Project Report No. 76

EFFECTS OF CONDENSER COOLING WATER DISCHARGE FROM PROJECTED ALLEN S. KING GENERATING PLANT ON WATER TEMPERATURES IN LAKE ST. CROIX

by
Edward Silberman and Heinz G. Stefan

Prepared for
NORTHERN STATES POWER COMPANY
Minneapolis, Minnesota

December 1964

CONTENTS

LIST OF FIGURES

EFFECTS OF CONDENSER COOLING WATER DISCHARGE FROM PROJECTED ALLEN S. KING GENERATING PLANT ON WATER TEMPERATURES IN LAKE ST. CROIX

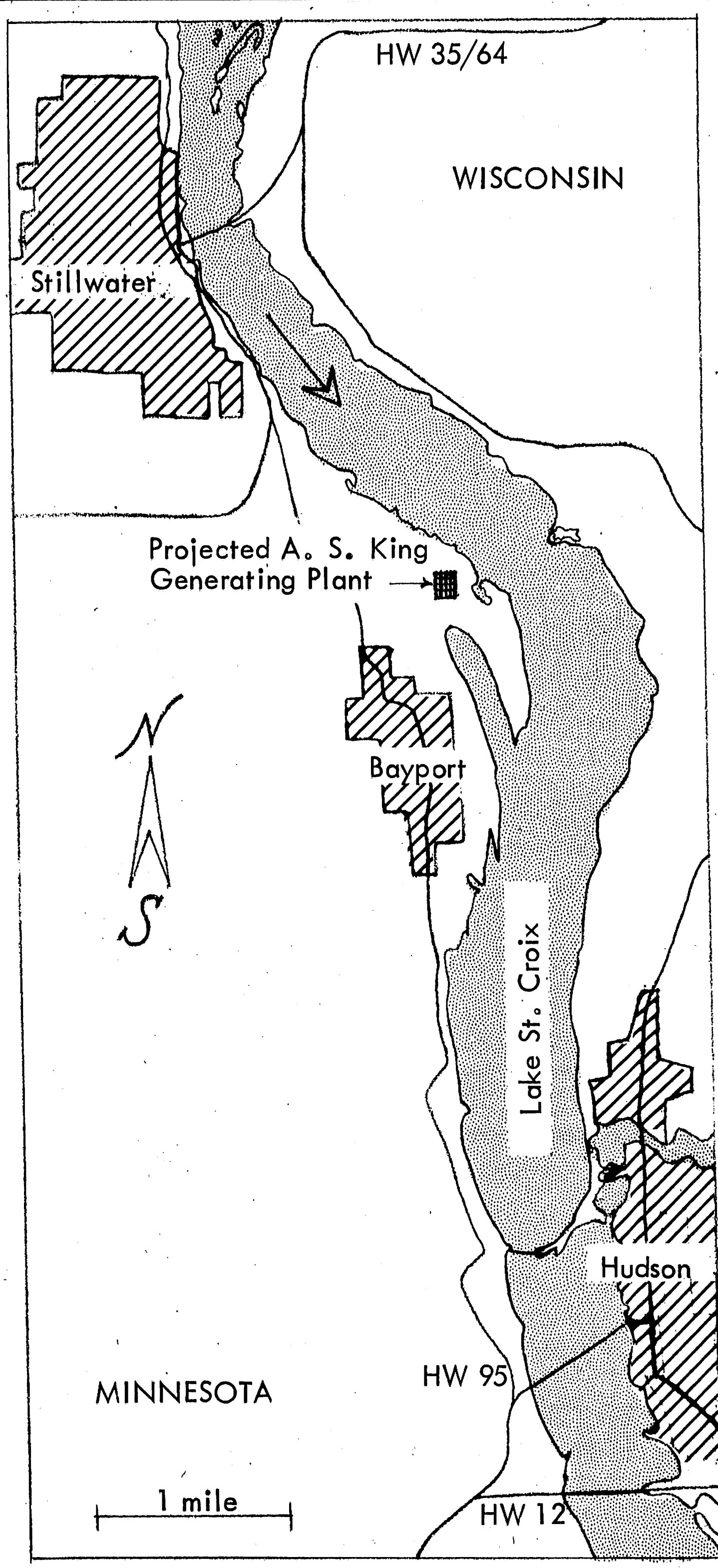
INTRODUCTION

The Northern States Power Company plans to build a thermal power plant near the St. Croix River at Lake St. Croix between Bayport and Stillwater, Minnesota, at the location shown in Fig. 1. The plant is to be known as the Allen S. King Generating Plant. Operation of the plant requires water for condenser cooling which will be drawn from nearby Lake St. Croix. After use, this water with a higher temperature will be returned to the lake at a location downstream from the intake.

At the request of Northern States Power Company, the St. Anthony Falls Hydraulic Laboratory, University of Minnesota, has studied effects of the withdrawal and return of condenser cooling water on water temperatures in Lake St. Croix. This report presents the results of the study, including mainly information on isotherms at the lake surface for summer and winter conditions and possible limits of ice cover. Also presented are temperature profiles in depth and time required for warm water to spread. In addition, a little information is given on flow of sewage water released from the Stillwater municipal sewage plant into the lake and on flow conditions near the cooling water intake. Results were obtained by analytical methods based on model tests.

Basic data for the study were obtained largely from a booklet dated August 21, 1964, and later revisions thereof prepared by the Northern States Power Company and entitled "Allen S. King Generating Plant Unit No. 1, Oak Park Heights, Minnesota." These data were supplemented by other information obtained from the power company, by a meeting with the Minnesota Department of Health on October 26, 1964, and by a report of the Minnesota Department of Conservation dated November 9, 1964, dealing with water temperatures and flows in the St. Croix River. Climatological data when required were obtained from various publications of the U. S. Weather Bureau, and the lake geometry was obtained from the 1932 soundings of the U. S. Army Corps of Engineers supplemented by soundings taken during 1964 by a firm engaged by the power company.

Fig. 1 - Location of Allen S. King Generating Plant Showing Limits of the Model (148B443-43). Lake St. Croix is from 20 to 40 ft deep from just below the highway bridge at Stillwater to the upstream constriction at Hudson.



NORTHERN STATES POWER COMPANY
ALLEN S. KING GENERATING PLANT
Location of Plant

SAINT ANTHONY FALLS HYDRAULIC LABORATORY
UNIVERSITY OF MINNESOTA

DRAWN JR	CHECKED	APPROVED
SCALE 1:60,000	DATE 12-11-64	NO. 148B443-43

Fig. 1

This study has been under the general direction of Professor Edward Silberman with technical supervision by Dr. Heinz Stefan. Professor C. E. Bowers also participated in the technical aspects of the study. Messrs. Warren Dahlin, A. C. Young, H. S. Chang, and J. R. Riis provided technical assistance.

THE NATURE OF THE PROBLEM

It is proposed to circulate approximately 700 cfs of condenser water from the lake through the Allen S. King Generating Plant during summer and to raise the temperature of this water 17° F. During winter, only about 400 cfs will be circulated, but its temperature will be increased by 30° F. In a possible future expansion of the plant, 1500 cfs will be raised 17° F during the summer months. The basic problem is to determine how the added heat will affect the maximum temperatures in Lake St. Croix during summer and the ice cover during winter.

Ultimately, all heat from the condenser cooling waters will be dissipated to the atmosphere. The first question to be resolved concerns the mechanism by which this dissipation will be accomplished. The following mechanisms are possible:

1. The cooling water mixes with the flow in the St. Croix River and is carried away by the river. Cooling is largely by dilution at first, the entire river flow becoming a few degrees warmer than normal. Heat rejection to the atmosphere proceeds at a slow rate as the flow proceeds downstream because of the small temperature excess at the water surface. This type of cooling is exemplified by the existing Northern States Power Company Riverside Plant on the Mississippi River in north Minneapolis.

2. The cooling water mixes very little with the river water but rather, due to its smaller density, forms an overriding warm layer at the surface. This layer spreads over the lake surface much like oil over water at a speed that is large compared to the river speed. Hence, the warm water may move upstream and recirculation is possible. However, heat rejection to the atmosphere proceeds much more rapidly than for the case of mixing because of the higher surface

temperatures. This mechanism is only possible at low river speeds and low injection speeds of the condenser water; high river speeds promote turbulence and mixing. This type of cooling is exemplified by the cooling pond technique used widely in the Southwestern United States [1]* as well as in other areas.

3. Combinations of the above two methods occur wherein there is some dilution by mixing and some cooling by ponding. The Northern States Power Company Blackdog Plant on the Minnesota River near Bloomington appears to be in this class, but more typical examples are described in a French paper [2]. The flow mechanism has been analyzed in detail by Bata [3].

It was at first believed that the projected plant on Lake St. Croix would operate by the third mechanism. Preliminary studies were based on this assumption and the model study described subsequently was at first designed with this mechanism in mind. However, as the study progressed and the model operation was observed, it became apparent that during critical periods of low flow it is the second mechanism, cooling by ponding, by which heat will be rejected to the atmosphere. The reasons for this conclusion are outlined in the following paragraphs.

The hottest natural water surface temperatures occur on Lake St. Croix during late July and early August of each year. Thus, heat addition from the generating plant will be most objectionable at this time. River flows are usually low during this period, the monthly mean falling below 2,000 cfs about 30 per cent of the time in August. With the known cross section of Lake St. Croix, 2,000 cfs corresponds to only about 0.015 fps average velocity. Thus, the river in this region is aptly called Lake St. Croix. The velocity is so low that the water surface remains essentially level at about 675 ft MSL as determined by the Red Wing Dam about 30 miles downstream.

The outlet from the proposed generating plant to Lake St. Croix will be by a wide, shallow surface canal or, alternatively, through the bay near Bayport. Velocity in the canal at its outlet would be of the order of 0.25

---

*Numbers in brackets refer to the List of References.

fps in the first-stage development and about 0.50 fps in the ultimate plant. For discharges through the bay, velocities will be only about one-fourth of the canal velocities. Thus, warm water will be discharged near the lake surface and, with the small river velocity and not very large canal or bay velocity, there will be only a little mixing. (See Appendix C.) The warm water will float because of its lesser density. Observations in the model study described later support this conclusion. Even though there may be some mixing with the lake water near the outlet, the mixture will simply form a somewhat thicker, warm, floating layer of only slightly less maximum temperature than would have formed without mixing, and this layer will then spread over the lake surface.

Calculations described in Appendix C show that the spreading velocity of the warm layer is of the order of 0.30 fps near the outlet, twenty times the average river flow velocity. Hence, under midsummer conditions, the warm layer can be expected to spread almost as if there were no river flow at all. The problem then becomes the typical cooling pond situation described above as the second mechanism, and the actual river flow has little influence on cooling.

At larger river flows, there will be more mixing and, because of dilution, maximum temperatures will be less than those calculated from the cooling pond situation. (The increased temperature will also persist further downstream, of course, and will not reach as far upstream.) The cooling pond situation is thus the critical one and has been chosen for detailed study. In fact, to obtain the worst possible situation the study has been carried out in detail for zero flow in the river as well as for flows as large as 2,000 cfs.

The winter situation in January is very similar to the summer situation. Low flows of the order of 2,000 cfs or less may be expected about 50 per cent of the time and the lake will act like a cooling pond. Cooling pond calculations may then be used to estimate the location of open water areas, and this has been done in the report. Of course, when the river discharge increases, the open area will shift downstream in the same manner as the warm water areas shift downstream in summer.

Once it was determined that the critical heat dissipation problem was largely a cooling pond problem it was possible to divide the study into two

independent steps. First, the hydromechanic flow problem was studied in a hydraulic model to obtain flow patterns. Then, the heat transfer to the air was calculated separately and this calculation was applied to the flow patterns to obtain surface isotherms. These two steps are described in the two following sections.

THE MODEL STUDY

The purpose of the hydraulic model study was mainly to determine the surface flow patterns produced by the spreading of hot water over Lake St. Croix. It was also possible to use the model to estimate depths of the hot water layer and times for the hot water to progress from one position to another on the lake surface, but these purposes were secondary and are better accomplished by direct calculation as will be discussed later.

To model the flow patterns, it was decided to build a geometric model of the Lake St. Croix area from downstream of the Stillwater bridge to just upstream of the railroad bridge at Hudson. The model was limited to this reach. This was done first, to avoid making the model scale too small (4 miles is involved here); secondly, there would be little point to modeling a longer reach because the river is narrower and shallower at the Stillwater bridge and much narrower at the railroad bridge in Hudson; velocities at these constricted regions would be large enough to raise a question as to whether or not the warm layer would remain stratified if it reached this far. The model could not answer this question and could not reproduce the flow if mixing occurred; hence, there was no use in extending the model beyond these points.

The area that was modeled is indicated on Fig. 1; Fig. 2 is a photograph of the model showing key structures. A distorted scale was used. A 1/500 horizontal scale was chosen to accommodate the model in the area available, while a 1/30 vertical scale was needed to assure that the stratified surface layer would be thin compared to the depth of water in the model, a requirement that will become apparent from further discussion. A submerged intake structure and an outlet canal for the condenser cooling water were incorporated in the model in accordance with the design plans for the power plant. The model was constructed so that the condenser discharge could flow either to the bay or through the canal directly to the lake. More detailed information on the construction of the model may be found in Appendix A.

Fig. 2 - The Hydraulic Model of Lake St. Croix (Photo No. 148-624). The photograph is taken looking downstream toward the proposed generating plant. Condenser water could be discharged either through the bay (D) or the cooling water outlet (C).

A = Location of Plant
B = Cooling Water Intake
C = Cooling Water Outlet
D = Bay
E = Sewage Outlet

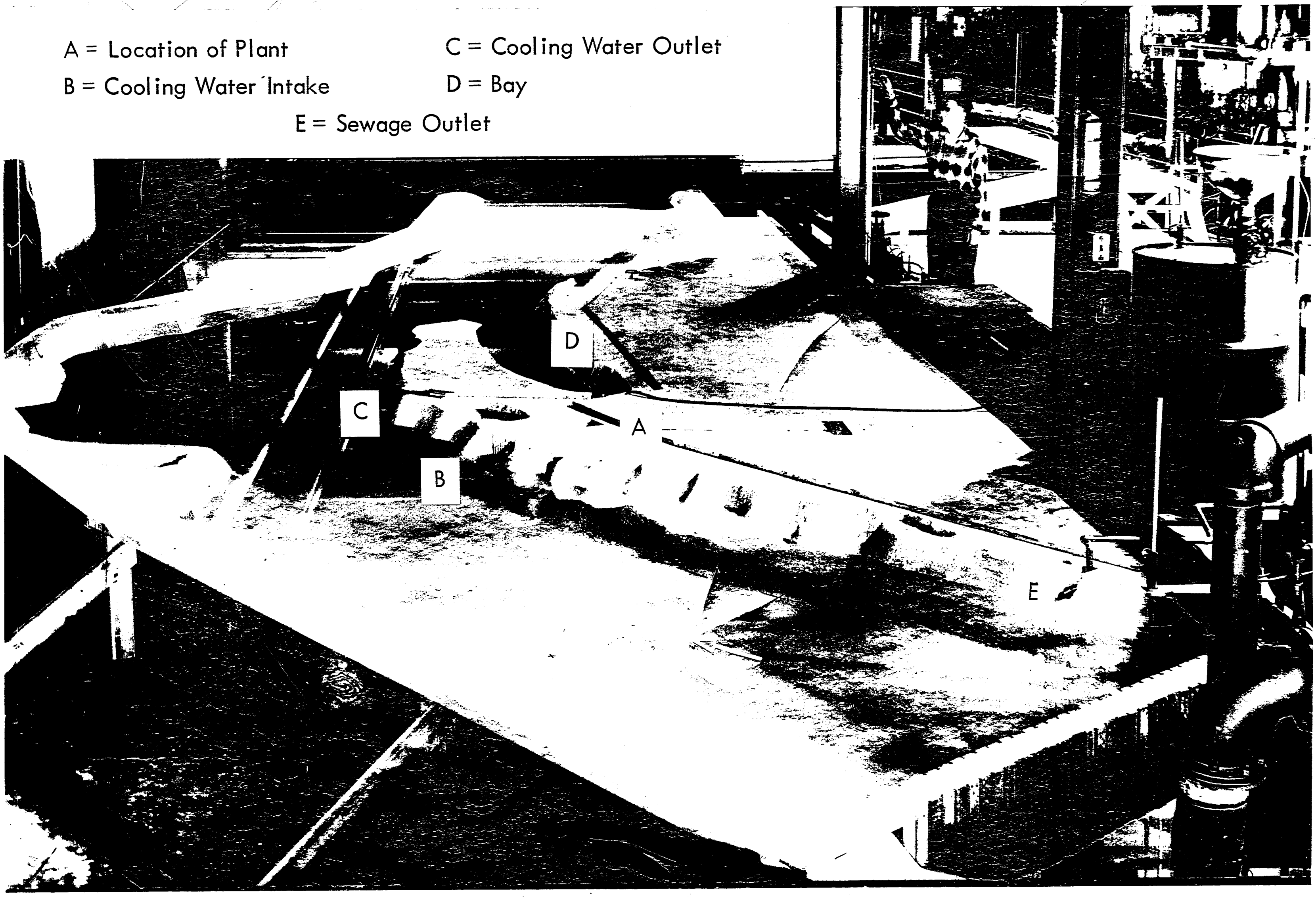


Fig. 2

The method of studying flow patterns in stratified flow which is used in this model study has been previously used by other investigators. Barr has been particularly active in this field and his 1959 paper [4] is typical of this type of study. Barr used heated and cold water in the investigations for the paper referred to in order to obtain stratified flow, but both he and other investigators have generally found it better to use fresh and salt water for this purpose. In the present study, since it is mainly flow patterns which are being sought in the model, it matters not how the stratification is produced. The model discharge flow rates were so large that the use of heated water was impracticable in this case and only the fresh and salt water combination was available. (Even when hot water is used in the model to represent the surface layer, it is not possible to model the cooling because so many factors other than flow rate become important; the wind speed, relative humidity, sun, and other factors cannot be modeled satisfactorily at the same time.) Hence, in the model, cold heavy water was represented by brine or salt water while warmer, less dense water was represented by fresh water. To facilitate photographic data recording, the fresh water was dyed red with a vegetable dye.

The model was operated by pumping salt water through the lake to represent the river flow, by withdrawing water (usually brine) at the submerged plant intake at the specified intake rate, and by returning colored fresh water at the same rate through the outlet. A control weir at the downstream end of the model was manipulated to maintain the lake surface at 675 ft MSL elevation during operation of the model.

River discharges of 0, 700, 1300, and 2000 cfs were initially chosen for study after consideration of the hydrologic data outlined in Appendix B. The results obtained for these discharges showed that there was little influence on flow patterns due to flow rate and that results for intermediate discharges could be obtained by interpolation between the maximum and minimum discharges. Later experiments were confined to 0 and 2,000 cfs river discharges. Condenser discharge rates used in the study were based on the plant design mentioned earlier and were 400, 700, and 1500 cfs. The 400 cfs rate (corresponding to 395 cfs in the plans) applies to one-pump operation during cool weather, the 700 cfs rate (corresponding to 660 cfs in the plans) applies to two-pump operation during warmer weather, and the 1500 cfs rate to a possible future expansion of the plant.

A discharge scale ratio of 1/12,000 was applied to the condenser discharge so that turbulent flow would be guaranteed in the outlet cross section of the bay and the discharge canal for the 400 cfs condenser rate. The discharge scale ratio for the river flow was properly about 1/25,000, but it was not very important and 1/12,000 was also used for this ratio in some of the experiments.

The scale ratios between model and prototype are listed in Table I and are completely analyzed in Appendix C.

Model tests were conducted for several combinations of river and condenser flow rates. The combinations fow which heat loss calculations were eventually made are shown in the last column of Table III, but a few other combinations were also tested. In the model tests, condenser outlet water was discharged to the bay in the first set of experiments and directly to the lake through the excavated canal in subsequent experiments as shown in Table III. In the experiments with discharge through the canal, a narrow canal cross section was used at first, but the experiments reported upon herein are based only on the use of the wide canal with a surface width of about 330 ft.

In all the experiments it appeared that the lighter water, on reaching the lake, formed a thinning, wedge-shaped layer over the salt water. The lighter layer spread over the lake in all directions, the exact pattern depending somewhat on the flow in the river. The fresh water layer was quite thin compared to the depth of the lake and mixed very little with the heavier bottom water except in the immediate vicinity of the outlet and the intake. The spreading patterns were observed photographically at short time intervals from the beginning of each test. Figures 3a and 3b illustrate the spreading for two separate flow conditions; each pair of pictures shows two successive photographs taken near the canal outlet as the dyed, fresh water spread over the clear, salt water in the lake. A composite picture showing the dye fronts corresponding to Fig. 3a as time progresses may be seen in Fig. 4. The fronts seen in Figs. 3 and 4 are lines of constant density in the model. They separate fresh water from salt water at the surface. Such lines were plotted for each model test from photographs like those shown in Fig. 3 without actually making composite pictures like Fig. 4. (The resulting plots are similar in appearance to Charts 1 through 30,

Fig. 3 - Spread of Density Front near the Canal Outlet in the Model.

