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**POTENTIAL THERMAL EFFECTS
OF AN EXPANDING POWER INDUSTRY:
UPPER MISSISSIPPI RIVER BASIN**

D. E. Peterson and R. T. Jaske

June 1970

**AEC RESEARCH &
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POWER INDUSTRY: UPPER MISSISSIPPI RIVER BASIN

By

D. E. Peterson and R. T. Jaske

Water and Land Resources Department
Environmental and Life Sciences Division

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D. E. Peterson and R. T. Jaske

ABSTRACT

Direct cooling capacities of the main stem Mississippi River and eight major tributaries between Royalton, Minnesota and Alton, Illinois for average and low flow conditions were simulated within a temperature constraint of 5 °F above natural background. Total assimilative and dissipative capacity of the upper Mississippi Basin ranged from a high of 130 GW_T to a low of 46 GW_T . Analyses of projected power growth patterns indicate that the main stem has adequate cooling capacity to accommodate forecasted loads through the year 1990, except in the St. Paul-Minneapolis area. Partial recirculatory cooling facilities appear to be a possible solution to tributary basin cooling water requirements beyond the year 1980.

TABLE OF CONTENTS

LIST OF FIGURES	vii
LIST OF TABLES	ix
INTRODUCTION	1
Objectives.	4
State Water Temperature Standards	4
Simulation Model.	6
SUMMARY AND CONCLUSIONS	8
SIMULATIONS	11
Minnesota River Basin	12
Projected Cooling Capacities.	13
St. Croix River Basin	17
Projected Cooling Capacities.	18
Chippewa River Basin	22
Projected Cooling Capacities.	23
Wisconsin River Basin	23
Projected Cooling Capacities.	27
Rock River Basin.	31
Projected Cooling Capacities.	31
Cedar-Iowa River Basin.	32
Des Moines River Basin.	40
Projected Cooling Capacities.	41
Illinois River Basin	41
Projected Cooling Capacities.	46
Upper Mississippi River	55
Projected Cooling Capacities.	56
PROJECTED GENERATING PATTERNS. 1970. 1980 and 1990	66
ACKNOWLEDGMENTS	77
REFERENCES.	78
BIBLIOGRAPHY	79
APPENDIX - MAXPWR COMPUTER PROGRAM.	A.1

LIST OF FIGURES

1	Upper Mississippi River Basin	2
2	Upper Mississippi River, River Profiles Main Stem and Major Tributaries	3
3	Average Direct Cooling Capacity of Minnesota River	14
4	Low Flow Direct Cooling Capacity of Minnesota River	16
5	Average Direct Cooling Capacity of St. Croix River	19
6	Low Flow Direct Cooling Capacity of St. Croix River	21
7	Average Direct Cooling Capacity of Chippewa River	24
8	Low Flow Direct Cooling Capacity of Chippewa River	25
9	Average Direct Cooling Capacity of Wisconsin River	28
10	Low Flow Direct Cooling Capacity of Wisconsin River	29
11	Average Direct Cooling Capacity of Rock River	33
12	Low Flow Direct Cooling Capacity of Rock River	34
13	Average Direct Cooling Capacity of Cedar-Iowa River	37
14	Low Flow Direct Cooling Capacity of Cedar-Iowa River	38
15	Average Direct Cooling Capacity of Des Moines River	42
16	Low Flow Direct Cooling Capacity of Des Moines River	43
17a	Average Direct Cooling Capacity of Illinois River	47

17b	Average Direct Cooling Capacity of Illinois River	48
17c	Average Direct Cooling Capacity of Illinois River	49
18a	Low Flow Direct Cooling Capacity of Illinois River	51
18b	Low Flow Direct Cooling Capacity of Illinois River	52
18c	Low Flow Direct Cooling Capacity of Illinois River	53
19a	Average Direct Cooling Capacity of Upper Mississippi River	57
19b	Average Direct Cooling Capacity of Upper Mississippi River	58
20a	Low Flow Direct Cooling Capacity of Mississippi River	62
20b	Low Flow Direct Cooling Capacity of Upper Mississippi River	63
21	Upper Mississippi River Basin Local Direct Cooling Capacity Probabilities	65
22	FPC-West Central Region Generation Areas	68

LIST OF TABLES

1	Summary of Average and Low Annual Cooling Capacities (MW _T) of Upper Mississippi River Basin	9
2	Average Direct Cooling Capacity (MW _T) of Minnesota River	15
3	Low Flow Direct Cooling Capacity (MW _T) of Minnesota River	17
4	Average Direct Cooling Capacity (MW _T) of St. Croix River	20
5	Low Flow Direct Cooling Capacity (MW _T) of St. Croix River	20
6	Average Direct Cooling Capacity (MW _T) of Chippewa River	26
7	Low Flow Direct Cooling Capacity (MW _T) of Chippewa River	26
8	Average Direct Cooling Capacity (MW _T) of Wisconsin River	30
9	Low Flow Direct Cooling Capacity (MW _T) of Wisconsin River	30
10	Average Direct Cooling Capacity (MW _T) of Rock River	35
11	Low Flow Direct Cooling Capacity (MW _T) of Rock River	35
12	Average Direct Cooling Capacity (MW _T) of Cedar-Iowa River	39
13	Low Flow Direct Cooling Capacity (MW _T) of Cedar-Iowa River	39
14	Average Direct Cooling Capacity (MW _T) of Des Moines River	44
15	Low Flow Direct Cooling Capacity (MW _T) of Des Moines River	44
16a	Average Direct Cooling Capacity (MW _T) of Illinois River	50

16b	Average Direct Cooling Capacity (MW_T) of Illinois River	50
17a	Low Flow Direct Cooling Capacity (MW_T) of Illinois River	54
17b	Low Flow Direct Cooling Capacity (MW_T) of Illinois River	54
18a	Average Direct Cooling Capacity (MW_T) of Upper Mississippi River	59
18b	Average Direct Cooling Capacity (MW_T) of Upper Mississippi River	60
19a	Low Flow Direct Cooling Capacity (MW_T) of Upper Mississippi River	64
19b	Low Flow Direct Cooling Capacity (MW_T) of Upper Mississippi River	64
20	Scheduled and Installed Nuclear Capacity in the UMRB Power Region	67
21	FPC - West Central Region Generation Patterns	69

POTENTIAL THERMAL EFFECTS OF AN EXPANDING
POWER INDUSTRY: UPPER MISSISSIPPI RIVER BASIN

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INTRODUCTION

The projected expansion of steam electric generation facilities in the United States at a rate of approximately 7%, compounded annually, between 1970 and 1990 has created a need for an assessment of the capacities of natural watercourses to assimilate and dissipate the waste heat associated with these facilities. As a consequence, in FY-1969, the Environmental and Sanitary Engineering Branch, Division of Reactor Development and Technology, U. S. Atomic Energy Commission, requested that Battelle-Northwest undertake reconnaissance studies of the thermal regimes of major rivers in the United States. The studies are a partial outgrowth of research and development, which has been supported since 1963 by the Atomic Energy Commission, for the purpose of examining the response of receiving waters to thermal effluents, and of developing simulation capabilities applicable to cause and effect problems associated with steam generating plants.

This report is the second of a series; the first, "Potential Thermal Effects of an Expanding Power Industry: Ohio River Basin I," BNWL-1299, February 1970, was concerned with the relationship of the average heat sink capacity of the Ohio River and major tributaries to projected power growth in the Ohio Basin through the year 1990.⁽²⁾ The format of this report differs in that both average and low flow thermal capacities are examined in terms of projected power growth.

The 1960 population of the Upper Mississippi River Basin (Figures 1 and 2) was approximately 19 million. The 1970, 1980 and 1990 populations are projected to be 21 million, 25 million and 29 million respectively, based on an annual

FIGURE 1. Upper Mississippi River Basin

FIGURE 2. Upper Mississippi River, River Profiles Main Stem and Major Tributaries

growth rate of 1.4%. Energy production in the Upper Mississippi Power Region of the Federal Power Commission, which required condenser cooling, was 58.5×10^9 kW-hr in 1960; 1970, 1980 and 1990 thermal-electric supply requiring condenser cooling is estimated at 130×10^9 kW-hr, 270×10^9 kW-hr and 490×10^9 kW-hr respectively.

Average and low flow monthly capacities of the main stem and eight major tributaries to assimilate and dissipate heat are discussed in terms of projected thermal loads associated with electric power generation in 1980 and 1990.

OBJECTIVES

The objectives of the Upper Mississippi River Basin study included the following:

- The modification of the COLHEAT computer code for operation within a set of stream temperature constraints
- Utilization of long-term streamflow and weather data to simulate monthly average and low flow heat sink capacities of the Upper Mississippi River and major tributaries
- Review Federal Power Commission projections of electric energy requirements and generating capacity for the years 1980 and 1990, and analyze the potential long-term significance of the projections in terms of cooling requirements.

STATE WATER TEMPERATURE STANDARDS

Temperature criteria under the various State Water Quality Standards generally specify a maximum allowable temperature for streams or sectors of streams in a given use category. In addition, limits may be placed on incremental increases above background and also on rates of increase. The Temperature Standards for the five states of interest in the Upper Mississippi River Basin are summarized below. At present,

uncertainty exists concerning standard methods of measuring and defining maximum temperatures, and natural unpolluted background in rivers receiving thermal effluents. It appears unlikely that acceptable standard methods and tolerances will be developed in the near future (1 to 3 yr); consequently, the precise meaning of a 5 °F increment is not clear at this time.

Upper Mississippi River Basin-Water Temperature Standards

Illinois: Public Water Supply - 93 °F maximum.

Industrial Water Supply - not to exceed 95 °F at any time.

Recreation - no criteria.

Lake Michigan - (shore water) not more than 85 °F.

(open water) not more than 85 °F.

(Aquatic Life other than Lake Michigan - not approved.)

Iowa: Public water supply - no criteria.

Warm water fishery - 93 °F May through November;
73 °F December through April.

Cold water fishery - 70 °F maximum.

(All criteria excepted from approval except Missouri and Mississippi River.)

Minnesota: Fisheries and Recreation - 2A - no material increase

2B - 86 °F

2C - 93 °F (not approved)

Industrial - 3A - 75 °F, 3B - 86 °F, 3C - 90 °F

Missouri: Effluents shall not elevate or depress the average cross-sectional temperature of the stream more than 5 °F. The stream temperature shall not exceed 90 °F due to effluents.

Lakes and Reservoirs - temperature not to be increased due to cooling water discharge.

(Exceptions include: Des Moines, White, Current, and Eleven Point Rivers.)

Wisconsin: Fish and other Aquatic Life: In waters where this use is of primary importance, the temperature shall not exceed 84 °F. No change from natural unpolluted background by more than 5 °F at any time nor at a rate in excess of 2 °F per hour. Where fishing is desirable in conjunction with other uses, the temperature shall not exceed 89 °F for warm water fish. There shall be no abrupt change from background by more than 5 °F at any time. In addition, authorization must be obtained for proposed installations where the discharge of a thermal pollutant may increase the natural maximum of a stream by more than 3 °F.

