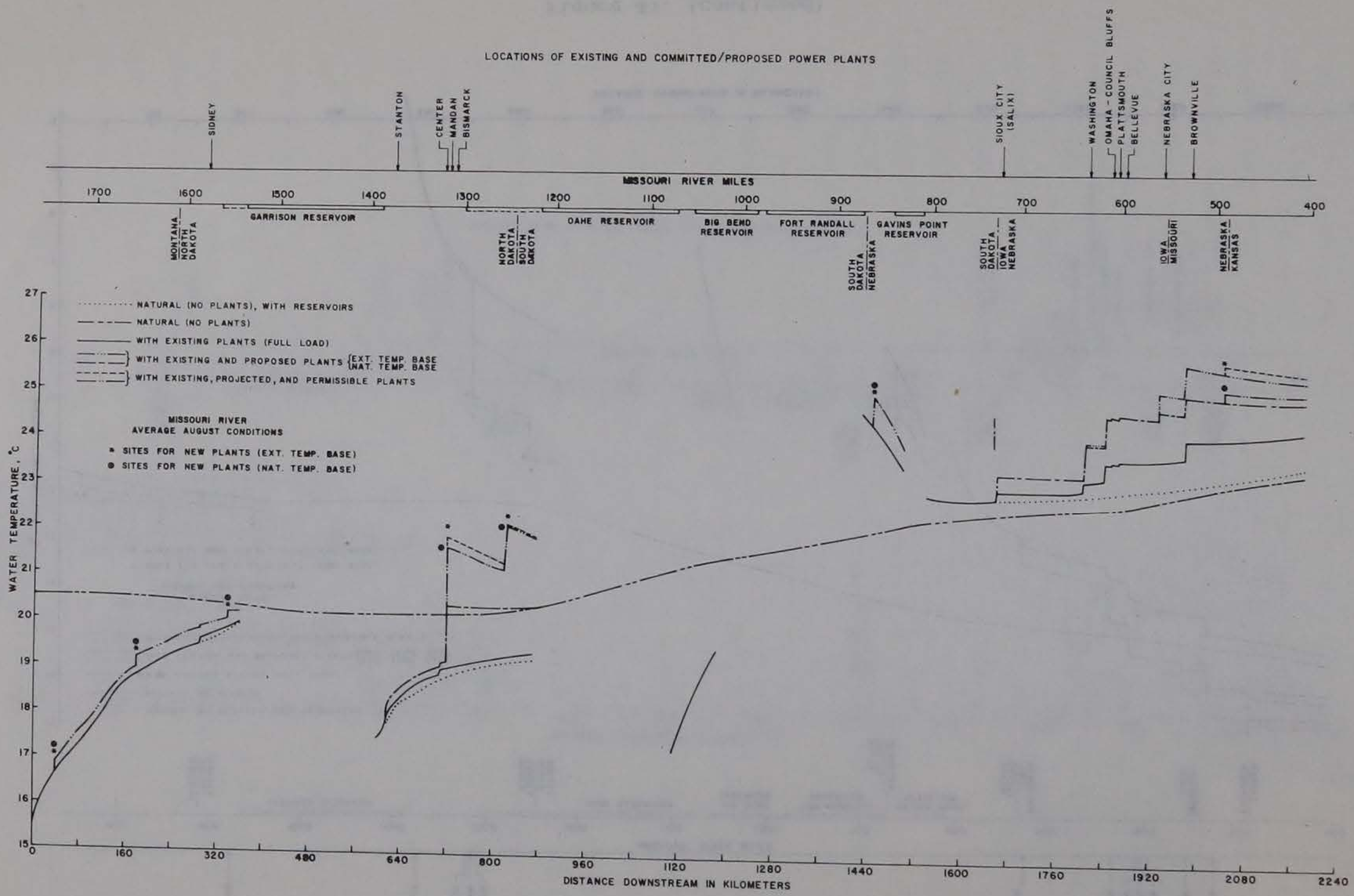

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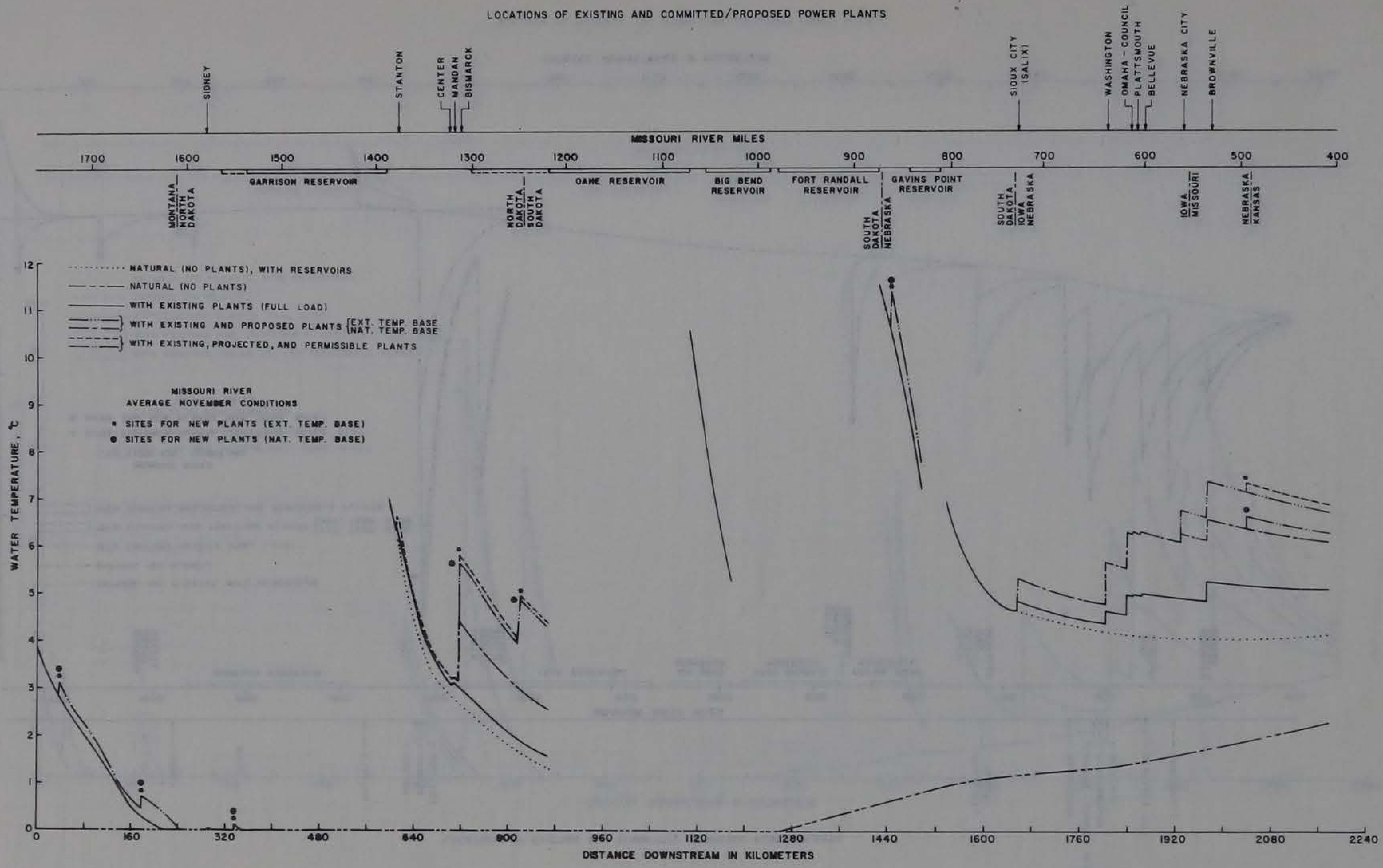


Figure 43. (continued)

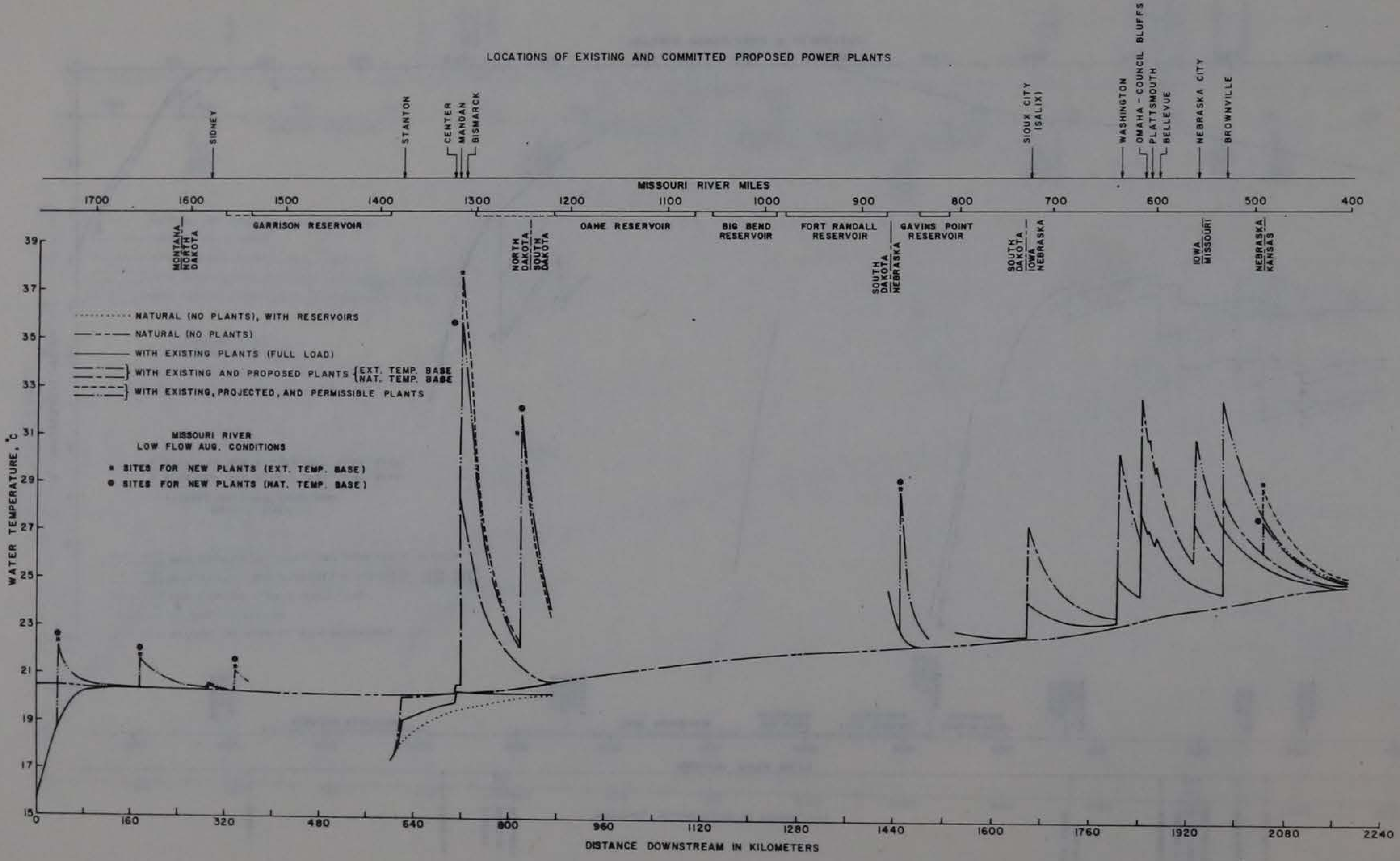


Figure 44. Temperature distributions along the Missouri River for low flow conditions with full-load operation and reservoir release effects

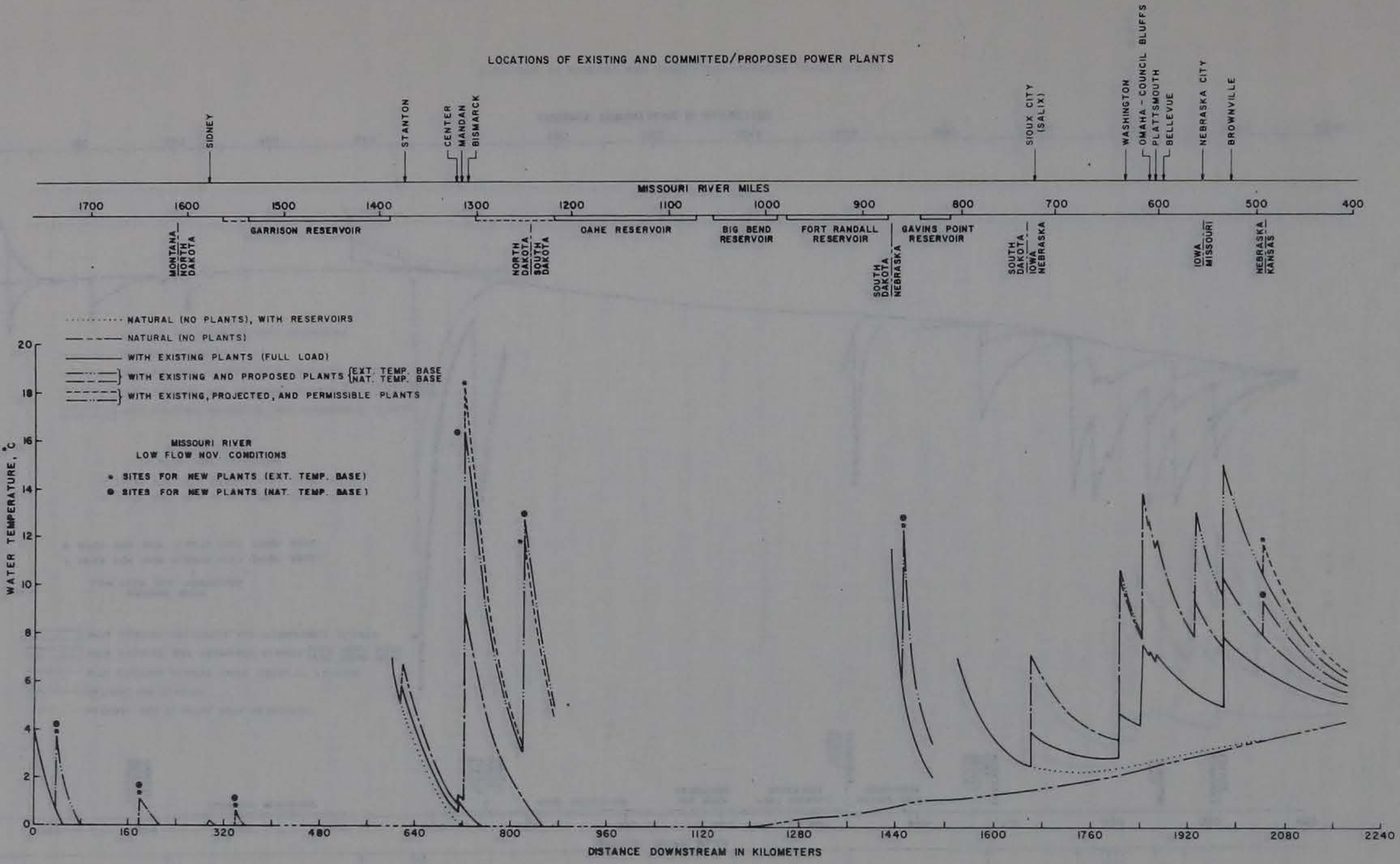


Figure 44. (continued)

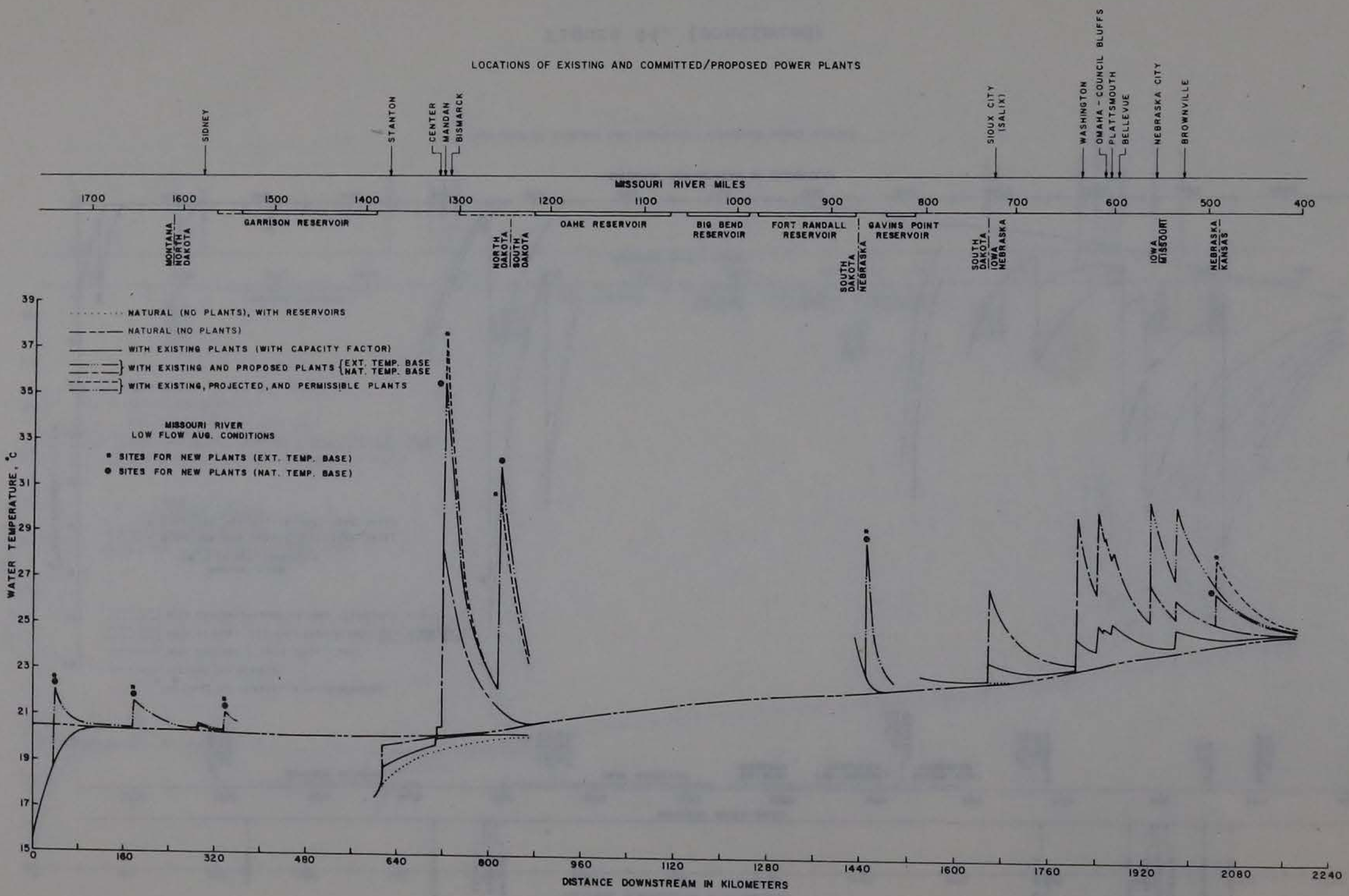


Figure 45. Temperature distributions along the Missouri River for low flow conditions with 1974 capacity factors and reservoir release effects