3a (Photo Nos. 148-333 and -334)

River Flow	0 cfs
Condenser Flow	400 cfs

3b (Photos Nos. 148-449 and -450)

River Flow	2000 cfs
Condenser Flow	1500 cfs

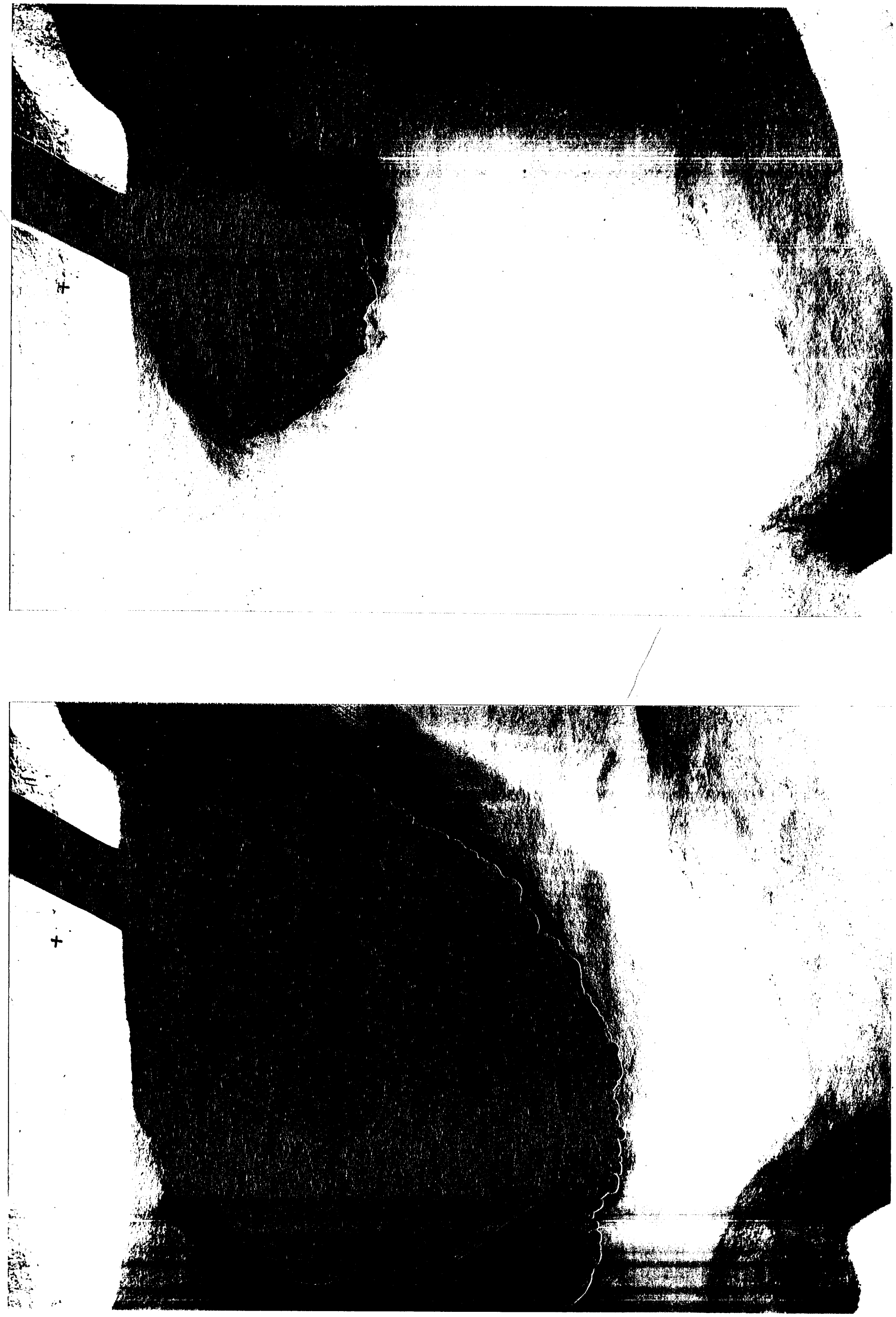


Fig. 3a

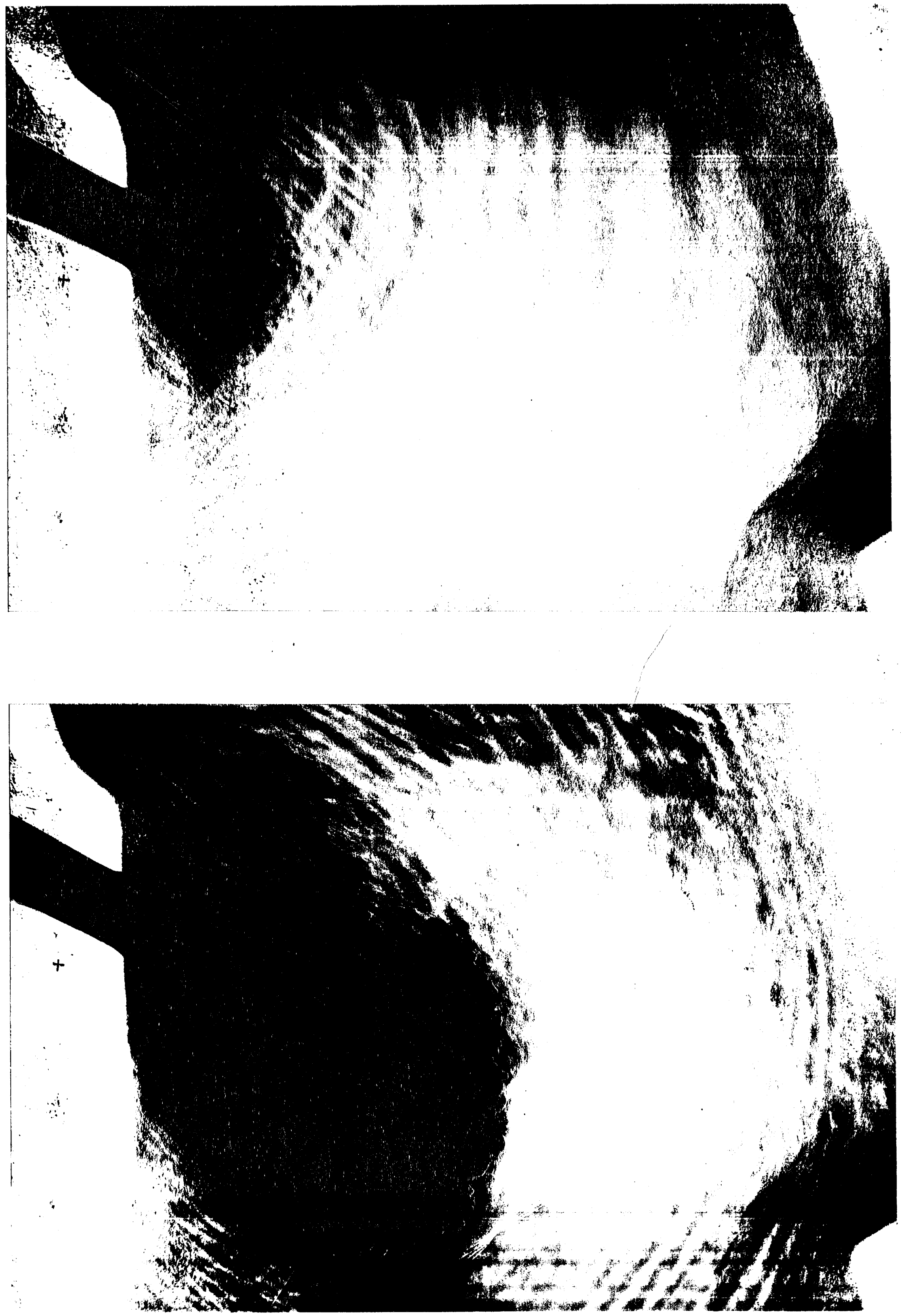


Fig. 3b

but with fewer lines since many of the lines in the charts have been obtained by interpolation.)

Most of the model experiments were made using a brine solution with a specific gravity of 1.01 compared to the fresh water. However, some additional experiments were made using a solution with a specific gravity of 1.04. The photographs of the flow patterns show no difference in the shapes of the fronts for differing specific gravity with the flow rates held constant. It was thus concluded that the pattern of spread would be independent of the choice of density scales. (However, the thickness of the layer and the time scale do depend on the time of relative density as discussed in Appendix C.) This is an important fact which makes it possible to represent the varying density on the lake surface due to cooling by a surface layer of constant density in the model. A similar result was found by Barr [4].

It is thus apparent that the dye fronts of Figs. 3 and 4, which are lines of constant density in the model, represent lines of constant density in the prototype and, thus, isotherms, on the lake surface. The differences between model and prototype are that each line of constant density in the model has the same density, while in the lake each line has a greater density than the previous one because of cooling at the lake surface; also, the times involved in going from one line to another are not proportional in model and prototype as discussed in Appendix C. An additional assumption involved is that local mixing between the upper layer and the rest of the fluid is of the same relative intensity at a given point in the model and prototype. Since it is shown in Appendix C that the mixing is small everywhere away from the intake and outlet, the latter is not an important assumption.

Photographs like those in Figs. 3 and 4 also showed that the flow pattern was little influenced by flow rate (only the time was affected) within the ranges used for the model study. This is well illustrated by comparing Figs. 3a and 3b, which are for flow near the outlet with extreme ranges in discharge. Further from the outlet, small differences in pattern become apparent as the flow rate varied over the complete range, but the changes were still small enough that patterns associated with intermediate river discharges between 0 and 2000 cfs could be obtained by interpolation.

Once the flow patterns and lines of constant density were obtained from the model photographs, the surface temperatures on Lake St. Croix were

Fig. 4 - Composite Picture of Density Fronts (Photo Nos. 148-625 and -660). The upper photograph has been produced by montaging photographs like those shown in Fig. 3. The photographs cover the entire time required for the front to spread from the outlet to the limits of the model. The lower photograph shows the successive density fronts more clearly, the background having been painted out. The river flow is 0 cfs and the condenser flow is 400 cfs.

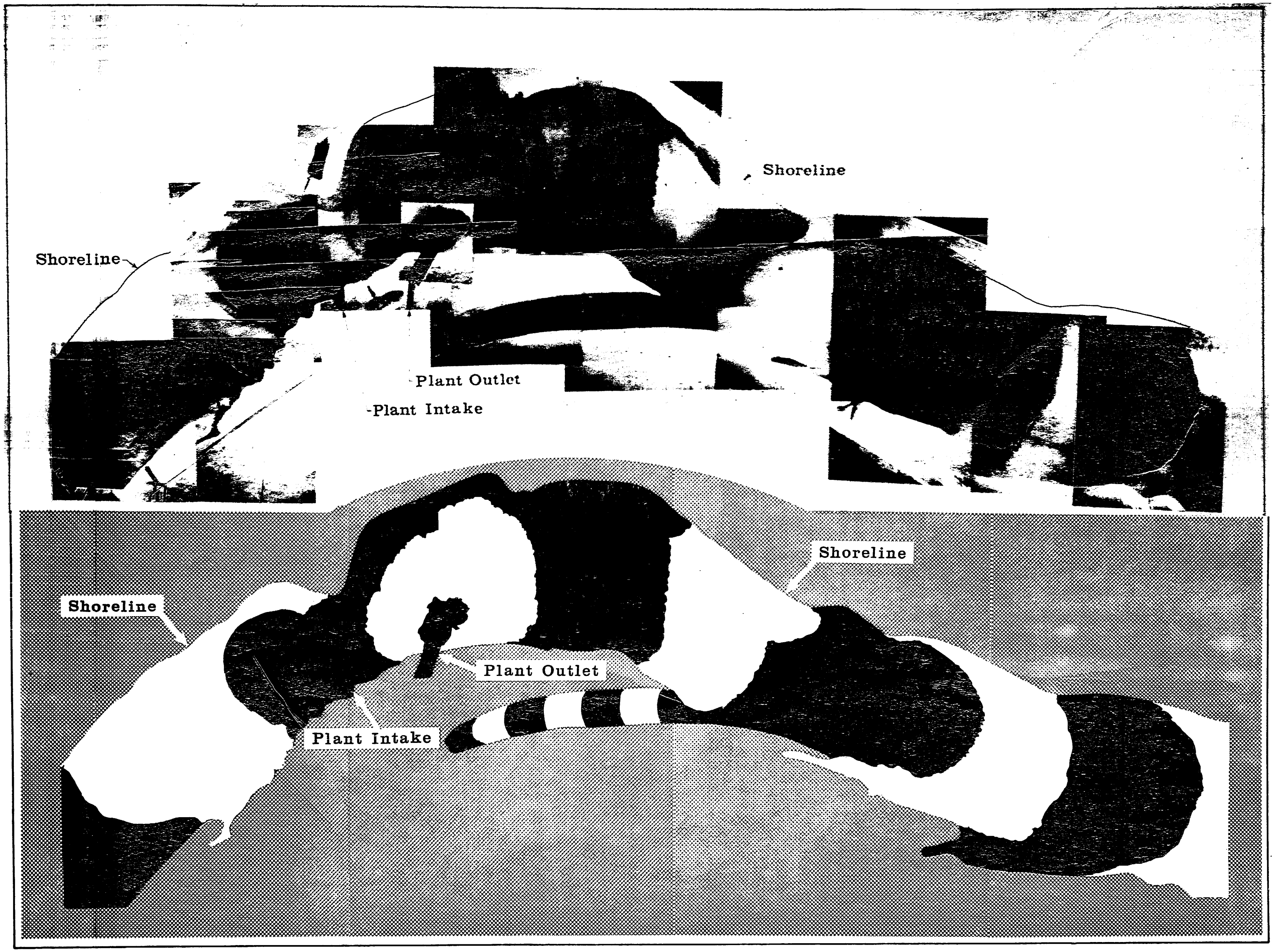

Shoreline
Shoreline
Plant Outlet
Plant Intake
Shoreline
Shoreline
Plant Outlet
Plant Intake

Fig. 4

determined by calculating the heat loss from the lake surface. This step is discussed in the next section of this report and the final results are then presented in Charts 1 through 30 and 33 and are discussed in the last section of the report.

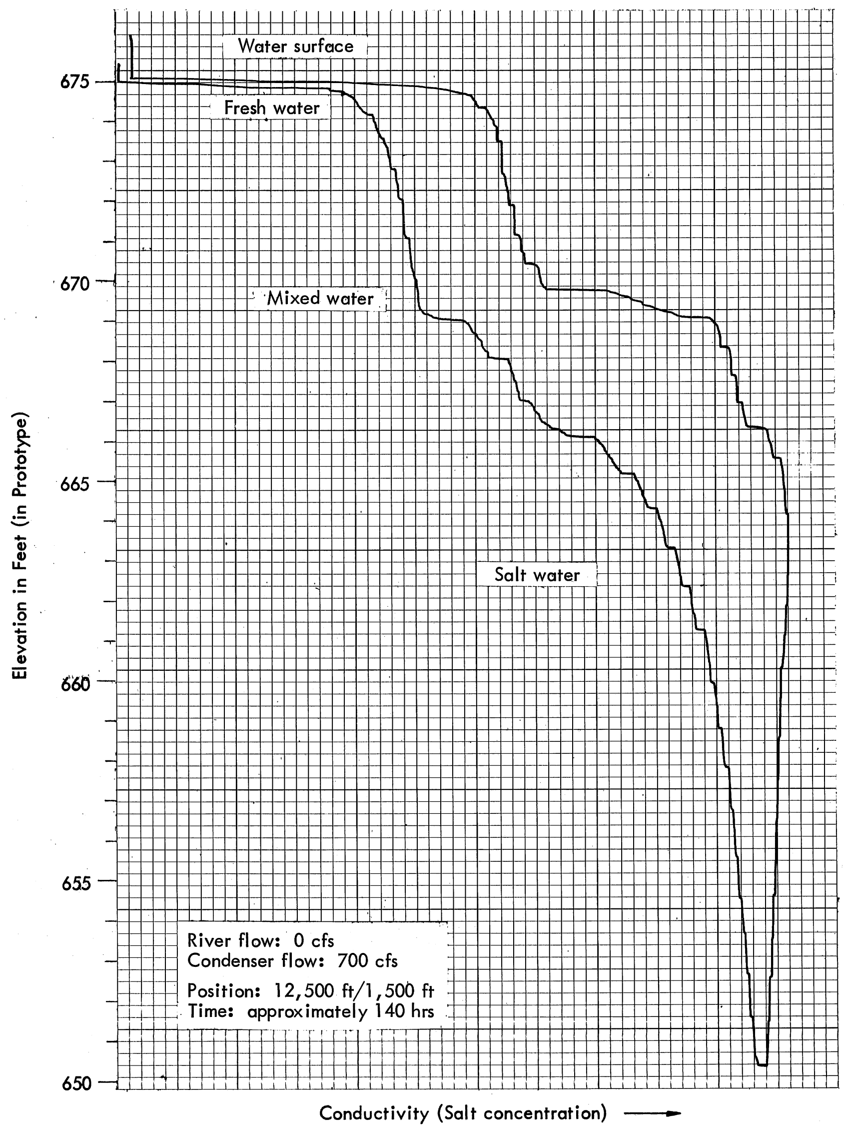
In order to have an appreciation of how accurately the model represents the actual warm water flow in the lake, phenomena which have not been represented adequately in the model have to be taken into account. The two most important of these are mixing due to turbulence at the interface between the warm and cold water and wind effects. The criterion for intensity of mixing at the interface in a stratified flow is the Richardson number which is discussed in Appendix C. For Richardson numbers smaller than unity [5], mixing tends to become important. Small Richardson numbers may occur in the intake and outlet regions and, hence, it may be expected that the flow in this immediate vicinity may not be correctly represented in the model. In fact, it is shown in Appendix C that there is likely to be more relative mixing in the model at these locations than there is in the actual lake. With the exception of these two locations, however, the Richardson number is easily shown to be of the order of unity or larger, and mixing is not an important phenomenon in the spreading of warm water, at least as long as there is a temperature difference of a few degrees between the cold and warm water. Therefore, the spreading patterns of the warm water are relatively unaffected by mixing and are adequately represented in the model.

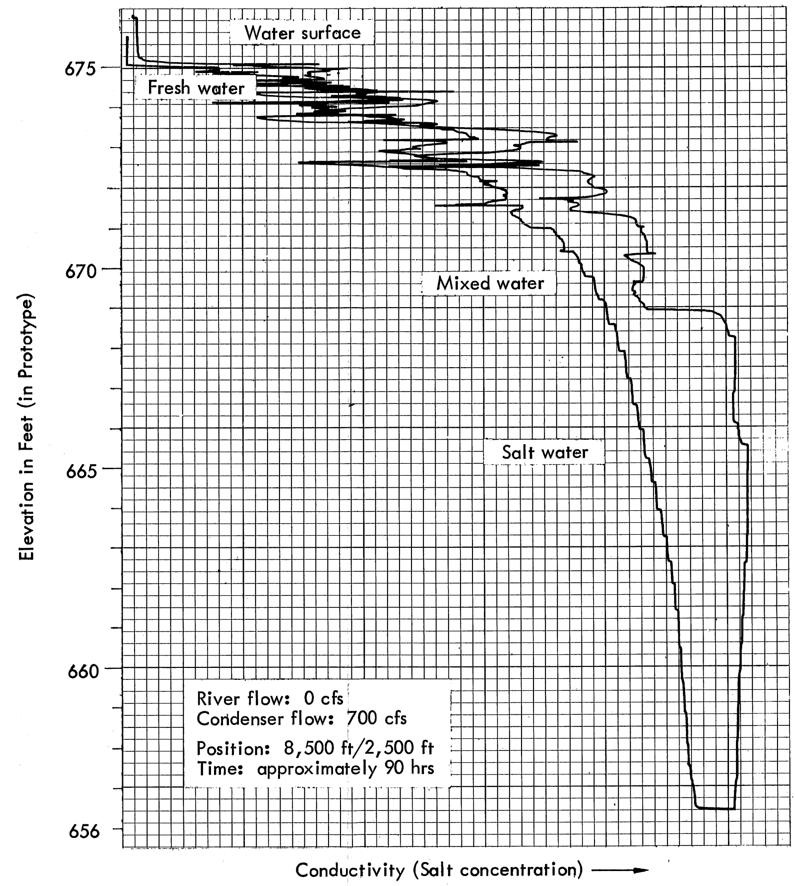
Wind effects may be twofold; besides creating surface waves and thereby mixing the surface and lower layers, the wind also changes the surface slope of the lake through surface friction. The mixing associated with waves is counter-balanced by additional cooling as discussed in the next section. Surface friction tends to shift the warm water in the wind direction, cooling at the same time, and "piles up" warm water on the lake shore. The "piling up" of surface water may set up large-scale circulations in the lake since the "piled up" water needs to return upwind at a lower level. Thus, warmer waters may be brought beneath the surface during strong winds. Fortunately, the plant intake is so favorably located with respect to the lake topography that these returning currents will not bring surface water to the intake until it has been greatly cooled by evaporation from the wind at the lake surface and by dilution in the lake interior.