Streams classified by law as trout waters shall not be altered from natural background by effluents that affect the stream environment to such an extent that trout population are adversely affected in any manner.

Industrial Water Supply - Temperature not to exceed 89 °F.

SIMULATION MODEL

The COLHEAT simulation model has been discussed in a previous publication and, consequently, will not be examined here.⁽³⁾ The model applies a heat budget to a given section of a river in order to calculate the water temperature as a function of radiation exchange, evaporation, condition and advected energy. For this study the code was modified to a quasi-steady

state form which determined the maximum number of power plants of a fixed size that could be placed along a stream within a given temperature increment above natural background. The modified code, which has been entitled MAXPWR, is discussed in the appendix.

SUMMARY AND CONCLUSIONS

As a general conclusion, the upper Mississippi main stem has adequate cooling capacity to assimilate and dissipate forecasted loads through the year 1990, except in the St Paul-Minneapolis metropolitan area, if full advantage is taken of energy exchange with the atmosphere by proper spacing of thermal effluent sites. If significantly nonoptimal siting is practiced, Quad Cities and St. Louis sections would also have insufficient cooling capacities for projected 1990 loads. Tributary streams, with the possible exception of the Wisconsin River, have inadequate heat sink capacities under low flow conditions to assimilate and dissipate projected 1990 loads within a temperature envelope of 5 °F above background. Partial recirculatory cooling facilities could be employed in the eight major tributary basins of interest. Table 1 summarizes cooling capacities for a broad range of conditions in the upper Mississippi Basin.

The above conclusions indicate a need of guidelines and coordinated advanced planning of thermal effluent releases in the Upper Mississippi River Basin in order to maximize benefits associated with the development of a limited natural resource, cooling water supply. In addition to minimizing residual effects of upstream thermal releases upon downstream users of cooling water supply, coordinated planning could provide significant benefits to navigation, and to fish and wildlife during the winter months.

At the present time ice generally halts navigation above Hannibal, Missouri from early December to April. By 1990, thermal effluent could be significant in opening winter navigation to the Quad Cities, or possibly as far north as the confluence with the Wisconsin River. Projected 1990 thermal loads in the Twin Cities area could provide open water conditions downstream to Lake Pepin. Power growth in the reach between Lake Pepin (confluence with the Chippewa River) and the

confluence with the Wisconsin River, as presently projected for 1990 does not appear to be adequate for major midwinter open water conditions. Whether the benefit-cost ratio of extending a 12-month navigation season to the Twin Cities, by locating some generating plants in the above reach instead of closer to the St Paul-Minneapolis utility market area, would be adequate is unknown. Also unknown is the benefit-cost ratio associated with conjunctive use of thermal effluent and icebreakers for winter navigation.

TABLE 1. Summary of Average and Low Annual Cooling Capacities (MW_T) of Upper Mississippi River Basin

	<u>April, avg</u>	<u>Nov, avg, (c)</u>	<u>April, low (c)</u>	<u>Nov, low (c)</u>	<u>1970 Steam Generating Capacity, MWe</u>
Minnesota River (a)	4,500	350+	350+	100+	1,622
St. Croix River (a)	7,800	3,100	1,800	750+	598
Chippewa River (a)	7,300	2,900	2,800	1,100	None
Wisconsin River (a)	11,700	7,000	5,600	2,500	166
Rock River (a)	6,800	3,000	2,200	650+	570
Cedar Iowa River (a)	7,000	1,700	650+	250+	382
Des Moines River (a)	7,400	500+	250+	100+	683
Illinois River (a)	33,000	20,000	12,000	4,000	3,702
Mississippi River (a)	100,000	49,000	67,000	42,000	4,300
Upper Mississippi River Basin (b)	130,000	61,000	79,000	46,000	28,400

a. *Independent capacities*

b. *Integrated capacities*

c. *Maximum assimilative capacity given where total is less than 800 MW_T*

Condenser discharges from generating plants are objected to by many concerned persons because of possible detrimental effects on fish and wildlife. In the case of winter conditions, however, open water could possibly benefit waterfowl by providing additional habitat, and also fish by increasing the dissolved oxygen content of the water in reservoirs. As an example of the latter, ice and snow, combined with the biochemical oxygen demand of waterborne organic materials (including natural pollutants, such as tree leaves) in the Hastings Pool, which is formed by Lock and Dam No. 2, have in the immediate past resulted in undesirably low dissolved oxygen levels. Open water would provide greater reaeration by the atmosphere and also a higher level of oxygen production in association with photosynthesis.

The detailed ramifications of the above considerations are beyond the scope of the present study, which in these aspects is only indicative in nature. In the case of navigation, further examination of heat distribution requirements for open water conditions, or partial open water conditions in the case of conjunctive use of thermal effluent and icebreakers, is needed in order to provide input for benefit-cost analysis of extending a 12-month navigational season to the head of the Mississippi Waterway.

SIMULATIONS

In a previous study of the Upper Mississippi Basin the COLHEAT model was used in conjunction with calendar year 1964 streamflows, solar radiation, and weather to simulate river temperatures.⁽¹⁾ The study revealed that temperatures of the main stem and major tributaries respond strongly to day-by-day fluctuations in atmospheric conditions. The only significant modifying factor from the viewpoint of a regional reconnaissance study was noted in simulations of the Chippewa and Wisconsin Rivers. The lower reaches of both streams pass through areas of relatively permeable sedimentary materials, including sandstones, sandy soils and extensive alluvial sand and gravel deposits. As a result, groundwater effluent flow becomes an important source of inflow to the rivers during periods of low streamflow. Since groundwater from near surface deposits typically varies only a few degrees about the mean annual air (dry bulb) temperature, the effect for summer low flow or drought periods is that stream temperatures will be lower than those normally associated with ambient atmospheric conditions. The converse occurs during the winter, when overland runoff may be limited by a lack of precipitation or freezing conditions. The Illinois River also flows in a valley of permeable alluvium, especially in the 230 mile sector from Starved Rock Dam to the confluence with the Mississippi main stem. However, diversions from Lake Michigan via the Chicago Sanitary and Ship Canal-Des Plaines River, and its relatively low velocity appear to minimize the influence of groundwater on stream temperatures.

For computations of average and low flow thermal sink capacities, the MAXPWR computer code was utilized. It is similar to COLHEAT in that it is based upon the concept of a heat budget. The primary difference between the two models resides in the time mode; COLHEAT was designed to simulate

one-dimensional transients for time increments of an hour or a day, whereas ~~MAXWR~~ can be applied only to steady state, or quasi-steady state conditions represented by monthly or annual averages. Since it was assumed that calculations of daily temperatures over a period of 366 days for a specific stream was an adequate test of the procedure for reconnaissance purposes, the parameters used in this study did not differ from the COLHEAT simulation of the 1964 thermal regimen.

MINNESOTA RIVER BASIN

The Minnesota River drains an area of 16,920 square miles, 88% of which are located in southwestern and south-central Minnesota, 10% in South Dakota and 2% in Iowa. The source is at Big Stone Lake (RM 329) in western Minnesota, from there it trends in a southeasterly direction toward Mankato (RM 106), where it changes direction and flows along a northeasterly course to the confluence with the Mississippi at the Twin Cities (Minneapolis-St. Paul).

The climate in the area is continental, with wide variations in temperature, ample summer rainfall and relatively low precipitation in winter. Mean air temperatures at St. Paul range between 14 °F in January and 73 °F in July. Average annual precipitation in the Minnesota River Subbasin varies from 20 in. in the headwaters to 27 in. in Minneapolis-St. Paul International Airport. The annual mean at the Twin Cities during the period 1930-1964, ranged from a low of 16 in. to a high of 35 in. Precipitation generally peaks in June, with 65% falling in the period May through September.

Runoff in the Subbasin averages 2.7 in. per year (12% of precipitation); median runoff is 0.7 in. Average annual discharge at Mankato (RM 106) and Jordan (RM 34) is 2511 ft³/sec and 3183 ft³/sec respectively. Median flow at Mankato is 760 ft³/sec. At the mouth, median flow is estimated to be 900 ft³/sec. The minimum of record (Mankato) was 26 ft³/sec on August 4, 1934.

Projected Cooling Capacities

Figure 3 and Table 2 indicate the mean monthly direct cooling capacity of the Minnesota River between River Mile 106 and the mouth based on 1950-1960 monthly flow. Capacity was arbitrarily defined as the heat that could be assimilated by a stream and dissipated to the atmosphere within a temperature envelope of 5 °F above background. A further constraint was that no advected pulses less than 800 MW_T were admitted to the system. The only exception to the latter was at the mouth of a river, or the most downstream point of interest in the case of Mississippi main stem simulations, where the heat associated with the difference between the residual temperature (the temperature, above background remaining from an 800 MW_T pulse) and 5 °F was included in the total. The above constraints were coded into the MAXPWR model for automatic readout. The total curve in Figure 3 represents the mean assimilative and dissipative direct cooling capacity for the reach of interest. The two lower curves indicate the assimilative capacities at River Miles 106 and 0. Where the assimilative capacity was less than 800 MW_T, no dissipation to the atmosphere was calculated. Average total capacity attains a high of 4500 MW_T during April, the normal peak month for snowmelt runoff. March and August totals are 1200 MW_T and 1700 MW_T respectively. From September through February the assimilative capacity is less than 800 MW_T. Figure 4 and Table 3 summarize low flow capacities for the same section and 1950-1960 period of record. Eight of the monthly low flows used in the simulation were from the 1959 water year. The river does not have sufficient capacity for any of the low flow months, within the study assumptions, to assimilate 800 MW_T.

Long-term flow probabilities are based on the 1929-1963 record of daily flows at Mankato and are not representative of flows within a given month. The probabilities indicate that

FIGURE 3. Average Direct Cooling Capacity of Minnesota River

TABLE 2. Average Direct Cooling Capacity (MW_T)
of Minnesota River (RM 106 to RM 0)^T

<u>Month</u>	<u>Total</u>	<u>Maximum Input, RM 0</u>	<u>Maximum Input, RM 106</u>
January		200+	200-
February		200+	200-
March		800+	700-
April	4500	4100	3300
May	3000	2300	1900
June	2900	2100	1700
July	2800	2100	1700
August	1700	1100	900
September		650	550
October		350	300
November		350-	250+
December		350-	250+
30%		800	640
50%		300	250

30% of the time the daily average flow of the Minnesota River would be adequate to assimilate 800 MW_T and remain within 5 °F above background. In addition, 50% of the time the temperature increase associated with 800 MW_T would be less than 13 °F.