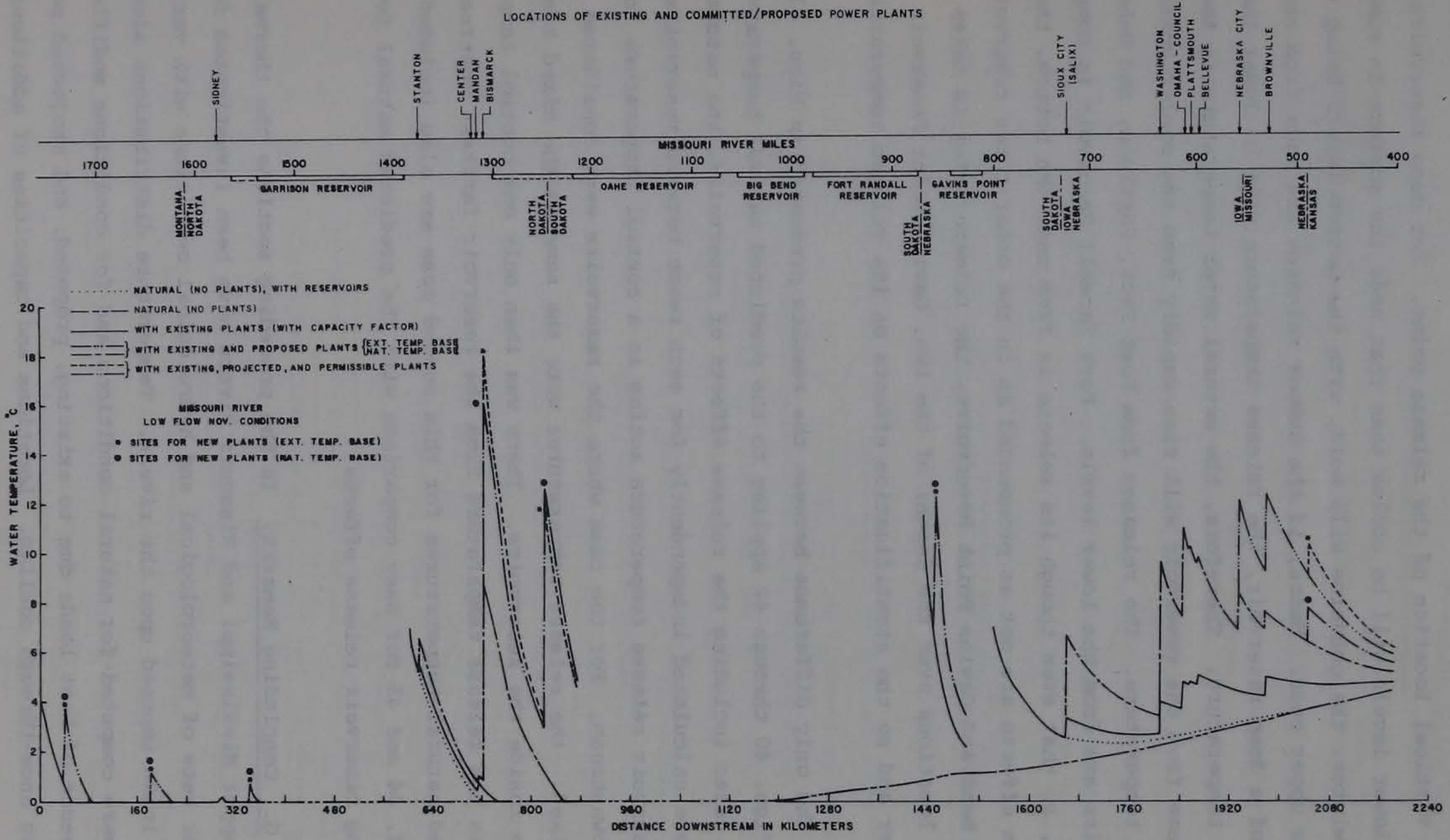


Figure 45. (continued)

and the vertical location of the release point. For deep reservoirs, water at the lower levels will be cooler than that near the surface in summer. During winter, the converse will hold, with the bottom layers being warmer than the upper ones. Hence, if the summer releases are made from near the bottom of a deep reservoir, the release temperature will be lower than the natural temperature. Therefore, the natural water temperature in the river downstream from the reservoir will rise rapidly from the cooler upstream control temperature. The releases from Fort Peck, Garrison, and Oahe Reservoirs are from the lower levels. Fort Randall Reservoir is comparatively shallow, so that even though its release is from near the bottom, the stratification effects are not as pronounced as in the other three reservoirs. For Big Bend and Gavins Point Reservoirs, the release water is taken from several locations over the depth; of the two, Gavins Point Reservoir is shallower and so the stratification effects on its release temperature are lower.

The only difference between the results presented in Figs. 43 through 45 and Figs. 40 through 42 applies to the predicted natural temperatures. For the cases including the release effects of reservoirs, the natural temperatures were calculated independently for each reach between reservoirs with each reservoir release temperature acting as a control temperature for the reach downstream. For the case where the reservoirs were considered as fully mixed, the release temperatures were the same as the mixed temperatures inside the reservoirs. There was then only one control temperature, which was the release temperature from the reservoir farthest upstream. The predicted natural temperatures for this second case are also included in Figs. 43, 44 and 45 for easy comparison with the predicted natural temperatures including reservoir release effects.

G. Concluding Remarks. In the preceding sections the thermal regimes of the upper Mississippi and Missouri Rivers have been investigated for different sets of meteorological and hydrological conditions with various thermal loads imposed upon the rivers. Temperature distributions along the rivers were computed for natural conditions and for conditions modified by the presence of heat loads due to existing, proposed, and projected power plants employing once-through cooling. Locations and capacities of additional future

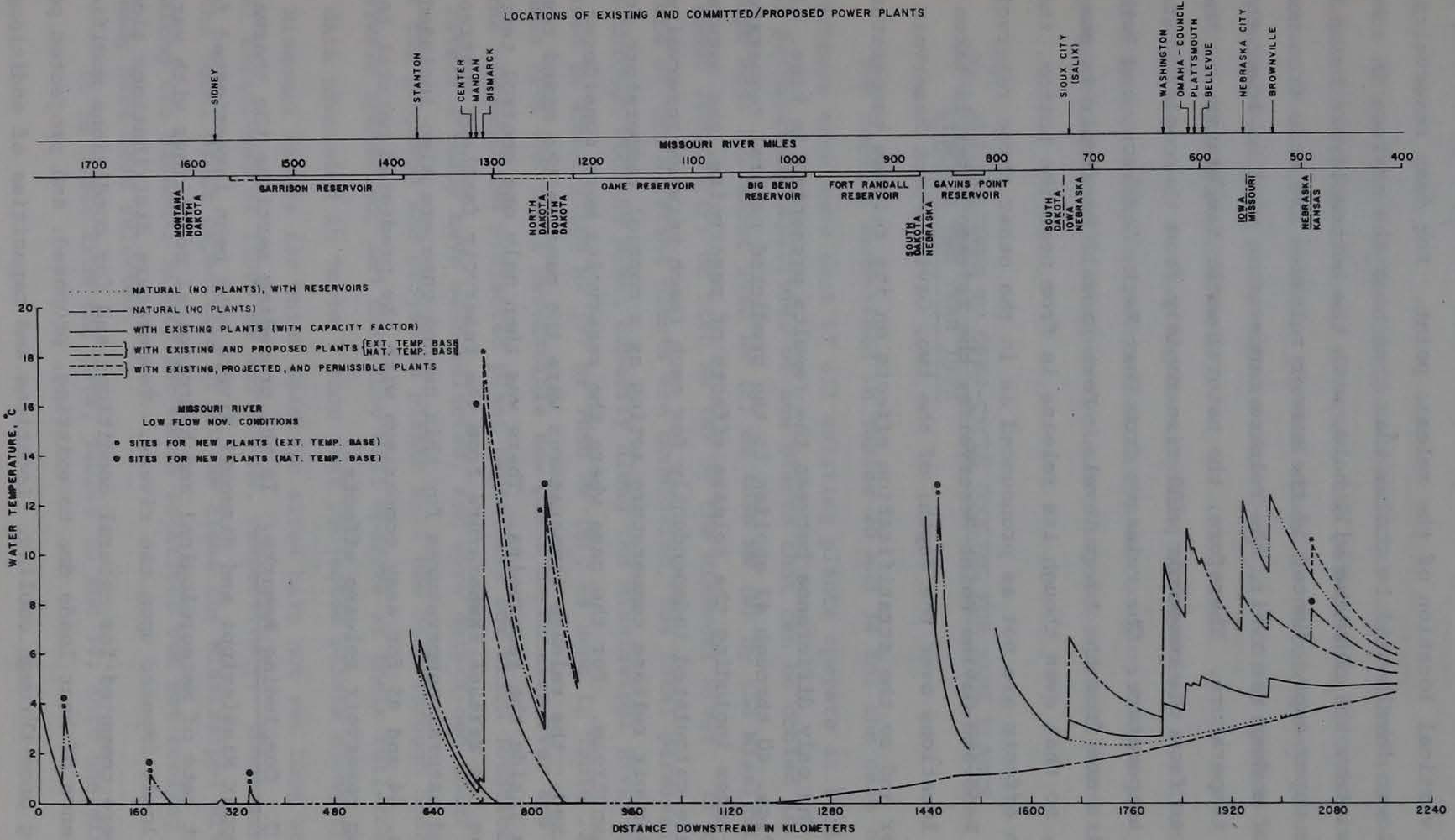


Figure 45. (continued)

and the vertical location of the release point. For deep reservoirs, water at the lower levels will be cooler than that near the surface in summer. During winter, the converse will hold, with the bottom layers being warmer than the upper ones. Hence, if the summer releases are made from near the bottom of a deep reservoir, the release temperature will be lower than the natural temperature. Therefore, the natural water temperature in the river downstream from the reservoir will rise rapidly from the cooler upstream control temperature. The releases from Fort Peck, Garrison, and Oahe Reservoirs are from the lower levels. Fort Randall Reservoir is comparatively shallow, so that even though its release is from near the bottom, the stratification effects are not as pronounced as in the other three reservoirs. For Big Bend and Gavins Point Reservoirs, the release water is taken from several locations over the depth; of the two, Gavins Point Reservoir is shallower and so the stratification effects on its release temperature are lower.

The only difference between the results presented in Figs. 43 through 45 and Figs. 40 through 42 applies to the predicted natural temperatures. For the cases including the release effects of reservoirs, the natural temperatures were calculated independently for each reach between reservoirs with each reservoir release temperature acting as a control temperature for the reach downstream. For the case where the reservoirs were considered as fully mixed, the release temperatures were the same as the mixed temperatures inside the reservoirs. There was then only one control temperature, which was the release temperature from the reservoir farthest upstream. The predicted natural temperatures for this second case are also included in Figs. 43, 44 and 45 for easy comparison with the predicted natural temperatures including reservoir release effects.

G. Concluding Remarks. In the preceding sections the thermal regimes of the upper Mississippi and Missouri Rivers have been investigated for different sets of meteorological and hydrological conditions with various thermal loads imposed upon the rivers. Temperature distributions along the rivers were computed for natural conditions and for conditions modified by the presence of heat loads due to existing, proposed, and projected power plants employing once-through cooling. Locations and capacities of additional future power plants, permissible under existing thermal standards, were also determined.

It was found that there is substantial heat assimilation capacity available in the two rivers. However, the permissible locations are not in all cases consistent with the planned sites for future power plants. Therefore, some new plants will require closed-cycle cooling systems resulting in certain economic penalties.

In the next section various cooling alternatives are discussed. Cooling system costs for mechanical draft wet cooling towers are presented and compared with costs of open-cycle cooling for various plant capacities.

V. ALTERNATIVES TO OPEN-CYCLE COOLING FOR MAPP PLANTS THROUGH THE YEAR 1993

The results summarized in Tables 20 and 34 for the case of the natural-temperature base show that if all existing plants operate at full load, the total permissible capacities of new plants that can be cooled in the once-through mode are about 5840 MW (F) or 4030 MW (N) by the Mississippi River, and about 7480 MW (F) or 5160 MW (N) by the Missouri River. If the capacity factors of the existing plants are considered, the total permissible new once-through cooling plant capacity along the Mississippi River can be increased to about 11100 MW (F) or 7650 MW (N), as seen in Table 21. These figures give the total permissible new plant capacities over and above those of the proposed and projected plant capacities for which locations along the two rivers already have been selected, and were determined under the assumption that the proposed and projected plants will use once-through cooling, unless otherwise specified, and that they will operate at their full-load capacities. The data presented in Table 7 show that projected plants along the Mississippi and Missouri Rivers for which specific sites have not yet been selected have total capacities of 15000 MW and 800 MW, respectively. These are in addition to the total plant capacities of 955 MW along the Mississippi River and 7120 MW along the Missouri River, for which locations but not cooling systems already have been selected.

It is clear from the data, Tables 20 and 34, that the Missouri River has adequate heat transfer and assimilation capacities for once-through cooling of the projected new plant capacity. However, the bulk of the projected plant capacity along the Mississippi River will have to use alternate cooling systems.

A. Cooling Alternatives. Cooling ponds and mechanical draft wet cooling towers appear to be the most attractive alternatives for steam-electric plants in the MAPP region which cannot be cooled in the once-through mode. In cooling-pond systems, cooling water from the pond is passed through the condensers, and the heated water is returned to the pond for cooling prior to being recirculated through the condensers. The system involves considerable evaporative loss of water and requires large land area. The feasibility of using cooling ponds for condenser cooling is also strongly influenced by the meteorological and topographical conditions at the plant site.

Cooling tower systems can be either the evaporative wet type or the nonevaporative, dry type, and both can be built as natural draft or mechanical draft. In wet cooling towers, the heat is transferred to the atmosphere primarily by the evaporation of a small portion of the cooling water. The dry type towers, on the other hand, transfer the sensible heat directly to the air from an array of cooling tubes. The capital costs of dry towers are very high compared to wet towers, and dry towers also lead to turbine derating due to higher back pressures. In the United States, about 13 percent of the presently installed steam-electric generating stations utilize wet cooling towers, while some 30 percent use cooling lakes or ponds. It is estimated that about 35 percent of the new generating facilities built between now and 1980 will require cooling towers, with the proportion rising to 75 percent by 1990 [1]. For the management of waste heat from power plants, the trend in the Midwest is definitely toward the use of wet cooling towers as the favored alternative to once-through cooling.

B. Economic Evaluation of Alternatives. The capital cost penalties for alternative cooling systems, reported by Hauser [5], taking the cost of a fresh-water once-through system as a base, are presented in Table 37. The costs are based on an estimated capital cost for a 1000 MW nuclear plant, using a 14 percent annual charge rate and an 80 percent capacity factor.

Table 37

COST ADDITION* TO GENERATION COST FOR ALTERNATE COOLING SYSTEMS [5]

Type of Cooling System (1)	Incremental Cost to Generation Cost, mills/kwh				
	Incremental Capital Cost (2)	Incremental Direct Cost (3)	Incremental Cost Equivalent for (Capacity Loss in MW) (4)	Incremental Fuel Cost (5)	Total Cost Addition to Generation Cost (Sum of Columns (2) to (5) (6)
Once-through, Fresh	Base	Base	Base	Base	Base
Once-through, Saline	0.0336	Base	Base	Base	0.0336
Cooling Ponds	0.0331	Base	0.0300 (20 MW)*	0.0240	0.0871
Wet Cooling Towers-Mechanical Draft	0.0785	0.0771	0.0300 (20 MW)	0.0240	0.2097
Wet Cooling Towers-Natural Draft	0.1235	0.0211	0.0300 (20MW)	0.0240	0.1986
Dry Cooling Towers	0.4369	0.0937	0.1590 (106 MW)	0.1272	0.8168

* Costs based on estimated capital cost for a 1000 MW nuclear plant.

The second and third columns of Table 37 show the contributions of incremental capital cost and incremental direct cost, respectively, to generating cost. The cost equivalent, in mills per kilowatt-hour, of the incremental generating capacity loss, in megawatts, of each alternative method is shown in the fourth column. This capacity loss occurs with closed-cycle systems because their condensing temperatures are higher, and consequently the turbine back pressures are also higher. The cost equivalent of the capacity loss due to the higher turbine back pressure is determined by assuming that the loss has to be replaced by additional plant capacity. Higher back pressure also leads to a higher heat rate for the turbine, causing an increase in fuel costs. The incremental fuel costs are shown in the fifth column of Table 37, and the sum of all the cost penalties is given in the last column. The data given in Table 37 are averages of values from numerous plant cost estimates from various geographical locations in the United States, and may vary greatly from plant site to plant site. However, the data indicate that the alternative heat dissipation methods do not give rise to prohibitive additional generation costs.