Not only were flow patterns obtained from the model study, but also an attempt was made to verify the theoretical law for thickness and spreading velocity of the surface layer as discussed in Appendix C. To this end, the time from the beginning of flow was recorded for each flow photograph like those shown in Fig. 3; thus, the plotted flow pattern charts showed a time interval from one flow pattern to another. By multiplying the time interval between two pattern lines by the known discharge from the condenser and dividing the result by the surface area contained between the lines, an average thickness was obtained for the layer in the model. (The calculation is carried out in Appendix E.) This calculation was possible because it was observed in the model that the colored water layer spread in approximately the same pattern throughout its thickness. (This calculation assumed no mixing. If mixing was so great as to entrain 50 per cent more flow--an unlikely result--the calculated thickness would also have increased approximately 50 per cent.) Some typical thicknesses in the model measured in this manner are shown in column (2) of Table II, where they are compared with calculations by the method of Appendix C, shown in column (4).

The thickness of the stratified layer in the model was also obtained by the use of electrical conductivity probes. These probes measured the variation of salt concentration with depth. Two typical recordings are plotted in Fig. 5, where depths are shown at prototype scale but should be interpreted as prototype depths with caution for the reasons explained below. The graph on the left represents a point about a mile from the canal outlet near the Wisconsin side of the lake; it shows a thin, constant density layer of less than one-foot thickness followed by a mixed layer of much greater density and of about 5-ft thickness and, finally, the original salt water at about 9-ft depth. It must be understood that in the model, fresh water of constant density is being continually added at the water surface, whereas with the zero river flow, salt water is being withdrawn at the same rate from the bottom. Thus, as time goes on, the fresh water layer penetrates deeper in the model. By the time the data of the left graph of Fig. 5 were taken, fresh water equivalent in depth to 3 ft over the lake surface had been added to the model. However, in the prototype, the surface water is being cooled as it spreads so that warm water penetration will reach an equilibrium condition at a lesser depth than indicated by this graph.

Fig. 5 - Salt Concentration Profiles as Measured with Conductivity Probe (148B443-59). The two lines on each graph result because fresh water from the surface layer clings to the probe as it is lowered into the salt water and salt water clings to the probe as it is raised into the fresh water. The true profile lies somewhere between the two lines.





NORTHERN STATES POWER COMPANY
ALLEN S. KING GENERATING PLANT
Salt Concentration Profiles as Measured with Conductivity Probe

SAINT ANTHONY FALLS HYDRAULIC LABORATORY
UNIVERSITY OF MINNESOTA

DRAWN ACY	CHECKED	APPROVED
SCALE	DATE 12-22-64	NO. 148B443-59

Fig. 5

The right graph of Fig. 5 was obtained near the canal outlet; this shows much turbulence near the surface with a rapid increase in density until the water reaches its original salt density at 6-ft depth. As explained in Appendix C, this initial depth is probably too great in the model because of excessive mixing.

Although the depths cannot be interpreted too literally, the qualitative picture given by the records in Fig. 5 probably represents quite well the situation that will be encountered in Lake St. Croix during operation of the plant. This model result is similar to results found in a model study by Hamada [12]. (It should be explained that the double lines in the graphs of Fig. 5 are produced by fresh water clinging to the probes and insulating them as they are traversed downward, while some salt water clings to the probes as they are raised. Also, the probes were only traversed far enough to reach the original salt water and were not traversed to the bottom of the lake.)

As Table II shows, the methods of Appendix C can be applied with some success to calculating the thickness of the stratified layer in the model, especially away from the outlets. On this basis, it was assumed that the same methods could be applied to obtain the thickness and spread velocity of the warm water on Lake St. Croix. Typical calculations for the prototype have been carried out in Appendix E and are also tabulated in Table II.

The model was also used for a brief study of sewage flow from the Stillwater outlet into Lake St. Croix. This model study is described in Appendix G.

HEAT TRANSFER FROM THE LAKE SURFACE

Having determined the shapes of the surface isotherms on Lake St. Croix in the model study, the next step was the establishment of the temperature value on each isotherm. Prediction was accomplished using the methods of cooling pond calculations [13, 2]. These methods are well established and will only be outlined in this report as they apply to the Lake St. Croix situation.

The discharge of heated water into Lake St. Croix upsets its natural heat balance. The natural balance may be inferred from the report of the Minnesota Department of Conservation dated November 9, 1964, which is discussed in Appendix B. It should be observed that the natural heat balance is a statement of average conditions measured during daytime hours. Lake surface temperatures fluctuate about their average values from day to night and from day to day. The maximum surface temperatures, on the average, occur during late July and early August. During this period, temperatures at 10-ft depth will be of the order of 2° F less and at the lake bottom 4° F less than the surface temperatures.

Once the plant is in continuous operation, a new heat balance will be established. This new balance involves a surface water temperature sufficiently higher than the natural state so that the excess heat energy added by the condenser cooling water will be dissipated to the atmosphere. Under the cooling pond conditions that exist in Lake St. Croix, it is only necessary to calculate the increase in surface temperature required to dissipate this excess heat; it is not necessary to recalculate the entire natural heat balance of the lake.

Having taken no credit for cooling by dilution in accordance with the earlier statement of the problem, it can be shown that the excess heat is dissipated through the lake surface mainly by radiation, conduction, convection, and evaporation. These phenomena are related to water temperature, air temperature, relative humidity, and wind speed. The necessary climatological data are summarized and discussed in Appendix B. The methods of Throne [13] and Mandelbrot [2] which have been used in this report permit the calculation of an excess heat transfer coefficient from the data. It turns out that a large fraction of the heat transfer is associated with evaporation and thus the water pressure in the air or dew point temperature (which is obtained from air temperature and relative humidity) is an important parameter. Because of the great heat capacity of water, the calculations refer to average conditions and are superimposed on the average natural lake conditions. In order to obtain results from the calculations which represent extreme conditions in the summer months, the basic data have all been taken on the conservative side. Thus, the intake water temperature has been taken at 80° F (corresponding to a surface temperature in the natural lake of about 83° F), the wind speed has been taken at a low value of 6 mph, and the dew point temperature has been arbitrarily set at a high value of 80° F. For winter conditions, the intake temperature was set at 35° F, wind speed at 10 mph, and dew point temperature at 9° F.

The method of calculating the heat transfer coefficient from the data is outlined in Appendix D. The coefficients are 10.3 and 5.75 BTU/hr, ft^2, °F for summer and winter respectively. The temperature difference is to be measured between the surface water temperature and the dew point. It should be observed that by taking the dew point temperature at 80° F in summer, which is practically equal to the highest natural temperature in the lake, all the heat transfer calculated in this manner is excess transfer beyond that which occurs in the natural lake.

Using these coefficients, it was then possible to calculate the heat dissipated through the surface area between the condenser outlet and any given isotherm determined in the model study. The dissipation was measured in terms of the still unknown temperature difference between the outlet and the given isotherm. This dissipated heat must just balance the loss in heat content of the condenser water due to the unknown temperature drop as the heated water moves across the lake surface. Thus, the temperature drop could be calculated and the temperature value of each isotherm could be specified. The method is outlined in some detail in Appendix D and finally leads to the formula

$$\frac{T - T_D}{T_o - T_D} = e^{-\frac{KS}{C\gamma c}}$$

Here, T is the temperature of the given isotherm which is to be determined, T_o is the condenser discharge temperature (80 + 17 = 97° F in summer and 35 + 30 = 65° F in winter), T_D is the dew point temperature known from the climatological data, S is the surface area between the condenser outlet and the given isotherm determined from the model, K is the additional surface heat transfer coefficient given in the previous paragraph, C is the condenser discharge rate in cfs, γ is the unit weight of water in lbs/ft^3, and c is its specific heat in BTU/lb.

Using the above formula, temperature values were placed on each isotherm determined in the model study. Lines showing isotherms at equal interval spacings were then interpolated from the original computations. These final isotherms are shown on Charts 1 through 30 contained in Appendix H. The charts also show the basic data used in their evaluation. Table III shows how the charts are grouped and gives some further information about them. With condenser discharge through the excavated canal, isotherms were computed for river flows of 900, 1200, 1500, and 2000 cfs as agreed in conversations with the Minnesota State Board of Health, as well as for 0 cfs.

Since model experiments were conducted at only 0 and 2000 cfs and results were found to be very similar, the same isotherm patterns could be used for prediction at intermediate values of river discharge.

The surface temperatures given on the charts extend to only 2 ft or less in depth before they begin to decrease. This is shown by computations in Appendix E based on the method outlined in Appendix C, the results being tabulated in column (6) of Table II. From Fig. 5 and similar data obtained by others in model studies, it is estimated that the temperature gradient will extend to a depth of the order of 5 ft before normal lake conditions are approached. The gradient is produced both by molecular heat conduction and by mixing due to turbulence at the interface.

If there is considerable mixing near the canal outlet where it discharges into Lake St. Croix, the effective warm water layer will have a greater discharge rate and lower temperature than assumed in the calculations with no mixing. To investigate the effect of mixing, an additional calculation was made assuming that at 0 cfs river flow a condenser water flow of 1500 cfs at 97° F would entrain an equal quantity of lake water at 80° F; this is a very high mixing rate. The isotherm calculations were then carried out with $T_o = 88.5^\circ$ F and the resulting isotherms are shown in Chart 33 in Appendix H. These isotherms may be compared with those in Chart 20 for no mixing. The thickness of the spreading layer was calculated for this condition (in Appendix E) and the results are displayed in Table II where they may be compared with the results for the same flow without mixing.

Associated with the surface cooling, a certain quantity of water is evaporated. This has been calculated and found to be about 20 cfs when the plant is heating 1500 cfs by 17° F and there is no mixing at the canal outlet.

Some assessment should now be made of the effects of other factors different from those used in the calculations for heat transfer. Since conservative values have been used for all the summer calculations, variations will generally tend to produce more favorable conditions and smaller surface temperatures. Wind is probably the largest variable. Increased wind speeds will increase evaporation and cooling at the surface. However, winds greater than the 6 mph used in the calculations are likely to produce waves on the surface; waves increase surface area and cause a thicker mixing zone so that the temperature gradient extends to greater depth. Both factors are favorable in that they reduce surface temperature, the former by increased dissipation to the atmosphere and the latter by dilution. From another viewpoint, the mixing may be looked upon as an unfavorable effect because it brings warm surface waters to greater depth; it must be noted, though, that the warm surface waters are materially less warm than they would have been without the excess wind. On the other hand, winds less than 6 mph would reduce surface cooling. When such conditions occur, the surface temperature may increase, but only slowly because of the great heat capacity of water. Relatively calm periods last for a day or less at a time, and to maintain the average wind of record following periods should have stronger winds which will then reverse the temperature trend. Similarly, there are brief periods with relative humidity higher than the values used in the computations. Many of these are accompanied by rain which has a temperature less than that of the water surface. Whether or not there is rain, periods of high relative humidity are followed by periods of low relative humidity to maintain average values, and any tendency for the surface temperature to start rising during one period should be counteracted during the following period.

It is believed that the climatological data chosen for the computations are sufficiently conservative to encompass the normal variations described above and that, therefore, the computations represent the maximum temperatures likely to be found at any given isotherm. It is apparent from Appendix B that if the normal or average climatological data for July and August were used in the computations, the surface temperatures would drop considerably more rapidly than shown in the charts. As a mater of fact, results of computations with a more reasonable dew point temperature of 75.5° F rather than 80° F are shown for comparative purposes in Charts 8, 9, 25, and 26 and may be compared with Charts 3, 6, 14, and 24, respectively, to see the effect of a small decrease in dew point temperature.

No attempt was made to represent extreme conditions in calculating the winter isotherms, Charts 27 through 30. Hence, increased winds can be expected to decrease surface temperature by evaporation but to increase it somewhat by mixing with warmer water beneath the surface. The opposite is true of decreased winds. The winter calculations are simply intended to represent average conditions at the coldest part of the year.

CONCLUSIONS

The combined results of the model study and calculations of heat loss are depicted in Charts 1 through 30 and 33 contained in Appendix H, and these are the main results of the study. Table III lists these charts.

The first group of nine charts deals with discharge of the condenser water through the bay under midsummer conditions. The next group of seventeen charts deals with discharge directly to the lake through the excavated canal shown on the charts, also under midsummer conditions. The next set of two charts is for discharge directly to the river under midwinter conditions, and the last set of two charts is for discharge through the bay under midwinter conditions. Chart 33 is an additional chart showing the effect of mixing at the canal outlet.

In the first seven charts for discharge through the bay and in Charts 10 through 24 for direct discharge to the lake, predictions have been made under rather conservative conditions and should be looked upon as surface temperatures that are not likely to be exceeded (barring local anomalies which exist in all lakes). Under the conditions for which the charts were computed, these surface temperatures extend to about a one-foot depth (see Table II). (Because of the nature of the assumptions, the calculations for thickness of the warm layer are much rougher than those for the surface isotherms, but even if the calculation is in error by 50 per cent, there is no need for concern.)

Beneath the warm surface layer there is a thermocline or temperature gradient to a depth of the order of 5 ft (except in the immediate vicinity of the condenser intake and outlet, where the warm layer may be thicker). The temperature gradient is given qualitatively by the density gradient obtained in the model study and shown in Fig. 5. Beneath the thermocline, normal lake temperatures should prevail. This is an idealized picture, of course, and is subject to the many vagaries of nature which are also found in a natural lake.

Using the calculated thickness of the warm layer and its associated velocity, it has been determined that for the flow conditions of Chart 3 (1500 cfs plant discharge and no river flow), for example, more than 12 hours would be required for warm water entering the bay to return to the region of the intake; but, by this time, the water will have cooled to the normal surface temperature and there will be no problem. On the other hand, for direct discharge to the lake the chart for the corresponding flow is Chart 20 and calculation shows that the warm surface waters will have returned to the vicinity of the intake at a temperature of about 90° F after only about 2-1/2 hours (see Table II).

It is therefore very important if discharge is taken directly to the lake to design the intake for minimum drawdown of surface waters. The method of design is outlined in Appendix F.

As the charts show, there is little influence on the isotherms due to river flow. The reason is apparent when it is realized that even at 2000 cfs river flow the mean velocity in Lake St. Croix is only about 0.015 fps, whereas the spreading velocity of the hot water is of the order of 0.30 fps near the outlet channel--twenty times as great. Had this study been extended to larger river flows, the effects of river flow both in shifting the isotherm patterns downstream and in cooling by dilution would have become apparent.

The charts do not always bring the predicted surface temperature back to the assumed intake temperature of 80° F during summer. However, it should be noted that the surface temperature in summer even in the natural lake is always of the order of 3° higher than at intake depth (Appendix B). It is believed that the remaining differences are of minor importance. Furthermore, the method of computing the temperatures of the isotherms is not of great precision when the lake surface temperature is close to its natural value. It may be worth commenting that there is a constriction in the channel just above the railroad bridge at Hudson and any remaining temperature differences at this point may be obliterated by mixing. The model cannot determine whether or not mixing will take place. If mixing does not take place here, the surface isotherms could be extrapolated using the spacing gradient between preceding isotherms to get a rough idea of where the normal lake temperature is reached. If mixing does take place, the surface temperature will drop more rapidly, of course, but the temperature difference from normal conditions will persist for a greater distance. In any event, the temperature of the water near the lake bottom is determined by the inflow of cooler water from both upstream and downstream and not by the surface water temperature above the plant intake.

Harbeck and others [14] have measured and calculated the temperature rise in an artificial lake operated as a cooling pond. It is informative to compare their results with the present calculations. The lake studied had about 2000 acres of surface (comparable to Lake St. Croix between the Stillwater bridge and the railroad bridge above Hudson) but was only about 16 ft deep on the average. The reservoir was fed by a stream of only 17.3 cfs average flow, of which up to 2.5 cfs was withdrawn for municipal use. The condenser water flow was about 300 cfs maximum heated about 10° F. Unfortunately, measurements were on a yearly basis; during a 363 day period selected for study, 1.3×10^{9} Kwhr of power was generated (compared to about 5.25×10^{9} Kwhr for the Allen S. King plant if operated continuously at a 600 megawatt rate). The average temperature rise of the entire lake was measured as only 1.4° F and the report states that the rise was twice as great in winter as in summer. This rise was verified by calculation by a method somewhat similar to the method used in the present report.

Charts 27 through 30 show limits of possible and probable ice cover in midwinter. These ice cover charts should be looked upon as giving rough estimates under average conditions; they represent neither minimum nor maximum possible ice cover. The ice cover was estimated by first computing isotherms during midwinter assuming that there was no ice cover. The isotherms were determined from model runs with 400 cfs plant flow. The ice cover was then assumed to form between the 39 and 32° F isotherms and is so indicated in the charts. Since both the model studies and the calculations were performed without ice cover, the results are not as refined as those for midsummer but should give a satisfactory estimate of the ice cover.

Questions may arise as to the effect of strong winds, boat motions, or precipitation on the predicted isotherm patterns. All of these factors will have some influence, of course, but they were not studied in the model. Strong winds will increase the rate of evaporation and also the surface area by generating waves; by this mechanism, winds would increase surface cooling. Winds also tend to promote mixing through wave action and this would slow down surface cooling and thicken the warm layer, but at a lower temperature level. The net effect should be no worse than that predicted on the charts. The thicker warm layer could cause the plant to draw slightly warmer intake water when the discharge is directly to the lake, and this should be guarded against by proper intake design.

Mixing by boat traffic will be largely confined to the upper warm layer where it will make little difference anyway. Over a small area, mixed water could become slightly cooler than the surface water and sink to form an intermediate layer between the warm water and colder water on the bottom.

Precipitation is likely to have two effects. It will cause some mixing at the lake surface and it will also influence the incoming river water. Since rainwater is generally colder and heavier than the surface water in summer, the river water during or following heavy rain is likely to plunge to greater depths on entering the lake (rather than remain near the surface as it would under ordinary summer conditions) and to become available for direct withdrawal at the plant intake or to replenish the cold bottom water in the lake. This is a favorable effect which far outweighs any thickening of the surface layer by mixing.

An additional factor that was considered was the effect of mixing at the point of warm water discharge to the lake. An extreme situation involving the entrainment of 1500 cfs of lake water at 80° F by 1500 cfs of condenser water at 97° F with no river flow was analyzed. The results are shown in Chart 33 and in Table II and may be compared with the results for no mixing in Chart 20 and Table II. It is apparent that with mixing the maximum temperatures are much reduced, but so is the rate of cooling. The greater thickness of the warm layer also becomes apparent, but the spreading time does not change significantly.

A final phase of the study concerned the influence of the plant intake on the sewage discharge from Stillwater. A model study was undertaken for this purpose and details are given in Appendix G. Since sewage lighter than the river flow would float past the intake without effect, only the case of heavier sewage was studied. The model showed that some sewage may be drawn into the intake. However, the total sewage discharge (of which only a part would reach the intake) is less than 7 cfs compared to an intake of 700 cfs at the plant during summer. The model also indicated that removal of some sewage at the plant intake would reduce the tendency for sewage to find its way to the beach area at Bayport if the cooling water is discharged directly to the lake and not to the bay.