At the present time, two steam generating facilities are located along the 106 mile study zone, the 25 MW_e Wilmarth unit at Mankato and the 481 MW_e Black Dog plant at Minneapolis. In 1964 the average thermal discharge of the latter is estimated to have been slightly greater than 600 MW_T . A 5 °F increase under a 600 MW_T rejection rate would require a flow of $\sim 1800 \text{ ft}^3/\text{sec}$, which would be equaled or exceeded 36% of the time. The probabilities discussed in this section are biased slightly toward underestimating flows because they were extrapolated from runoff rates per unit area at Mankato;

FIGURE 4. Low Flow Direct Cooling Capacity of Minnesota River

TABLE 3. Low Flow Direct Cooling Capacity (MW_T)
of Minnesota River (RM 106 to RM 0)

<u>Month</u>	<u>Total</u>	<u>Maximum Input, RM 0</u>	<u>Maximum Input, RM 106</u>
January		70	60
February		70	60
March		220	180
April		330	270
May		330	270
June		400	320
July		400	320
August		220	180
September		140	120
October		110	90
November		110	90
December		70	60
30%		800	640
50%		290	250
90%		50	40
95%		40	30

whereas, unit runoff tends to increase between Mankato and Minneapolis. Despite this limitation, it is apparent why a cooling pond is utilized for ancillary cooling of condenser discharges from the Black Dog Plant during periods of low streamflow. Because of trends in plant size, any future steam generating unit located along the Minnesota River could be expected to utilize at least partial auxiliary cooling loops to meet low flow load conditions.

ST. CROIX RIVER BASIN

The St. Croix River has its headwaters adjacent to the Lake Superior drainage basin. The main stem forms the boundary between the states of Minnesota and Wisconsin for a distance

of ~125 miles as it flows in a southerly direction toward the confluence with the Mississippi at Prescott (Upper Mississippi River Mile 811); total drainage area is 7650 square miles.

As is the case with the Upper Mississippi River Basin as a whole, the climate is of the continental type. Average July air temperatures range from 67 °F in the headwaters to 73 °F in the lower reaches; January means range between 8 °F and 15 °F. At Danbury (RM 119), maximum and minimum temperatures of record are 108 °F and -54 °F respectively. Mean annual precipitation is ~30 in. Monthly rainfall normally peaks in late spring and summer. Annual runoff varies from 15 in. in the upper basin to less than 6 in. near the mouth. Long-term average discharge at St. Croix Falls (RM 52) is 4051 ft³/sec; mean and median discharges for the 1950-1960 period of record were 5070 and 4870 ft³/sec respectively. The minimum daily flow recorded at St. Croix Falls was 75 ft³/sec on July 17, 1910.

Projected Cooling Capacities

Heat sink capacities of the St. Croix River for mean monthly flow and weather conditions are illustrated in Figures 5 and 6 and summarized in Tables 4 and 5. Total capacity between Grantsburg (RM 102) and the mouth varies from 7800 MW_T in April to 3100 MW_T in November. Since MAXPWR was designed to calculate heat dissipation to the atmosphere for the liquid phase, no totals were determined for the winter months. Mean air temperatures at Minneapolis for the months of November through March are -0.6 °C (31 °F), -7.8 °C (18 °F), -11.1 °C (12 °F), -8.9 °C (16 °F) and -2.2 °C (28 °F) respectively. Since dissipation is proportional to streamflow and the differential between the water and air temperatures, it is apparent that November is the minimum month in terms of mean heat sink capacity, within the study assumptions. Under low flow conditions, cooling capacities would be marginal to those required by an 800 MW_T output during August and November.

FIGURE 5. Average **Direct** Cooling Capacity of St. Croix River

TABLE 4. Average Direct Cooling Capacity (MW_T)
of St. Croix River (RM 102 to RM 0)^T

<u>Month</u>	<u>Total</u>	<u>Maximum Input, RM 0</u>	<u>Maximum Input, RM 102</u>
January		750	550
February		750	500
March		1,050	650
April	7,800	4,050	1,800
May	6,400	2,400	1,250
June	6,700	2,350	1,200
July	6,600	2,400	1,200
August	5,100	1,500	800
September	4,700	1,500	900
October	3,400	1,200	750
November	3,100	1,200	800
December		900	600

TABLE 5. Low Flow Direct Cooling Capacity (MW_T)
of St. Croix River (RM 102 to RM 0)

<u>Month</u>	<u>Total</u>	<u>Maximum Input, RM 0</u>	<u>Maximum Input, RM 102</u>
January		550	350
February		550	350
March		700	450
April	1800	950	650
May	2100	950	600
June	3300	1300	650
July	2000	800	500
August		700	450
September	1400	800	500
October	1300	800	550
November		750	550
December		650	450

FIGURE 6. Low Flow Direct Cooling Capacity of St. Croix River

At the present time a 598 MW_e steam plant is located at Bayport, Minnesota (RM 20). A mechanical draft cooling tower is available for supplementary cooling. The only other power facility for the section under study is a 23.2 MW_e hydroelectric unit at St. Croix Falls.

CHIPPEWA RIVER BASIN

The Chippewa River Subbasin lies directly to the east of the St. Croix Subbasin. Its drainage area of 9480 square miles lies entirely within the state of Wisconsin. The upper reaches traverse a highland known as the Wisconsin Arch, in which igneous and metamorphic rocks predominate. The surface has been subject to continental glaciation, resulting in a veneer of till. The alluvium in river valleys tends to be highly permeable. Downstream of Chippewa Falls (RM 75) sandstones, shales and dolomites form bedrock, overlain by a mantle of soil. Permeable sand and gravel are also found throughout the lower reaches. The abundance of sand is indicated by the fact that the natural constriction at the lower end of Lake Pepin on the Mississippi River (Upper Mississippi River Mile 762) is largely the result of sand deposits from the Chippewa River.

The climate is continental, with a range in temperatures similar to that found in the St. Croix Subbasin. Rainfall and runoff patterns are also similar. The ratio of runoff to rainfall is greater in the St. Croix and Chippewa Subbasins than in any other area of the Upper Mississippi River Basin. Unit runoff is also higher than in the remaining tributary valleys under study. Long-term mean annual discharge at Durand (RM 18) is 7206 ft³/sec; 1950-1960 average flow was 7429, with a median of 7455. The minimum of record was 1020 ft³/sec on November 24, 1950.

Projected Cooling Capacities

In 1966 the installed hydroelectric capacity in the Chippewa Subbasin was 162 MW_e . Two units are located along the section simulated in this study, 21.6 MW_e at Chippewa Falls (RM 75) and 9.5 MW_e at Eau Claire (RM 63). Steam plants have not been located in the area to date.

Figures 7 and 8 and Tables 6 and 7 summarize the average and low flow direct cooling capacities of the Chippewa River from Chippewa Falls to the confluence with the Mississippi River (U.M.R.M. 762). Total average capacity ranges from 7300 MW_T in April to 2900 MW_T in November. Low flow capacities vary from 2800 MW_T in April to 1100 in November. On a long-term basis only 6% of the time would flows be insufficient to assimilate 800 MW_T in the reach downstream of River Mile 29.

WISCONSIN RIVER BASIN

The Wisconsin River, with a mean annual flow of $8423 \text{ ft}^3/\text{sec}$ is second in rank behind the Illinois River among Upper Mississippi Tributary Streams. Drainage area is 11,700 square miles. Its headwaters originate on the Wisconsin Arch, to the east of the Flambeau-Chippewa drainage; from there it flows toward the south for 320 miles, then changes direction near Portage and follows a west-southwesterly trend for another 110 miles to its confluence with the Mississippi (U.M.R.M. 632). Upstream of Petenwell Flowage (RM 200) the area is covered by a veneer of glacial till and/or alluvium overlying a complex of relatively impervious rocks. Bedrock in the lower basin is composed of sandstones, shales and dolomites that dip away from the highland to the north. From Prairie du Sac (RM 90) to its mouth the river passes through a region known as the Driftless Area, which in contrast to the remainder of the basin is characterized by well-developed drainage.

FIGURE 7. Average Direct Cooling Capacity of Chippewa River

FIGURE 8. Low Flow Direct Cooling Capacity of Chippewa River

TABLE 6. Average Direct Cooling Capacity (MW_T)
of Chippewa River (RM 75 to RM 0)

<u>Month</u>	<u>Total</u>	<u>Maximum Input, RM 0</u>	<u>Maximum Input, RM 75</u>
January		1400	900
February		1400	1000
March		2300	1550
April	7300	5450	3850
May	5800	3700	2600
June	5300	3100	2150
July	4800	2650	1850
August	3800	2000	1450
September	4300	2550	1850
October	3400	2050	1450
November	2900	1800	1200
December		1600	700
50%		1650	

TABLE 7. Low Flow Direct Cooling Capacity (MW_T)
of Chippewa River (RM 75 to RM 0)

<u>Month</u>	<u>Total</u>	<u>Maximum Input, RM 0</u>	<u>Maximum Input, RM 75</u>
January		950	650
February		1100	650
March		1400	950
April	2800	2200	1400
May	2400	1550	1000
June	2400	1450	900
July	2500	1500	950
August	2100	1200	650
September	2100	1300	800
October	1300	950	550
November	1100	950	600
December		1000	650
50%		1650	
90%		900	
94%		800	
95%		750	
99%		550	

Air temperatures in July range from 68 °F in the north to 72 °F in the southern part of the area. January temperatures vary from 12 °F in the north to 16 °F in the lower basin. Extreme temperatures of 114 °F and -55 °F have been recorded.

Annual precipitation decreases from 32 in. in the north to 30 in the middle basin and then increases again to 32 in. near the Mississippi River. Runoff ranges from 14 in. in the upper basin to 8 in. in the lower. The 1950-1960 mean and median annual flows were 8019 and 7696 ft³/sec respectively at Muscoda (RM 39). Extreme low flow was 2000 ft³/sec on February 11, 1918.

Projected Cooling Capacities

In 1966 the Wisconsin River Subbasin had an installed hydroelectric capacity of 149 MW; steam generating capacity was 166 MW_e, with 80% concentrated in the vicinity of Wausau (RM 250).

Figure 9 and Table 8 indicate a broad peak of mean monthly heat sink capacities during spring and early summer. Totals range from 11,700 MW_T in May to 7000 MW_T in November for the section of the river downstream of Wisconsin Dells (RM 132). Low flow totals (Figure 10 and Table 9) are more sharply peaked, with a maximum of 7700 MW_T occurring in June (coincidental with high rainfall and evaporation), and a minimum of 2500 MW_T in November. August is the limiting month in terms of assimilative capacity associated with low flow.

Long-term flow probabilities indicate that 99% of the time, daily average flows downstream of Muscoda (RM 37) would be adequate to assimilate 900 MW_T within a temperature rise of 2.8 °C (5 °F).