C. Background Data for Determining the Optimum Sizes of Wet Cooling Towers. The optimum sizes of mechanical draft wet cooling 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]. The details of the formulation and calculation procedures are available in the references cited and are not repeated here. In addition to the plant capacity, the heat rejection rate and plant heat rate associated with each power level, determined using the method developed in Section II, 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.

1. Design Conditions. The design conditions used in this study in determining the sizes of cooling towers for projected plants operating at rated capacities in the MAPP area are the following:

Design wet-bulb temperature	75^oF
Design dry-bulb temperature	89^oF
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/^{o}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

2. Unit Costs. The following unit cost values reported by Giaquinta et al. [4] were used in computing the capital and operating costs of wet cooling towers:

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

3. Capital Costs. The total capital cost for a mechanical draft wet cooling tower includes the initial costs of tower, pump and pipe systems,

condensers, and replacement capacity (usually from gas turbines). The initial cost of the tower depends on the cooling water flow rate and the number of tower units. The latter is a function of the range, approach, and wet-bulb temperature, and is obtained from rating curves. The cost of the pump and pipe systems also can be obtained from a rating curve relating the cost to cooling water flow rate. The amount of replacement capacity can be obtained as a function of the tower length, turbine type, and the location of the plant. The rating curves and other details for calculating these components of the capital cost are given by Croley et al. [1] and Giaquinta et al. [4]. Capital costs were amortized over the expected plant life by means of the fixed charge rate. In the present study, an expected plant life of 35 years and a corresponding fixed charge rate of 0.147 [4] were adopted.

4. Operating Costs. The operating costs include the costs of the energy consumed by the closed-cycle cooling system (energy loss), supply water, treatment of blowdown water, and tower maintenance. These values can be calculated from their unit cost figures. Annual maintenance cost is based on the number of cells, which equals the number of fans, and is related to the tower length and the distance between fan centers.

5. Rates of Evaporation and Blowdown. The amount of water lost by evaporation is a function of the total air flow rate through the tower and of the specific humidity differential of the air between the inlet and outlet. For a tower of given size, the air flow rate is a specific design parameter, while its specific humidity depends on the dry- and wet-bulb temperatures and the saturation vapor pressure. The rate of blowdown from the tower is related to the rate of evaporative water loss by the concentration ratio. For a concentration of 100 ppm for supply water and maximum permissible concentration of 330 ppm for blowdown water, the concentration ratio is 3.3. Therefore, if E is the rate of evaporation, the rate of blowdown, B, is given by $B = E/(3.3-1)$.

D. Optimum Sizes and Total Costs of Wet Cooling Towers Along the Mississippi and Missouri Rivers. The total unit costs of mechanical draft wet cooling towers, in mills per kilowatt-hour, for different size combinations at various power levels in the MAPP area are tabulated in Tables 38 and 39 for fossil plants and nuclear plants, respectively. These values were deter-

Table 38

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

Power Level,* (MW)	Tower Height, H (ft)	Total Unit Cost in mills/kwh for Different Tower Lengths							
Tower Length, L (ft)		75	100	150	200	250	300	350	450
200	55	7.06855	4.83695	3.02140	2.94291	2.98749	3.07492	3.14386	3.29242
	50	7.52215	5.41458	3.13283	2.91771	2.96545	3.02113	3.08089	3.27999
	45	7.99362	6.01949	3.28401	2.91714	2.95112	3.00047	3.05589	3.17247
Tower Length, L (ft)		250	300	350	400	450	500	550	700
400	55	3.47436	3.01148	2.89960	2.93081	2.93688	2.96732	2.99563	3.12409
	50	3.75436	3.12472	2.90052	2.90560	2.92294	2.94718	2.97384	3.06113
	45	4.17041	3.27733	2.95100	2.90503	2.91500	2.93370	2.95653	3.03614
Tower Length, L (ft)		450	500	550	600	650	700	750	850
600	55	3.00513	2.89518	2.89675	2.92401	2.93930	2.93779	2.95808	3.02426
	50	3.11913	2.91420	2.89367	2.89880	2.90904	2.92215	2.93868	2.97503
	45	3.27202	3.02708	2.90150	2.89822	2.90333	2.91285	2.92552	2.95658
Tower Length, L (ft)		600	700	750	800	850	900	1000	1100
800	55	3.00257	2.88970	2.90935	2.91781	2.93073	2.92460	2.95249	2.98202
	50	3.11582	2.89063	2.89020	2.89375	2.90147	2.91065	2.93347	2.96023
	45	3.26843	2.94111	2.89507	2.89358	2.89690	2.90272	2.92043	2.94292

* Rated capacity

Table 39

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

Power Level,* (MW)	Tower Height, H (ft)	Total Unit Cost in mills/kwh for Different Tower Lengths							
Tower Length, L (ft)		250	300	350	400	450	500	550	700
400	55	4.51224	3.51274	3.11698	2.97936	3.00322	3.02716	3.03052	3.15174
	50	5.07248	3.78466	3.24925	2.98403	2.97976	2.99236	3.01168	3.09147
	45	5.70655	4.19141	3.40618	3.09355	2.98424	2.98731	3.00072	3.06847
Tower Length, L (ft)		450	500	550	600	650	700	750	850
600	55	3.50639	3.20930	3.03617	2.97256	2.97476	3.00119	3.01792	3.03216
	50	3.77905	3.36783	3.14208	2.97722	2.97114	2.97436	2.98385	3.01090
	45	4.18607	3.60635	3.27879	3.08674	2.98066	2.97565	2.97910	2.99829
Tower Length, L (ft)		800	900	1000	1100	1200	1300	1450	1600
1100	60	3.41934	3.13411	2.97129	2.97049	2.98013	2.99641	3.02651	3.06079
	55	3.62321	3.24590	3.04145	2.96263	2.96589	2.99506	2.99915	3.02765
	50	3.93680	3.40680	3.14788	2.96811	2.96191	2.96626	2.98306	3.00613
Tower Length, L (ft)		1100	1200	1250	1300	1350	1400	1450	1550
1300	60	3.07783	2.96797	2.96619	2.96847	2.97091	2.97607	2.98112	2.99556
	55	3.15783	3.01488	2.06315	2.96060	2.96047	2.96287	2.98259	2.99397
	50	3.31892	3.12036	3.02575	2.96594	2.96100	2.95965	2.95992	2.96453
Tower Length, L (ft)		1200	1300	1400	1500	1600	1750	1900	2000
1500	60	3.17944	3.03796	2.96549	2.96564	2.97177	2.98854	3.00888	3.02511
	55	3.29934	3.11635	2.99533	2.95787	2.95943	2.98774	3.00515	2.99680
	50	3.49198	3.25640	3.10014	2.96376	2.95748	2.96026	2.97060	2.98018

* Rated capacity

mined using the design conditions and unit cost values summarized in the previous section. The total unit cost includes all costs related directly or indirectly to rejection of waste heat, among them the cost of all the fuel consumed by the plant. Total unit cost is not the total cost of power production (sometimes referred to as bus-bar cost) which also includes the capital and operating costs of the reactor or boiler, turbines, etc.

The variations of total unit cost with tower size are shown in Figs. 46 for fossil plants, and in Figs. 47 for nuclear plants. The optimum total unit costs of cooling for fossil and nuclear plants at various power levels are given in Tables 40 and 41, respectively. The variations with plant capacity of the optimum sizes and the corresponding minimum costs for wet cooling towers are illustrated in Figs. 48 and 49 for fossil plants and nuclear plants, respectively. Tables 40 and 41 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 40 and 41 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

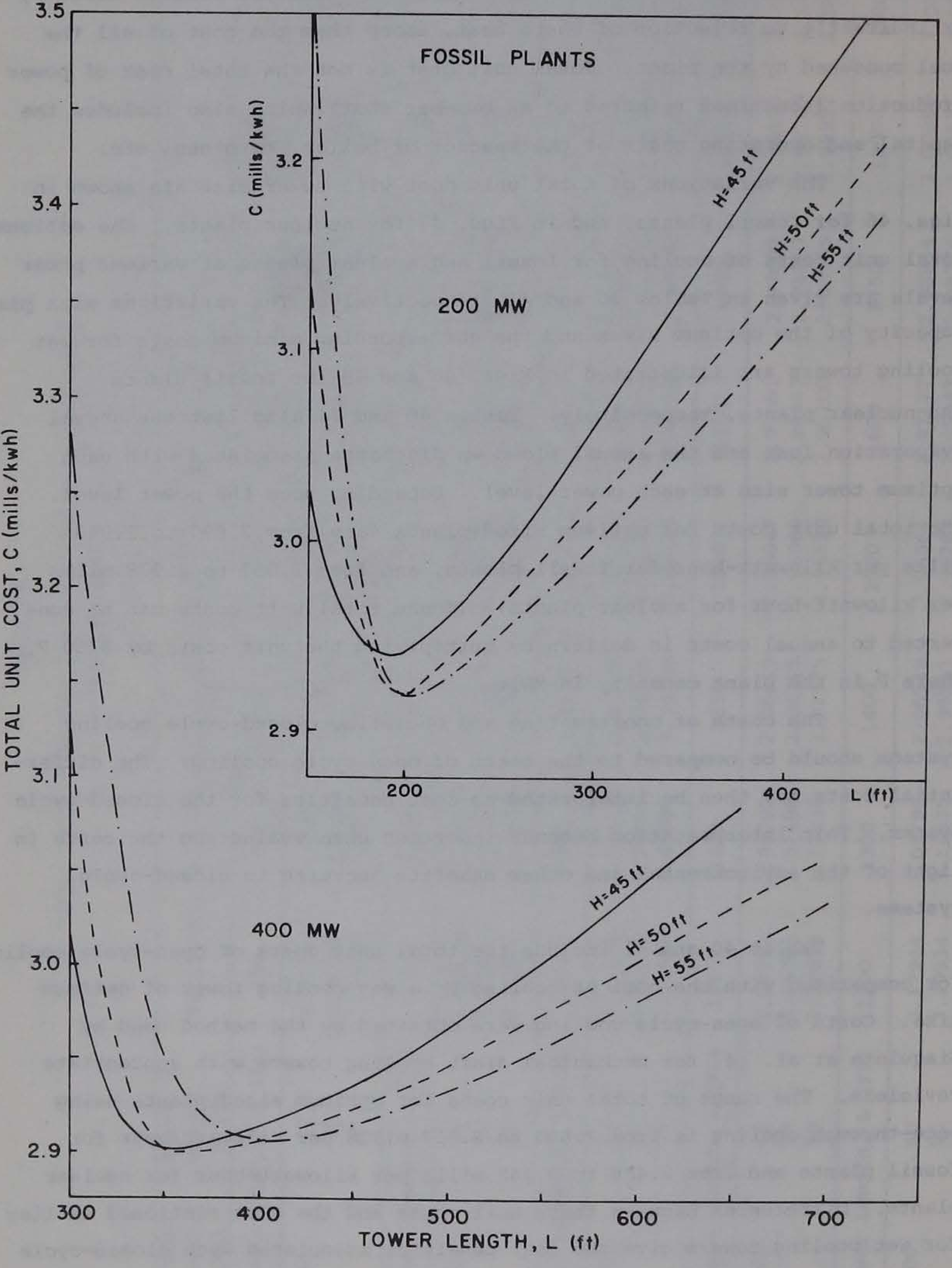


Figure 46. Total unit costs of wet cooling towers -- fossil plants

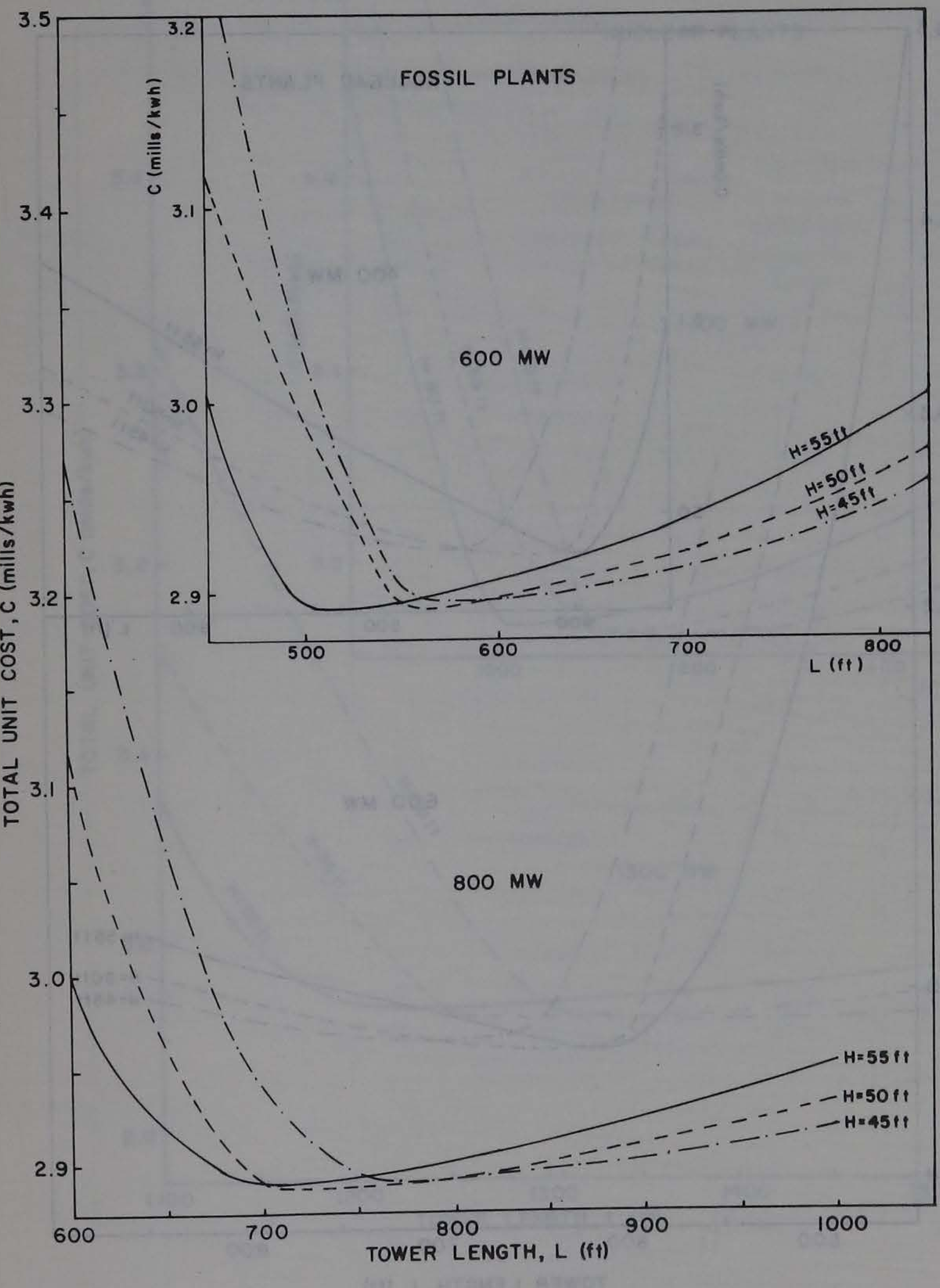


Figure 46. (continued)