TABLE I

MODEL-PROTOTYPE RELATIONSHIPS

Item	Parameter	Symbol	Model-Prototype Scale Ratios: Numerical Value: Range	Normal Value#
	Pre-assigned Ratios			
1.	Horizontal distance, b or x	x_*	1/500	
2.	Vertical distance, h or y	y_*	1/30	
3.	Relative density differance, $\frac{\Delta\rho}{\rho}$	$(\frac{\Delta\rho}{\rho})_*$	$\geq 3/1$, $\leq 40/1$	5/1
4.	Condenser discharge, C	C_*	1/12,000	
	Ratios Fixed by Use of Water in Model			
5.	Average density, ρ	ρ_*	1/1	
6.	Kinematic viscosity, ν	ν_*	1/1	
	Derived Ratios (see Appendix C)			
7.	Cross sectional areas, S	$S_* = x_* y_*$	1/15,000	
8.	Condenser discharge per unit width, $q = \frac{C}{b}$	$q_* = C_*/x_*$	1/24	
9.	Canal or bay mean velocity, $v = \frac{C}{S}$	$v_* = q_*/y_*$	5/4	
10.	Thickness of warm water layer, d	$d_* = q_*^{2/3} (\frac{\rho}{\Delta\rho})_*^{1/3}$	$\leq 1/2$, $\geq 7/200$	7/100
11.	Spreading speed of warm layer, $u = \frac{q}{d}$	$u_* = q_*^{1/3} (\frac{\Delta\rho}{\rho})_*^{1/3}$	$\geq 1/2$, $\leq 13/11$	3/5
12.	Time of spreading, $t = \frac{x}{u}$	$t_* = \frac{x_*}{q_*^{1/3}} (\frac{\rho}{\Delta\rho})_*^{1/3}$	$\leq 1/250$, $\geq 1/591$	1/300
13.	River velocity, $V = \frac{Q}{S}$	$V_* = u_*$		3/5
14.	River discharge, Q = VS	$Q_* = q_*^{1/3} (\frac{\Delta\rho}{\rho})_*^{1/3} x_* y_*$		1/25,000
15.	Densimetric Froude number, $Fr_\Delta = \frac{u}{\sqrt{g \frac{\Delta\rho}{\rho} d}}$	$Fr_{\Delta_*} = 1$	1	
16.	River Froude number, $Fr = \frac{V}{\sqrt{gh}}$	$Fr^* = \frac{Q_*}{x_* y_*^{3/2}}$		10/3
17.	Canal or bay Froude number, $Fr' = \frac{v}{\sqrt{gh}}$	$Fr' = \frac{q_*}{y_*^{3/2}}$	20/3	

TABLE I (Continued)

MODEL-PROTOTYPE RELATIONSHIPS

		Model-Prototype Scale Ratios		
			Numerical Value	
			Range	Normal Value
	Derived Ratios (see Appendix C) (Cont.)			
18.	Canal or bay Reynolds number, $Re' = \frac{Ch}{S\nu}$	$Re'_* = q_*$	1/24	
19.	River Reynolds number, $Re = \frac{Qh}{S\nu}$	$Re_* = Q_*/x_*$		1/50

#Normal values refer to a ratio $(\frac{\Delta\rho}{\rho})_* = 5$, which was most frequently used in the model test. It corresponds to a brine density of 1.01 in the model and an average warm water density in the lake of 1.002.

TABLE II

THICKNESS OF WARM WATER LAYER AND TIME OF SPREAD IN MODEL AND PROTOTYPE

Measured in Model		Computed for Model		Computed for Prototype				Prototype Results Scaled from Model	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Time Since Start t sec	Thickness of Warm Water at Front d ft	Time Since Start t sec	Thickness of Warm Water at Front d ft	Isotherm Temperature T °F	Thickness of Warm Water at Front d ft	Spreading Velocity of Warm Water Front u_f fps	Time for Flow to Reach Isotherm t hrs	Thickness (Based on Local $\Delta\rho/\rho$) d ft	Time for Flow to Reach Isotherm (Based on Normal $\Delta\rho/\rho$ from Table I) t hrs
River Flow, Q = 0 cfs, Condenser Flow, C= 400 cfs (Prototype) [See Chart No. 10]									
0	-	0	-	97	2.91	0.46	0		
17.3	0.300	3.9	0.135	96	0.79	0.26	0.3	3.8	1.44
34.6	0.078	12.9	0.046	94	0.53	0.20	0.8		
57.7	0.026	39.8	0.034	92	0.47	0.17	1.1	1.1	2.9
75.0	0.033	55.6	0.028	90	0.41	0.16	1.5		
86.5	0.033	66.7	0.033	88	0.40	0.13	2.1		
103.8	0.041	79.7	0.031	86	0.47	0.12	2.9	0.47	4.8
121.1	0.034	92.1	0.030	84	0.60	0.12	4.1		
138.4	0.027	106.3	0.024	82	0.77	0.10	6.8	1.00	8.6
155.7	0.025	121.0	0.022	81	0.70	0.07	10.1		
River Flow, Q = 0 cfs, Condenser Flow, C = 1500 cfs (Prototype) [See Chart No. 20]									
0	-	0	-	97	6.40	0.78	0		
17.3	0.107	10.3	0.288	96	1.07	0.31	0.4		
34.6	0.052	30.3	0.061	94	0.78	0.25	1.0	1.37	1.4
51.9	0.072	44.7	0.060	92	0.75	0.22	1.6		
69.2	0.067	60.5	0.061	90	1.08	0.24	2.7	0.78	2.9
86.5	0.064	76.9	0.061	88	1.00	0.21	4.1	1.16	4.3
103.8	0.060	94.6	0.061	86	1.05	0.18	5.8	1.20	5.8
121.1	0.062	111.5	0.060	84	1.21	0.17	8.8	1.21	8.6
138.4	0.063	128.3	0.061	83	1.28	0.15	10.9	1.35	10.1
River Flow, Q = 0 cfs, Condenser Flow, C = 1500 cfs + 1500 cfs of Lake Water [See Chart No. 33]									
				88.5	10.0	1.00	0		
				88	1.66	0.271	0.55		
				86	1.80	0.240	3.52		
				84	1.91	0.212	7.96		
				83	2.19	0.197	11.34		
				80					

TABLE III

LIST OF CHARTS

Chart No.	Dew Point Temp. °F	Condenser Flow, cfs	River Flow cfs	Model Study
	Discharge to Bay during Midsummer, 80° F Intake and 97° F Discharge Temperatures			
1	80	400	0	Yes
2	80	700	0	Yes
3	80	1500	0	Yes
4	80	400	1300	Yes
5	80	700	1300	Yes
6	80	1500	1300	Yes
7	80	700	2000	Yes
8	75.5	1500	0	Yes
9	75.5	1500	1300	Yes
	Discharge Directly to Lake during Midsummer, 80° Intake and 97° F Discharge Temperatures			
10	80	400	0	Yes
11	80	400	900	No
12	80	400	1200	No
13	80	400	1500	No
14	80	400	2000	Yes
15	80	700	0	Yes
16	80	700	900	No
17	80	700	1200	No
18	80	700	1500	No
19	80	700	2000	Yes
20	80	1500	0	Yes
21	80	1500	900	No
22	80	1500	1200	No
23	80	1500	1500	No
24	80	1500	2000	Yes
25	75.5	400	2000	Yes
26	75.5	1500	2000	Yes
	Discharge Directly to Lake during Midwinter, 35° F Intake and 65° F Discharge Temperatures			
27	9.0	400	0	Yes
28	9.0	400	2000	Yes

TABLE III (continued)

LIST OF CHARTS

Chart No.	Dew Point Temp. °F	Condenser Flow, cfs	River Flow cfs	Model Study
	Discharge to Bay during Midwinter, 35° F Intake and 65° F Discharge Temperatures			
29	9.0	400	0	Yes
30	9.0	400	2000	Yes
	Stillwater Sewage Plant Flow of 6.75 cfs			
31	--	0	2000	Yes
32	--	700	2000	Yes
	Discharge Directly to Lake during Midsummer, 80° F Intake and 88.5° F Discharge Temperatures			
33	80	3000	0	No

LIST OF REFERENCES

[1] Cotter, T. S. and Lotz, A. W. "Cooling Pond Design in the Southwest," ASCE Jour. Power Division, 87:85-103, July 1961.

[2] Mandelbrot, L. "Le refroidissement des condenseurs des centrales électriques thermiques" (Condenser Cooling in Thermal Power Plants), Bulletin Du Centre de Recherches et D'essais de Chatou, Electricité de France, No. 7, March 1964, pp. 51-91.

[3] Bata, G. "Recirculation of Cooling Water in Rivers and Canals," Proceedings, ASCE, Vol. 83:HY 3, June 1957, Paper No. 1265, 27 pp.

[4] Barr, D. I. H. "Some Observations of Small Scale Thermal Density Currents," IAHR, Proceedings 8th Congress, 1959, Paper 6C.

[5] Ellison, T. H. and Turner, J. S. "Turbulent Entrainment in Stratified Flows," Journal of Fluid Mechanics, 6:423-448, 1959.

[6] Barr, D. I. H. and Hassan, A. M. "Densimetric Exchange Flow in a Rectangular Channel," La Houille Blanche, November 1963, pp. 757-766.

[7] Minami, I. "On the Transport of Salinity in Stratified Turbulent Flows," Proceedings 12th Japan National Congress for Applied Mechanics, 1962, pp. 133-136 (in English).

[8] Abbott, M. B. "On the Spreading of One Fluid Over Another," Part I, La Houille Blanche, October 1961, pp. 622-628.

[9] Abbott, M. B. "On the Spreading of One Fluid Over Another," Parts II and III, La Houille Blanche, December 1961, pp. 827-846.

[10] Abraham, G. and Squarer, D. "Literature Survey about Interfacial Resistance of Laminar Stratified Flow," W. L. Delft, Informatie V-148, Code 19.40, June 1964 (in English).

[11] Squarer, D. "Interfacial Resistance of Laminar and Turbulent Stratified Flow," W. L. Delft, Informatie V-149, Code 19.40, September 1964 (in English).

[12] Hamada, T. "Two Properties of the Stratified Density Current at a River Mouth," IAHR, Proceedings 8th Congress, 1959, Paper 2C.

[13] Throne, R. F. "How to Predict Lake Cooling Action," Power, Vol. 95, pp. 86-89 and 210, 1951.

[14] Harbeck, G. E. Jr, Koberg, G. E., and Hughes, G. H. "The Effect of the Addition of Heat from a Powerplant on the Thermal Structure and Evaporation of Lake Colorado City, Texas," U.S. Geological Survey, Professional Paper No. 272-B, 1959, 49 pp.

[15] Harleman, D. R. F. and Goda, Y. "Control Structures in Stratfield Flows," Hydrodynamics Laboratory, Massachusetts Institute of Technology Report No. 54, May 1962, 22 pp.

[16] Elder, R. A. and Dougherty, G. B. "Thermal Density Underflow Diversion, Kingston Steam Plant," American Society Civil Engineers Journal Hydraulics Division, Vol. 84:HY2, April 1958, 20 pp.

APPENDIX A

Description of the Model

The size of the model was based on a 1/500 horizontal scale ratio which was fixed by the available space in the Laboratory and a 1/30 vertical scale ratio, which was chosen to obtain sufficient depth for the study of stratification in the approximately 35 ft deep lake. The model represents approximately 4 miles of lake; the width of the lake in this stretch is greater than half a mile.

The geometry of the model was obtained by applying the model scales to depth soundings by the U.S. Army Corps of Engineers taken in 1932 and verified by Gorman-Anderson, Civil Engineers and Land Surveyors, Minneapolis, in the summer of 1964. Intake and outlet structures were modeled according to drawings NF-E5577-P1B, NF-E5577-P10, SK. NL-E5577-P4, and SK. NL-E5577-P5 furnished by Northern States Power Company. The original intake structure is reproduced in the model. This is an open channel excavated 32 ft below lake level at its mouth, 66 ft wide on the bottom, and partially obstructed by a skimmer wall across the entrance with a bottom opening of 15-ft height. The purpose of the skimmer wall is to draw in water from the bottom of the lake where it is coldest, rather than from the lake surface. A wider intake structure was designed subsequently but is not represented in this model. Flow near the intake cannot be modeled in any event in this distorted model.

Two outlets were provided. In the first tests, there was an open channel, 15 ft deep and 40 ft wide on the bottom, leading into the bay south of the generating plant. Later, another open channel 10 ft deep and 330 ft wide at the surface leading directly into the lake at a point approximately 1450 ft downstream from the intake was added. Each of the outlets was tested separately. The Stillwater sewage treatment plant outlet, which discharges about 6.75 cfs, was also represented in the model.

Construction of the model followed customary procedures. Starting with a water-tight basin, 51 ft by 17 ft, templets giving the contours of the lake bottom were inserted and, after addition of a few contour lines between the templets, the model was molded in perlite-concrete, a mixture of perlite, cement, and water. Figure A-1 shows a stage in this process. The finished surface of the concrete was sealed with several layers of epoxy paint. The model filled with water is shown in Fig. 2.

Fig. A-1

The Model Under Construction (Photo No. 148-41).
This photograph is taken looking upstream from Hudson.
It shows the distorted scale of the model and the lake-like nature of this stretch of the St. Croix River.

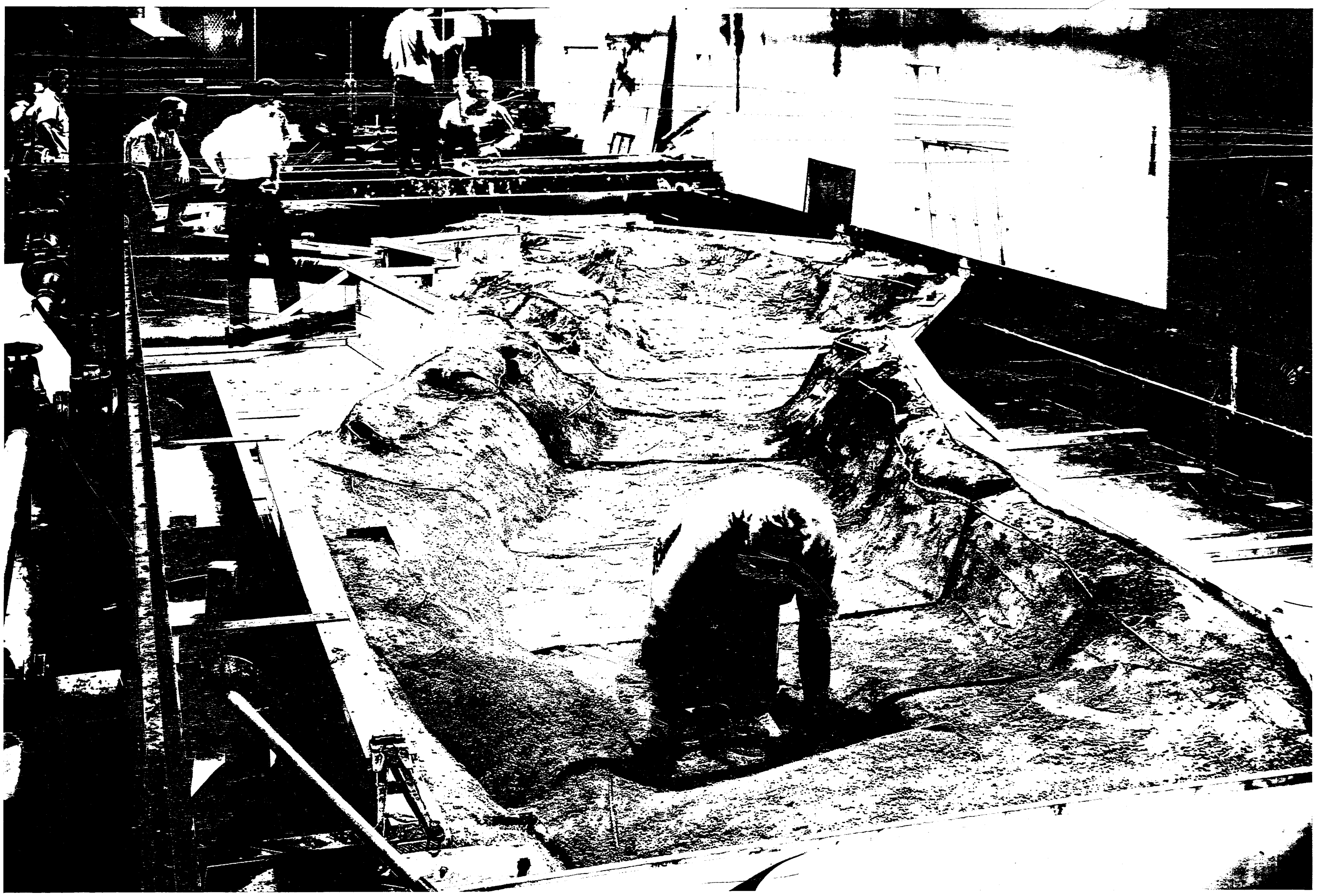


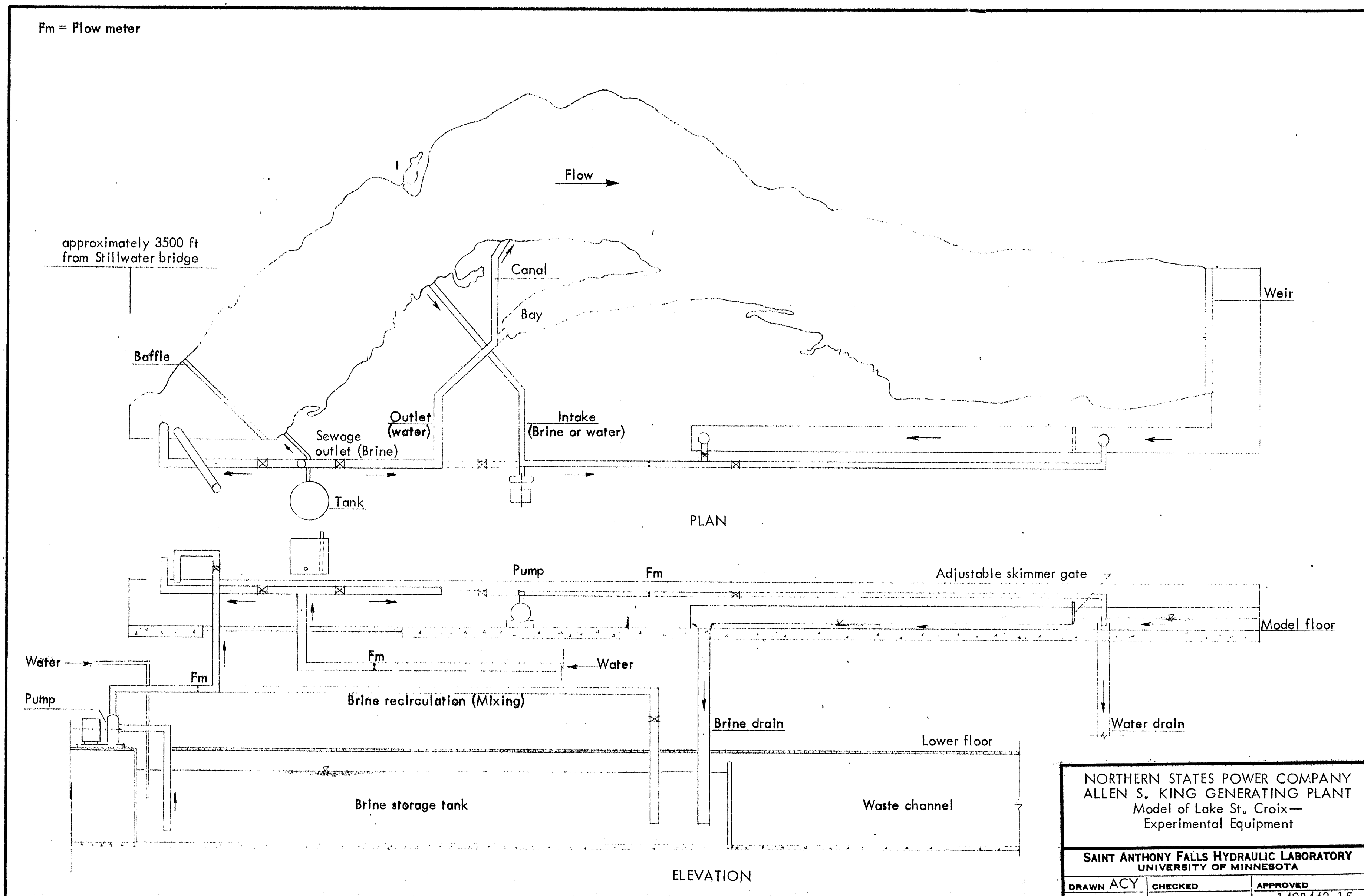
Fig. A-1

Circulation and pumping facilities were provided to meet the operating requirements. A layout of the various circulation systems is shown in Fig. A-2. The brine was premixed to the desired specific gravity in a channel on a floor below the model floor and pumped to the head end of the model. Brine was returned to the storage tank from the discharge end of the model by passing under a skimmer gate where much of the fresh water was removed and wasted. It was possible to continue the model in operation for about half a day without significant change in specific gravity of the brine.

The specific gravity of the brine was selected as 1.01 compared to fresh water as a minimum value. This made it unnecessary to be concerned about specific gravity variations in the model produced by small temperature differences.