FIGURE 9. Average Direct Cooling Capacity of Wisconsin River

FIGURE 10. Low Flow Direct Cooling Capacity of Wisconsin River

TABLE 8. Average Direct Cooling Capacity (MW_T)
of Wisconsin River (RM 132 to RM 0)

<u>Month</u>	<u>Total</u>	<u>Maximum Input, RM 0</u>	<u>Maximum Input, RM 132</u>	<u>Maximum Input, RM 259</u>
January		2,100	1,650	800
February		2,100	1,600	750
March		2,600	1,900	1,000
April	11,700	5,000	3,900	2,500
May	11,900	3,950	3,200	1,500
June	11,500	2,850	2,300	1,200
July	10,800	2,700	2,050	1,150
August	8,700	2,050	1,550	900
September	8,900	1,900	1,600	1,050
October	8,400	2,400	1,950	1,100
November	7,000	2,250	1,800	850
December		2,100	1,650	800
50%		2,200		

TABLE 9. Low Flow Direct Cooling Capacity (MW_T)
of Wisconsin River (RM 132 to RM 0)

<u>Month</u>	<u>Total</u>	<u>Maximum Input, RM 0</u>	<u>Maximum Input, RM 132</u>	<u>Maximum Input, RM 259</u>
January		1400	1050	600
February		1500	1200	550
March		2000	1400	550
April	5600	2150	1650	1200
May	6200	1900	1400	700
June	7700	1800	1400	550
July	6500	1500	950	550
August	4000	1100	750	450
September	4300	1200	900	650
October	3100	1150	850	550
November	2500	1350	1000	550
December		1350	1000	550
50%		2200		
90%		1300		
95%		1100		
99%		900		

ROCK RIVER BASIN

The Rock River Subbasin covers an area of 10,710 square miles in southern Wisconsin and northwestern Illinois. The lower 2/3 of its 293 mile course lies in Illinois, where it trends in a southwesterly direction from the state line at Beloit to the Quad-Cities (Moline, East Moline, Rock Island and Davenport). The northern part of the basin is characterized by rolling terrain and fertile sandy soils, with thick deposits of alluvial sand and gravel in the main valley. The Illinois portion is an alluvial plain, largely covered with loess deposits. Total relief is approximately 370 ft; the steepest slopes are found near the Mississippi River.

The climate of the area is temperate continental, with a wide temperature range. July means range from 81 °F in the upper basin to 86 °F in the middle and lower sections. January temperatures vary from 25 °F in the north to 31 °F near the confluence with the Mississippi.

Annual precipitation averages 31 in. in the Wisconsin portion of the basin and 34 in. in Illinois. Unit runoff is approximately 8 in. Runoff for the 1950-1960 period averaged 7.8 in., with high and low values of 13.5 and 3.9 in. respectively. Mean annual flow at Joslin, Illinois (RM 27) is 5257 ft³/sec. The 1950-1960 average was 5450 ft³/sec; median flow was 5090 ft³/sec. The extreme low flow of record was 834 ft³/sec on January 3, 1940. At Como (RM 68), where a longer gaging station record is available, mean annual flows are 5093 ft³/sec and the extreme is 498 ft³/sec for August 20, 1934.

Eleven small hydroelectric units are in operation in the Rock River Subbasin, with a total capacity of 11 MW_e in 1966; 8 MW_e of the total was installed within the study area (that

is, downstream of RM 139). In 1964 fossil-fueled steam-generating capacity along the Rock River was 570 MW_e, 73% of which was located in Illinois.

Average direct cooling capacity (Figure 11 and Table 10) of the Rock River from Rockford (RM 139) to the mouth ranges from 6800 MW_T in April to 2000 MW_T in September. Maximum local input is adequate in September to assimilate 800 MW_T, within a temperature envelope of 5 °F above background, from Como (RM 68) to the mouth. In the Rockford area average flow would be inadequate in September to assimilate 800 MW_T within the study assumptions. Under conditions of the low flow months for the 1950-1960 period, 800 MW_T could be assimilated only during periods of high snowmelt (March-April), and high rainfall and evaporation (June-July). On a daily basis 67% of the time 800 MW_T could be assimilated downstream of Como.

CEDAR-IOWA RIVER BASIN

The drainage area of the Cedar-Iowa Subbasin is 12,640 square miles, 92% of which is in Iowa and the remainder in southern Minnesota. The Cedar River, which flows subparallel to the Iowa River, trends in a southeasterly direction across east-central Iowa to where it joins the Iowa River at Columbus Junction (RM 30). The confluence of the combined stream and the Mississippi River is at Upper Mississippi River Mile 434, downstream of Lock and Dam No. 17. In general, the basin is characterized by low relief, due in part to repeated continental glaciation.

The economy of the area is largely related to agriculture. Dairying is predominant in the Upper Cedar Basin; grain production is most important in the Upper Iowa Basin and livestock production in the lower Cedar-Iowa drainage area. Food processing and the manufacture of farm machinery are the most important industries. Major water-using industries are concentrated in the Cedar Subbasin.

FIGURE 11. Average Direct Cooling Capacity of Rock River

FIGURE 12. Low Flow Direct Cooling Capacity of Rock River

TABLE 10. Average Direct Cooling Capacity (MW_T)
of Rock River (RM 139 to RM 0)

Month	Total	Maximum Input, RM 0	Maximum Input, RM 68	Maximum Input, RM 139
January		1500	1350	900
February		1900	1700	1100
March	5500	2950	2650	1950
April	6800	3500	3150	2500
May	6200	2500	2200	1650
June	5800	1850	1650	1200
July	5000	1700	1500	1000
August	4100	1300	1150	900
September	2000	850	800	650
October	3200	1200	1100	850
November	3000	1300	1150	850
December		1100	1000	750
50%		1150		
67%		800		

TABLE 11. Low Flow Direct Cooling Capacity (MW_T)
of Rock River (RM 139 to RM 0)

Month	Total	Maximum Input, RM 0	Maximum Input, RM 68	Maximum Input, RM 139
January		450	400	250
February		750	700	500
March	1300	900	800	550
April	2200	1300	1100	850
May		650	600	350
June	1700	900	750	500
July	1500	850	800	350
August		450	400	250
September		350	300	250
October		450	400	350
November		650	600	450
December		500	450	350
50%			1150	
67%			800	
90%			500	
95%			430	
99%			300	

Mean July temperatures range from 73 °F in southern Minnesota to 75 °F near the Mississippi River. The January range is 14 °F and 25 °F. Rainfall increase from 29 in. in the north to 35 in. in the lower basin. Approximately 70% of the annual precipitation occurs during the growing season. Runoff averages 6.6 in./yr. The average flow of the Cedar-Iowa River at Wapello (RM 16) is $6253 \text{ ft}^3/\text{sec}$. The 7-day in 10-year low flow at mile 16 is $540 \text{ ft}^3/\text{sec}$. At Cedar Rapids, which is the upstream end of the study section, the mean annual flow is $3094 \text{ ft}^3/\text{sec}$, with a 7-day in 10-year low flow of $300 \text{ ft}^3/\text{sec}$.

In 1964 the steam electric capacity along the Cedar-Iowa River was 382 MW_e , 38 near Mason City in the Upper Basin, 150 near Cedar Falls and 194 near Cedar Rapids. In 1973 a nuclear steam plant with a capacity of 550 MW_e is scheduled for completion near Cedar Rapids; a second unit is envisioned for later installation in the same site.

Figures 13 and 14 and Tables 12 and 13 indicate the mean and low flow direct cooling capacity of the Cedar-Iowa River from Cedar Rapids to the mouth. Mean total capacity ranges from 7000 MW_T in April to 1700 MW_T in November. Average assimilative capacity below the confluence of the Cedar and Iowa Rivers at River Mile 30 is 800 MW_T or more except in December. However, for the low flow condition of the 1950-1960 period of record, the local capacity in the lower river was less than 800 MW_T . At Cedar Rapids (RM 139), the average local input for a 5 °F increase in temperature is greater than 800 MW_T only during the months March through July.

In terms of daily probabilities, 50% of the time assimilative capacity would exceed 1200 MW_T in the lower 30 miles of the river. The 90, 95 and 99% capacities are 350, 250 and 200 MW_T respectively. At Cedar Rapids the local capacity for

FIGURE 13. Average Direct Cooling Capacity of Cedar-Iowa River

FIGURE 14. Low Flow Direct Cooling Capacity of Cedar-Iowa River

TABLE 12. Average Direct Cooling Capacity (MW_T)
of Cedar-Iowa River (RM 139 to RM 0)

<u>Month</u>	<u>Total</u>	<u>Maximum Input, RM 0</u>	<u>Maximum Input, RM 139</u>
January		1000	400
February		1450	550
March	4500	2750	1350
April	7000	4350	2200
May	5400	2950	1400
June	5600	2850	1400
July	4600	2200	1050
August	2300	1200	750
September	1900	950	500
October	1800	900	450
November	1700	850	450
December		650	350
50 %		1200	

TABLE 13. Low Flow Direct Cooling Capacity (MW_T)
of Cedar-Iowa River (RM 139 to RM 0)

<u>Month</u>	<u>Total</u>	<u>Maximum Input, RM 0</u>	<u>Maximum Input, RM 139</u>
January		150	100
February		350	150
March		450	300
April		650	350
May		650	350
June		500	300
July		450	250
August		350	200
September		250	150
October		250	150
November		250	150
December		200	150
50 %		1200	600
66 %		800	
90 %		350	200
95 %		250	150
99 %		200	100

a 5 °F increase above background for 50, 90, 95 and 99% of the time are 600, 200, 150 and 100 MW_T respectively. At Cedar Rapids, two generating units, Cedar Rapids (98 MW_e) and Prairie Creek (96 MW_e) are on-line. Based on Federal Power Commission data for the Prairie Creek Plant, it is estimated that the average heat rejection by both units in 1964 was 204 MW_T. Consequently, 10% of the time, present loads can be expected to be below or marginal to the study constraint. In general the greatest problem would occur during the fall, although August is also a marginal month under low flow conditions.

DES MOINES RIVER BASIN

The Des Moines Basin extends from southwestern Minnesota across central Iowa to the Mississippi River near Keokuk. It is a long, narrow basin with a length of ~360 miles and a width of 40 miles. Total drainage area is 14,540 square miles, 89% of which lies in Iowa. The region has been subjected to continental glaciation. From Des Moines to Keokuk, which includes the study section, the basin is characterized by loess-covered, rolling terrain.

As is the case for the Cedar-Iowa Subbasin, the economy of the region is closely related to agriculture, both as a source of raw materials and a consumer. Grain and livestock are the most important farm products.