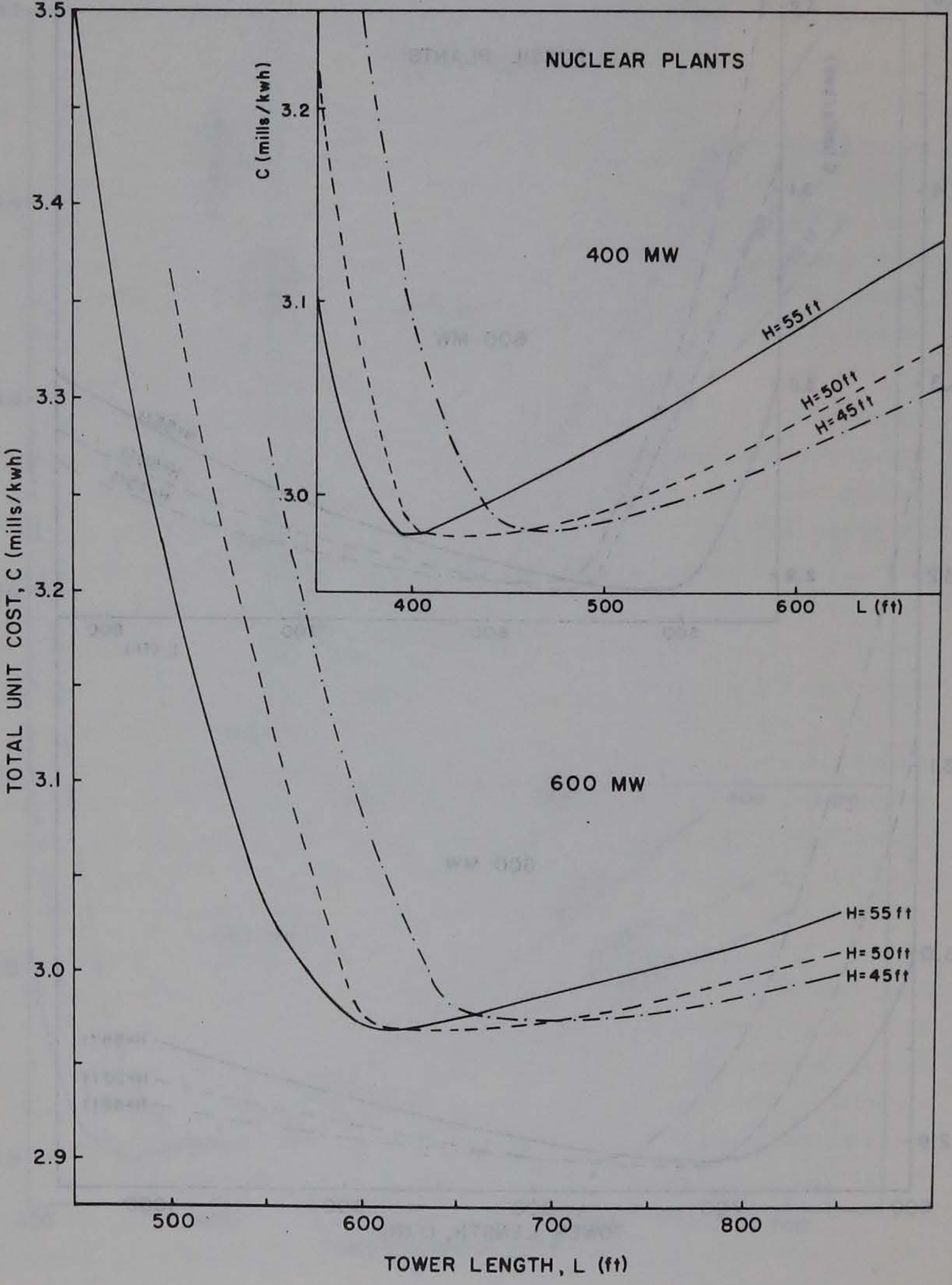
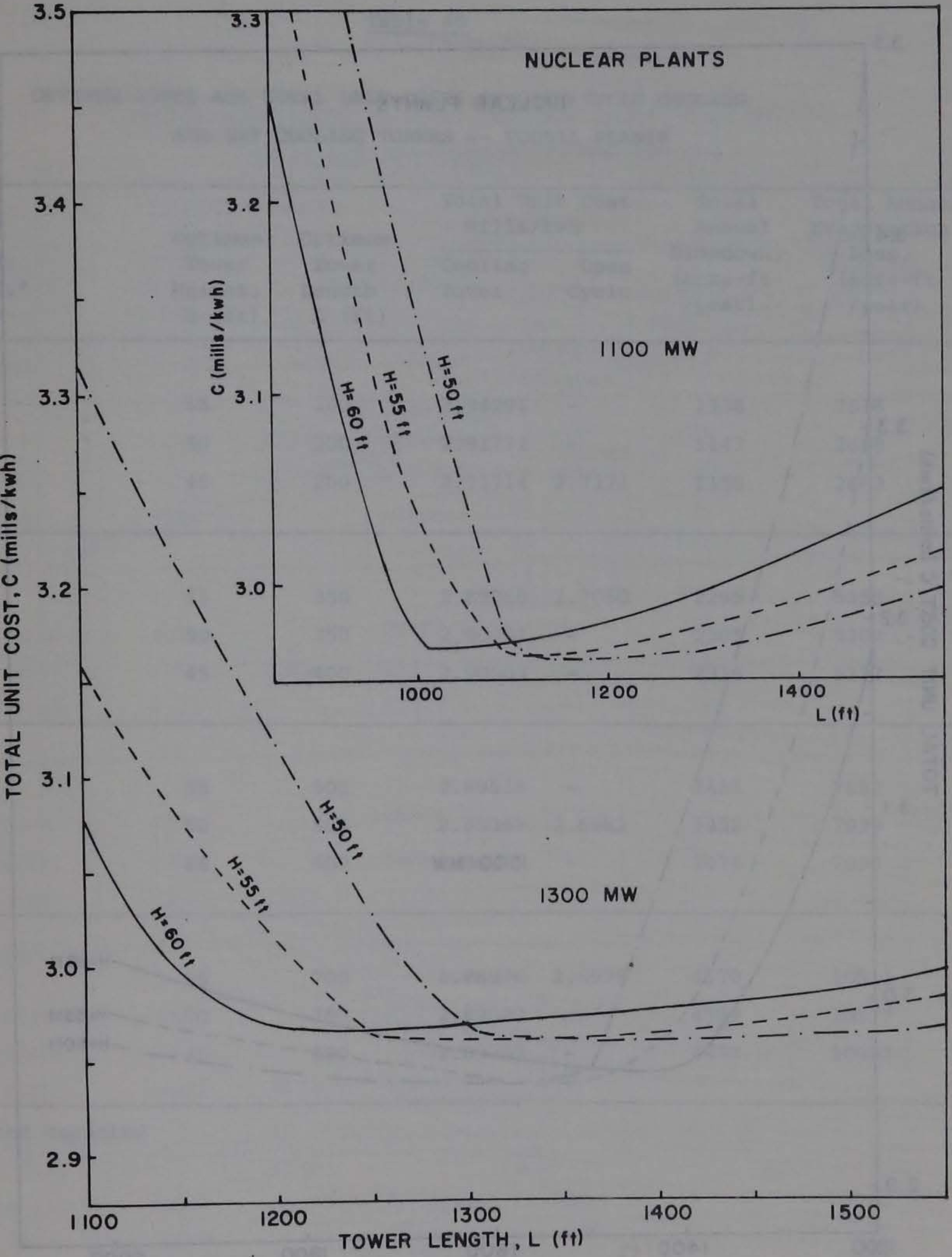


Figure 47. Total unit costs of wet cooling towers -- nuclear plants



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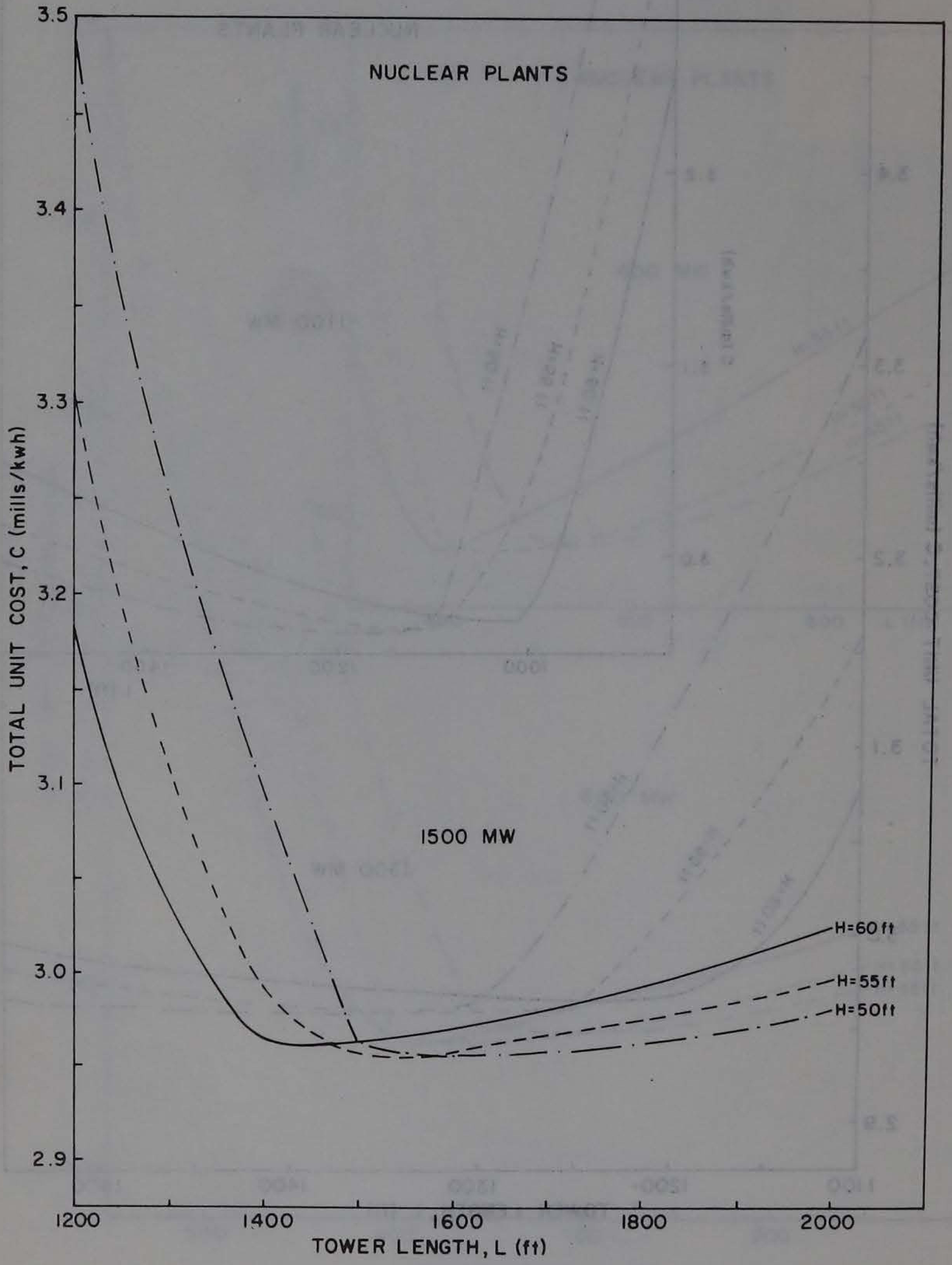

Figure 47. (continued)

Table 40

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 41

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

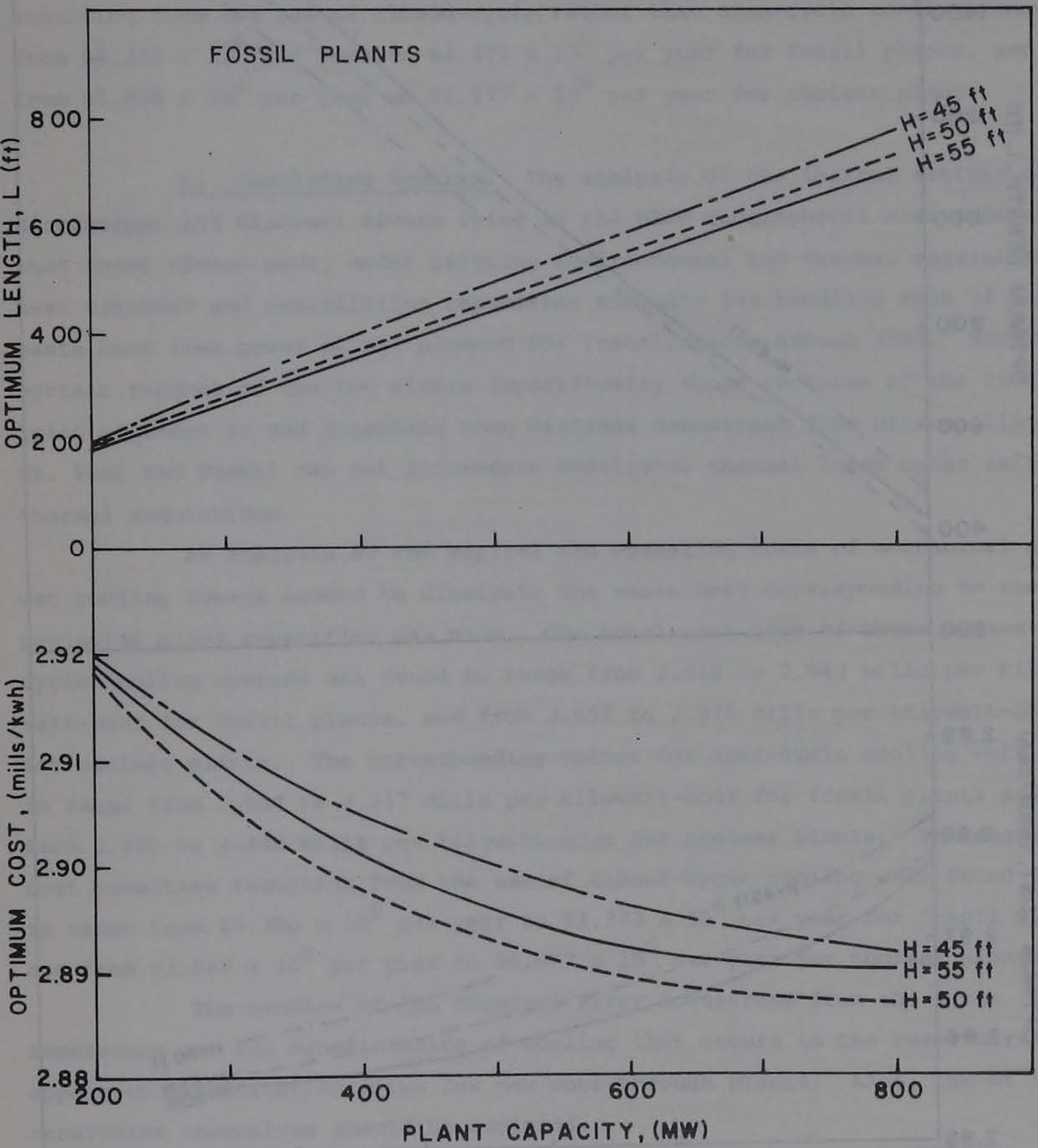

Figure 48. Optimum sizes and total unit costs of wet cooling towers -- fossil plants

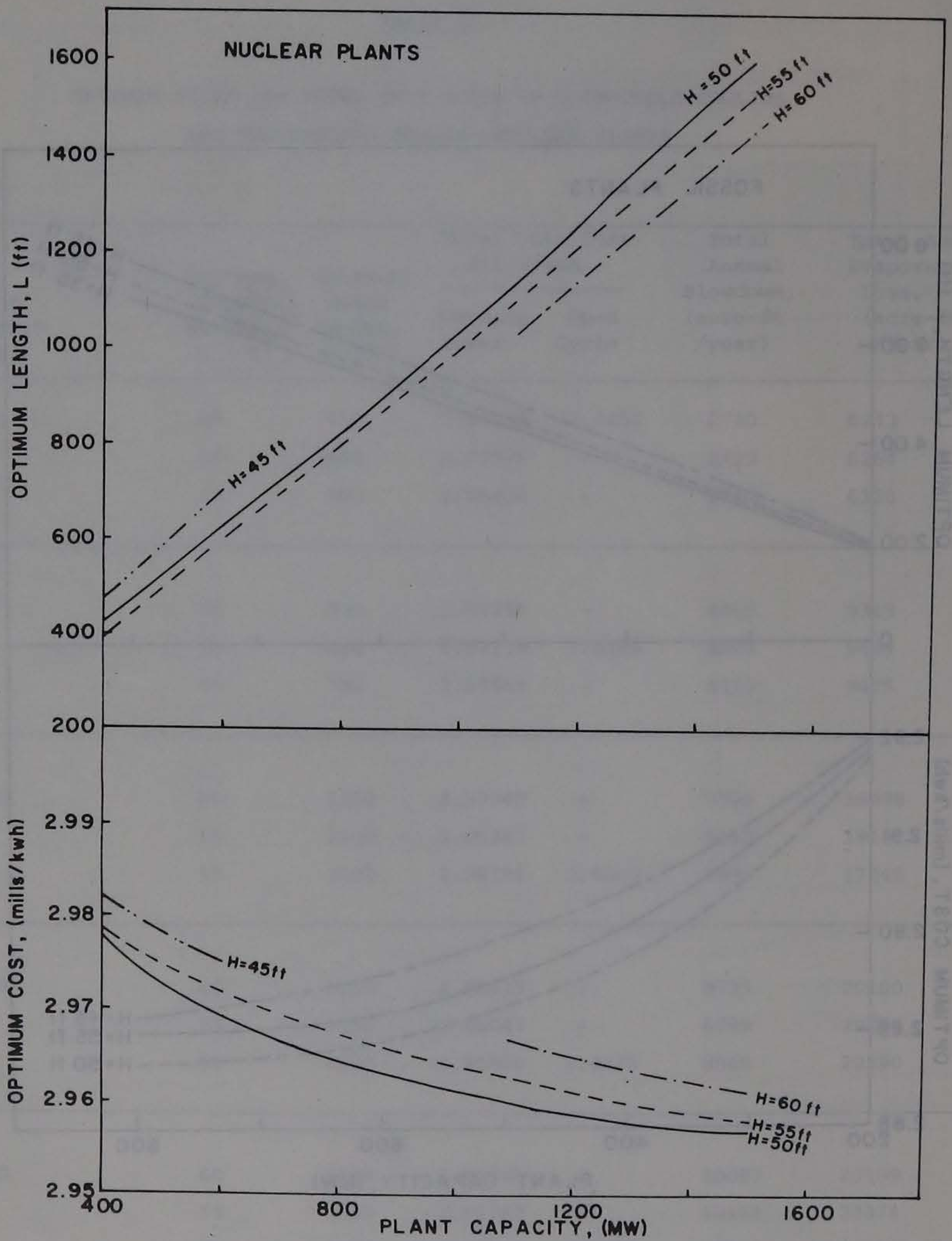

Figure 49. Optimum sizes and total unit costs of wet cooling towers -- nuclear plants

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 40 and 41 the 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.

E. Concluding Remarks. The analysis of the thermal regimes of the Mississippi and Missouri Rivers lying in the MAPP geographical area indicates that these rivers 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 two rivers (specifically those sections of the rivers lying adjacent to and extending some distance downstream from Minneapolis-St. Paul and Omaha) 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.

The reaches of the Missouri River downstream from the large reservoirs are the beneficiaries of cooling that occurs in the reservoirs and appear to be attractive sites for new once-through plants. Also, use of the reservoirs themselves should be explored.

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.

APPENDICES (PART TWO)

APPENDIX A (PART TWO)

LIST OF REFERENCES

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APPENDIX B (PART TWO)

THERMAL CRITERIA OF THE VARIOUS STATE GOVERNMENT AGENCIES APPLICABLE TO THE MISSOURI AND UPPER MISSISSIPPI RIVERS

MONTANA STATE

The Montana State Department of Health and Environmental Sciences Water Quality Standards (No: MAC 16-2.14 (10) - S14480) classify the main stem Missouri River under the category of B-D_2. The specific water quality criteria for the B-D_2 classification for temperature are as follows:

> A 1°F maximum increase above naturally occuring water temperature is allowed within the range of 32°F to 66°F; within the naturally occurring range of 66°F to 66.5°F, no discharge is allowed which will cause the water temperature to exceed 67°F; and where the naturally occurring water temperature is 66.5°F or greater, the maximum allowable increase in water temperature is 0.5°F. A 2°F per hour maximum decrease below naturally occurring water temperature is allowed when the water temperature is above 55°F, and a 2°F maximum decrease below naturally occurring water temperature is allowed within the range of 55°F to 32°F.