Fig. A-2

Model layout showing experimental arrangement (148B-443-15). River flow is produced by pumping salt water from the brine storage tank to the upstream end (left end) of the model. The effluent flows over the adjustable control weir at the downstream end (which maintains the water level at 675 ft MSL), around and over the water drain line, and returns to the brine tank through the brine drain. Water is pumped from the lake through the intake at the specified condenser flow rate and may be returned to either the brine drain or the water drain. Fresh water is returned to the lake at the same rate by gravity through the canal or the bay. The fresh water so returned is skimmed from the effluent and wasted through the water drain by adjustment of the skimmer gate.



NORTHERN STATES POWER COMPANY
ALLEN S. KING GENERATING PLANT
Model of Lake St. Croix—
Experimental Equipment

SAINT ANTHONY FALLS HYDRAULIC LABORATORY
UNIVERSITY OF MINNESOTA

DRAWN ACY	CHECKED	APPROVED
SCALE	DATE	NO. 148B443-15

Fig. A-2

APPENDIX B

Hydrologic and Climatological Data for the Model Study

Descriptions of the hydrology of Lake St. Croix in connection with the projected Allen S. King Generating Plant may be found in various reports and letters as outlined in the introduction to this report. It appears from these reports that the sources of information on flow in the St. Croix River are the U.S. Geological Survey and Northern States Power Company records at St. Croix Falls and Somerset (Apple River), Wisconsin. Temperature recordings were made by the Minnesota Department of Health and the Northern States Power Company.

Lake St. Croix is an artificial lake formed in the St. Croix River by a dam at Red Wing in the Mississippi River, of which the St. Croix River is a tributary. Pool elevation is controlled at Red Wing and usually kept at 675 ft MSL. Flow into the lake is regulated at the St. Croix hydroelectric plant and the Somerset hydroelectric plant on the Apple River, both operated by Northern States Power Company. Under low flow conditions Lake St. Croix is about 35 ft deep and 3000 ft wide.

From the duration curves of monthly mean flows it appears that the smallest flow rates in Lake St. Croix at Oak Park Heights occur during August. According to the duration curve for this month the monthly mean flow exceeds:

900 cfs	100 per cent of the time
1500 cfs	90 per cent of the time, and
2000 cfs	70 per cent of the time

Maximum surface water temperatures occur on Lake St. Croix during July and August each year. August mean daily water temperatures near the surface range between 64° F and 84° F. According to the report of the Minnesota Department of Conservation dated November 9, 1964, a water temperature of 80° F at the surface will be exceeded 3 per cent of the time during August and 8 per cent of the time during July. At 10-ft depth 80° F will be exceeded only 0.5 per cent of the time during both July and August. The report further shows that during these summer months temperatures at the 10-ft depth will be of the order of 2° F less and at the bottom, 4° less than the surface temperatures. 35° F is the minimum water temperature measured during midwinter at Stillwater and Prescott.

For computational purposes, in order to be on the conservative side, it was assumed that the water taken out of the lake would have a temperature of 80° F during midsummer and a temperature of 35° F during midwinter. These values were informally agreed to in discussion with the Minnesota State Board of Health.

Climatological data were required for surface cooling computations. Air temperature measurements were available at Stillwater, Minnesota and Hudson, Wisconsin, but humidity and wind measurements were also needed. The closest point for which such information was available was Minneapolis-St. Paul International Airport, about 30 miles from the plant site. Normal values based on the 1931 to 1960 period were found in "Local Climatological Data, Minneapolis-St. Paul Minnesota" for 1963 published by the U.S. Weather Bureau. Pertinent values are:

	January	July	August
Daily maximum temperature, °F	22.2	84.7	81.8
Daily minimum temperature, °F	2.5	61.2	59.1
Daily average temperature, °F	12.4	73.0	70.5
Relative humidity at 6:00 A.M.	76	89	90
Relative humidity at noon	67	59	60
Mean hourly wind velocity, mph	10.5	9.4	9.2
Prevailing wind direction	NW	S	SE

These data were supplemented for July and August by studying the daily records for 1963 at the Minneapolis-St. Paul International Airport on file at the U.S. Weather Bureau Office in Minneapolis. The latter records showed that the lowest daily average wind was of the order of 6 mph and this lower figure was used rather than the long-time average in order to obtain conservative conditions for the summer computations. For winter computations, the mean wind was rounded off to 10 mph and this figure was used.

The dew point temperature is required for the calculations and this was obtained from the air temperature and relative humidity using tables from the Handbook of Chemistry and Physics (page 2142 of the 1952-53 edition). The following values were obtained for dew point temperature from the above tabulated values:

	January	July	August
From daily temperature maximum and noon relative humidity	12.9° F	68.9° F	66.7° F
From daily temperature minimum and 6:00 A.M. relative humidity	-3.3° F	57.8° F	56.1° F
Average of above	4.8° F	63.4° F	61.4° F

Again, the mean data were supplemented for July and August by studying daily Weather Bureau records for 1963. Using the few highest daily temperatures and relative humidities led to an average high dew point temperature of 75.5° F (corresponding to 74 per cent relative humidity at 85° F air temperature). The latter figure was rounded to 80° F (corresponding to 86 per cent relative humidity at 85° F air temperature) in order to obtain conservative values in the summer months and to simplify computations as explained in Appendix E. For the winter computations, the dew point temperature was taken at 9° F rather than the average 4.8° F during January to allow for the frequent formation during winter of a nearly saturated air layer near the surface. This layer insulates the open water surface to some extent and the increase in dew point temperature is a rough method of allowing for this factor in the calculation.

APPENDIX C

Model-Prototype Relationships

As stated in the text, the model was a distorted one with the horizontal and vertical scales chosen as 1/500 and 1/30, respectively. In addition, the condenser discharge scale was chosen as 1/12,000. Since water was used in the model, the average density and viscosity in model and prototype are nearly the same and do not enter into the modeling. However, it is still possible to choose arbitrarily the difference in density between the lighter surface layer and heavier bottom layer, $\Delta\rho$. The relative model density $\Delta\rho/\rho$ was selected as 0.01 for most of the model experiments, although a larger ratio was used for some experiments. Since $\Delta\rho/\rho$ in the prototype varies from about 0.003 for a temperature difference of 97° to 80° F between layers to about 0.001 for a difference of 87° to 80° F, it is seen that the relative density scale varies over the surface of the model.

All other model-prototype relations must be determined from these arbitrarily chosen ones using suitable equations describing the physical relationships. All of the ratios, both assigned and calculated, have been displayed in Table I and will be explained in this appendix.

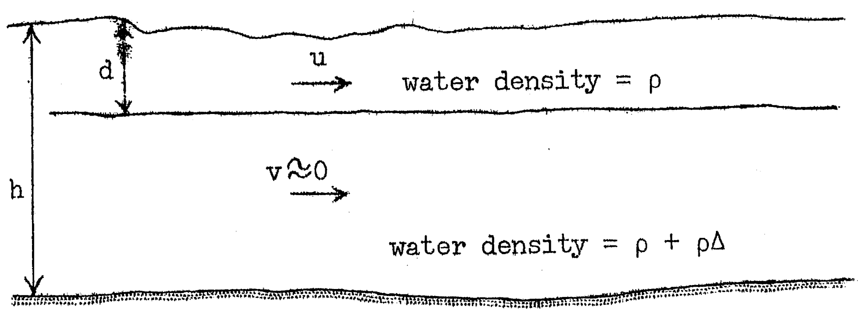
In ordinary hydraulic models, it is desirable to maintain the river Froude number, item 16, Table I, identical in model and prototype. In this study, however, wherein the stratified current created by the warm water is being modeled, it is the densimetric Froude number, item 15 [6], which must be maintained constant. This has been done in this study. The average river Froude number ratio of 3.33 simply means that the lake surface slope is greater in the model than in the prototype in order to scale average river velocities at the same scale as spreading velocities (item 13). Since the lake velocities are so small anyway, the larger slope has no bearing on the problem. In the discharge canal, where the Froude number scale is twice as great as in the river (item 17), the main influence is on mixing as will be discussed later.

As already noted, the horizontal scale was chosen to fit the model to the available area and the vertical scale was chosen mainly to insure that the total depth in the model would be great compared to the stratified layer on top. The discharge scale was then chosen to assure that there would be turbulent flow in the bay or canal with the minimum condenser flow of 400 cfs.

At this flow, the bay Reynolds number governs and is approximately 5×10^4. By item 18 in Table I, with the condenser discharge ratio of 1/12,000, this makes the bay Reynolds number just over 2000 which is the minimum for turbulent flow. Thus, with the scale ratios chosen, the condenser flows into the lake will always be turbulent and the mixing in this region will be appropriate to turbulent flow as it would be in the prototype.

It is out of the question to make the river flow turbulent in the model at the low river flow rates under study, but this is unnecessary anyway. Observation shows that mixing at an interface, in the absence of large-scale turbulence which is the case in Lake St. Croix, is determined by the magnitude of the Richardson number, Ri [5]. For conditions defined in the sketch

$$Ri \approx \frac{gd}{u^2}\frac{\Delta\rho}{\rho} \qquad \text{(C-1)}$$



where g is the acceleration of gravity, d is the thickness of the upper, moving layer, u is the average speed of this layer and $\frac{\Delta\rho}{\rho}$ is the ratio of the density difference between the layers to the average density (called relative density difference). It is apparent that the Richardson number can be written in terms of the densimetric Froude number as

$$Ri = \frac{1}{{Fr_\Delta}^2} \qquad \text{where} \qquad Fr_\Delta = \frac{u}{\sqrt{g\frac{\Delta\rho}{\rho}d}} \qquad \text{(C-2)}$$

According to Ellison and Turner [5] for the situation being considered, entrainment or mixing approaches zero as Ri approaches unity ($Fr_\Delta \rightarrow 1$) and is large for small Ri ($Fr_\Delta \gg 1$). Minami [7] gives a similar result for eddy mixing coefficient, showing that it decreases with $Ri^{3/2}$.

Thus, with $Fr_\Delta \approx 1$ there should be little mixing. It will be shown presently that this is the case throughout most of the lake surface. Near the condenser outlet or intake, however, larger values may be expected. Mixing can only be averted in these key areas by judicious widening of the structures to reduce velocities. It may be noted at this point that the outlet canal in the most recent design (Drawing NF-30556 by Northern States Power Company) has a depth of 10 ft and an average velocity of about 0.5 fps for 1500 cfs condenser flow. In the canal $\Delta\rho/\rho \approx 0.003$ if the temperature is 97° F compared to a lake surface temperature of 80° F. Thus $Fr_\Delta \approx 0.5$. However, the warm water will float somewhat at the channel exit so that d will be smaller than 10 ft and u larger than 0.5 fps, making Fr_Δ closer to unity or even a little larger. In any event little mixing need be anticipated at this point in the prototype except that due to large-scale turbulence at the immediate outlet. On the other hand, in the model if the condenser flow fills the canal, u is about 5/4 x 0.5 fps, d is 10/30 ft, and $\frac{\Delta\rho}{\rho}$ is usually 0.01. Hence, $Fr_\Delta \approx 2.0$ and will even be larger when it is considered that the stratified layer is partially floating and does not fill the canal. More mixing may then be expected in the model than in the prototype canal and depths of the stratified layer near the outlet are likely to be too great in the model. This will limit direct transfer of thickness data from model to prototype.

To obtain the velocity u, it is necessary to resort to developments by several investigators, perhaps best stated in papers by Abbott [8, 9]. Barr has also investigated this problem in a number of papers of which reference [6] is, perhaps, typical. It can be shown that in two-dimensional flow, a thin surface layer of lesser density floating on a deep lower fluid will move with a front velocity u_f given by

$$u_f = k\sqrt{g \frac{\Delta\rho}{\rho} d} \qquad \text{(C-3)}$$

where k is a dimensionless coefficient close to unity [8, 9]. (Barr [6] works with the so-called dam burst analogy where in place of d the total depth h is used and k is then near 0.5, but $d \approx h/4$.) Abbott's development is conceived on the basis that the lighter fluid spreads as a series of overriding waves at wave speed in fluid of reduced gravity $g\frac{\Delta\rho}{\rho}$. The coefficient k is supposed to take account of friction and entrainment of ambient fluid. The same result may be obtained by a direct application of the momentum and continuity equations on the assumptions that (a) there is no entrainment, (b) there is no interfacial friction, and (c) there is zero average velocity in the lower fluid. Experiments indicate that $k \leq 2$ [9] whereas theory gives $k \simeq 1$.

It is now possible to assume that the stratified layer will follow behind the front at the same velocity u_f--that is, $u = u_f$. This is true if the front remains of constant shape as it moves and contains the same fluid always. Observation shows that this is closely but not exactly true, there being some entrainment of fluid at the front with a mixed layer left trailing behind to form an intermediate layer between the top and bottom layers. It is this mixing at the front which requires more inflow from behind that has been used to explain the fact that $k > 1$ [6]. Normally, friction would be expected to reduce k below unity, but with the intermediate layer acting as a buffer, friction does not have too much influence. (Abraham and Squarer [10, 11] made a literature survey of work done on interfacial friction, but apparently more research is required, particularly for turbulent flow. For laminar flow, computation showed that interfacial friction would be very small compared to momentum. Probably the same is true in the present case.) Experiments show that the zero velocity line in a stratified flow is below the zero $\Delta\rho/\rho$ line [12].

With $u = u_f$ from Eq. (C-3), $Fr_\Delta = k$ by Eq. (C-2). Since $k \approx 1$, the previous assumption of little mixing appears to have been correct. Abbott [9] shows that in three-dimensional flow, as on the lake surface, $k < 1$ and the assumption of little mixing is even more likely to be correct.

Using Eq. (C-3) for u, it is now possible to calculate the thickness of the warm layer from $d = q/u$ where q is the discharge per unit width. Thus,

$$d = \sqrt[3]{\left(\frac{q}{k}\right)^2 \frac{1}{g} \frac{\rho}{\Delta\rho}} \qquad \text{(C-4)}$$

and

$$u = \sqrt[3]{k^2 \, q \, g \frac{\Delta\rho}{\rho}} \qquad \text{(C-5)}$$

Here, $q = C/b$ where C is the condenser discharge and b is the canal or bay width in the two-dimensional case and is the length of the front of the spreading layer in the three-dimensional case. The time to reach any given front position is given by

$$\Delta t_i = \frac{\Delta x_i}{u_i} = \frac{\Delta x_i}{\sqrt[3]{k^2 \, q_i \, g \, \frac{\Delta \rho_i}{\rho}}}; \quad t = \sum_{i=1}^{n} \Delta t_i \qquad \text{(C-6)}$$

It is now possible to calculate model-prototype relations from these formulas. This has been done assuming that the k-ratio is unity and the corresponding results are tabulated in lines 10 through 19 of Table I. Note that it was not necessary to make an assumption for the absolute value of k--it was only necessary to assume that the k-values were the same in model and prototype.

To obtain the river discharge ratio, it was assumed that the velocity scale for spreading of the stratified layer should be the same as the mean river velocity in order to obtain the correct spreading pattern (line 13 of Table I). The discharge scale (line 14 of Table I) then follows. However, as already noted in the report, the river discharge is so small that it hardly affects the pattern and strict adherence to this river discharge scale ratio was not necessary. Hence, for many tests runs, especially the earlier ones, a uniform discharge scale of 1/12,000 was used for both the condenser flow and river flow.

Some numerical values in the model and prototype are cited below for reference.

Quantity	Prototype	Model
Average river velocity at 2,000 cfs	0.016 fps	0.010 fps
Spreading velocity of heated water at 97° F over 80° F bottom water for 1-ft thickness	0.31 fps	0.15 fps
Reynolds number for river flow at 2000 cfs	50,000	1,000

APPENDIX E

Calculations of Thickness and Time of Spread

Thickness, spreading velocity, and spreading time were calculated by the methods of Appendix C. The computations were carried out first for model conditions and the computed results were compared with measurements in the model to verify the relations used. Two computations are outlined in Table E-1 and the results are assembled in Table II. As may be seen in Table II, if the area near the outlet could be excluded, computed and measured values of thickness and time compare reasonably well. Thus, it was concluded that the basic assumptions of the computational method--namely, that mixing and friction at the interface were unimportant to the spreading of the stratified layer except near the outlet--appear to be verified.

Similar computations were then carried out for prototype conditions taking into account the decrease in temperature with distance from the outlet shown in the charts of Appendix H. The computations are shown in Table E-2 and are also summarized in Table II. The first two computations in Table E-2 are for equivalent conditions to those represented in Table E-1 for the model. The last computation in Table E-2 represents an assumed condition wherein there is sufficient mixing at the outlet that the 1500 cfs of condenser flow water at 97° F entrains an equal volume of lake water at 80° making a total discharge of 3,000 cfs at 88.5° F.

Attention should be drawn to the fact that the decrease in temperature and corresponding increase of density in the warm water layer as it spreads from the outlet produces two effects not exactly compatible in model and prototype. First, the method of computation implies that the temperature distribution displayed by the surface isotherms is constant throughout the thickness of the warm water layer; that is, in a given cross section the isotherms are assumed to be vertical lines. Because of the increase of density with distance in the prototype, it must be expected that the isotherms will actually become inclined as the warm layer progresses. Furthermore, the verification of the method of computation using quantities measured in the model relates to a relatively large density difference. The method of computation may become less reliable as the edges of the spreading area in the prototype are reached because of the smaller density differences.

In the computations, Eqs. (C-4), (C-5), and (C-6) of Appendix C were used for thickness, velocity, and time of travel of the stratified layer, respectively. In the equations, $k = 1$ was used. For this reason, as well as those given in the preceding paragraph, the computed results should be considered rough estimates only. The computational steps used in Tables E-1 and E-2 are self-explanatory. Front lengths in the model computations were measured from photographs like those in Fig. 3 taken at approximately equal time intervals. In the prototype computations, lengths were measured from the interpolated isotherms shown in the charts of Appendix H.

The model-prototype relationships given in Table I, lines (10) and (12), have been used to estimate the thickness of the warm layer and its time of spread in the prototype. These results are displayed in columns (9) and (10) of Table II and may be compared with the calculated results in columns (6) and (8), respectively. The latter results are probably the more reliable for the reasons explained in Appendix C, but the comparison is not unreasonable, especially for the second flow.