Climate is continental. July temperatures range from 73 °F in the north to 77 °F near the Mississippi River. January temperatures are 14 °F in the north and 24 °F in the south. Precipitation ranges from 28 in. in southwestern Minnesota to 36 in. in southeastern Iowa. Runoff averages 5 in./year. The mean annual flow at Keosauqua (RM 51) is 5254 ft³/sec; 7-day in 10-yr low flow is 124 ft³/sec. The low flow of record was 40 ft³/sec on January 30, 1940. At the present time a reservoir is under construction at Saylorville, 11 miles

upstream of Des Moines. Low flow augmentation associated with releases from its conservation pool are expected to maintain a flow of $200 \text{ ft}^3/\text{sec}$ at Des Moines (RM 200) and a minimum flow of $300 \text{ ft}^3/\text{sec}$ below River Mile 100.

Projected Cooling Capacities

In 1964, steam generating plants, with a total capacity of 683 MW_e , utilized Des Moines River water for cooling purposes. Approximately 50% of the capacity was located near the city of Des Moines.

Average direct cooling capacity (Figure 15 and Table 14) for the lower 200 miles of the river ranges from 7400 MW_T in April to 2000 MW_T in September. Assimilative capacity is less than 800 MW_T from October through January along the entire study section. Under low-flow conditions (Figure 16 and Table 15), modified by regulation at Saylorville, all months have an assimilative capacity less than 800 MW_T .

On a probability basis, the daily assimilative capacity 50% of the time would range from 600 MW_T at Des Moines to 850 MW_T near the mouth; 90% of the time local capacity would equal or exceed a range of 100 MW_T to 150 MW_T . Because of projected flow regulation, extreme minimum capacities should range between 50 MW_T at Des Moines and 100 MW_T in the lower river. In 1964, the capacity of Des Moines No. 2 steam plant was 325 MW_e . The estimated average thermal rejection, based on Federal Power Commission production data, was 300 MW_T . Without ancillary cooling, flows would be adequate to assimilate 300 MW_T , within the study assumptions, 62% of the time. A reservoir which extends from River Mile 160 to Des Moines apparently functions as a cooling pond during low-flow periods.

ILLINOIS RIVER BASIN

The Illinois River is formed by the confluence of the Des Plaines and Kankakee Rivers at River Mile 273 of the

FIGURE 15. Average Direct Cooling Capacity of Des Moines River

FIGURE 16. Low Flow Direct Cooling Capacity of Des Moines River

TABLE 14. Average Direct Cooling Capacity (MW_T)
of Des Moines River (RM 205 to RM 0)

<u>Month</u>	<u>Total</u>	<u>Maximum Input, RM 0</u>	<u>Maximum Input, RM 100</u>	<u>Maximum Input, RM 200</u>
January		500	450	250
February		900	750	450
March	4400	2050	1650	1200
April	7400	3850	3350	2650
May	6700	3150	2650	1900
June	7600	3500	3150	2600
July	6400	2600	2250	1750
August	3600	1200	1000	850
September	2000	850+	750	550
October		650	550	450
November		500	400	300
December		350	300	250
50%		850-		600

TABLE 15. Low Flow Direct Cooling Capacity (MW_T)
of Des Moines River (RM 205 to RM0)

<u>Month</u>	<u>Total</u>	<u>Maximum Input, RM 0</u>	<u>Maximum Input, RM 100</u>	<u>Maximum Input, RM 200</u>
January		100	100	50+
February		100	100	50+
March		200-	150+	200-
April		250-	250-	200-
May		200	200	200-
June		300	250	200-
July		150	150-	100
August		200	150	100-
September		100+	100+	50+
October		100	100	50+
November		100	100+	50+
December		100	100	50+
50%		850		600
90%		150		100-
99+%		100		50+

Illinois Waterway. The waterway extends up the Des Plaines River-Chicago Sanitary and Ship Canal to Chicago Harbor (RM 327) on Lake Michigan, and the Calumet Sag Channel to Calumet Harbor (RM 333) and Indiana Harbor (RM 336). From its origin the river flows west for 63 miles, then trends to the southwest for 130 miles. The lower 80 miles are oriented to the south. Total drainage area of the subbasin is 24,254 square miles. The watershed is characterized by gently rolling terrain, covered largely by fertile soils derived from loess. The main valley has broad floodplains which increase in width from 1/4 to 1/2 mile upstream of Starved Rock Lock and Dam (RM 231), to 8 miles at La Grange Lock and Dam (RM 80). The wide valley and low gradient (0.00006) are important factors affecting the broad peak normally associated with spring and early summer runoff.

The climate in the basin is continental, with July temperature varying from 74 °F in the north to 80 °F near the Mississippi River; January means range from 25 °F to 32 °F. Extremes of record are 113 °F and -32 °F. Rainfall and runoff average 34 and 8 in. respectively. Average annual flow of the Illinois River at the Meredosia gaging station (RM 71) is 19,800 ft³/sec. The 1950-1960 mean flow was 19,300 ft³/sec. Diversions from Lake Michigan watershed to the Illinois River via the Chicago Sanitary and Ship Canal are ~2500 ft³/sec, excluding consumptive losses of 700 ft³/sec. During periods of low streamflow the quantity diverted may make up 60% of total flow in the main stem. The low flow of record at Meredosia was 3060 ft³/sec on September 1, 1945. Records were first tabulated at Meredosia in 1938. Consequently, flows lower than indicated above may have occurred during 1934, the most severe hydrologic drought year of record in the Upper Mississippi Basin.

Projected Cooling Capacities

Hydroelectric capacity in 1966 in the Illinois Basin was 25.6 MW_e, of which only one unit with a capacity of 2 MW_e was located in the area under study. Steam generating capacity of 1972 MW_e, including a 209 MW_e nuclear plant, was on-line in 1964. By 1970, capacity additions of 301 MW_e, fossil-fueled and 1430, nuclear-fueled were in place or in the final stages of construction, for a total capacity of 3702 MW_e.

Average direct cooling capacity (Figures 17a, b, and c and Table 16 a and b) for the 273 mile section under study ranges from 36,000 MW_T in June to 19,800 MW_T in November. Assimilative capacity normally reaches a high for the year in April and a low in September. However, increased evaporation during the summer results in a greater total heat sink capacity within the constraint of 5 °F above background than is observed in November. Low flow thermal capacities (Figures 18a, b, and c and Table 17a and b) exhibit a similar pattern, with a total of 23,500 MW_T during the high rainfall-high evaporation month of June and 4100 MW_T during the low rainfall-low evaporation month of November. Assimilative capacity has a low value of 1300 MW_T in the upper reaches, 1600 in the middle and 1500 in the lower reaches of the river during the month of October. The decrease from the middle to lower river is related to a diminution of flow of 180 ft³/sec in the downstream direction. Whether the loss of flow is related to recharge of groundwater aquifers or other causes is undetermined. In summary, ~15% of the total capacity lies between RM 278 and 231, 60% between RM 231 and 80, and 25% downstream of RM 80. The Lake Peoria area in the middle sector has the largest capacity of any part of the Illinois drainage.

On a long-term daily probability basis, assimilative capacities at Meredosia for 50, 90, 95, and 99% of the time

FIGURE 17a. Average Direct Cooling Capacity of Illinois River

FIGURE 17b. Average Direct Cooling Capacity of Illinois River

FIGURE 17c. Average Direct Cooling Capacity of Illinois River

TABLE 16a. Average Direct Cooling Capacity (MW_T)
of Illinois River (RM 278 to RM 0)

<u>Month</u>	<u>Total</u>	<u>Maximum Input, RM 0</u>	<u>Maximum Input, RM 145</u>	<u>Maximum Input, RM 247</u>
January		5,550	4,400	3,100
February		7,150	5,100	3,650
March	27,900	8,700	6,200	3,550
April	33,300	10,800	7,350	4,650
May	34,300	9,800	6,000	3,900
June	36,000	8,850	5,850	3,850
July	35,500	8,050	5,300	3,450
August	26,900	4,800	3,000	2,100
September	21,900	2,500	2,000	1,700
October	20,600	3,150	2,750	2,100
November	19,800	3,500	3,050	2,200
December		3,750	3,100	2,400
50%		5,150		

TABLE 16b. Average Direct Cooling Capacity (MW_T)
of Illinois River (RM 278 to RM 0)

<u>Month</u>	<u>Total</u>	<u>Subtotal (RM 80)</u>	<u>Subtotal (RM 231)</u>
January			
February			
March	27,900	20,962	4,946
April	33,400	24,645	6,296
May	34,300	25,332	5,881
June	36,000	26,629	5,881
July	35,500	26,903	5,457
August	26,900	19,584	3,859
September	21,900	16,798	3,233
October	20,600	16,383	3,452
November	19,800	15,785	3,496
December

FIGURE 18a. Low Flow Direct Cooling Capacity of Illinois River

FIGURE 18b. Low Flow Direct Cooling Capacity of Illinois River

FIGURE 18c. Low Flow Direct Cooling Capacity of Illinois River

TABLE 17a. Low Flow Direct Cooling Capacity (MW_T)
of Illinois River (RM 278 to RM 0)

<u>Month</u>	<u>Total</u>	<u>Subtotal (RM 80)</u>	<u>Subtotal (RM 231)</u>
January			
February			
March	9,200	6,081	2,145
April	12,200	9,457	3,112
May	16,300	11,764	2,869
June	23,500	17,085	3,409
July	19,200	14,529	3,269
August	16,600	12,457	2,885
September	12,100	8,751	2,265
October	7,700	6,328	1,874
November	4,100	3,393	1,629
December			

TABLE 17b. Low Flow Direct Cooling Capacity (MW_T)
of Illinois River (RM 278 to RM 0)

<u>Month</u>	<u>Total</u>	<u>Maximum Input, RM 0</u>	<u>Maximum Input, RM 145</u>	<u>Maximum Input, RM 247</u>
January		2,150	1,800	1,450
February		2,900	2,450	1,850
March	9,200	4,100	2,550	1,850
April	12,200	3,300	2,900	2,550
May	16,300	3,950	2,650	2,050
June	23,500	5,150	3,300	2,300
July	19,200	3,150	2,450	2,100
August	16,600	2,650	2,100	1,800
September	12,100	2,050	1,450	1,500
October	7,700	1,500	1,600	1,300
November	4,100	1,800	1,700	1,300
December		2,300	1,900	1,600
50%		5,150		
90%		2,300		
95%		1,800		
99%		1,400		

are 5150, 2300, 1800 and 1400 MW_T respectively. Since monthly low flows for October averaged at the 98% level, it is estimated that the 99% assimilative capacity in the upper river would be approximately 1200 MW_T .

UPPER MISSISSIPPI RIVER

Total drainage area of the Upper Mississippi Basin upstream of Alton, Illinois (RM 203) is 171,500 square miles. Source of the main stem is Lake Itasca (RM 1366) in north-central Minnesota. From there, the river follows a question-mark shaped course in its uppermost 400 miles, then trends in a general southerly direction toward the confluence with the Missouri River at River Mile 196 between Alton and St. Louis. The headwaters area is characterized by rolling topography, formed largely from glacial moraines and outwash. Lakes are numerous. The main stem in the central part of the study section traverses the western edge of the Driftless area, a region essentially devoid of natural lakes, but featuring well-developed drainage and a large number of small streams. Steep bluffs, capped with sandstone or dolomite, generally border the Mississippi Valley in the central section. Below the Quad-Cities area the valley widens and the relief becomes somewhat less pronounced.