NORTH DAKOTA STATE

The Standards of Surface Water Quality for the State of North Dakota given by Regulation 61-28-05.2 of the North Dakota State Department of Health classify the Missouri River, including Lake Sakakawea and Oahe Reservoir as Class I. The temperature criteria for Class I waters are the following:

> The limit of temperature is 85°F. The maximum increase shall not be greater than 5°F above natural background conditions. Natural background conditions are those that exist before the addition of any controllable heat source.
>
> Mixing Zones:
>
> The size and configurations of a mixing zone cannot be uniformly prescribed for all streams due to the particular characteristics of each stream as to volumes of flow, current characteristics, velocities of flow, and stream width and depth. However, the following considerations are to be taken into account when mixing zones are determined. The Water Quality Standards must be met at every point outside the mixing zone. The Department may require a means of expediting mixing and dispersion of wastes, if found necessary.
>
> 1. The total mixing zone (or zones) at any cross-sectional area of the stream should not be larger than 25 percent of the cross-section area or volume of flow and shall not extend more than 50% of the width. Mixing zones shall provide an acceptable passageway for movement of fish and other aquatic organisms.
> 2. Mixing zone characteristics: The 96-hour TL_m for indigenous fish and fish food organisms shall not be exceeded at any point in the mixing zone.
> 3. Mixing zones shall be as small as possible and shall not intersect spawning and nursery areas, migratory routes, or municipal water intakes. Overlapping of mixing zones should be avoided or minimized to prevent adverse synergistic effects.

SOUTH DAKOTA STATE

The Surface Water Quality Standards (Chapter 34) of the South Dakota State Department of Environmental Protection classify the Missouri River between the North Dakota border and the Big Bend Dam as "Cold Water Permanent Fish Life Propagation Waters", and between the Big Bend Dam and the Iowa border as "Warm Water Permanent Fish Life Propagation Waters". The temperature criteria for these two classes of waters are:

> Cold Water Permanent Fish Life Propagation Waters: Temperature shall be less than $65^{\circ}F$. This criterion shall be maintained at all times, without exception.
>
> Hot Water Permanent Fish Life Propagation Waters: Temperature shall not exceed $80^{\circ}F$. This criterion shall be maintained at all times, without exception.
>
> Temperature Change in Fish Life Propagation Waters: No discharge or discharges shall affect the temperature by more than $4^{\circ}F$ in streams classified for the beneficial use of cold water permanent, ..., or warm water permanent fish life propagation; .... In addition, the maximum incremental temperature shall not exceed $2^{\circ}F$ per hour. There shall be no induced temperature change over spawning beds.
>
> Mixing Zones:
>
> Each discharge to a flowing water shall be entitled to a mixing zone at the edge of which the criterion established for the beneficial uses of the receiving water shall be met. Mixing zones in streams must permit an acceptable passageway for movement of aquatic organisms. The total mixing zone or zones, at any transect of a stream shall not contain more than seventy-five percent of the cross-sectional area of the stream; shall not extend over more than seventy-five percent of the width of the stream or one hundred yards, whichever is the least; and the dimensions parallel to the stream flow shall not exceed one half mile. Mixing zone characteristics must not be lethal to aquatic organisms. The median tolerance limit for indigenous fish or fish food organisms, whichever is more stringent, shall not be exceeded at any point in the mixing zone. Mixing zones shall not intersect spawning or nursery areas, migratory routes, water intakes, or

mouths of rivers. Mixing zones should not overlap, but where they do, measures shall be taken to prevent adverse synergistic effects.

NEBRASKA STATE

The State of Nebraska Department of Environmental Control Water Quality Standards Applicable to Nebraska Waters classify the Missouri River among Class "A" waters. The temperature criteria for Class "A" waters are as follows:

> The temperature of the receiving water shall not be increased by a total of more than 5°F from natural. Maximum rate of change limited to 2°F per hour.
>
> For Missouri River, from South Dakota-Nebraska State line near Ft. Randall Dam to Sioux City, Iowa, maximum temperature limit is 85°F with an allowable change of 4°F from natural. For trout waters, the maximum limit is 65°F with an allowable change of 5°F from natural. For warm waters, the maximum limit is 90°F. For impoundments, the temperature of the epilimnion or surface water shall not be raised more than 3°F above that which existed before the addition of heat of artificial origin. Unless a special study shows that the discharge of heated effluent into the hypolimnion will be desirable, such practice is not recommended and water for cooling shall not be pumped from the hypolimnion to be discharged to the same body of water.
>
> Mixing Zone and Zone of Passage:
>
> The (above) Water Quality Criteria for water uses shall apply at and/or beyond the mixing zone boundaries. The boundary limits of the mixing zone shall be a specified linear distance, volume, or area, and should meet the following conditions:
>
> 1. The mixing zone should be kept as small as possible and shall not be of a size or shape as to cause or contribute to the impairment of water uses.
> 2. The mixing zone should allow a zone of passage, as described below.
> 3. When there are several mixing areas close together, they should all be on the same side of the river so the passageway is continuous.
> 4. The mixing zone shall not intersect any area of any such waters in such a manner that the maintenance of aquatic life in the body of water, as a whole, would be adversely affected.

In determining the size and location of the mixing zones for any discharge on a case-by-case basis, the following guideline characteristics shall be considered:

1. The physical characteristics of the receiving waters.
2. The present and anticipated future uses of the body of water.
3. The water quality of the water.
4. The effect of the discharge on the body of water.
5. The dilution ratio (ratio of the 7-day, once-in-10-year low flow of the receiving stream to the average dry weather flow of the treatment works for the design year)
6. The zone of passage.

A zone of passage is necessary to provide at all times for the movement or drift of aquatic biota. The width of the zone and the volume of flow in it will depend on the character and size of the body of water. Because of the varying character of bodies of water, the zone of passage shall be determined by the following guidelines:

1. Mixing zones shall be limited to no more than 1/4 of the cross-sectional area and/or volume of flow of the body of water.
2. At least 3/4 of the cross-sectional area and/or volume will be left free as a zone of passage.

Facilities for expediting, mixing and dispersing all waste water in receiving waters shall be required, when deemed necessary by the Nebraska Department of Environmental Control, to maintain the quality of the receiving waters in accordance with applicable water quality criteria.

NEBRASKA STATE

The State of Nebraska Department of Environmental Control Water Quality Standards Applicable to Nebraska Waters classify the Missouri River among Class "A" waters. The temperature criteria for Class "A" waters are as follows:

> The temperature of the receiving water shall not be increased by a total of more than 5°F from natural. Maximum rate of change limited to 2°F per hour.
>
> For Missouri River, from South Dakota-Nebraska State line near Ft. Randall Dam to Sioux City, Iowa, maximum temperature limit is 85°F with an allowable change of 4°F from natural. For trout waters, the maximum limit is 65°F with an allowable change of 5°F from natural. For warm waters, the maximum limit is 90°F. For impoundments, the temperature of the epilimnion or surface water shall not be raised more than 3°F above that which existed before the addition of heat of artificial origin. Unless a special study shows that the discharge of heated effluent into the hypolimnion will be desirable, such practice is not recommended and water for cooling shall not be pumped from the hypolimnion to be discharged to the same body of water.
>
> Mixing Zone and Zone of Passage:
>
> The (above) Water Quality Criteria for water uses shall apply at and/or beyond the mixing zone boundaries. The boundary limits of the mixing zone shall be a specified linear distance, volume, or area, and should meet the following conditions:
>
> 1. The mixing zone should be kept as small as possible and shall not be of a size or shape as to cause or contribute to the impairment of water uses.
> 2. The mixing zone should allow a zone of passage, as described below.
> 3. When there are several mixing areas close together, they should all be on the same side of the river so the passageway is continuous.
> 4. The mixing zone shall not intersect any area of any such waters in such a manner that the maintenance of aquatic life in the body of water, as a whole, would be adversely affected.

In determining the size and location of the mixing zones for any discharge on a case-by-case basis, the following guideline characteristics shall be considered:

1. The physical characteristics of the receiving waters.
2. The present and anticipated future uses of the body of water.
3. The water quality of the water.
4. The effect of the discharge on the body of water.
5. The dilution ratio (ratio of the 7-day, once-in-10-year low flow of the receiving stream to the average dry weather flow of the treatment works for the design year)
6. The zone of passage.

A zone of passage is necessary to provide at all times for the movement or drift of aquatic biota. The width of the zone and the volume of flow in it will depend on the character and size of the body of water. Because of the varying character of bodies of water, the zone of passage shall be determined by the following guidelines:

1. Mixing zones shall be limited to no more than 1/4 of the cross-sectional area and/or volume of flow of the body of water.
2. At least 3/4 of the cross-sectional area and/or volume will be left free as a zone of passage.

Facilities for expediting, mixing and dispersing all waste water in receiving waters shall be required, when deemed necessary by the Nebraska Department of Environmental Control, to maintain the quality of the receiving waters in accordance with applicable water quality criteria.

KANSAS STATE

Kansas State Board of Health Regulations, article 28-16-28, Water Quality Criteria for Interstate and Intrastate Waters of Kansas, classify the Missouri River as Class B. The temperature criteria for Class B waters are as follows:

> Man-made point source discharges shall not elevate the temperature of the receiving water above 90°F. Heat of artificial origin shall not be added to a stream in excess of the amount that will raise the temperature of the water more than 5°F above natural conditions. The epilimnion of lakes shall not be raised more than 3°F above that temperature that existed before the addition of heat of artificial origin. The normal daily and seasonal temperature variations before the addition of heat due to other than natural causes should be maintained. The measurement system used in each case should provide for temperature measurements which reflect the temperature differential induced after a reasonable mixing zone. A zone of passage for free-swimming and drifting aquatic biota must be provided for the water affected by each discharge.
>
> It is recognized that on occasion natural thermal conditions may exceed the maximum allowable temperature requirements. Deviations from temperature requirements as a result of waste discharge will not be allowed without special permission.
>
> Mixing Zones:
>
> The water quality criteria listed herein shall apply below the mixing zone for each individual discharge. The total area and/or volume of a receiving stream assigned to mixing zones shall be limited to that which will: 1) not interfere with biological communities or populations of important species to a degree which is damaging to the ecosystem; and 2) not diminish other beneficial uses disproportionately.
>
> Zones of Passage:
>
> Zones of passage must be provided in streams, reservoirs, or lakes wherever mixing zones are allowed, and such zones shall be continuous water routes of the volume, area, and quality necessary to allow passage of free-swimming and drifting organisms with no

significant effects on their populations. Because of varying local physical and chemical conditions and biological phenomena, no single value can be given on the percentage of river width necessary to allow a sufficient zone of passage. As a guideline, mixing zones should be limited to no more than 1/4 of the cross-sectional area and/or volume of flow of a stream or reservoir, leaving at least 3/4 free as a zone of passage.

MISSOURI STATE

The Effluent Regulations and Water Quality Standards of the Missouri Clean Water Commission designate the Missouri River and Lower Mississippi River (From Alton Lock and Dam to Missouri-Arkansas Boundary Line) in one class and the Upper Mississippi River from Missouri-Iowa Boundary Line (Des Moines River) to Alton Lock and Dam in another class. The temperature criteria applicable to these waters are the following:

> Effluents will not elevate or depress the temperature of the stream more than 5°F. The stream temperature shall not exceed 90°F due to effluents.
>
> For reaches of streams designated for stocking or propagation of trout, the temperature shall not be elevated more than 2°F due to effluents. No activity of man shall cause reaches of streams used for stocking or propagation of trout to exceed 68°F.
>
> No elevation in the temperature of lakes shall be due to effluents. (It is recognized that Lake Springfield and Thomas Hill Reservoir were constructed especially to provide industrial cooling water, and so will have a mixing zone of heated water.)
>
> For the Mississippi River:
>
>> The river water temperature outside the mixing zone shall not exceed the maximum limits indicated in the following table during more than one percent of the time in any calendar year. At no time shall the river water temperature outside the mixing zone exceed the listed limits by more than 3°F. Immediate reduction of thermal loading shall be initiated at any time that the temperature limits are exceeded.
>>
>> The Clean Water Commission will consider granting exceptions to these limits. Environmental Protection Agency concurrence will be obtained before any exceptions are granted. The Missouri Department of Conservation will be consulted before an exception is granted.

Zone 1 - Des Moines River to Alton Lock and Dam

Zone 2 - Alton Lock and Dam to the Missouri-Arkansas State Line

	Zone 1	Zone 2		Zone 1	Zone 2
January	45(°F)	50	July	88	89
February	45	50	August	88	89
March	57	60	September	86	87
April	68	70	October	75	78
May	78	80	November	65	70
June	86	87	December	52	57

(The above criteria for Zone 2 apply to the Missouri River also.)

Mixing Zone:

The area of diffusing of an effluent in the receiving water is a mixing zone and the water quality standards shall be applied at and/or beyond the mixing zone boundaries.

The boundary limits of the mixing zone shall be a specified linear distance, volume, or area which is determined on a case-by-case basis and shall meet the following conditions:

1. The mixing zone shall be kept as small as possible and shall not be of a size or shape as to cause or contribute to the impairment of water uses.
2. The mixing zone shall contain preferably no more than 25 percent of the cross-sectional area and/or volume of flow of the river.
3. The mixing zone shall be designed to allow an adequate passageway at all times for the movement or drift of aquatic life.
4. When there are several mixing areas close together, they should all be on the same side of the river so the passageway is continuous.
5. The mixing zone shall not intersect any area of any such waters in such a manner that the maintenance of aquatic life in the body of water as a whole would be adversely affected.

In determining the size and location of the mixing zone for any discharge on a case-by-case basis, the following guideline characteristics must be considered:

1. The character of the body of water, such as the size of the river, the volume of discharge, the stream bank

configuration, the mixing velocities, and other hydrologic or physiographic characteristics.

2. The present and anticipated future use of body of water.
3. The present and anticipated water quality of the body of water.
4. The effect of the discharge on the present and anticipated future water quality.
5. The dilution ratio (dilution ratio means the ratio of the 7-day, once-in-10-years low flow of the receiving stream to the average dry weather flow of the treatment works for the design year).
6. The free passage of fish between the outfall and shoreline.

Zones of Passage:

In river systems, reservoirs, and lakes, zones of passage are continuous water routes of the volume, area and quality necessary to allow passage of free-swimming and drifting organisms with no significant effects produced on their populations. These zones must be provided wherever mixing zones are allowed.

Because of varying local physical and chemical conditions and biological phenomena no single value can be given on the percentage of river width necessary to allow passage of critical free-swimming and drifting organisms so that negligible or no effects are produced on their populations. As a guideline, at least three-quarters of the cross-sectional area and/or volume of flow of a stream should be left free as a zone of passage.

MINNESOTA STATE

The Mississippi River is classified among the Fish and Recreation category in the Minnesota Regulations WPC-14 and 15, Minnesota Criteria for Interstate Waters of the Minnesota Pollution Control Agency. The Class B and Class C subdivisions of the Fish and Recreation Classification apply to the Mississippi River. The thermal criteria for these cases are the following:

Class B: The temperature limit is 5°F above natural in streams and 3°F above natural in lakes, based on monthly average of the maximum daily temperature, except in no case shall it exceed the daily average temperature of 86°F.

The following temperature criteria will be applicable for the Mississippi River from Lake Itasca to the outlet of the Metro Wastewater Treatment Works in St. Paul in addition to or superceding the above. The weekly average temperature shall not exceed the following temperatures during the specified months:

January	40°F	July	83°F
February	40°	August	83°
March	48°	September	78°
April	60°	October	68°
May	72°	November	50°
June	78°	December	40°

For the Mississippi River from the Lock and Dam No.2 at Hastings to the Iowa border, the weekly average temperature shall not exceed the following temperatures during the specified months:

January	40°F	July	84°F
February	40°	August	84°
March	54°	September	82°
April	65°	October	73°
May	75°	November	58°
June	84°	December	48°

Class C: The temperature limit is 5°F above natural in streams and 3°F above natural in lakes, based on monthly average of the maximum daily temperature, except in no case shall it exceed the daily average temperature of 90°F.

The following temperature criteria will be applicable for the Mississippi River from the outlet of the Metro Wastewater Treatment Works in St. Paul to Lock and Dam No.2 at Hastings in addition to or superceding the above. The weekly average temperature shall not exceed the following temperatures during the specified months:

configuration, the mixing velocities, and other hydrologic or physiographic characteristics.

2. The present and anticipated future use of body of water.
3. The present and anticipated water quality of the body of water.
4. The effect of the discharge on the present and anticipated future water quality.
5. The dilution ratio (dilution ratio means the ratio of the 7-day, once-in-10-years low flow of the receiving stream to the average dry weather flow of the treatment works for the design year).
6. The free passage of fish between the outfall and shoreline.

Zones of Passage:

In river systems, reservoirs, and lakes, zones of passage are continuous water routes of the volume, area and quality necessary to allow passage of free-swimming and drifting organisms with no significant effects produced on their populations. These zones must be provided wherever mixing zones are allowed.

Because of varying local physical and chemical conditions and biological phenomena no single value can be given on the percentage of river width necessary to allow passage of critical free-swimming and drifting organisms so that negligible or no effects are produced on their populations. As a guideline, at least three-quarters of the cross-sectional area and/or volume of flow of a stream should be left free as a zone of passage.

MINNESOTA STATE

The Mississippi River is classified among the Fish and Recreation category in the Minnesota Regulations WPC-14 and 15, Minnesota Criteria for Interstate Waters of the Minnesota Pollution Control Agency. The Class B and Class C subdivisions of the Fish and Recreation Classification apply to the Mississippi River. The thermal criteria for these cases are the following:

Class B: The temperature limit is 5°F above natural in streams and 3°F above natural in lakes, based on monthly average of the maximum daily temperature, except in no case shall it exceed the daily average temperature of 86°F.