TABLE E-1

THICKNESS AND TIME OF FLOW FOR THE MODEL

Calculated Results													Measured Results			
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
Front No.	Density ρ	Relative Density Difference $\Delta\rho/\rho$	Length of Front b ft	Unit Discharge $q = c/b$ cfs/ft	Thickness of Layer d (Eq. C-4) ft	Front Velocity u_f (Eq. C-5) fps	Average Front Velocity $\bar{u}_f$ fps	Surface Area Between Fronts ΔS ft^2	Average Length of Front $\bar{b}$ ft	Average Spacing of Fronts $\overline{\Delta x} = \frac{\Delta S}{\bar{b}}$ ft	Time Interval $\Delta t = \frac{\overline{\Delta x}}{\bar{u}_f}$ sec	Total Time t sec	Total Time t sec	Time Interval Δt sec	Average Thickness $C\,\Delta t/\Delta S$ sec	Average Thickness $\bar{d}$ Col (6) ft
River Flow, Q = 0 cfs, Condenser Flow, C = 1/30 cfs (400 cfs Prototype)																
1	const	0.01	0.6	0.0555	0.212	0.262	0.199	1.9	2.45	0.78	3.92	0	0	17.3	0.300	0.135
2	const	0.01	4.3	0.00774	0.0571	0.136	0.120	7.4	6.85	1.08	9.0	3.92	17.3	17.3	0.078	0.0455
3	const	0.01	9.4	0.00354	0.0339	0.104	0.099	29.3	11.03	2.66	26.87	12.92	34.6	23.1	0.026	0.0309
4	const	0.01	12.65	0.00263	0.0279	0.094	0.0985	17.5	11.23	1.56	15.84	39.79	57.7	17.3	0.033	0.0305
5	const	0.01	9.8	0.00340	0.0330	0.103	0.102	11.5	10.15	1.13	11.08	55.63	75.0	11.5	0.033	0.0322
6	const	0.01	10.5	0.00317	0.0314	0.101	0.0995	14.1	10.95	1.29	12.96	66.71	86.5	17.3	0.041	0.0306
7	const	0.01	11.4	0.00292	0.0298	0.098	0.0975	16.8	13.85	1.21	12.41	79.67	103.8	17.3	0.034	0.0267
8	const	0.01	16.3	0.00204	0.0235	0.087	0.085	21.1	17.45	1.21	14.23	92.08	121.1	17.3	0.027	0.0225
9	const	0.01	18.6	0.00179	0.0215	0.083	0.083	22.9	18.7	1.22	14.70	106.31	138.4	17.3	0.025	0.0214
10	const	0.01	18.8	0.00177	0.0213	0.083						121.01	155.7			
River Flow, Q = 0 cfs, Condenser Flow, C = 1/8 cfs (1500 cfs Prototype)																
1	const	0.01	0.6	0.208	0.512	0.406	0.275	20.16	7.15	2.820	10.25	0	0	17.3	0.107	0.2879
2	const	0.01	13.7	0.00912	0.0638	0.143	0.1395	41.76	14.9	2.803	20.09	10.25	17.3	17.3	0.052	0.0605
3	const	0.01	16.1	0.00776	0.0572	0.136	0.139	30.08	15.05	1.999	14.38	30.34	34.6	17.3	0.072	0.0600
4	const	0.01	14.0	0.00893	0.0628	0.142	0.140	32.32	14.65	2.206	15.76	44.72	51.9	17.3	0.067	0.0611
5	const	0.01	15.3	0.00817	0.0593	0.138	0.1395	33.92	14.8	2.292	16.43	60.48	69.2	17.3	0.064	0.0606
6	const	0.01	14.3	0.00874	0.0619	0.141	0.140	36.00	14.55	2.474	17.67	76.91	86.5	17.3	0.06	0.0613
7	const	0.01	14.8	0.00845	0.0606	0.139	0.1385	35.04	15.0	2.336	16.87	94.58	103.8	17.3	0.062	0.0600
8	const	0.01	15.2	0.00822	0.0594	0.138	0.140	34.4	14.6	2.356	16.83	111.45	121.1	17.3	0.063	0.0611
9	const	0.01	14.0	0.00893	0.0628	0.142						128.28	138.4			

TABLE E-2

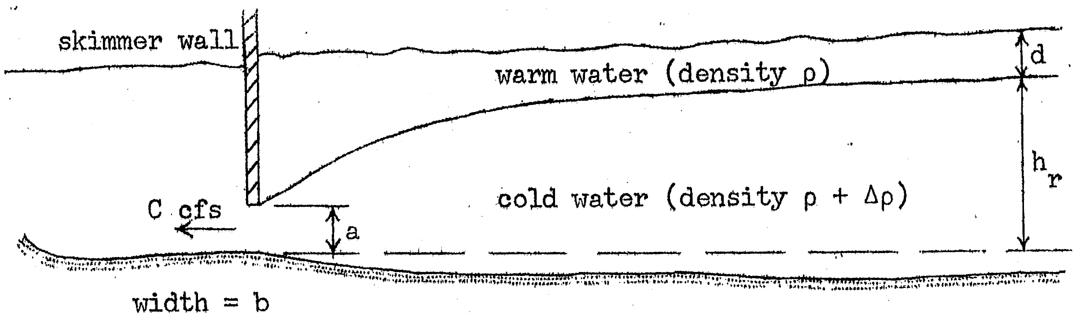
THICKNESS AND TIME OF FLOW COMPUTATIONS FOR THE PROTOTYPE

(1) Iso-therm Temp. T °F	(2) Density ρ gm/cm³ x 10³	(3) Relative Density Differ-ence Δρ/ρ x 10³	(4) Length of Iso-therm b ft	(5) Unit Dis-charge q = C/b cfs/ft	(6) Thickness of Layer d (Eq. C-4) ft	(7) Front Velocity u_f (Eq. C-5) fps	(8) Average Front Velocity $\bar{u}_f$ fps	(9) Surface Area Between Isotherms ΔS ft²	(10) Average Length of Iso-therms $\bar{b}$ ft	(11) Average Spacing of Iso-therms $\overline{\Delta x} = \frac{\Delta S}{\bar{b}}$ ft	(12) Time Inter-val $\Delta x/\bar{u}_f$ hrs	(13) Total Time t hrs
				River Flow, Q = 0 cfs, Condenser Flow, C = 400 cfs (See Chart No. 10)								
97	993.75	2.97	300	1.33	2.91	0.458	0.360	0.4	1135	353	0.27	0
96	994.0	2.72	1970	0.205	0.786	0.261	0.233	1.16	2860	405	0.48	0.27
94	994.3	2.41	3750	0.107	0.525	0.204	0.189	1.12	4325	259	0.38	0.75
92	994.7	2.01	4900	0.082	0.471	0.174	0.165	1.24	5580	222	0.37	1.13
90	995.0	1.71	6260	0.064	0.413	0.155	0.144	2.0	6880	291	0.56	1.50
88	995.35	1.36	7500	0.053	0.399	0.133	0.128	2.76	7200	383	0.83	2.06
86	995.1	1.00	6900	0.058	0.472	0.123	0.120	3.24	6300	514	1.19	2.89
84	996.0	0.70	5700	0.070	0.601	0.116	0.109	5.92	5485	1082	2.76	4.08
82	996.3	0.40	5270	0.076	0.766	0.099	0.084	6.76	6855	987	3.26	6.84
81	996.5	0.20	8440	0.047	0.695	0.068						10.10
80	996.7	0										
				River Flow, Q = 0 cfs, Condenser Flow, C = 1500 cfs (See Chart No. 20)								
97	993.75	2.97	300	5.00	6.40	0.782	0.544	1.80	2450	735	0.38	0
96	994.00	2.72	4600	0.326	1.07	0.305	0.275	4.64	6250	742	0.75	0.38
94	994.3	2.41	7900	0.190	0.78	0.245	0.232	4.32	8500	508	0.61	1.03
92	994.7	2.01	9100	0.165	0.75	0.220	0.232	6.72	7400	908	1.09	1.64
90	995.0	1.71	5700	0.263	1.08	0.244	0.227	7.08	6450	1100	1.35	2.73
88	995.35	1.36	7200	0.208	1.00	0.208	0.196	9.00	7500	1200	1.70	4.08
86	995.7	1.00	7750	0.1935	1.05	0.184	0.175	14.56	7610	1910	3.03	5.78
84	996.0	0.703	7470	0.201	1.21	0.166	0.158	9.16	7610	1200	2.11	8.81
83	996.15	0.552	7750	0.1935	1.28	0.151						10.92
80	996.7	0										
				River Flow, Q = 0 cfs, Condenser Flow, C = 3000 cfs (See Chart No. 33)								
88.5	995.28	1.43	300	10.0	10.0	1.00	0.636	4.40	3490	1260	0.55	0
88	995.35	1.36	6675	0.450	1.66	0.271	0.255	18.60	6820	2730	2.97	0.55
86	995.7	1.00	6960	0.431	1.80	0.240	0.226	26.00	7180	3620	4.44	3.52
84	996.0	0.703	7400	0.405	1.91	0.212	0.204	17.76	7175	2480	3.38	7.96
83	996.15	0.552	6950	0.432	2.19	0.197						11.34
80	996.7	0										

APPENDIX F

Some Notes on Intake Structure Design

The sketch shows a hypothetical cross section through an intake structure for the proposed thermal plant on Lake St. Croix. Based on model studies conducted at Massachusetts Institute of Technology [15], partially verified by experience of the U.S. Tennessee Valley Authority [16], it is possible to select the dimensions of the structure so that minimum drawdown of the warm surface water will occur.



From reference [15]

$$\frac{C}{b} \leq f\left(\frac{2}{3} h_r\right) \sqrt{q \frac{\Delta\rho}{\rho} \left(\frac{2}{3} h_r\right)}$$

where for not more than 1 per cent withdrawal, f is given by a chart as 0.83 for $h_r/a = 3.0$, 0.77 for $h_r/a = 2.0$, and 0.61 for $h_r/a = 1.5$. It is apparent that C/b is a unit discharge which must not be exceeded to avoid mixing at the interface.

The above equation may be applied to estimate the required dimensions of the intake at the proposed power plant. It is estimated that d will be of the order of 5 ft and h_r of the order of 24 ft. If the warm water above the intake is at 90° F and the cold water at 75° F, $\frac{\Delta\rho}{\rho} = 0.002$; while if the warm water is at 83° F and the cold water at 75° F, $\frac{\Delta\rho}{\rho} = 0.001$. Then possible widths b are given in the following table based on an ultimate intake capacity of 1500 cfs.

Widths b, ft for C = 1500 cfs

a, ft	$\frac{\Delta\rho}{\rho} = 0.002$	$\frac{\Delta\rho}{\rho} = 0.001$
8	111	157
12	120	170
16	151	214

APPENDIX G

Sewage Water Flow

The Stillwater sewage treatment plant discharges, on the average, 6.75 cfs of waste water into Lake St. Croix at approximately 4,600 ft upstream from the cooling water intake of the proposed Allen S. King generating plant. There was some concern that the waste water would be drawn into the plant intake and pumped to the vicinity of the Bayport beach which lies near the exit of the bay. The Stillwater sewage outlet was therefore represented in the model and a brief study was made of the sewage flow pattern with and without the plant in operation. More extensive tests were originally planned but these were curtailed when it became apparent that direct discharge to the lake was feasible; with direct discharge less adverse effects would be expected than with the originally planned discharge through the bay.

The waste water from Stillwater may be lighter or heavier than the lake water, depending on its relative temperature, air content, and dissolved or suspended solids. If it is lighter, it will float on the surface much like the warm water discharged at the condenser outlet and will not be drawn into the plant intake. Therefore, there was no need to study flow with lighter waste water and only flow with waste water heavier than the lake water was studied in the model. The heavier waste water flows are also those likely to be encountered during summer when the presence of sewage would be most objectionable.

In the model study, waste water flow was represented by salt water with a specific gravity of 1.002 wheras the lake water was fresh water. The first test was intended to represent the existing condition without the power plant. A 2,000 cfs river flow was modeled. Colored salt water was discharged from the Stillwater outlet at 6.75 cfs. Being heavier than the lake water, the waste water settled to the bottom and spread across the lake as it moved downstream along the bottom. The spread was due mainly to gravity acting on the heavier waste water, but there was also a little entrainment by the river flow.

Spreading patterns were photographed through the clear lake water and the photographs were interpolated to produce Chart 31 in Appendix H. Chart 31 shows a successive front of the waste water as it moves downstream and is diluted by the lake water and reduced by bacteriological and chemical actions.

The latter phenomena could not, of course, be reproduced in the model. However, if these actions proceed at a uniform rate across the front, the points can be interpreted to represent lines of constant sewage concentration.

After Chart 31 was obtained, the plant was placed in operation at the 700 cfs condenser flow rate, the river flow remaining at 2,000 cfs and waste water flow at 6.75 cfs. Again, photographs were taken and the fronts seen in the photographs were interpolated to yield Chart 32 in Appendix H. Condenser water was returned through the canal to the lake and not to the bay in these experiments.

A comparison of Chart 31 and 32 shows that upstream of the plant intake, the operation of the plant has little effect on the waste water spread. Differences become noticeable downstream, however. There are two prominent differences. First, some of the waste water is drawn into the intake; this is only a portion of the total, however, because the waste water has spread all across the lake bottom by the time it reaches the plant intake. Some of the heavier water passes by the plant intake as can be seen on Chart 32. Bearing in mind that the total waste water flow is only 6.75 cfs and that the plant intake withdraws 700 cfs, the sewage strength recirculated by the plant is indeed small. Second, the remaining waste water not withdrawn by the plant does not spread back to the Minnesota side; thus, the Bayport beach area is left relatively free from waste water flow. In interpreting this last result, it must be recognized that the condenser water flow was returned to the lake at the same density as the lake water and did not float as it normally would. Hence, there was strong interference between this returning condenser water flow and the river flow. Qualitatively, however, the result observed in the model is probably correct.

Since the waste water concentration in the condenser water is so small, no effort was made to trace its course from the outlet.

TABLE III

LIST OF CHARTS

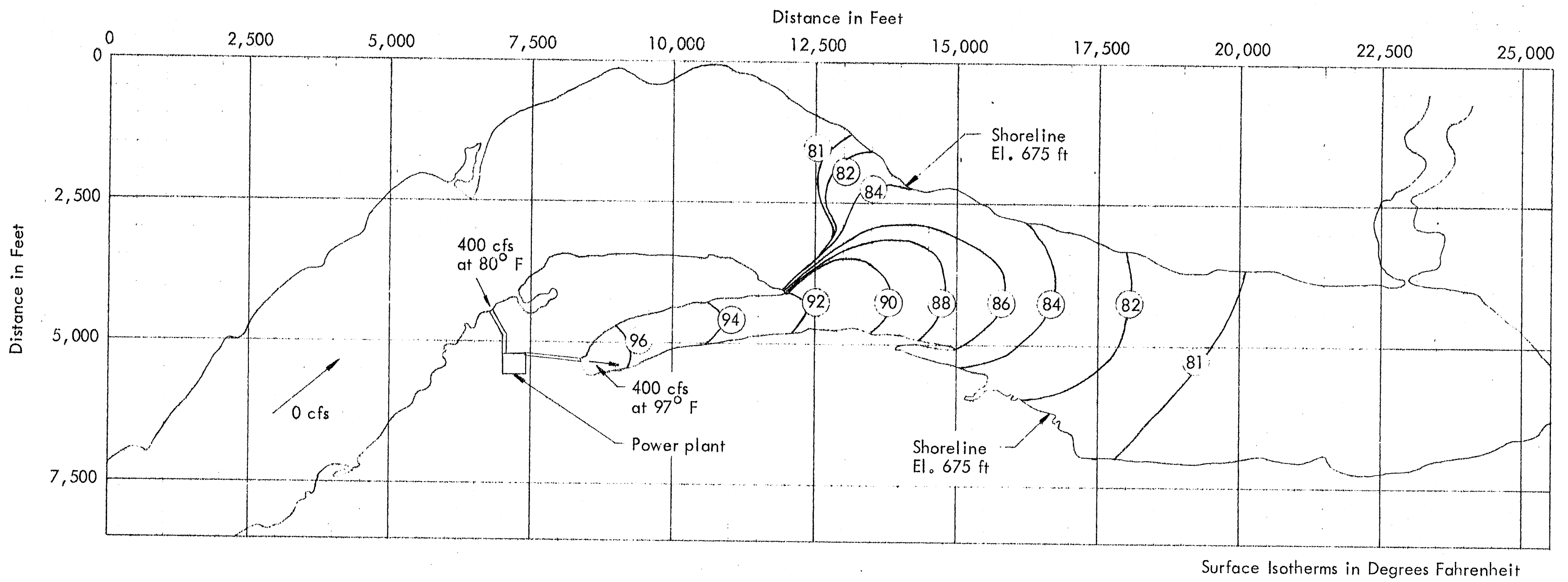
Chart No.	Dew Point Temp. °F	Condenser Flow, cfs	River Flow cfs	Model Study
	Discharge to Bay during Midsummer, 80° F Intake and 97° F Discharge Temperatures			
1	80	400	0	Yes
2	80	700	0	Yes
3	80	1500	0	Yes
4	80	400	1300	Yes
5	80	700	1300	Yes
6	80	1500	1300	Yes
7	80	700	2000	Yes
8	75.5	1500	0	Yes
9	75.5	1500	1300	Yes
	Discharge Directly to Lake during Midsummer, 80° Intake and 97° F Discharge Temperatures			
10	80	400	0	Yes
11	80	400	900	No
12	80	400	1200	No
13	80	400	1500	No
14	80	400	2000	Yes
15	80	700	0	Yes
16	80	700	900	No
17	80	700	1200	No
18	80	700	1500	No
19	80	700	2000	Yes
20	80	1500	0	Yes
21	80	1500	900	No
22	80	1500	1200	No
23	80	1500	1500	No
24	80	1500	2000	Yes
25	75.5	400	2000	Yes
26	75.5	1500	2000	Yes
	Discharge Directly to Lake during Midwinter, 35° F Intake and 65° F Discharge Temperatures			
27	9.0	400	0	Yes
28	9.0	400	2000	Yes

TABLE III (continued)

LIST OF CHARTS

Chart No.	Dew Point Temp. °F	Condenser Flow, cfs	River Flow cfs	Model Study
	Discharge to Bay during Midwinter, 35° F Intake and 65° F Discharge Temperatures			
29	9.0	400	0	Yes
30	9.0	400	2000	Yes
	Stillwater Sewage Plant Flow of 6.75 cfs			
31	--	0	2000	Yes
32	--	700	2000	Yes
	Discharge Directly to Lake during Midsummer, 80° F Intake and 88.5° F Discharge Temperatures			
33	80	3000	0	No

CHART 1

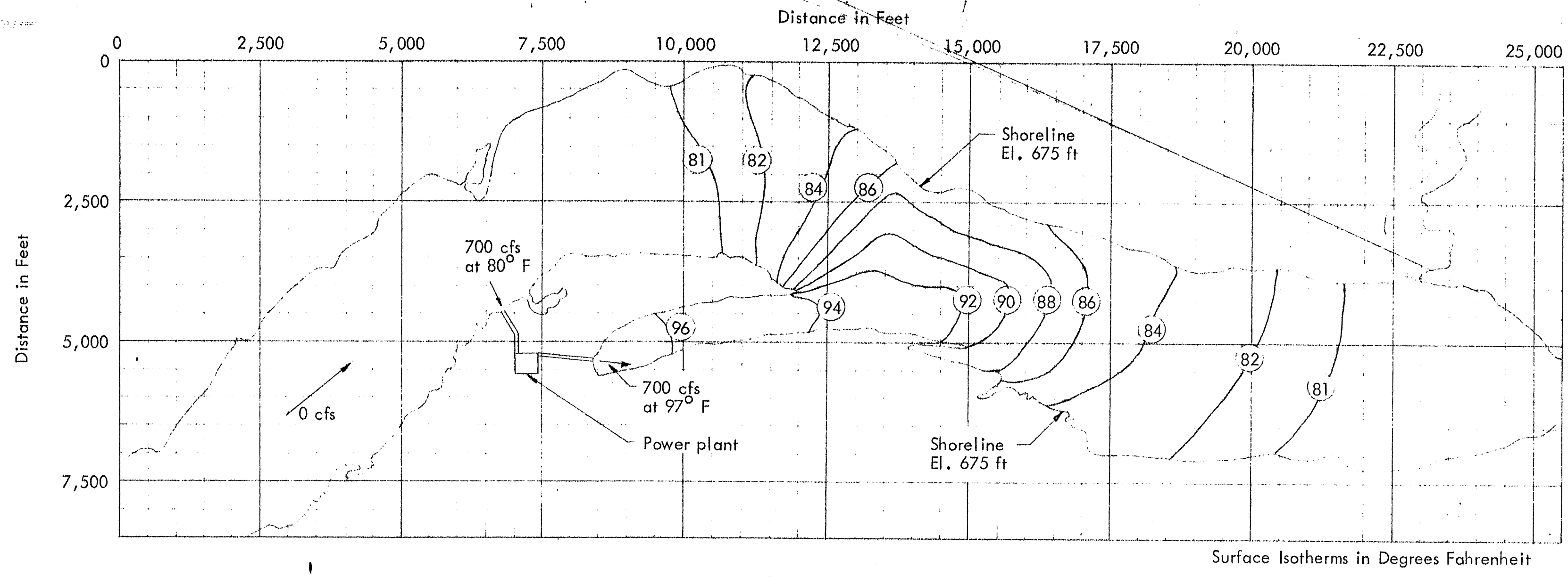


Assumed Meteorological Data:
Wind 6 mph from South
Dew point temperature 80° F

NORTHERN STATES POWER COMPANY
ALLEN S. KING GENERATING PLANT
Predicted Isotherms on Lake St. Croix
During Midsummer

SAINT ANTHONY FALLS HYDRAULIC LABORATORY
UNIVERSITY OF MINNESOTA

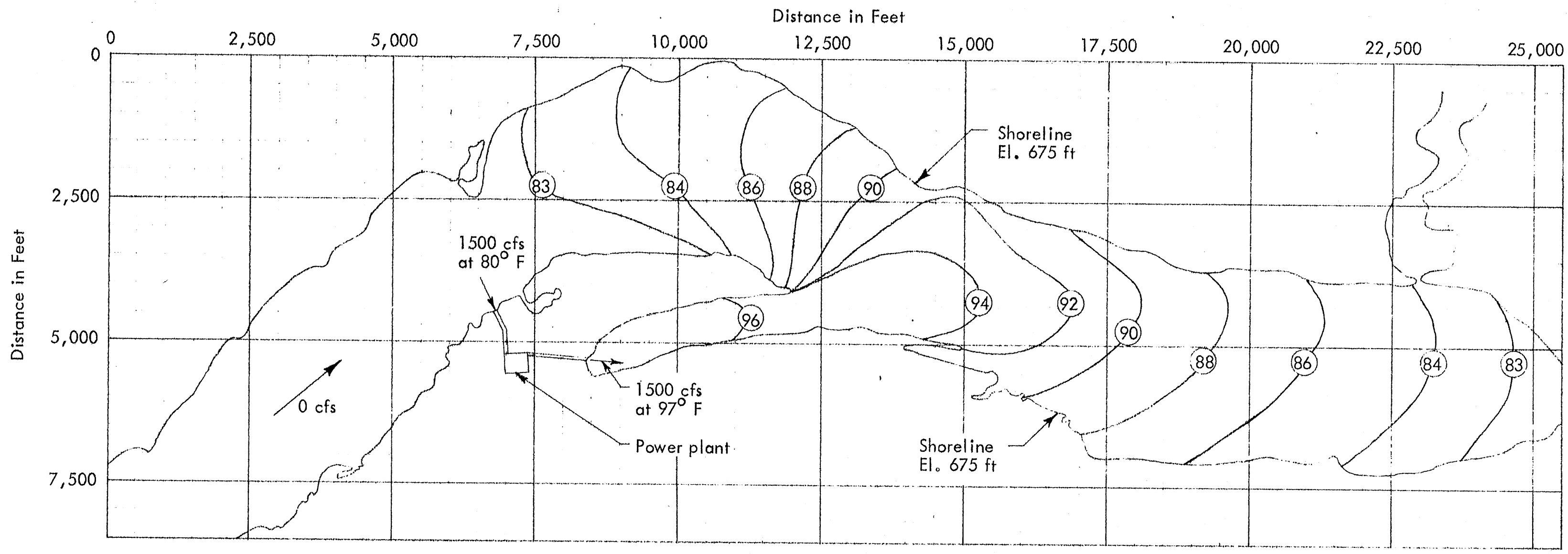
DRAWN WQD	CHECKED	APPROVED
SCALE	DATE 11-17-64	NO. 148B443-19