Except for the headwaters area, where iron mining and wood products are important factors in the economy, the study area is dominated by agriculture, both as a producer of raw materials and as a consumer of finished products. Along the main stem, dairying is dominant in the northern half and livestock production in the southern section. Three major population centers, Twin-Cities, Quad-Cities and St. Louis are located along the Mississippi River. St. Louis technically is downstream of the section included in this report; however, its proximity affects cooling water requirements in the study area.

The section of the river for which heat sink capacities were calculated lies between River Miles 956 at Royalton, Minnesota and 203 at Alton. Downstream of Minneapolis (RM 858) the main stem is part of the Mississippi Waterway. The present navigational channel is maintained at 9 ft by a series of 26 locks and dams (see Figure 2) upstream of the confluence with the Missouri River. Because of subfreezing temperatures during the winter months, the navigation season is limited to 8 months upstream of Lock and Dam No. 22 (RM 301) at Hannibal, Missouri. The average ice thickness at Hannibal is 5 in. and at the Quad-Cities (RM 483), 15 in.

The climate along the main stem is continental. Mean monthly air temperatures range from 4 °F to 66 °F in the north and 30 °F to 80 °F in the lower basin. Extremes of record range from 103 °F and -59 °F at Pokegame Falls in Itasca County, Minnesota to 105 °F and -11 °F at Alton-St. Louis. Precipitation averages 24 in. in the headwaters region and 36 in. near the Missouri River. Average runoff is 7 in./year. At Alton the mean annual discharge is 93,130 ft³/sec; the average for the 1950-1960 period was 90,070 ft³/sec.

Projected Cooling Capacities

The average direct cooling capacity of the main stem between Royalton and Alton (Figure 19a and Tables 18a and b) ranges from 100,000 MW_T in April to 49,000 MW_T in November, within the study constraints of a 5 °F increase above background and minimum advected pulses of 800 MW_T. Under low-flow conditions, the minimum for the year of 41,900 MW_T also occurs in November. The relatively small decrease in total capacity from mean to low-flow conditions probably is associated with the reservoir capacity of the Lock and Dam System. The low-flow maximum, 92,100 MW_T, reflects the persistence of June rainfall and runoff over the basin as a whole. In the upper

FIGURE 19a. Average Direct Cooling Capacity of Upper Mississippi River

FIGURE 19b. Average Direct Cooling Capacity of Upper Mississippi River

TABLE 18a. Average Direct Cooling Capacity (MW_T)
of Upper Mississippi River (RM 956 to RM 203)

<u>Month</u>	<u>Total</u>		<u>Subtotal</u>	
	<u>Basin</u>	<u>Main Stem</u>	<u>RM 478</u>	<u>RM 762</u>
January				
February				
March				
April	130,000	100,000	53,000	24,800
May	136,000	100,000	51,000	19,000
June	140,000	95,000	49,000	18,400
July	131,000	91,000	48,000	17,300
August	107,000	74,000	42,000	13,600
September	89,000	64,000	35,000	9,200
October	73,000	54,000	29,000	8,300
November	61,000	49,000	26,000	7,600
December				

river the effects are more pronounced; at River Mile 762, downstream of the confluence of the Chippewa and Mississippi Rivers, the November mean and low-flow main stem subtotals are 7600 MW_T , and 5800 MW_T , respectively. Mean assimilative capacity decreases from 53,800 MW_T at River Mile 203 to 4200 MW_T at River Mile 956 during April and from 16,900 MW_T to 1100 MW_T during November. Minimum assimilative capacities for the 1950-1960 period of record were 7500 MW_T at River Mile 203 and 400 MW_T at River Mile 956.

Local capacities, based on long-term probabilities (see Figure 21) were calculated at Alton (RM 203), Keokuk (RM 364), Clinton (RM 512), Winona (RM 726) and St. Paul (RM 839). The respective 50% capacities at these locations are 19,800, 14,800, 10,800, 5500, and 2050 MW_T ; 99% of the time assimilative capacity would equal or exceed 6000, 4600, 4100, 1950, and 400 MW_T respectively. At Alton the 99% condition would be in

TABLE 18b Average Direct Cooling Capacity (MW_T) of Upper Mississippi
River (RM 956 to RM 203)

Month	Maximum Input								
	RM 203	RM 360	RM 432	RM 478	RM 629	RM 762	RM 810	RM 843	RM 956
January	18,300	12,800	10,100	9,100	7,600	3,800	2,400	1,600	950
February	21,400	14,300	10,800	9,400	7,400	3,600	2,200	1,500	900
March	30,200	21,600	17,400	14,600	11,700	5,800	3,400	2,400	1,000
April	53,800	43,000	35,600	31,200	27,600	18,800	13,400	9,400	4,200
May	46,000	36,200	27,100	24,200	21,700	12,300	8,700	6,200	2,600
June	37,300	28,400	21,800	18,800	17,000	11,000	8,000	5,700	2,300
July	35,200	27,000	21,900	19,700	18,000	10,400	7,800	5,400	1,950
August	22,900	18,100	15,300	14,000	12,800	7,400	5,400	3,800	1,750
September	16,800	14,400	13,000	12,000	11,200	7,000	4,400	3,000	1,350
October	17,200	14,000	12,000	11,200	10,000	5,400	4,000	2,200	1,200
November	16,900	13,400	11,600	10,800	9,500	5,100	4,000	2,200	1,200
December	15,400	11,700	10,000	9,400	8,300	4,300	2,800	1,800	1,100

excess of 6000 MW_T . It should be emphasized that the assimilative capacities discussed in this report have been calculated under the assumption of no residual heat above background at a given location.

The upper curves in Figures 19a and 20a and b indicate the total capacity of the main stem Upper Mississippi plus the dissipative capacities of the tributary streams examined in this study. The total for June is quite stable, varying only 14% from mean to low-flow conditions. The total for November varies 25% from a mean of 61,400 MW_T to a low of 46,000 MW_T . Tables 19a and 19b show the low flow direct cooling capacities.

FIGURE 20a. Low Flow Direct Cooling Capacity of Mississippi River

FIGURE 20b. Low Flow Direct Cooling Capacity of Upper Mississippi River

TABLE 19a. Low Flow Direct Cooling Capacity (MW_T) of Upper Mississippi River (RM 956 to RM 203)

<u>Month</u>	<u>Total</u>		<u>Subtotal</u>	
	<u>Basin</u>	<u>Main Stem</u>	<u>Main 478</u>	<u>RM 762</u>
January				
February				
March				
April	78,800	67,200	38,600	8,400
May	91,600	72,900	35,300	10,000
June	120,100	92,100	41,700	11,500
July	102,100	78,200	38,500	9,200
August	87,200	69,400	30,000	6,300
September	72,900	58,300	29,400	7,500
October	53,900	44,900	23,400	5,900
November	46,000	41,900	21,500	5,800
December				

TABLE 19b. Low Flow Direct Cooling Capacity (MW_T) of Upper Mississippi River (RM 956 to RM 203)

<u>Month</u>	<u>Maximum Input,</u>						
	<u>RM 203</u>	<u>RM 364</u>	<u>RM 512</u>	<u>RM 633</u>	<u>RM 726</u>	<u>RM 839</u>	<u>RM 956</u>
Jan	9,600	6,200	4,800	3,350	3,000	850	400
Feb	11,500	8,500	5,200	3,450	2,900	650	400
Mar	17,900	12,700	10,200	6,350	4,900	1,050	500
Apr	26,600	18,400	15,800	10,600	5,550	1,500	750
May	18,600	11,200	9,600	6,950	6,100	2,450	650
June	29,700	15,200	11,100	8,600	7,150	2,400	950
July	20,900	14,200	11,000	8,150	6,250	2,000	600
Aug	16,200	8,800	5,700	4,250	3,500	1,100	500
Sept	10,800	8,000	7,400	5,100	4,250	1,550	550
Oct	7,500	6,000	5,800	4,200	3,700	1,100	550
Nov	9,700	7,000	6,400	4,600	4,450	1,250	700
Dec	9,800	6,800	5,200	3,850	3,300	950	500
50% (a)	20,000+	14,800	10,800		5,500	2,050	
90% (a)		7,400	6,000		2,950	800	
95% (a)		6,100	5,500		2,150	600	
99% (a)	6,000+	4,600	4,100		1,950	400	

a. Probability.

FIGURE 21. Upper Mississippi River Basin Local Direct Cooling Capacity Probabilities

PROJECTED GENERATING PATTERNS, 1970, 1980 AND 1990

At the present time $\sim 90\%$ of the electric energy produced in the Upper Mississippi River Basin is generated by conventional steam-electric plants. Three nuclear plants, with a total capacity of 280 MW_e (see Table 20) were in operation prior to 1970. In 1970 two nuclear generating units were scheduled for startup at Mississippi River sites: Monticello, Minnesota (472 MW_e) and Quad-Cities, Illinois-Iowa (715 MW_e). The Dresden plant on the Illinois River was scheduled for expansion from 208 MW_e to 1838 MW_e in 1970. Total steam capacity in the Basin was estimated to be $28,400 \text{ MW}_e$ for 1970; 1980 and 1990 totals are projected to be $56,800 \text{ MW}_e$ and 110 MW_e respectively.⁽⁴⁾ In 1980 nuclear capacity is expected to comprise 37% of the total electrical generating capacity; in 1990, 57%. Approximately $1/4$ of the 1980 capacity is projected by the Federal Power Commission to be 800 MW_e or larger. By 1990, $\sim 1/2$ is expected to be 800 MW_e or larger.

Figure 22 and Table 21 indicate Federal Power Commission estimated patterns of generation of the years 1970, 1980, and 1990. The following discussion is based upon the assumption that the estimated patterns are a most likely condition. It is also assumed that the average heat rejection for 1980 and 1990 would be approximately equal, numerically, to the plant capacities. The latter is based upon a net heat rate of 9500 Btu/kW-hr and a capacity factor of 70% for a fossil-fuel plant. Thermal efficiencies of nuclear generating plants are expected to approach those associated with fossil-fueled units during the decade of the 1980's.

G.A.8: This area is located at the upper end of the main stem study section in the vicinity of St. Cloud, Minnesota. The projected generating capacity through 1990 is well below the associated low-flow thermal capacity of 400 MW_T at RM 956.