The following temperature criteria will be applicable for the Mississippi River from Lake Itasca to the outlet of the Metro Wastewater Treatment Works in St. Paul in addition to or superceding the above. The weekly average temperature shall not exceed the following temperatures during the specified months:

January	40°F	July	83°F
February	40°	August	83°
March	48°	September	78°
April	60°	October	68°
May	72°	November	50°
June	78°	December	40°

For the Mississippi River from the Lock and Dam No.2 at Hastings to the Iowa border, the weekly average temperature shall not exceed the following temperatures during the specified months:

January	40°F	July	84°F
February	40°	August	84°
March	54°	September	82°
April	65°	October	73°
May	75°	November	58°
June	84°	December	48°

Class C: The temperature limit is 5°F above natural in streams and 3°F above natural in lakes, based on monthly average of the maximum daily temperature, except in no case shall it exceed the daily average temperature of 90°F.

The following temperature criteria will be applicable for the Mississippi River from the outlet of the Metro Wastewater Treatment Works in St. Paul to Lock and Dam No.2 at Hastings in addition to or superceding the above. The weekly average temperature shall not exceed the following temperatures during the specified months:

January	40°F	July	83°F
February	40°	August	83°
March	48°	September	78°
April	60°	October	68°
May	72°	November	50°
June	78°	December	40°

Mixing Zone:

Means for expediting mixing and dispersion of sewage, industrial waste, or other waste effluents in the receiving intrastate waters are to be provided so far as practicable when deemed necessary by the Agency to maintain the quality of the receiving intrastate waters in accordance with applicable standards. Mixing zones be established by the Agency on an individual basis, with primary consideration being given to the following guidelines:

(a) mixing zones in rivers shall permit an acceptable passageway for the movement of fish

(b) the total mixing zone or zones at any transect of the stream should contain no more than 25 percent of the cross-sectional area and/or volume of flow of the stream, and should not extend over more than 50 percent of the width

(c) mixing zone characteristics shall not be lethal to aquatic organisms

(d) for contaminants other than heat, the 96 hour median tolerance limit for indigenous fish and fish food organisms should not be exceeded at any point in the mixing zone

(e) mixing zones should be as small as possible, and not intersect spawning or nursery areas, migratory routes, water intakes, nor mouths of rivers

(f) overlapping of mixing zones should be minimized and measures taken to prevent adverse synergistic effects.

WISCONSIN STATE

The Wisconsin Administrative Code of the Department of Natural Resources, Chapter NR 102, Water Quality Standards for Wisconsin Surface Waters, classifies the Mississippi River among the Waters for Fish and Aquatic Life. The temperature criteria for these waters are:

1. There shall be no temperature changes that may adversely affect aquatic life.
2. Natural daily and seasonal temperature fluctuations shall be maintained.
3. The maximum temperature rise at the edge of the mixing zone above the existing natural temperature shall not exceed 5°F for streams and 3°F for lakes.
4. The temperature shall not exceed 89°F for warm water fish.

In addition to the above standards for fish and aquatic life, the monthly average of the maximum daily temperature in the Mississippi River outside the mixing zone shall not exceed the following limits:

January	40°F	July	84°F
February	40°	August	84°
March	54°	September	82°
April	65°	October	73°
May	75°	November	58°
June	84°	December	48°

Mixing Zones:

Water quality standards must be met at every point outside of a mixing zone. The size of the mixing zone cannot be uniformly prescribed but shall be based on such factors as effluent quality and quantity, available dilution, temperature, current, type of outfall, channel configuration and restrictions to fish movement. As a guide to the delineation of a mixing zone, the following shall be taken into consideration:

(a) Limiting mixing zones to as small an area as practicable, and conforming to the time exposure responses of aquatic life.

(b) Providing passage ways in rivers for fish and other mobile aquatic organisms.

(c) Where possible, mixing zones being no longer than 25% of the cross-sectional area or volume of flow of the stream and not extending more than 50% of the width.

(d) For contaminants other than heat, the 96-hour TL_m to indigenous fish and fish food organisms not being exceeded at any point in the mixing zone.

(e) mixing zones not exceeding 10% of a lake's surface area.

(f) Mixing zones not interfering with spawning or nursery areas, migratory routes, nor mouths of tributary streams.

(g) Mixing zones not overlapping, but where they do, taking measures to prevent adverse synergistic effects.

IOWA STATE

The Water Quality Standards (Chapter 16, Code of Iowa, 1973) of the Iowa Water Quality Commission, Department of Environmental Quality classify the Missouri and Mississippi Rivers among the Class A waters. The temperature criteria for this classification are as follows:

1. No heat shall be added to interior streams that would cause an increase of more than 5^{o} Fahrenheit. The rate of temperature change shall not exceed 2^{o} Fahrenheit per hour. In no case shall heat be added in excess of that amount that would raise the stream temperature above 90^{o} Fahrenheit.

2. No heat shall be added to streams designated as cold water fisheries that would cause an increase of more than 3^{o} Fahrenheit. The rate of temperature change shall not exceed 2^{o} Fahrenheit per hour. In no case shall heat be added in excess of that amount that would raise the stream temperature above 68^{o} Fahrenheit.

3. No heat shall be added to lakes and reservoirs that would cause an increase of more than 3^{o} Fahrenheit per hour. In no case shall heat be added in excess of that amount that would raise the temperature of the lake or reservoirs above 90^{o} Fahrenheit.

4. No heat shall be added to the Missouri River that would cause an increase of more than 5^{o} Fahrenheit. The rate of temperature change shall not exceed 2^{o} Fahrenheit per hour. In no case shall heat be added that would raise the stream temperature above 90^{o} Fahrenheit.

5. No heat shall be added to the Mississippi River that would cause an increase of more than 5^{o} Fahrenheit. The rate of temperature change shall not exceed 2^{o} Fahrenheit per hour. In addition, the water temperature at representative locations in the Mississippi River shall not exceed the maximum limits in the below table during more than one percent of the hours in the 12 month period ending with any month. Moreover, at no time shall the water temperature at such locations exceed the maximum limits in the below table by more than 3^{o} Fahrenheit.

Zone II - Iowa-Minnesota State line to the Northern Illinois border (Mile Point 1534.6)

Zone III - Northern Illinois border (Mile Point 1534.6) to Iowa-Missouri State line

Month	Zone II	Zone III
January	40°F	45°F
February	40°	45°
March	54°	57°
April	65°	68°
May	75°	78°
June	84°	85°
July	84°	86°
August	84°	86°
September	82°	85°
October	73°	75°
November	58°	65°
December	48°	52°

Mixing zone in the receiving water:

The area of diffusion of an effluent in the receiving water is a mixing zone and the Water Quality Standards shall be applied beyond the mixing zone.

The mixing zone shall be a specified linear distance, volume, or area which is determined on a case-by-case basis using the following criteria:

(a) The zone shall be as small as practicable and shall not be of such size or shape as to cause or contribute to the impairment of water uses.

(b) The mixing zone shall contain not more than twenty-five (25) percent of the cross-sectional area or volume of flow in the receiving body of water.

(c) The mixing zone shall be designed to allow an adequate passageway at all times for the movement or drift of aquatic life.

(d) Where there are two or more mixing zones in close proximity, they shall be so defined that a continuous passageway for aquatic life is available.

(e) The mixing zone shall not intersect any area of any waters in such a manner that the maintenance of aquatic life in the body of water as a whole would be adversely affected.

In determining the size and location of the mixing zone for any discharge on a case-by-case basis, the following shall be considered:

(f) The size of the receiving water, the volume of discharge, the stream bank configuration, the mixing velocities, and other hydrologic or physiographic characteristics.

(g) The present and anticipated future use of the body of water.

(h) The present and anticipated future water quality of the body of water.

(i) The ratio of the volume of waste being discharged to the 7-day, 10-year low flow of the receiving stream.

ILLINOIS STATE

The Illinois Pollution Control Board Rules and Regulations (Chapter 3: Water Pollution) specify the temperature criteria for the Mississippi River as follows:

1. There shall be no abnormal temperature changes that may adversely affect aquatic life unless caused by natural conditions.

2. The normal daily and seasonal temperature fluctuations that existed before the addition of heat due to other than natural causes shall be maintained.

3. The maximum temperature rise above natural temperatures shall not exceed 5°F.

4. In addition, the water temperature at representative locations in the main river shall not exceed the maximum limits in the following table during more than one percent of the hours in the 12-month period ending with any month. Moreover, at no time shall the water temperature at such locations exceed the maximum limits in the following table by more than 3°F.

Zone 1: Mississippi River (Wisconsin Border to Iowa Border)
Zone 2: Mississippi River (Iowa Border to Alton Lock and Dam)
Zone 3: Mississippi River (South of Alton Lock and Dam)

	Zone 1	Zone 2	Zone 3
January	45(°F)	45(°F)	50(°F)
February	45	45	50
March	57	57	60
April	68	68	70
May	78	78	80
June	85	86	87
July	86	88	89
August	86	88	89
September	85	86	87
October	75	75	78
November	65	65	70
December	52	52	57

5. The owner or operator of a source of heated effluent which discharges 0.5 billion British thermal units per hour or more shall denonstrate in a hearing before this Board not less than 5 nor more than 6 years after the effective date of these

regulations, or, in the case of new sources, after the commencement of operation, that discharges from that source have not caused and cannot be reasonably expected to cause significant ecological damage to the receiving waters. If such proof is not made to the satisfaction of the Board appropriate corrective measures shall be ordered to be taken within a reasonable time as determined by the Board.

6. Permits for heated effluent discharges, whether issued by the Board or the Environmental Protection Agency, shall be subject to revision in the event that reasonable future development creates a need for reallocation of the assimilative capacity of the receiving stream as defined in the regulation above.

7. The owner or operator of a source of heated effluent shall maintain such records and conduct such studies of the effluents from such source and of their effects as may be required by the Environmental Protection Agency or in any permit granted under the Environmental Protection Act.

8. Appropriate corrective measures will be required if, upon complaint filed in accordance with Board rules, it is found at any time that any heated effluent causes significant ecological damage to the receiving stream.

Mixing Zones:

(a) In the application of any of the rules and regulations, whenever a water quality standard is more restrictive than its corresponding effluent standard then an opportunity shall be allowed for the mixture of an effluent with its receiving waters. Water quality standards must be met at every point outside of the mixing zone. The size of the mixing zone cannot be uniformly prescribed. The governing principle is that the proportion of any body of water or segment thereof within mixing zones must be quite small if the water quality standards are to have any meaning. This principle shall be applied on a case-by-case basis to ensure that neither any individual source nor the aggregate of sources shall cause excessive zones to exceed the standards. The water quality standards must be met in the bulk of the body of water, and no body of water may be used totally as a mixing zone for a single outfall or combination of outfalls. Moreover, except as otherwise provided, no single mixing zone shall exceed the area of a circle with a radius of 600 feet. Single sources of effluents which have more than one outfall shall be limited to a total mixing area no larger than that allowable if a single outfall were used.

In determining the size of the mixing zone for any discharge, the following must be considered:

1. The character of the body of water,
2. the present and anticipated future use of body of water,
3. the present and anticipated water quality of the body of water,
4. the effect of the discharge on the present and anticipated future water quality
5. the dilution ratio, and
6. the nature of the contaminant.

(b) In addition to the above, the mixing zone shall be so designed as to assure a reasonable zone of passage for aquatic life in which the water quality standards are met. The mixing zone shall not intersect any area of any such waters in such a manner that the maintenance of aquatic life in the body of water as a whole would be adversely affected, nor shall any mixing zone contain more than 25% of the cross-sectional area or volume of flow of a stream except for those streams where the dilution ratio is less than 3:1.

APPENDIX C (PART TWO)

MONTHLY MEAN VALUES OF DAILY WEATHER CONDITIONS

Pages 257-274	Month of February
Pages 275-292	Month of May
Pages 293-310	Month of August
Pages 311-328	Month of November

Above all available on loan from the
Iowa Institute of Hydraulic Research

APPENDIX D (PART TWO)

MONTHLY MEAN VALUES OF DAILY FLOW RATES

Pages 331-349 Missouri River
Pages 350-366 Mississippi River

Above gaging station data available on loan
from the
Iowa Institute of Hydraulic Research

APPENDIX E (PART TWO)

DATA RELATED TO
POWER PLANT DISCHARGES

LIST OF UTILITIES

Austin Utilities, Austin, Minn.

Basin Electric Power Cooperative (BEPC), Bismark, N.D.

Cedar Falls Utilities (CFU), Cedar Falls, Ia.

City of Ames, Ames, Ia.

City of Grand Island Water & Light Dept., Grand Island, Neb.

City of Hastings, Hastings, Neb.

City of Muscatine Power & Water, Muscatine, Ia.

Corn-Belt Power Cooperative (CBPC), Humboldt, Ia.

Dairyland Power Cooperative (DPC), La Crosse, Wis.

Department of Utilities, Fremont, Neb.

Eastern Iowa Light and Power Cooperative (EILP), Wilton Junction, Ia.

Illinois Power Company (IPC)

Iowa Electric Light and Power Company (IELP), Cedar Rapids, Ia.

Iowa-Illinois Gas and Electric Company (IIGE), Davenport, Ia.

Iowa Power and Light Company (IPL), Des Moines, Ia.

Iowa Public Service Company (IPS), Sioux City, Ia.

Iowa Southern Utilities (ISU), Centerville, Ia.

Interstate Power Company (ISP), Dubuque, Ia.

Minnkota Power Cooperative Inc. (MPC), Grand Forks, N.D.

Minnesota Power and Light Company (MPL), Duluth, Minn.

Montana-Dakota Utilities Company (MDU), Owatonna, Minn.

Nebraska Public Power District (NPPD), Columbus, Neb.

Northern States Power Company (NSP), Minneapolis, Minn.

Omaha Public Power District (OPPD), Omaha, Neb.

Otter Tail Power Company (OTPC), Fergus Falls, Minn.

Pella Municipal Power and Light (PMPL), Pella, Ia.

Public Utilities Company (PUC), New Ulm, Minn.

Rochester Department of Public Utilities (RDPU), Rochester, Minn.

United Power Association (UPA), Elk River, Minn.

Wisconsin Power and Light Company (WPLC)

Wisconsin Public Service Corporation (WPSC)

STATE : MONTANA

CITY	ORGANIZATION	PLANT	INSTALLED CAPACITY	SOURCE OF ENERGY	TYPE OF COOLING	RECEIVING WATER BODY	REMARKS
Sidney	MDU	Lewis and Clark	50 MW	C,G	OTF	Yellowstone R.	

STATE : NORTH DAKOTA

CITY	ORGANIZATION	PLANT	INSTALLED CAPACITY	SOURCE OF ENERGY	TYPE OF COOLING	RECEIVING WATER BODY	REMARKS
Center	MPC	Milton R. Young No. 1	256.5 MW	C,O	CP	Nelson Lake (on Square Butte Creek)	
Stanton	BEPC	Leland Olds, 1	216 MW	C,O	OTF	Missouri R.	
Mandan	MDU	R.M. Heskett	100 MW	C	OTF	Missouri R.	
Stanton	UPA	Stanton	172 MW	C,O	OTF	Missouri R.	
Voltaire	BEPC	Neal	34 MW	C			
Underwood	CPA*	Coal Creek, 1	411 MW	C	WCT	Missouri R.	FU; 11/1/78+
Underwood	CPA*	Coal Creek, 2	426 MW	C	WCT	Missouri R.	FU; 11/1/79
Stanton	BEPC	Leland Olds, 2	438 MW	C	OTF	Missouri R.	FU; 10/1/75
Center	MPC	Milton R. Young, 2	408 MW	C	CP	Nelson Lake	FU; 5/1/77

* shared with UPA
FU = Future Unit
\+ in-service date

STATE : SOUTH DAKOTA

CITY	ORGANIZATION	PLANT	INSTALLED CAPACITY	SOURCE OF ENERGY	TYPE OF COOLING	RECEIVING WATER BODY	REMARKS
Sioux Falls	NSP	Lawrence	48.0 MW	C,O,G	WCT	Big Sioux R.	
Sioux Falls	NSP	Pathfinder	75.0 MW	O,G	WCT	Big Sioux R.	
Big Stone City	OTPC*	Big Stone	430.0 MW	C	CP	Big Stone Lake	

* share with MDU

STATE : NEBRASKA

CITY	ORGANI-ZATION	PLANT	INSTALLED CAPACITY	SOURCE OF ENERGY	TYPE OF COOLING	RECEIVING WATER BODY	REMARKS
Fremont	Dept of Utilities	Lon D. Wright Memorial	47 MW	C,G	OTF	Drainage Ditch	
Grand Island	City of Grand Island	C. W. Burdick	120 MW	O,G	OTF, CP	Wood R.	
Lincoln	NPPD	Lincoln "K" Street	30 MW	C,O,G,	WCT	Lincoln Storm Sewer	
Fort Calhoun	OPPD	Fort Calhoun, 1	475 MW	Nuclear	OTF	Missouri R.	
Omaha	OPPD	North Omaha, 1-5	646 MW	C	OTF	Missouri R.	
Omaha	OPPD	Jones Street	173.5 MW	O,G	OTF	Missouri R.	
Hastings	City of Hastings	Hastings	67 MW	O,G	WCT	Storm Sewer	
Brownville	NPPD	Cooper, 1	820 MW	Nuclear	OTF	Missouri R.	
Holdrege	NPPD	Canaday	700 MW	C	OTF	Phelps Canal/ Platte R.	
Hallem	NPPD	Sheldon, 1,2,3	228.6 MW	C	DCT	Well	
Bellevue	NPPD	Kramer, 1-3	113 MW	C,G	OTF	Missouri R.	
Nebraska City	OPPD	Nebraska City	575 MW	C	OTF	Missouri R.	FU; 1/1/79
Sutherland	NPPD*	Gentleman	600 MW	C	OTF	Sutherland Res./ Platte R.	FU; 5/1/77

*Share with Nebraska Municipality and others
FU = Future Unit

STATE : NEBRASKA (cont'd)

CITY	ORGANIZATION	PLANT	INSTALLED CAPACITY	SOURCE OF ENERGY	TYPE OF COOLING	RECEIVING WATER BODY	REMARKS
Scottsbluff	NPPD	Bluff	42.2 MW	O,G	OTF	Storm Sewer/ N. Platte R.	
Ogallala	NPPD	Ogallala		O,G	OTF,WCT	S. Platte R.	