Assumed Meteorological Data:
Wind 6 mph from South
Dew point temperature 80° F

NORTHERN STATES POWER COMPANY ALLEN S. KING GENERATING PLANT Predicted Isotherms on Lake St. Croix During Midsummer
SAINT ANTHONY FALLS HYDRAULIC LABORATORY UNIVERSITY OF MINNESOTA

DRAWN ACY	CHECKED	APPROVED
SCALE	DATE 11-17-64	NO. 148B443-20



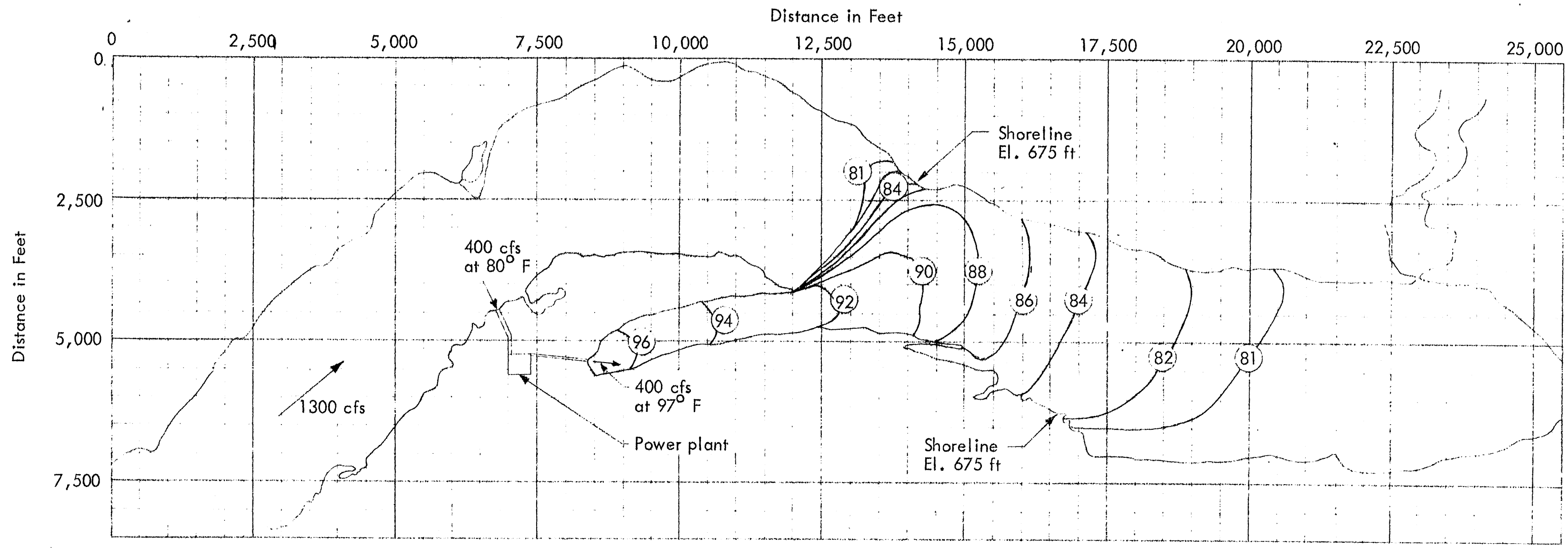
Surface Isotherms in Degrees Fahrenheit

Assumed Meteorological Data:
Wind 6 mph from South
Dew point temperature 80° F

NORTHERN STATES POWER COMPANY ALLEN S. KING GENERATING PLANT Predicted Isotherms on Lake St. Croix During Midsummer
SAINT ANTHONY FALLS HYDRAULIC LABORATORY UNIVERSITY OF MINNESOTA

DRAWN WQD	CHECKED WQL	APPROVED
SCALE	DATE 11-17-64	NO. 148B443-21

CHART 4



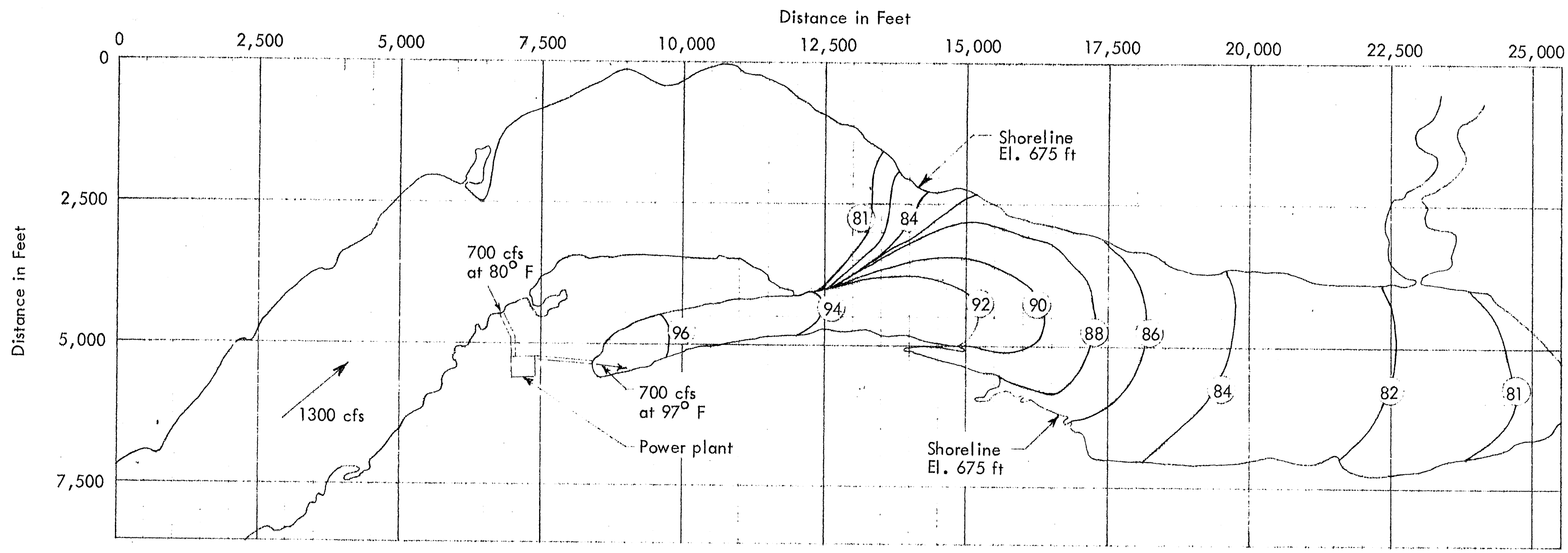
Surface Isotherms in Degrees Fahrenheit

Assumed Meteorological Data:
Wind 6 mph from South
Dew point temperature 80° F

NORTHERN STATES POWER COMPANY
ALLEN S. KING GENERATING PLANT
Predicted Isotherms on Lake St. Croix
During Midsummer

SAINT ANTHONY FALLS HYDRAULIC LABORATORY
UNIVERSITY OF MINNESOTA

DRAWN ACY	CHECKED	APPROVED
SCALE	DATE 11-17-64	NO. 148B443-23



Surface Isotherms in Degrees Fahrenheit

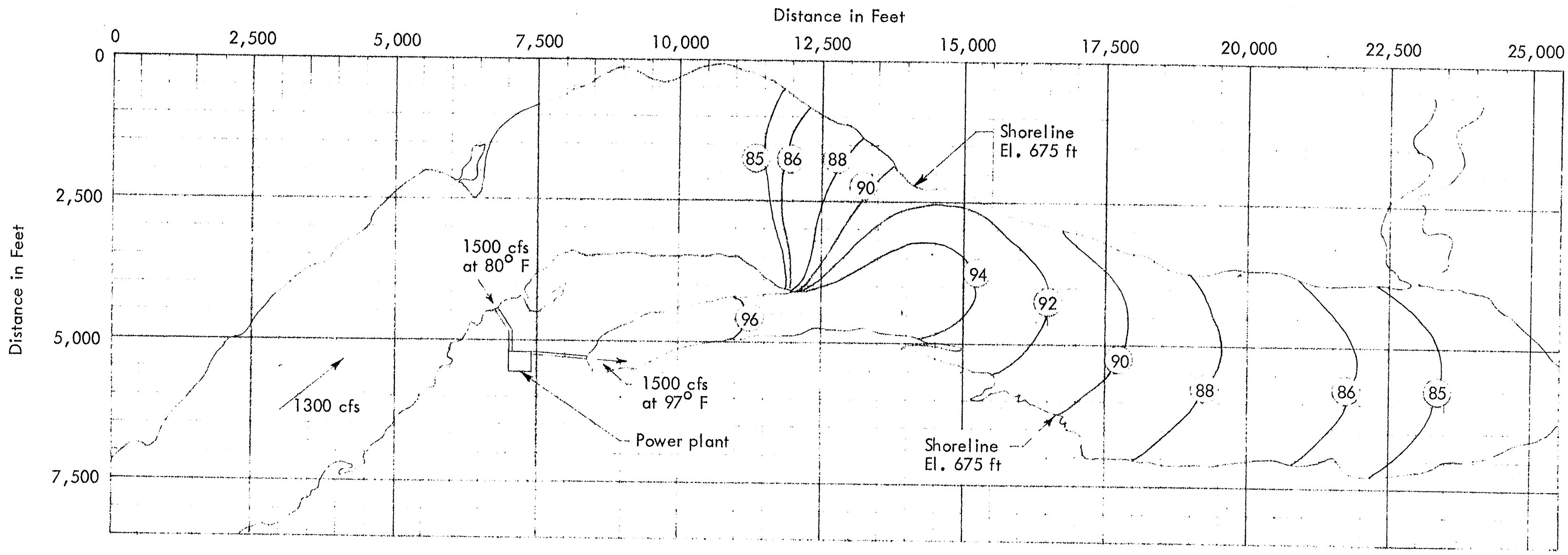
Assumed Meteorological Data:
Wind 6 mph from South
Dew point temperature 80° F

NORTHERN STATES POWER COMPANY
ALLEN S. KING GENERATING PLANT
Predicted Isotherms on Lake St. Croix
During Midsummer

SAINT ANTHONY FALLS HYDRAULIC LABORATORY
UNIVERSITY OF MINNESOTA

DRAWN AY	CHECKED	APPROVED
SCALE	DATE 11-17-64	NO. 148B443-24

CHART 6



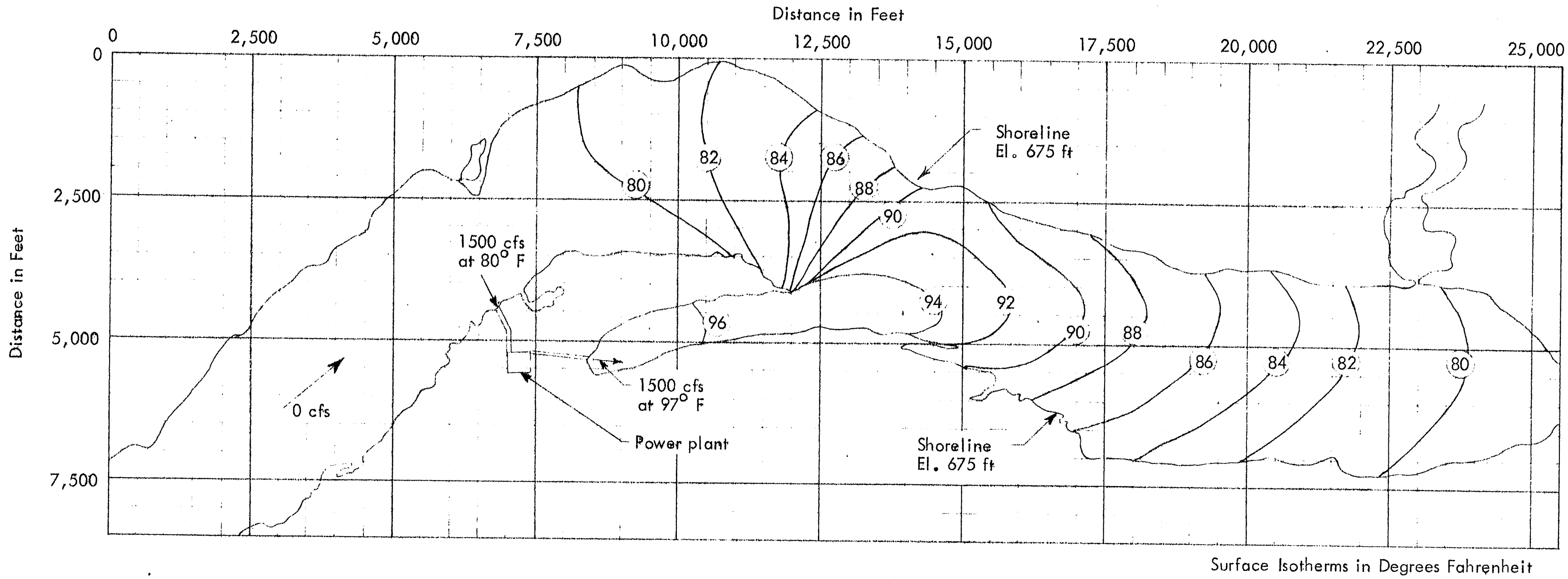
Surface Isotherms in Degrees Fahrenheit

Assumed Meteorological Data:
Wind 6 mph from South
Dew point temperature 80° F

NORTHERN STATES POWER COMPANY
ALLEN S. KING GENERATING PLANT
Predicted Isotherms on Lake St. Croix
During Midsummer

SAINT ANTHONY FALLS HYDRAULIC LABORATORY
UNIVERSITY OF MINNESOTA

DRAWN HC	CHECKED [illegible]	APPROVED
SCALE	DATE 11-17-64	NO. 148B443-25



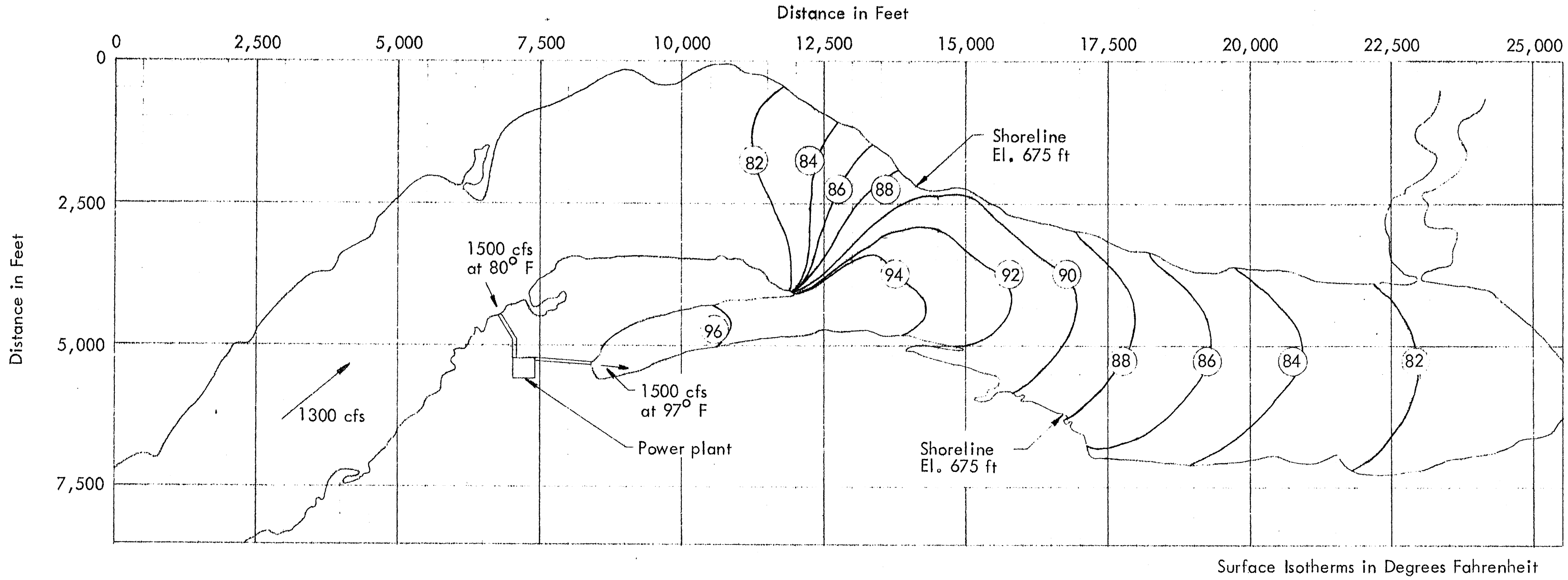
Assumed Meteorological Data:
Wind 6 mph from South
Dew point temperature 75.5° F

NORTHERN STATES POWER COMPANY
ALLEN S. KING GENERATING PLANT
Predicted Isotherms on Lake St. Croix
During Midsummer

SAINT ANTHONY FALLS HYDRAULIC LABORATORY
UNIVERSITY OF MINNESOTA

DRAWN HC	CHECKED [signature]	APPROVED
SCALE	DATE 11-17-64	NO. 148B443-22

CHART 9

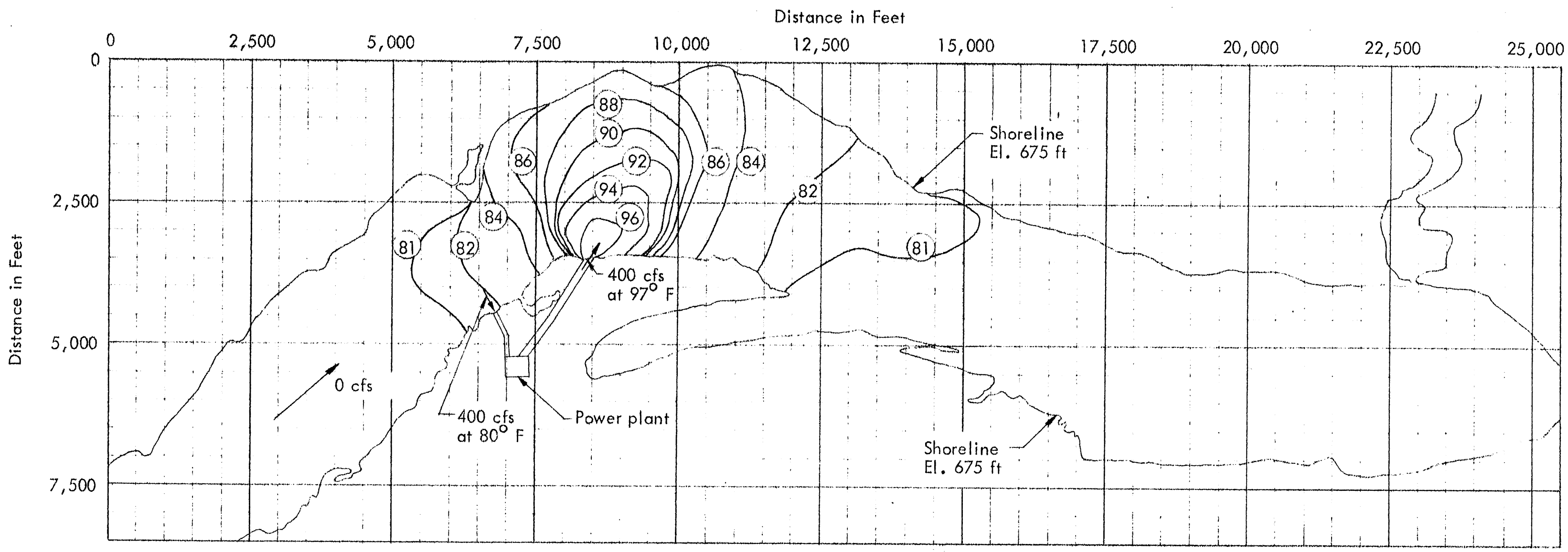


Assumed Meteorological Data:
Wind 6 mph from South
Dew point temperature 75.5° F

NORTHERN STATES POWER COMPANY
ALLEN S. KING GENERATING PLANT
Predicted Isotherms on Lake St. Croix
During Midsummer