**TABLE 20. Scheduled and Installed Nuclear Capacity
in the UMRB Power Region**

<u>PSA</u>	<u>Plant or Location</u>	<u>Utility</u>	<u>Capacity, MW</u>	<u>Scheduled Operation</u>
13	Genoa (Miss. R.)	Dairyland Power Cooperative	50	1967
14	Dresden #1 (Ill. R.)	Commonwealth Edison Company	208	1960
14	Dresden #2	Commonwealth Edison Company	715	1969
14	Dresden #3	Commonwealth Edison Company	715	1970
14	Zion #1 (L. Mich.)	Commonwealth Edison Company	1100	1972
14	Zion #2	Commonwealth Edison Company	1100	1973
16	Elk River (Miss. R.)	Rural Coop. Power Association	22	1963
16	Monticello (Miss. R.)	Northern States Power Co.	472	1970
16	Prairie Island #1 (Miss. R.)	Northern States Power Co.	550	1974
16	Prairie Island #2	Northern States Power Co.	550	1974
17	Quad Cities #1 (Miss. R.)	Commonwealth Edison Company	715	1970
17	Quad Cities #2	Iowa-Illinois Gas & Elec. Co.	715	1971
17	Cedar Rapids #1 (Cedar River)	Iowa Electric Light & Power Co.	550	1973
17	Cedar Rapids #2	Iowa Electric Light & Power Co.	550	?
17	Iowa Station (Des Moines R.)	Iowa Utilities	550-- 750	1975

FIGURE 22. FPC-West Central Region Generation Areas

TABLE 21. FPC - West Central Region Generation Patterns

Gener- ation Area	Power Supply Area	1970				1980				1990			
		Steam		Hydro	Peaking	Steam		Hydro	Peaking	Steam		Hydro	Peaking
		Fossil	Nuclear			Fossil	Nuclear			Fossil	Nuclear		
8	16	52	26		93	52	26		93	25	26		83
9	16	95			32	95			32	246			200
10	16	2098	520	6	58	2102	2705	6	208	2954	9405		397
12	16	66			172	66			322	1300			300
13	17	413			130	738			280	738	1300		329
14	17	429		2	76	458	500		137	414	2100		213
15	17	663		2	33	663	550	2	115	649	1100		255
20	17	578			204	578	750		198	778	1800		406
21	17	797	715	11	96	763	3918		126	743	7018		221
22	15			130				130			2400	130	
23	15										2600		
26	15	2607				5970	1600		1000	5970	4000		1200
27	40	1715			30	3365			230	3365	2400		830
32	40	3332				5280				6480	3700		
34	14	300				300	3000			300	6800		
35	14	4908	1742		1053	5858	7318		2253	3075	16618		4353
36	14	359			73	158			73		4200		373
37	16	630	60			630	590			530	590		
38	16	2		177	36	2	770	177	36		770	156	
39	13	185		126	62	227		126	62	282		126	82
43	13	641			169	641	1054		191	641	2908		529

- G.A.9: This area includes the upper reaches of the Minnesota River, upstream of the section simulated in this study. By 1990 the fossil steam capacity in the area is projected to be 246 MW_e. Average flows would be marginal with respect to assimilation of heat from a single unit during the fall. Low flows would be inadequate for 6 to 7 months of the low-flow year used in this study.
- G.A. 10: Includes the Twin-Cities metropolitan area. By 1980 2102 MW_e, fossil fueled, and 2705 MW_e, nuclear fueled, are projected to be on-line. Included within the estimate are generating plants at Monticello (472 MW_e), Twin-Cities (518 MW_e and 464 MW_e) and Prairie Island (1100 MW_e) on the Mississippi River, at Bloomington (487 MW_e) on the Minnesota River, and Bayport (598 MW_e) on the St. Croix River. The latter two units are presently equipped for auxiliary cooling during low-flow periods. The Monticello plant has a mechanical-draft cooling tower for supplementary cooling. Present loads in downtown Minneapolis-St. Paul are marginal with respect to low-flow capacities during August and the fall months. Winter low-flow cooling capacities would be inadequate for 1970 loads in the downtown sector when air temperatures are near freezing in contrast to normal subfreezing conditions. Cooling capacities appear adequate to assimilate and dissipate the projected 1980 loads 90% of the time, provided generating units and other sources of heat are not concentrated in a short reach. Between 1980 and 1990, an additional nuclear capacity of 6700 MW_e and fossil-fuel capacity of 852 MW_e are projected for G.A.10, providing a total of 11,359 MW_e in 1990. Direct cooling capacities of the main stem plus the St. Croix and Minnesota side-streams are less than the projected load over a period

- G.A.10:
(contd) of 6 to 7 months of the average year. Consequently, it appears that partial or total closed-loop ancillary cooling facilities would be necessary for generating units constructed beyond 1980.
- G.A.12: The 1980 capacity near Mankato in the central section of the Minnesota River Subbasin is projected to be 66 MW_e, conventional. The above load would be marginal to the low-flow stream capacity during periods of above-normal winter air temperatures. By 1990 the generation capacity is expected to increase to 1300 MW_e, conventional. The cooling capacity of the river near Mankato is too limited to assimilate and dissipate the energy associated with a single unit or even four equal, optimally spaced smaller units. Closed-loop cooling would be expected for 1990 conditions.
- G.A.13: This area includes the upper reaches of the Des Moines River and adjacent parts of the Missouri River Basin. The present Upper Des Moines capacity is 109 MW_e of the 413 MW_e tabulated for the area. If the upper basin capacity increases in proportion to the area as a whole, 1980 and 1990 generation would be 200 MW_e and 1400 MW_e respectively. At the present, the largest plant in the Upper Des Moines Basin is a 50 MW_e unit at Humbolt. Low-flow capacities are marginal with respect to a plant of this relatively small capacity. Consequently, additional generating plants would be expected to utilize supplementary cooling facilities.
- G.A.14: This area includes the Turkey and Wapeseponcon River Subbasins of northeastern Iowa and an adjacent reach of the Mississippi River lying between Dubuque and Clinton. By 1980, one 500 MW_e nuclear generating

G.A.14: (contd) plant is expected to be sited near Dubuque. In 1990 the total nuclear capacity in G.A.14 is projected to be 2100 MW_e. Tributary basins have satisfactory direct-cooling capacities to assimilate and dissipate reject heat from small units only, unless cooling reservoirs or other ancillary systems are provided. The Mississippi River at Clinton has an assimilative capacity of 4600 MW_T, 99% of the time. Consequently, cooling capacities would be adequate even if the nuclear capacity were concentrated.

G.A.15: Waterloo-Cedar Falls, Cedar Rapids and Iowa City, Iowa are within G.A. 15. The only power growth expected between 1970 and 1980 is a 550 MW_e nuclear generating plant at Cedar Rapids, which is scheduled for completion in 1973. Because of the limited direct-cooling capacity of the Cedar River, especially during low-flow periods, auxiliary cooling facilities are anticipated in conjunction with plant operations. By 1990 a second 550 MW_e unit is projected at Cedar Rapids.

G.A.20: Des Moines and adjacent areas in the Missouri Basin are included within G.A.20. Of the 578 MW_e tabulated for 1970, 347 MW_e are located near Des Moines. No change in fossil-fuel capacity is projected for 1980. However, a 500 to 700 MW_e nuclear plant is expected at Des Moines by 1975. Since the Des Moines River has insufficient direct-cooling capacity during periods of low flow to assimilate and dissipate waste thermal energy from a unit of 500 MW_e, it is anticipated either that a large reservoir downstream of Des Moines would be utilized in a partial ancillary cooling loop or some other form of supplementary

- G.A.20: (contd) cooling would be employed. Between 1980 and 1990, additions of 200 MW_e fossil fuel and 1050 nuclear are projected for G.A.20; auxiliary cooling would be required.
- G.A.21: Generation area 21 is one of the major metropolitan areas on the main stem Upper Mississippi River. It includes the lower section of the Cedar-Iowa River drainage as well as the Quad-Cities to Burlington section of the main stem. The 1970 generating capacity includes 797 MW_e conventional, and 715 nuclear. A slight decrease to 763 MW_e conventional, and an increase to 3918 MW_e nuclear, is projected for 1980. Direct-cooling capacity on main stem is adequate for 1980 loads if properly spaced with respect to upstream sources of advected heat. A further increase in nuclear capacity of 3100 MW_e, for a total of 7018 MW_e, is projected for 1990. If upstream and local sources of advected heat are adequately spaced, 1990 loads could be accommodated by direct cooling. Under low-flow conditions, October appears to be potentially the most marginal month; although December and January capacities could pose problems if low-flow conditions coincided with unseasonably warm air temperatures.
- G.A.22: Includes the main stem Upper Mississippi and lower Des Moines Rivers in the vicinity of Keokuk, Iowa. No steam capacity is projected for G.A.22 through 1980. A total thermal generating capacity of 2400 MW_e nuclear is expected by 1990. Direct cooling could be applicable if sites are selected with regard to upstream sources of advected heat.

- G.A.23: Generating area 23 includes Hannibal, Missouri and vicinity. A 1990 capacity of 2600 MW_e nuclear is projected for the area. Direct cooling is applicable.
- G.A.26 and 27: St. Louis, Missouri and vicinity. Present generating capacity largely relies on direct cooling. Other sources of heat from industrial sources, primarily the chemical industry. Sources of cooling water include Missouri and Mississippi Rivers. The 1980 capacity is projected to be 9335 MW_e, conventional, and 1600 MW_e, nuclear. Direct cooling could be utilized. By 1990 total capacity is projected at 9335 MW_e conventional and 6400 MW_e nuclear. With adequate spacing, direct cooling could be utilized ~95% of the time. Further discussion of the St. Louis area will be included in a report of the Missouri Basin, to be issued in FY-1970.
- G.A.32: Includes Springfield, Decatur, Bloomington and Peoria, Illinois. Major source of direct-cooling capacity is middle and lower sections of the Illinois River. Approximately 1/2 of the 1970 capacity uses the Illinois River for cooling purposes. The remainder uses reservoirs or other forms of ancillary cooling. Because of significant coal reserves in the area, the increased generating capacity of 948 MW_e between 1970 and 1980 is expected to be fossil fueled. If adequately spaced, 500 MW_e could be accommodated by direct cooling in the lower Illinois River under low-flow conditions; the remainder would need partial or total recirculatory cooling. In 1990, 6480 MW_e, fossil fuel, and 3700 MW_e, nuclear, are projected for G.A.32. Partial or total ancillary cooling would be expected for additions beyond 1980.