STATE : MINNESOTA

CITY	ORGANI-ZATION	PLANT	INSTALLED CAPACITY	SOURCE OF ENERGY	TYPE OF COOLING	RECEIVING WATER BODY	REMARKS
Fergus Falls	OTPC	Hoot Lake	136.9 MW	C,O	OTF or WCT	Otter Tail R.	
St. Paul	NSP	High Bridge	463.84 MW	C,O,G	OTF	Mississippi R.	
Monticello	NSP	Monticello	568.8 MW	Nuclear	OTF,WCT	Mississippi R.	
Red Wing	NSP	Prairie Island,1	593.1 MW	Nuclear	WCT	Mississippi R.	
Minneapolis	NSP	Riverside	455.85 MW	C,O,G	OTF	Mississippi R.	
Becker	NSP	Sherburne, 1	680 MW	C	WCT	Mississippi R.	FU; 5/1/76
Minneapolis	NSP	Southeast	40.0 MW	O,G	OTF	Mississippi R.	(Retired)
Red Wing	NSP	Red Wing	27 MW	C,G	OTF	Mississippi R.	
Winona	NSP	Winona	26 MW	C	OTF	Mississippi R.	(Retired)
Rochester	RDPU	Silver Lake	98.4 MW	C,G	OTF,CP	Zumbro R.	
Elk River	UPA	Elk River	48 MW	C,O,G	OTF	Mississippi R.	
Owatonna	MPU	Central (only)	34.5 MW	O,G	WCT	Straight R.	
Stillwater	NSP	A.S.King	598.4 MW	C	OTF,WCT	St. Croix R.	
Granite Falls	NSP	Minnesota Valley	46 MW	C,O,G	OTF	Minnesota R.	
Mankato	NSP	Wilmarth	28 MW	C,G	OTF	Minnesota R.	

STATE : MINNESOTA (cont'd)

CITY	ORGANIZATION	PLANT	INSTALLED CAPACITY	SOURCE OF ENERGY	TYPE OF COOLING	RECEIVING WATER BODY	REMARKS
New Ulm	PUC	New Ulm	51 MW	C	WCT	Storm Sewer	
Austin	Austin Utilities	Austin Utilities	65 MW	C,O,G	WCT,OTF	Red Cedar R.	
Cohasset	MPL	Clay Boswell,1,2	150 MW	C,O	OTF	Mississippi R.	
Cohasset	MPL	Clay Boswell, 3	350 MW	C	WCT	Mississippi R.	
Red Wing	NSP	Prairie Island,2	530 MW	Nuclear	WCT	Mississippi R.	
Becker	NSP	Sherburne, 2	680 MW	C	WCT	Mississippi R.	FU; 5/1/77
Minneapolis	NSP	Black Dog,1-4	486.66 MW	C,G	OTF,CP	Minnesota R.	
Aurora	MPL	Aurora,1,2	116 MW	C	OTF	Colby Lake	
Duluth	MPL	Hibbard,1-4	124 MW	C	OTF	St. Louis R.	

FU = Future Unit

STATE : WISCONSIN

CITY	ORGANI-ZATION	PLANT	INSTALLED CAPACITY	SOURCE OF ENERGY	TYPE OF COOLING	RECEIVING WATER BODY	REMARKS
Cassville	DPC	Stoneman	51.75 MW	C,O	OTF	Mississippi R.	
Alma	DPC	Alma	205.3 MW	C,O	OTF	Mississippi R.	
Genoa	DPC	Genoa-Nuclear (LACBWR)	50 MW	Nuclear	OTF	Mississippi R.	
Genoa	DPC	Genoa, No. 3	345.6 MW	C,O	OTF	Mississippi R.	
Alma	DPC*	Alma, No. 6	350 MW	C	OTF	Mississippi R.	FU; 5/1/78
Cassville	WPLC	Nelson Dewey	227.2 MW	C,O	OTF	Mississippi R.	
Beloit	WPLC	Blackhawk	50 MW	C,O	OTF	Rock R.	
Beloit	WPLC	Rock River	150 MW	C,O	OTF	Rock R.	
Green Bay	WPSC	Pulliam	392.5 MW	C,O	OTF	Fox R.	
Ashland	LSDP	Bay Front, 6	30 MW	C,G			
La Crosse	NSP	French Island	27 MW	C	OTF	Black R.	
Durand	**	Tyrone Energy Park No. 1	1150 MW	Nuclear	WCT	Chippewa R.	FU; 5/1/82
Durand	**	Tyrone Energy Park No. 2	1150 MW	Nuclear	WCT	Chippewa R.	FU; 5/1/84

* Shared with NSP

**Shared with several utilities

FU = Future Unit

STATE : IOWA

CITY	ORGANI-ZATION	PLANT	INSTALLED CAPACITY	SOURCE OF ENERGY	TYPE OF COOLING	RECEIVING WATER BODY	REMARKS
Pella	PMPL	Municipal Power & Light	43.5 MW	C,O	WCT	S. Skunk R.	
Montpelier	EILP	Fair	62.5 MW	C,G	OTF	Mississippi R.	
Salix	IPS	Neal,1,2	496.25 MW	C,G	OTF	Missouri R.	
Salix	IPS*	Neal, No. 4	576 MW		OTF	Missouri R.	FU; 1/1/79
Ames	City of Ames	Municipal Power Plant	89.15 MW	C,O,G	DCT		
Clinton	ISP	M.L. Kapp	237.2 MW	C,O,G	OTF	Mississippi R.	
Dubuque	ISP	Dubuque	91.25 MW	C,O,G	OTF	Mississippi R.	
Lansing	ISP	Lansing	64 MW	C,O	OTF	Mississippi R.	
Lansing	ISP	Lansing	250 MW	C	OTF	Mississippi R.	FU; 5/1/79
Des Moines	IPL	Des Moines,2	325 MW	C,O,G	WCT,CP	Des Moines R.	
Council Bluffs	IPL	Council Bluffs, Nos. 1,2	130.6 MW	C,G	OTF	Missouri R.	
Council Bluffs	IPL*	Council Bluffs, NO. 3	650 MW	C	OTF	Missouri R.	FU; 1/179
Muscatine	City of Muscatine	Municipal Ele. Plant	124 MW	C,G	OTF	Mississippi R.	

* Neal 4, shared with CBPC, ISP, and others

* C. Bluffs 3, chared with CBPC, EILP, IELP, IIGE, and IPL

FU = Future Unit

STATE : IOWA (cont'd)

CITY	ORGANIZATION	PLANT	INSTALLED CAPACITY	SOURCE OF ENERGY	TYPE OF COOLING	RECEIVING WATER BODY	REMARKS
Bettendorf	IIGE	Riverside	222 MW	C	OTF	Mississippi R.	
Cedar Rapids	IELP	Prairie Creek 1,2,3	96 MW	C,O,G	OTF	Cedar R.	
Cedar Rapids	IELP	Prairie Creek 4	148.7 MW	C,O,G	OTF	Cedar R.	
Clay	CBPC	Wisdom	37.5 MW	C,G	WCT	Ocheyedon Creek (tributary of Little Sioux R.)	
Humboldt	CBPC	Humboldt	43.8 MW	C,G	OTF	Des Moines R.	
Waterloo	IPS	Maynard	100 MW	C,O,G	OTF	Cedar R.	
Salix	IPS*	Neal, No. 3	520 MW	C	OTF	Missouri R.	FU; 1/1/76
Cedar Falls	CFU	Streeter	66.6 MW	C,G	OTF,WCT	Dry Run Creek (tributary of Cedar R.)	
Salix	IPS	Big Sioux, 1-4	40 MW	C,G	OTF	Big Sioux R.	
Burlington	ISU	Burlington, No.1	212 MW	C	OTF	Mississippi R.	
Eddyville	ISU*	Bridgeport	71 MW	C	WCT	Des Moines R. (Miller's Creek)	
Palo	IELP*	D. Arnold	553 MW	Nuclear	WCT	Cedar R.	

* Neal 3, shared with ISU, IPL, and IIGE
* D. Arnold, shared with CBPC
* Bridgeport, shared with IPL, and IPS

STATE : IOWA (cont'd)

CITY	ORGANIZATION	PLANT	INSTALLED CAPACITY	SOURCE OF ENERGY	TYPE OF COOLING	RECEIVING WATER BODY	REMARKS
Cedar Rapids	IELP	Sixth Street, Nos. 1-8	102 MW	C	CP	Local Runoff	
Marshalltown	IELP	Sutherland 1,2,3	156.6 MW	C,G	WCT	Well	

STATE : ILLINOIS

CITY	ORGANIZATION	PLANT	INSTALLED CAPACITY		SOURCE OF ENERGY	TYPE OF COOLING	RECEIVING WATER BODY	REMARKS
Moline	IIGE	Moline	99	MW	C,G,O	OTF	Mississippi R. (Sylvan Slough)	
Cordova	IIGE*	Quad Cities,1,2	1,600	MW	Nuclear	OTF	Mississippi R.	
East Alton	IPC	Wood River	650.1	MW	C	OTF	Mississippi R.	

* shared with Commonwealth Edison

APPENDIX F (PART TWO)

DATA RELATED TO INDUSTRIAL DISCHARGES

STATE : MONTANA / MISSOURI RIVER

CITY	RIVER MILE	PLANT	QUANTITY OF COOLING WATER DISCHARGE TO WATER BODY	TEMPERATURE DIFFERENCE INTAKE-DISCHARGE		REMARKS
				WINTER	SUMMER	
Great Falls		Copper Company	6.4 MGD	- 60 °F	- 87 °F	

STATE : NORTH DAKOTA / MISSOURI RIVER

CITY	RIVER MILE	PLANT	QUANTITY OF COOLING WATER DISCHARGE TO WATER BODY	TEMPERATURE DIFFERENCE INTAKE-DISCHARGE		REMARKS
				WINTER	SUMMER	
Mandan	1380	American Oil Company	1.2 MGD	- 33 °F	- 89 °F	

STATE : NEBRASKA / MISSOURI RIVER

CITY	RIVER MILE	PLANT	QUANTITY OF COOLING WATER DISCHARGE TO WATER BODY	TEMPERATURE DIFFERENCE INTAKE-DISCHARGE		REMARKS
				WINTER	SUMMER	
Omaha	616	Aaron Ferber & Sons	2,845 GPM	32 - °F	84 - °F	
Omaha (Plattsmouth)	609	Allied Chemical Company	19.7 MGD 19.7 MGD	12 - 30 °F 12 - 28 °F	13 - 30 °F 13 - 34 °F	
Nebraska City	579	American Meter	0.015 MGD	56 - 60 °F	59 - 60 °F	
Nebraska City	579	Morton House Kitchens	0.003 MGD	56 - 125 °F	56 - 125 °F	
Omaha	616	National By-Products	250,000 GPD	65 - 80 °F	65 - 80 °F	
Omaha	616	Quaker Oats	7.20 MGD	40 - 85 °F	70 - 115 °F	

STATE : IOWA / MISSOURI RIVER

CITY	RIVER MILE	PLANT	QUANTITY OF COOLING WATER DISCHARGE TO WATER BODY	TEMPERATURE DIFFERENCE INTAKE-DISCHARGE		REMARKS
				WINTER	SUMMER	
Council Bluffs	616	Griffin Pipe Products	480,000 GPD		58 - 99 °F	
Sioux City	731	Johnson Biscuit	500,000 GPD	56 - 80 °F	56 - 80 °F	
Sioux City	731	Kay-Dee Feeds (a/k/a nutra-flo)	0.864 MGD	33 - 38 °F	72 - 78 °F	
Sioux City	731	Midwest Walnut	1,617 GPM	50 - 90 °F	50 - 90 °F	
Sioux City	731	Raskin Packing	300,000 GPD	52 - 60 °F	52 - 60 °F	
Sioux City	731	Sioux City Cold Storage	55 GPM	55 - 78 °F	55 - 78 °F	
Sioux City	731	Stockyards Ser. & Supply	32,000 GPD	55 - °F	55 - 84 °F	
Sergeant Bluffs		Terra Chemicals	2.51 MGD	52 - 47 °F	100 - 89 °F	

STATE : MISSOURI / MISSOURI RIVER

CITY	RIVER MILE	PLANT	QUANTITY OF COOLING WATER DISCHARGE TO WATER BODY	TEMPERATURE DIFFERENCE INTAKE-DISCHARGE		REMARKS
				WINTER	SUMMER	
Sugar Creek	366	American Oil Company	0.006 MGD	33 - 35 °F	78 - 78 °F	
St. Joseph	448	Beaty Grocery	720,000 GPD	57 - 60 °F	57 - 73 °F	
Sugar Creek	366	Chevron Chem. Company	275 GPM	55 - 70 °F	55 - 70 °F	
Kansas City	366	Cook Paint & Varnish Company	1.50 MGD 0.476 MGD	58 - 68 °F 34 - 70 °F	58 - 68 °F 80 - 85 °F	
North Kansas City	368	Corn Products	12 MGD	40 - 96 °F	60 - 96 °F	
St. Joseph	448	Far-Mar Company	1.989 MGD 1.125 MGD	60 - 85 °F 60 - 85 °F	52 - 84 °F 52 - 84 °F	
Boonville	197	Mc Graw-Edison	400 GPM	45 - 97 °F	55 - 130 °F	
St. Louis		Missouri Portland Cement	0.01 MGD 0.225 MGD 0.55 MGD	60 - 65 °F 60 - 63 °F 60 - 65 °F	60 - 65 °F 60 - 65 °F 60 - 65 °F	
Sedalia		Olin Conductors	151,200 GPD	60 - 65 °F	65 - 73 °F	
St. Joseph	448	Seitz Packing	250,000 GPD	57 - 65 °F	57 - 65 °F	
Washington		Washington Metal Prod.	64,000 GPD	60 - °F	60 - °F	

STATE : MISSOURI / MISSOURI RIVER (cont'd)

CITY	RIVER MILE	PLANT	QUANTITY OF COOLING WATER DISCHARGE TO WATER BODY	TEMPERATURE DIFFERENCE INTAKE-DISCHARGE WINTER	TEMPERATURE DIFFERENCE INTAKE-DISCHARGE SUMMER	REMARKS
St. Joseph	448	Wire Rope Corporation	61,000 GPD	45 - °F	65 - °F	
North Kansas City	368	Wurst, Henry Incorporation	750,000 GPD	60 - 60 °F	60 - 60 °F	

STATE : MINNESOTA / MISSISSIPPI RIVER

CITY	RIVER MILE ABOVE OHIO RIVER	PLANT	QUANTITY OF COOLING WATER DISCHARGE TO WATER BODY	TEMPERATURE DIFFERENCE INTAKE-DISCHARGE		REMARKS
				WINTER	SUMMER	
		Blandin Paper Co.	4,000 GPM	34 - 42 °F	78 - 88 °F	
			8,000 GPM	34 - 44 °F	78 - 88 °F	
			1,000 GPM	34 - 44 °F	78 - 88 °F	
		Blandin Wood Prod. Co.	0.581 MGD	37 - 110 °F	76 - 110 °F	
		Dundee Cement Co.	0.00185MGD	54 - 64 °F	54 - 68 °F	
Redwing	796.9	Durkee-Atwood Co.	96,000 GPD	53 - 72 °F	53 - 72 °F	
Winona	728.5	Fiberite Corp.	0.0085 MGD	52 - 80 °F	52 - 82 °F	
		Hennipen Paper Co.	0.93 MGD	37 - 55 °F	72 - 77 °F	
			1.42 MGD	37 - 44 °F	72 - 80 °F	
		Koch Refinery Great No. Oil Co.	2.8 MGD	53 - 60 °F	53 - 88 °F	
		Little Falls Water Trt. Plant	6,000 GPM	50 - 55 °F	50 - 55 °F	
		Northwestern Refining Co.	850 GPM	50 - 45 °F	50 - 72 °F	

STATE : MINNESOTA / MISSISSIPPI RIVER (cont'd)

CITY	RIVER MILE ABOVE OHIO RIVER	PLANT	QUANTITY OF COOLING WATER DISCHARGE TO WATER BODY	TEMPERATURE DIFFERENCE INTAKE-DISCHARGE		REMARKS
				WINTER	SUMMER	
Brainerd		Northwest Paper Co.	7.56 MGD	34 - 36 °F	73 - 71 °F	
			0.200 MGD	34 - 42 °F	75 - 80 °F	
			1.23 MGD	34 - 71 °F	73 - 90 °F	
			3.57 MGD	34 - 68 °F	31 - 87 °F	
			2.5 MGD	34 - 65 °F	76 - 95 °F	

STATE : WISCONSIN / MISSISSIPPI RIVER

CITY	RIVER MILE ABOVE OHIO RIVER	PLANT	QUANTITY OF COOLING WATER DISCHARGE TO WATER BODY	TEMPERATURE DIFFERENCE INTAKE-DISCHARGE		REMARKS
				WINTER	SUMMER	
Alma	752.8	Associated Milk Producers	0.10 MGD	55 - 70 °F	55 - 70 °F	
		Bordon Foods Inc.	0.449 MGD	35 - 53 °F	80 - 93 °F	
Chippewa Falls		Consolidated Thermo-Plastics	135,000 GPD	49 - 75 °F	50 - 78 °F	on tributary 60 mi. from mouth
		Feroyville Cheese Co.	2,640 GPM	54 - 82 °F	54 - 82 °F	
		Pluowood Ind.	10,000 GPD	50 - 180 °F	70 - 180 °F	
Carville	607	Rapid Die & Molding Co.	48,000 GPD	58 - °F	59 - °F	
Lacrosse	698	Texaco Inc.				

STATE : IOWA / MISSISSIPPI RIVER

CITY	RIVER MILE ABOVE OHIO RIVER	PLANT	QUANTITY OF COOLING WATER DISCHARGE TO WATER BODY	TEMPERATURE DIFFERENCE INTAKE-DESCHARGE		REMARKS
				WINTER	SUMMER	
Davenport	483	Alcoa	0.38 MGD	51 - 60 °F	76 - 73 °F	
			0.70 MGD	51 - 63 °F	76 - 73 °F	
			5.14 MGD	51 - 64 °F	76 - 79 °F	
			0.30 MGD	51 - 61 °F	76 - 78 °F	
			11.6 MGD	51 - 71 °F	76 - 86 °F	
Ft. Madison	383	Arid Chemical Company	500 GPM	55 - 40 °F	58 - 70 °F	
Ft. Madison	383	Breck, John	1.2 MGD	56 - 65 °F	56 - 75 °F	
Clinton	522.5	Chemplex	1150,000 GPD	65 - 55 °F	65 - 76 °F	
Ft. Madison	383	Chevron	40,000 GPD	40 - 46 °F	77 - 83 °F	
Clinton	522.5	Clinton Corn Products	1.05 MGD	40 - °F	72 - 92 °F	
Clinton	522.5	Clinton Corn Products	1.05 MGD	40 - °F	72 - 92 °F	
			30.62 MGD	40 - 50 °F	72 - 90 °F	
			2.12 MGD	40 - 75 °F	72 - 110 °F	
			5.71 MGD	40 - 70 °F	72 - 87 °F	
			2.05 MGD	40 - 45 °F	72 - 78 °F	
			0.21 MGD	40 - 50 °F	72 - 80 °F	
			0.0009MGD	40 - 40 °F	72 - 72 °F	
			10.72 MGD	40 - 45 °F	72 - 85 °F	
			0.92 MGD	40 - 60 °F	72 - 85 °F	
			0.001 MGD	50 - 50 °F	80 - 80 °F	
			0.61 MGD	40 - 50 °F	72 - 78 °F	
			0.001 MGD	50 - 150 °F	80 - 160 °F	
			0.65 MGD	50 - 52 °F	80 - 82 °F	

STATE : IOWA / MISSISSIPPI RIVER (cont'd)

CITY	RIVER MILE ABOVE OHIO RIVER	PLANT	QUANTITY OF COOLING WATER DISCHARGE TO WATER BODY	TEMPERATURE DIFFERENCE INTAKE-DISCHARGE		REMARKS
				WINTER	SUMMER	
Clinton	522.5	Clinton Corn Products	0.29 MGD	50 - 52 °F	80 - 82 °F	
			0.0009 MGD	40 - 40 °F	72 - 72 °F	
			0.035 MGD	60 - 60 °F	80 - 82 °F	
			3.40 MGD	40 - 70 °F	72 - 100 °F	
			0.20 MGD	50 - 75 °F	80 - 85 °F	
			0.028 MGD	62 - 65 °F	65 - 77 °F	
Ft. Madison	383	Consolidated Package	440,000 GPD	35 - 75 °F	80 - 110 °F	
			490,000 GPD	35 - 80 °F	80 - 95 °F	
Davenport	483	Dewey Cement	1,390 GPM	33 - 35 °F	80 - 82 °F	
			878 GPM	33 - 58 °F	80 - 108 °F	
			650 GPM	33 - 33 °F	79 - 79 °F	
			15 GPM	33 - 33 °F	79 - 79 °F	
			694 GPM	33 - 35 °F	80 - 82 °F	
Clinton	522.5	Dupont	9.344 MGD	59.2- 94.2 °F	60.4- 88.5 °F	
			0.405 MGD	59.2- 45.0 °F	60.4- 70.0°F	
Keokuk	364.2	Foote Mineral	1.56 MGD		- 70 °F	
			1.56 MGD		- 70 °F	
			1.296 MGD		70 - 70 °F	
			36,000 GPD		66 - 66 °F	
			36,000 GPD		- 76 °F	
			12,000 GPD		66 - 60 °F	
			164,000 GPD		66 - 73 °F	
			500,000 GPD		66 - 65 °F	
Clinton	522.5	Hawkeye Chemical	1,300,000 GPD	65 - 44 °F	65 - 81 °F	

STATE : IOWA / MISSISSIPPI RIVER (cont'd)

CITY	RIVER MILE ABOVE OHIO RIVER	PLANT	QUANTITY OF COOLING WATER DISCHARGE TO WATER BODY	TEMPERATURE DIFFERENCE INTAKE-DISCHARGE		REMARKS
				WINTER	SUMMER	
Muscatine	457.2	Hon Industries	2,000 GPM	56 - 60 °F	58 - 70 °F	
Keokuk	364.2	Keokuk Steel Casting	0.106 MGD	56 - 60 °F	83 - 96 °F	
			100 GPM	56 - 200 °F		
			0.158 MGD	56 - 63 °F	83 - 96 °F	
Pleasant Valley	493.1	Lunex	35,000 GPD	58 - 58 °F	58 - 60 °F	
Muscatine	457.2	Monsanto	12.35 MGD	57 - 95 °F	57 - 95 °F	
Clinton	522.5	National By-Products	2,207,000 GPD	33 - 37 °F	81 - 86 °F	
Ft. Madison	383	Schaeffer Pen Company	960,000 GPD	56 - 58 °F	56 - 60 °F	
Clinton	522.5	Sethness Products	65,000 GPD	52 - 90 °F	52 - 95 °F	
Clinton	522.5	Swift Dairy & Poultry	40,000 GPD	67 - 80 °F	67 - 89 °F	
Muscatine	457.2	Thatcher Plastic	2.3 MGD	56 - 70 °F	58 - 78 °F	
Dubuque	583.0	U.S. Industrial Chemical	2.31 MGD	32 - 70 °F	80 - 110 °F	

STATE : IOWA / MISSISSIPPI RIVER (cont'd)

CITY	RIVER MILE ABOVE OHIO RIVER	PLANT	QUANTITY OF COOLING WATER DISCHARGE TO WATER BODY	TEMPERATURE DIFFERENCE INTAKE-DISCHARGE		REMARKS
				WINTER	SUMMER	
Muscatine	457.2	Grain Processing Co.	1.77 MGD	59 - 110 °F	59 - 110 °F	
			8.75 MGD	59 - 98 °F	85 - 114 °F	
			4.16 MGD	59 - 132 °F	60 - 132 °F	
			4.41 MGD	59 - 95 °F	80 - 95 °F	
			5.98 MGD	59 - 122 °F	60 - 122 °F	
			1,800,000 GPD	59 - 112 °F	59 - 112 °F	
			6,500,000 GPD	65 - 105 °F	86 - 105 °F	
			2.84 MGD	59 - 128 °F	59 - 128 °F	
			1.71 MGD	59 - 100 °F	86 - 105 °F	
			1.036 MGD	59 - 130 °F	59 - 132 °F	

STATE : ILLINOIS / MISSISSIPPI RIVER

CITY	RIVER MILE ABOVE OHIO RIVER	PLANT	QUANTITY OF COOLING WATER DISCHARGE TO WATER BODY	TEMPERATURE DIFFERENCE INTAKE-DISCHARGE		REMARKS
				WINTER	SUMMER	
Alton	202	Alton Box Board Co.	9.752 MGD	56 - 70 °F	56 - 70 °F	
Wood River	199	American Oil Co.	16.0 MGD 58,000 GPD	44 - 58 °F 55 - 109 °F	69 - 83 °F 57 - 90 °F	
		Central Ill. Pub. Service	1,825 GPD 1,850 GPD 136,000 GPD	42 - 42 °F 42 - 42 °F 42 - 42 °F	75 - 75 °F 75 - 75 °F 75 - 75 °F	
Hartford	197	Clark Oil & Refining Co.	1.512 MGD	60 - 38 °F	60 - 80 °F	
Wood River	199	Ill. Paper Co.	346,200 GPD 2,570 GPD	37 - 58 °F 37 - 37 °F	79 - 93 °F 79 - 79 °F	
E. Moline	480	John Deere Foundry	1.49 MGD	57 - 77 °F	57 - 77 °F	
Alton	202.9	Laclede Steel Wastes	0.33 MGD 2.618 MGD		60 - 90 °F 60 - 90 °F	
Hartford	197	National Marine Service	1,500 GPM	55 - 80 °F	60 - 80 °F	
		Packaging Corp. of America	1.2 MGD 2.85 MGD	36 - 50 °F 36 - 50 °F	80 - 85 °F 80 - 85 °F	
Wood River	199	Shell Oil Co.	4,760 GPM	55 - 70 °F	65 - 90 °F	

STATE : ILLINOIS / MISSISSIPPI RIVER (cont'd)

CITY	RIVER MILE ABOVE OHIO RIVER	PLANT	QUANTITY OF COOLING WATER DISCHARGE TO WATER BODY	TEMPERATURE DIFFERENCE INTAKE-DISCHARGE		REMARKS
				WINTER	SUMMER	
Venice	183	Union Electric Co.	763 GPM	37 - 37 °F	82 - 82 °F	
			570 GPM	37 - 37 °F	82 - 82 °F	
			763 GPM	37 - 37 °F	82 - 82 °F	
			104,722 GPM	37 - 65 °F	82 - 87 °F	
			104,722 GPM	37 - 65 °F	82 - 87 °F	
			2,222 GPM	37 - 37 °F	82 - 82 °F	
			2,222 GPM	37 - 37 °F	82 - 82 °F	
Kahokia		Union Electric Co.	5 GPM	37 - 43 °F	82 - 88 °F	
			162 GPM	37 - 37 °F	82 - 82 °F	
			162 GPM	37 - 37 °F	82 - 82 °F	
			162 GPM	37 - 37 °F	82 - 82 °F	
			143,282 GPM	37 - 42 °F	82 - 94 °F	
			2 GPM	37 - 43 °F	82 - 88 °F	
			1 GPM	37 - 37 °F	82 - 82 °F	
			359 GPM	37 - 37 °F	82 - 82 °F	
E. Moline	480	International Houses Stor.	0.68 MGD	54 - 64 °F	60 - 76 °F	
			0.39 MGD	54 - 64 °F	60 - 76 °F	
			0.0002 MGD	54 - 50 °F	60 - 70 °F	

STATE : MISSOURI / MISSISSIPPI RIVER

CITY	RIVER MILE ABOVE OHIO RIVER	PLANT	QUANTITY OF COOLING WATER DISCHARGE TO WATER BODY	TEMPERATURE DIFFERENCE INTAKE-DISCHARGE		REMARKS
				WINTER	SUMMER	
Hannibal	309	American Cyanamid	0.50 MGD	58 - 65 °F		
St. Louis	190.3	Anheuser-Busch	0.082 MGD	36 - 36 °F	81 - 81 °F	
St. Louis	190.3	Asphaltic Concrete Corp.	0.10 MGD	50 - 90 °F	80 - 140 °F	
Pevely	153	Dow Chemical	0.018 MGD	55 - 58 °F	55 - 66 °F	
Louisiana	283	Hercules	2.18 MGD	95 - °F	110 - °F	
			0.1 MGD	40 - °F	80 - °F	
			0.13 MGD	35 - °F	80 - °F	
Cape Girardeau	52	Marguette Cement Co.	410,000 GPD	34 - 37 °F	74 - 77 °F	
St. Genevieve	124	Mississippi Lime	0.144 MGD	58 - °F	58 - 71 °F	
			0.317 MGD	58 - °F	58 - 107 °F	
			0.32 MGD	58 - °F	58 - 91 °F	
			0.047 MGD	58 - °F	58 - 75 °F	
			0.173 MGD		57 - °F	
			0.72 MGD	58 - °F	58 - 67 °F	
			0.0005MGD	58 - °F	58 - 65 °F	
			0.144 MGD		47 - °F	
			0.144 MGD	58 - °F	58 - 62 °F	
			1.57 MGD	58 - °F	58 - 123 °F	
St. Louis	190.3	Missouri Portland Cement	0.78 MGD	40 - 41 °F	85 - 86 °F	

STATE : MISSOURI / MISSISSIPPI RIVER (cont'd)

CITY	RIVER MILE ABOVE OHIO RIVER	PLANT	QUANTITY OF COOLING WATER DISCHARGE TO WATER BODY	TEMPERATURE DIFFERENCE INTAKE-DISCHARGE		REMARKS
				WINTER	SUMMER	
St. Louis	190.3	Monsanto	200 MGD	50 - 50 °F	55 - 55 °F	
Festus	150	River Cement	1.4 MGD	40 - 50 °F	85 - 95 °F	
St. Louis	190.3	Titantium Pigment	2.0 MGD		55 - 93 °F	
			5.6 MGD		53 - 87 °F	
			0.165 MGD			
			11.83 MGD		49 - 86 °F	
			1.93 MGD		50 - 84 °F	
			0.144 MGD		55 - 106 °F	
			1.57 MGD		50 - 178 °F	
			15.70 MGD		63 - 96 °F	
			0.384 MGD		101- 157 °F	
			2.40 MGD		100- 157 °F	
			51.8 MGD		52 - 102 °F	
			0.0936MGD		185 - 210 °F	
			0.0140MGD		115 - 150 °F	
Crystal City	150	U.S. Steel Corporation	0.591 MGD	75 - °F	80 - °F	
			0.736 MGD	88 - °F	82 - °F	
			0.115 MGD	65 - °F	75 - °F	
			0.024 MGD	57 - °F	60 - °F	

APPENDIX G (PART TWO)

DATA RELATED TO
MUNICIPAL DISCHARGES

STATE : MONTANA / MISSOURI RIVER

CITY	RIVER MILE	QUANTITY OF COOLING WATER DISCHARGE TO WATER BODY	TEMPERATURE DIFFERENCE INTAKE-DISCHARGE		REMARKS
			WINTER	SUMMER	
Great Falls		29.3 MGD	- 58 °F	- 63 °F	

STATE : NORTH DAKOTA / MISSOURI RIVER

CITY	RIVER MILE	QUANTITY OF COOLING WATER DISCHARGE TO WATER BODY	TEMPERATURE DIFFERENCE INTAKE-DISCHARGE		REMARKS
			WINTER	SUMMER	
City of Mandan	1380	1.5 MGD	- 33 °F	- 58 °F	

STATE : SOUTH DAKOTA / MISSOURI RIVER

CITY	RIVER MILE	QUANTITY OF COOLING WATER DISCHARGE TO WATER BODY	TEMPERATURE DIFFERENCE INTAKE-DISCHARGE		REMARKS
			WINTER	SUMMER	
Yankton	841	1.6 MGD	- 59 °F	- 74 °F	

STATE : NEBRASKA / MISSOURI RIVER

CITY	RIVER MILE	QUANTITY OF COOLING WATER DISCHARGE TO WATER BODY	TEMPERATURE DIFFERENCE INTAKE-DISCHARGE		REMARKS
			WINTER	SUMMER	
Blair	647	1 MGD			
Omaha	616	5 MGD			
Plattsmouth	609	1 MGD			
Nebraska City	579	1 to 5 MGD			

STATE : IOWA / MISSOURI RIVER

CITY	RIVER MILE	QUANTITY OF COOLING WATER DISCHARGE TO WATER BODY	TEMPERATURE DIFFERENCE INTAKE-DISCHARGE WINTER	TEMPERATURE DIFFERENCE INTAKE-DISCHARGE SUMMER	REMARKS
Sioux City	731	14.6 MGD	- 68 °F	- 72 °F	
Council Bluffs	616	6.35 MGD	- 55 °F	- 80 °F	

STATE : MISSOURI / MISSOURI RIVER

CITY	RIVER MILE	QUANTITY OF COOLING WATER DISCHARGE TO WATER BODY	TEMPERATURE DIFFERENCE INTAKE-DISCHARGE		REMARKS
			WINTER	SUMMER	
St. Joseph	448	15.2 MGD	- 52 °F	- 73 °F	
Kansas City	366	77.8 MGD	- 50 °F	- 65 °F	
Lexington	317	1 MGD			
Jefferson City	143	5.1 MGD	- 60 °F	- 72 °F	
Boonville	197	1.5 MGD			
Hermann	98	0.5 MGD			

STATE : IOWA / MISSISSIPPI RIVER

CITY	RIVER MILE ABOVE OHIO RIVER	QUANTITY OF COOLING WATER DISCHARGE TO WATER BODY	TEMPERATURE DIFFERENCE INTAKE-DISCHARGE		REMARKS
			WINTER	SUMMER	
Dubuque	583	11.2 MGD	- 62 °F	- 74 °F	
Clinton	522.5	5.65 MGD	- 55 °F	- 68 °F	
Davenport	483	19.3 MGD	- 53 °F	- 74 °F	
Muscatine	457.2	5.69 MGD	- 50 °F	- 70 °F	
Burlington	410.5	2.8 MGD	- 93 °F	- 96 °F	
		3.5 MGD	- 61 °F	- 68 °F	
Ft. Madison	383	0.2 MGD			
Keokuk	364.2	3.16 MGD			

STATE : MISSOURI / MISSISSIPPI RIVER

CITY	RIVER MILE ABOVE OHIO RIVER	QUANTITY OF COOLING WATER DISCHARGE TO WATER BODY	TEMPERATURE DIFFERENCE INTAKE-DISCHARGE		REMARKS
			WINTER	SUMMER	
Hannibal	309	2.7 MGD	- 68 °F(ave.)	- 70 °F(ave.)	
Louisiana	283	1 MGD			
St. Louis	190.3	2.5 MGD	- 48 °F(ave.)	- 78 °F(ave.)	
		1.2 MGD	- 51 °F(ave.)	- 69 °F(ave.)	
		3.7 MGD	- 58 °F(ave.)	- 80 °F(ave.)	
		117 MGD	- 51 °F(ave.)	- 75 °F(ave.)	
		116 MGD		- 76 °F(ave.)	
St. Genevieve	124	5 MGD			
Cape Girardeau	52	0.006 MGD			