- G.A.34: Lake Peoria section of the Illinois River. Present capacity is $\sim 300 \text{ MW}_e$; 1980 and 1990 nuclear capacities are projected to be 3000 MW_e and 6800 MW_e respectively. Approximately 1000 MW_e could be accommodated by direct cooling under low-flow conditions. Assimilative and dissipative capacities would be adequate during the average year and for 5 to 6 months of the low-flow year for direct cooling of projected 1990 loads.
- G.A.35: Chicago area. Also includes upper Illinois River to Starved Rock Dam. Present capacity of 8650 MW_e includes 1742 MW_e , nuclear plant at Morris. A cooling pond is presently under development for supplementary supply at the above plant. Expected 1970 loads are submarginal with respect to average cooling capacities during September in the Illinois River. Low-flow capacities are inadequate during the fall. Low-flow capacities during the winter months would also be submarginal if air temperatures approach water temperatures. Except for sites on Lake Michigan, increases in thermal loads beyond 1970 can be expected to require partial or full recirculatory cooling facilities. The 1980 and 1990 total steam generating capacity in G.A.35 is projected to be $13,176 \text{ MW}_e$ and $19,693 \text{ MW}_e$ respectively.
- G.A.36: Northwestern Illinois, including the Rock River Basin. Present capacity of 359 MW_e is expected to decrease to 158 MW_e by 1980. Projected 1990 capacity is 4200 MW_e , nuclear. If adequately spaced, partial recirculation and partial direct cooling with Rock River water could be utilized for 1990 loads. Maximum local capacities in the lower river are 1150 MW_T , 50% of the time and 300 MW_T , 99% of the time.

- G.A. 37: This area includes a section of the main stem Upper Mississippi River in the vicinity of La Crosse, Wisconsin. Projected 1980 generating capacity is 663 MW_e conventional and 550 MW_e nuclear. Direct cooling could be utilized for entire load. Total projected capacity for 1990 is 1120 MW_e; direct cooling is applicable.
- G.A.38: Chippewa River Subbasin, with population center at Eau Claire-Chippewa Falls, Wisconsin. Projected 1980 and 1990 steam generating capacity is 770 MW_e nuclear. Partial recirculation would be required during low-flow periods.
- G.A.39: Wausau-Stevens Point area of the Wisconsin River Subbasin. The 1980 and 1990 projected fossil-fuel generating capacities are 227 MW_e and 282 MW_e respectively. Direct cooling capacity is adequate.
- G.A.40: Generating area includes Madison, Wisconsin population center. Lower Wisconsin River and section of main stem Upper Mississippi River from mouth of Wisconsin River to state line are sources of direct-cooling water supply. Lakes in Madison area are headwaters of Rock River Basin. Projected increased capacity of 1980 is 1054 MW_e nuclear. If concentrated in a single plant, partial recirculation would be expected if not located on Mississippi River. The 1990 nuclear capacity is expected to be 2908 MW_e. Direct cooling could be utilized with several possible combinations of sites on the Mississippi and Wisconsin Rivers.

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APPENDIX

MAXPWR COMPUTER PROGRAM

APPENDIX

MAXPWR COMPUTER PROGRAMMAXPWR

MAXPWR was developed in coordination with J. L. Spurgeon of Computer Sciences Corporation. MAXPWR is a computer program used to determine the maximum number of power plants of a fixed size (megawatts) that can be placed at intervals specified by river section cards along a stream without exceeding a set maximum increment in temperature above the natural river temperature.

The system uses the heat budget method to determine the net loss of heat through the water surface. This method is represented by the equation

$$Q_t = Q_r - Q_e - Q_b + Q_h \quad \text{Btu/hr} * \text{ft}^2 \quad (1)$$

which is composed of the four equations which follow. The application of these equations is best understood by following the MAXPWR flow diagrams and flow diagram description.

Conduction

$$Q_h = 0.004665 * P * AMH * U * (T_a - T_w) \quad \text{Btu/hr} * \text{SF}$$

$$\text{COND} = 0.004665 \text{ Btu}/(\text{in Hg} * ^\circ\text{F} * \text{SQFT} * \text{mile})$$

$$P = 29.159 \text{ in Hg Standard Atmospheric Pressure}$$

$$AMH = 1. \text{ for } U \text{ in mi/hr}$$

$$U = \text{Wind speed at 400 ft in mi/hr}$$

$$T_a = \text{Air temperature, } ^\circ\text{F}$$

$$T_w = \text{Water temperature, } ^\circ\text{F}$$

Effective Net Insulation

$$Q_r = 3.6869 * \text{ABSORB} * \text{RAD}/24. \quad \text{Btu/hr} * \text{SQFT}$$

$$3.6869 \text{ Langleys} = 1 \text{ Btu/SQFT}$$

$$\text{ABSORB} = 1. \text{ Absorption}$$

$$\text{RAD} = \text{Net solar radiation for 24 hr period measured by radiometer} \quad - \text{Langleys}$$

$$24. = 24 \text{ hr}$$

Evaporation

$$Q_e = \text{EVAP} * U * (E_w - E_a) \quad \text{Btu/hr} * \text{SQFT}$$

$$\text{EVAP} = 13.766$$

$$U = \text{Wind Speed in mi/hr}$$

$$E_w = \text{Vapor pressure of saturated air at the water surface temperature} \quad \text{in. Hg}$$

$$E_a = \text{Vapor pressure of air at the dew point temperature}$$

Back Radiation

$$Q_b = \text{EMISS} * 1.714 \times 10^{-9} * ([T_w + 460.1 * * 4 - \beta * [T_a + 460.1 * * 4]) \quad \text{Btu/hr} * \text{SQFT}$$

$$\text{EMIS} = 0.970$$

$$1.714 \times 10^{-9} = \text{Stefan Boltzman radiation Constant}$$

$$\beta = \text{Atmospheric radiation factor derived from cloud cover (USGS, 1954)}$$

$$T_w = \text{Temperature at the water surface, } ^\circ\text{F}$$

$$T_a = \text{Air temperature above 20 meters, } ^\circ\text{F}$$

The MAXPWR system works on the following principles:

Let P be a unit volume of water. P enters the river system at the input temperature, $T_1 = T_{IN}$, as specified by the weather card. Let V_1 (cubic feet) and S_1 (square feet) represent the volume and surface area respectively. The 1st river section, then P has S_1/V_1 (square feet) of surface area while in river section 1. If the flow through RS_1 is F KCFS or FLOW, $- 3.6 \times 10^6 * F$ CFH, then the travel time for P through RS_1 is $H = V_1/FLOW$, hours. At this point the heat budget equations are evaluated with $Q_t = BTUS(T_1)$ Btu/hr * ft^2 . Now the value T_2 , the upstream end temperature of RS_2 and be determined

$$T_2 = T_1 + CONST * Q_t * S_1/V_1 * \frac{(V_1)}{Flow_1} \quad (2)$$

Equation (2) would tend to overstep in the direction of the sign of Q_t . To dampen or eliminate this effect, several smaller steps are taken within the river section. The effect of this is that Q_t alternates in sign and becomes smaller in absolute value. Thus T_2 can be determined with a fair degree of accuracy. This procedure can be controlled by the Control Card parameter DTLIM.(0 C°) where the first step cannot exceed DTLIM in absolute value. See the MAXPWR diagram and diagram description for further details on this procedure.

The procedure for determining T_{i+1} given T_i given T_I is analogous to the above procedure. T_i denote the temperature of the water as it passes the river cross section at the upstream end of river section i.

In addition to the proceeding, the MAXPWR system also injects heat into the water and adds flow by means of sidestreams.

To satisfy the requirement that the heated river does not exceed the natural river temperature plus a prescribed limit

DTMAX ($^{\circ}\text{C}$), the system computes both the natural river temperature T_{N_1} and heated river temperature T_1 as described earlier. When the two temperatures differ sufficiently to accept a unit of advected heat into the heated river without violating the above limit, the heat is injected at the upstream end of the river section and T_1 is adjusted to reflect the added energy.

MAXPWR DIAGRAM DESCRIPTION

10: Re-entry point of program for running multiple cases.

CONTROL CARD:

- NI: Number of river section cards. Enter 0 if river section from previous case are to be used.
- IFMT: Weather card format type. Enter 0 for Hanford type, or 1 for Illinois type. (See reference for description of this difference).
- NST: Number of sidestream temperature cards.
- NSF: Number of sidestream flow cards.
- DTMAX: The maximum temperature increment that the heated river is allowed to rise above the natural river, $^{\circ}\text{C}$.
- DPWR: The power increment (megawatts) for injecting into the stream whenever possible.

WEATHER CARD:

As used in the COLHEAT system and described in Appendix 'A'.

- INITIALIZE: The program is initialized from information supplied by the control and weather cards.
- NI: See CONTROL CARD.
- MAXRES: Reads the river section cards and sets up the model.
- FTIME: Reads the sidestream cards if any, determines river section flows and flow times.

MAXQ: Evaluates all values for the heat budget equation except those values dependent upon water temperature.

INLET: Set the system inlet temperature to the inlet temperature specified on the weather card for the natural river T_{N1} , and to $T_{IN} + DTMAX$ for the heated river T_1 .

Determine the rise in Temperature, (C°), from advesting $DPWR$ megawatts into the upstream end of river section I.

SIDESTREAM: The efforts of a sidestream have already been determined with a flow rate and travel time in subroute FTIME. The sidestream is considered completely mixed at the upstream end of the river section, and it may come in at a specified temperature, the natural river temperature or the heated river temperature. When the sidestream goes into the heated river at the heated river temperature, it goes into the natural river at the natural river temperature.

POWER
INJECTION: The rise in temperature (C°) from injection of $DPWR$ megawatts at the upstream end of river section I with $FLOW$: (CFH) is known. $T_N + DTMAX$ is the maximum river temperature allowed, T is the current temperature of the heated river, and ST is the rise per injection. Thus $N = \text{largest integer in } (T_N + DTMAX - T) / ST$ is the number of plants to install.

$T_i = T_1 + N * ST_i$ is the new temperature at the upstream end of river section I after installation of N plants. Note: N is commonly 0.

HEAT BUDGET:

TAU: Travel time of water through river section I.

AV: $1/(1.8 \text{ } ^\circ\text{F}/^\circ\text{C} * 62.4 \text{ lb/CF})$

S: Surface of river section I SQ FT.

V: Volume of river section I CU FT.

BTUS

(Ti): Evaluation of heat budget equations for heated
temperature, T BTU/(SF*HR)

BTUS

(TNi): Evaluation of heat budget equations for natural
river temperature BTU/(SF*HR)

DTLIM: See control card.

N: Number of iterations through river section I to
determine $T_I + 1$ and $TNi + 1$ without exceeding
DTLIM on any one iteration.

TN1: Natural river temperatures between the upstream
and downstream ends of river Section I.

T1: Same as TN1 except for heated river.

PRINT: Print results of the above computation. River
section name and location natural and heated
river temperature, power injected if any, and
sidestream affect if any.

NEXT I $\leftarrow$ I + 1: If I = NI continue the process for river
section I + 1 form D200.

PRINT: Print summary of the above results.

10 Return to beginning for next case.

MAXPWR Diagram

MAXPWR (contd)

MAXPWR (contd)

MAXRES Subroutine Diagram

FTIME Subroutine Diagram

FTIME (contd)

BTUS Subroutine Diagram

MAXQ Subroutine Diagram

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