SAINT ANTHONY FALLS HYDRAULIC LABORATORY
UNIVERSITY OF MINNESOTA

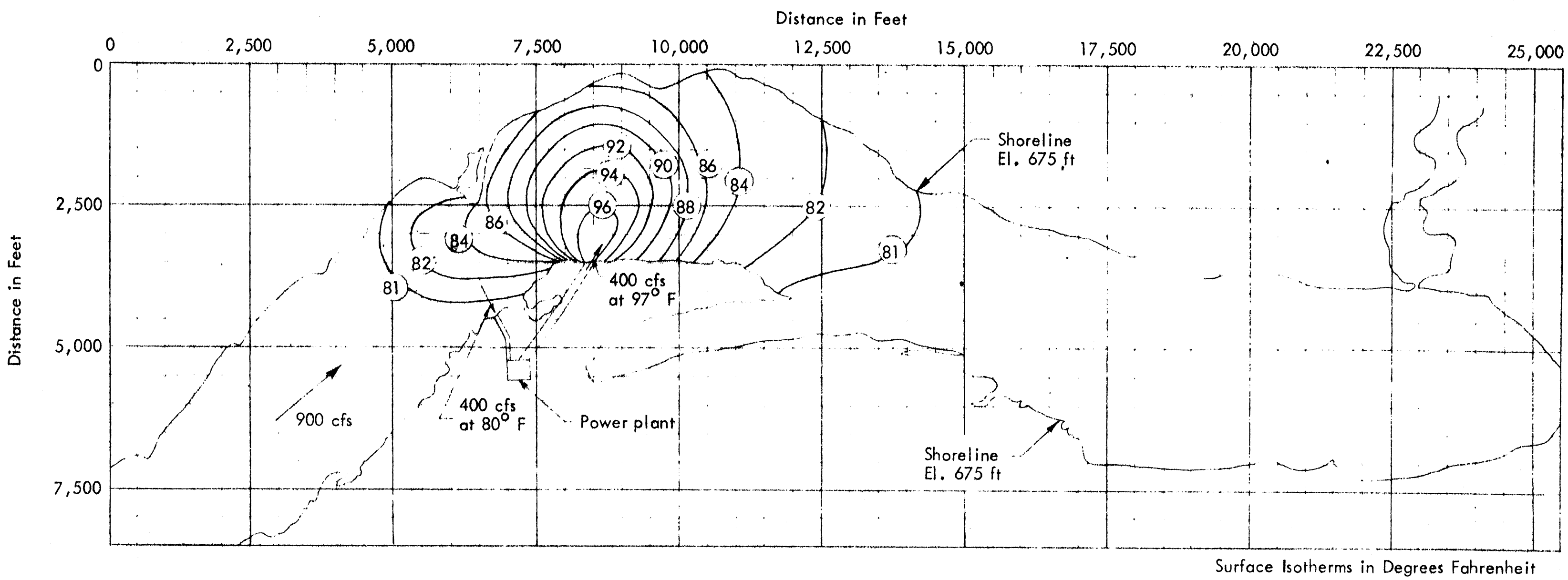
DRAWN HC	CHECKED	APPROVED
SCALE	DATE 11-17-64	NO. 148B443-26



Surface Isotherms in Degrees Fahrenheit

Assumed Meteorological Data:
Wind 6 mph from South
Dew point temperature 80° F

NORTHERN STATES POWER COMPANY ALLEN S. KING GENERATING PLANT Predicted Isotherms on Lake St. Croix During Midsummer		
SAINT ANTHONY FALLS HYDRAULIC LABORATORY UNIVERSITY OF MINNESOTA		
DRAWN ACY	CHECKED	APPROVED
SCALE	DATE 12-8-64	NO. 148B443-34

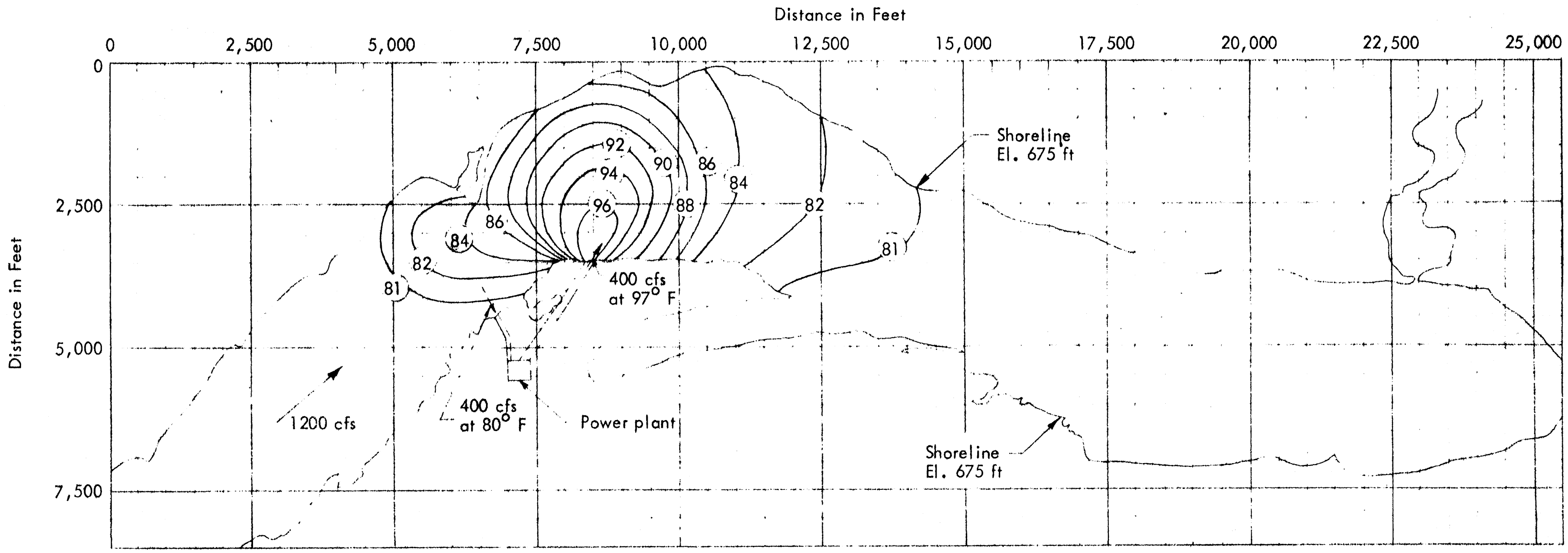


Assumed Meteorological Data:
Wind 6 mph from South
Dew point temperature 80° F

NORTHERN STATES POWER COMPANY
ALLEN S. KING GENERATING PLANT
Predicted Isotherms on Lake St. Croix
During Midsummer

SAINT ANTHONY FALLS HYDRAULIC LABORATORY
UNIVERSITY OF MINNESOTA

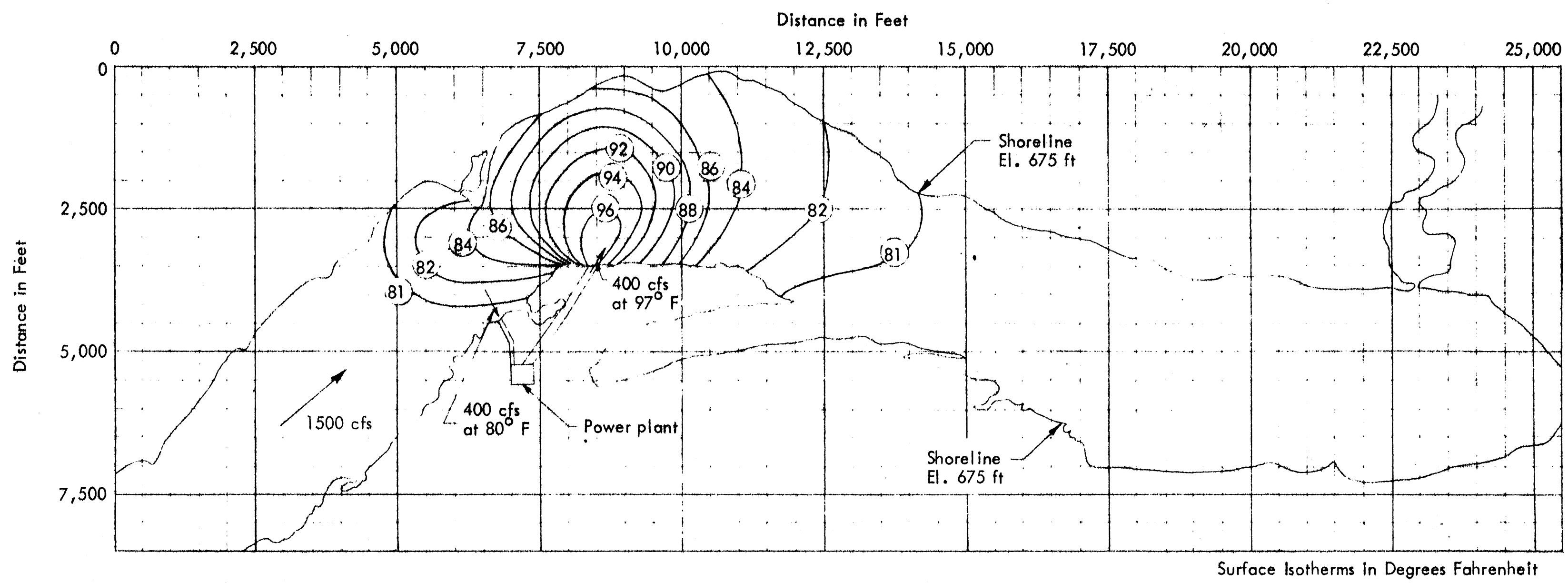
DRAWN HC	CHECKED	APPROVED
SCALE	DATE 12-11-64	NO. 148B443-47



Surface Isotherms in Degrees Fahrenheit

Assumed Meteorological Data:
Wind 6 mph from South
Dew point temperature 80° F

NORTHERN STATES POWER COMPANY ALLEN S. KING GENERATING PLANT Predicted Isotherms on Lake St. Croix During Midsummer		
SAINT ANTHONY FALLS HYDRAULIC LABORATORY UNIVERSITY OF MINNESOTA		
DRAWN HC	CHECKED	APPROVED
SCALE	DATE 12-11-64	NO. 148B443-48

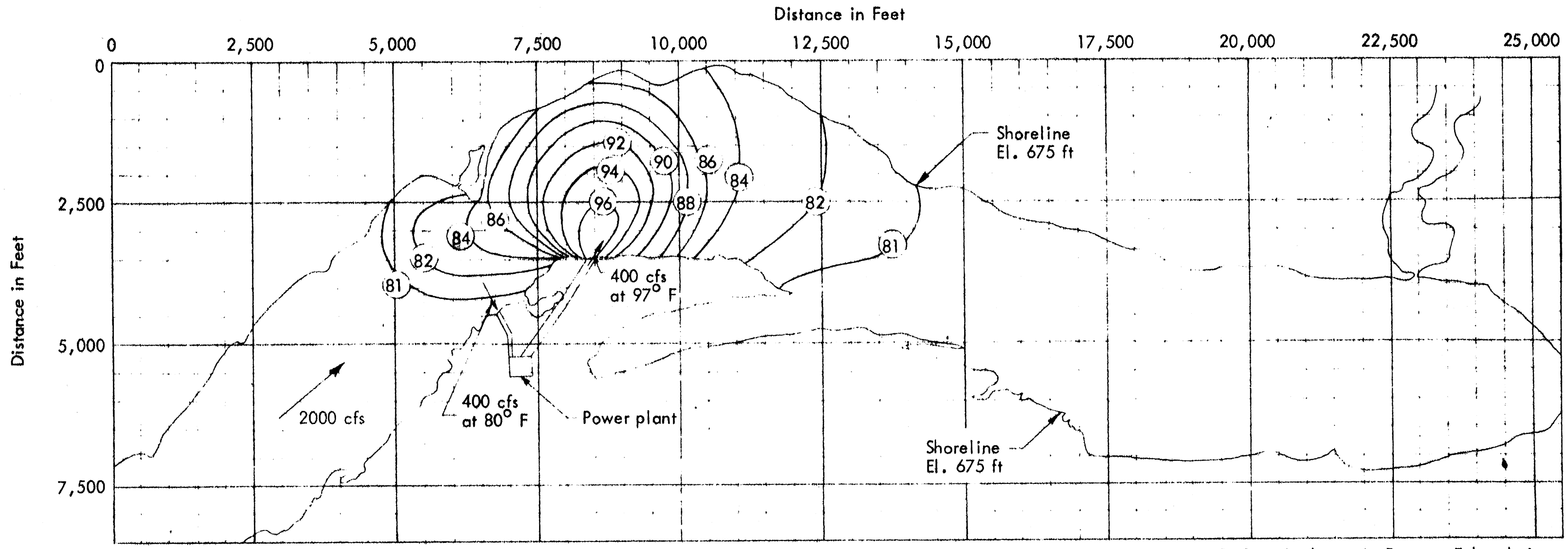


Assumed Meteorological Data:
Wind 6 mph from South
Dew point temperature 80° F

NORTHERN STATES POWER COMPANY
ALLEN S. KING GENERATING PLANT
Predicted Isotherms on Lake St. Croix
During Midsummer

SAINT ANTHONY FALLS HYDRAULIC LABORATORY
UNIVERSITY OF MINNESOTA

DRAWN HC	CHECKED	APPROVED
SCALE	DATE 12-11-64	NO. 148B443-49



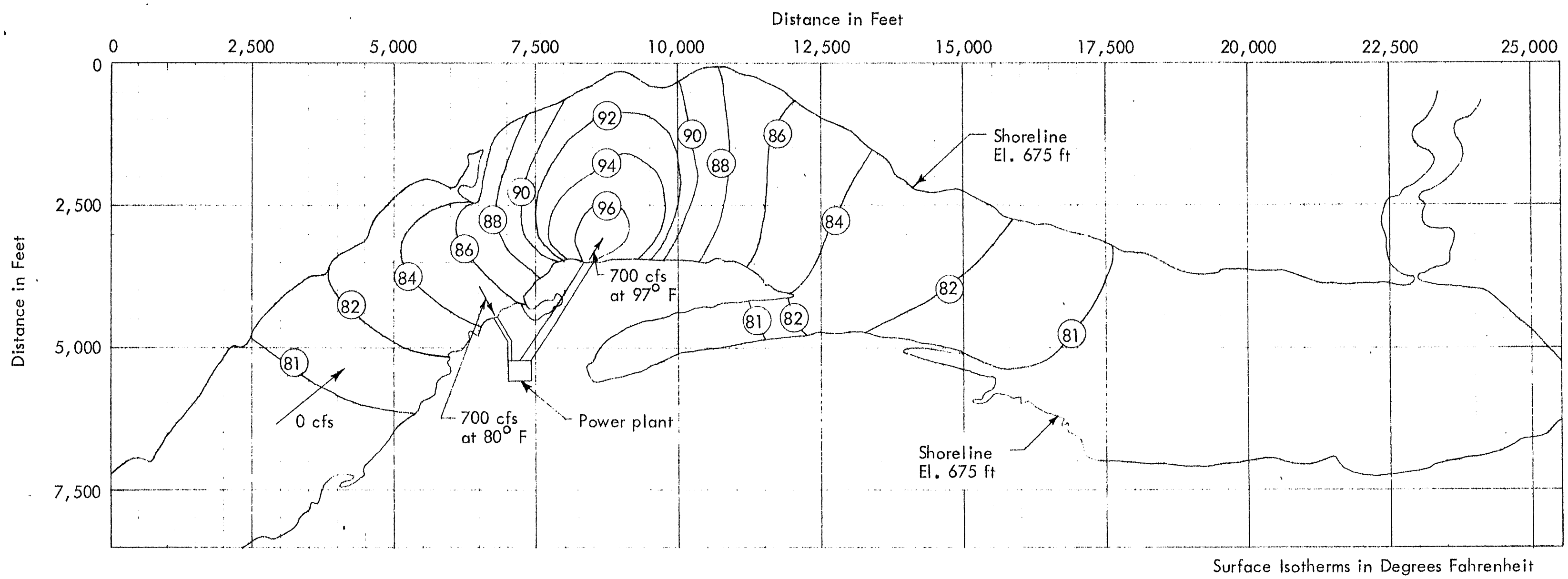
Surface Isotherms in Degrees Fahrenheit

Assumed Meteorological Data:
Wind 6 mph from South
Dew point temperature 80° F

NORTHERN STATES POWER COMPANY
ALLEN S. KING GENERATING PLANT
Predicted Isotherms on Lake St. Croix
During Midsummer

SAINT ANTHONY FALLS HYDRAULIC LABORATORY
UNIVERSITY OF MINNESOTA

DRAWN HC	CHECKED	APPROVED
SCALE	DATE 12-11-64	NO. 148B443-50

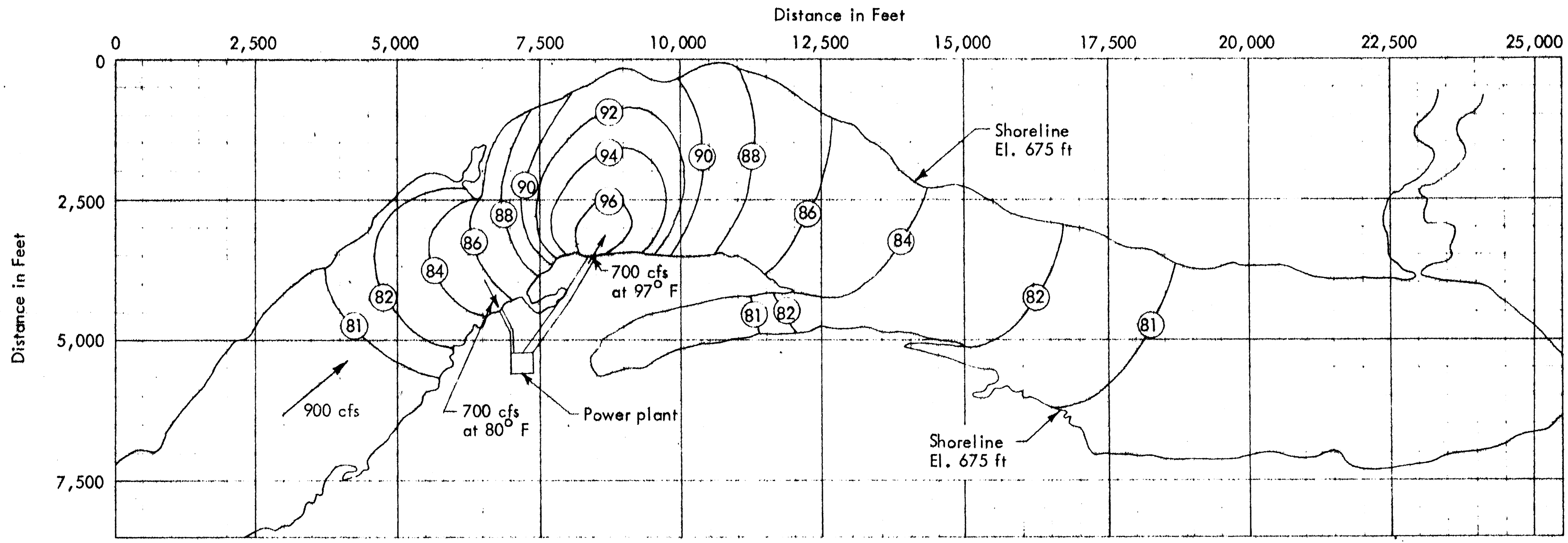


Assumed Meteorological Data:
Wind 6 mph from South
Dew point temperature 80° F

NORTHERN STATES POWER COMPANY
ALLEN S. KING GENERATING PLANT
Predicted Isotherms on Lake St. Croix
During Midsummer

SAINT ANTHONY FALLS HYDRAULIC LABORATORY
UNIVERSITY OF MINNESOTA

DRAWN WQD	CHECKED	APPROVED
SCALE	DATE 12-8-64	NO. 148B443-36



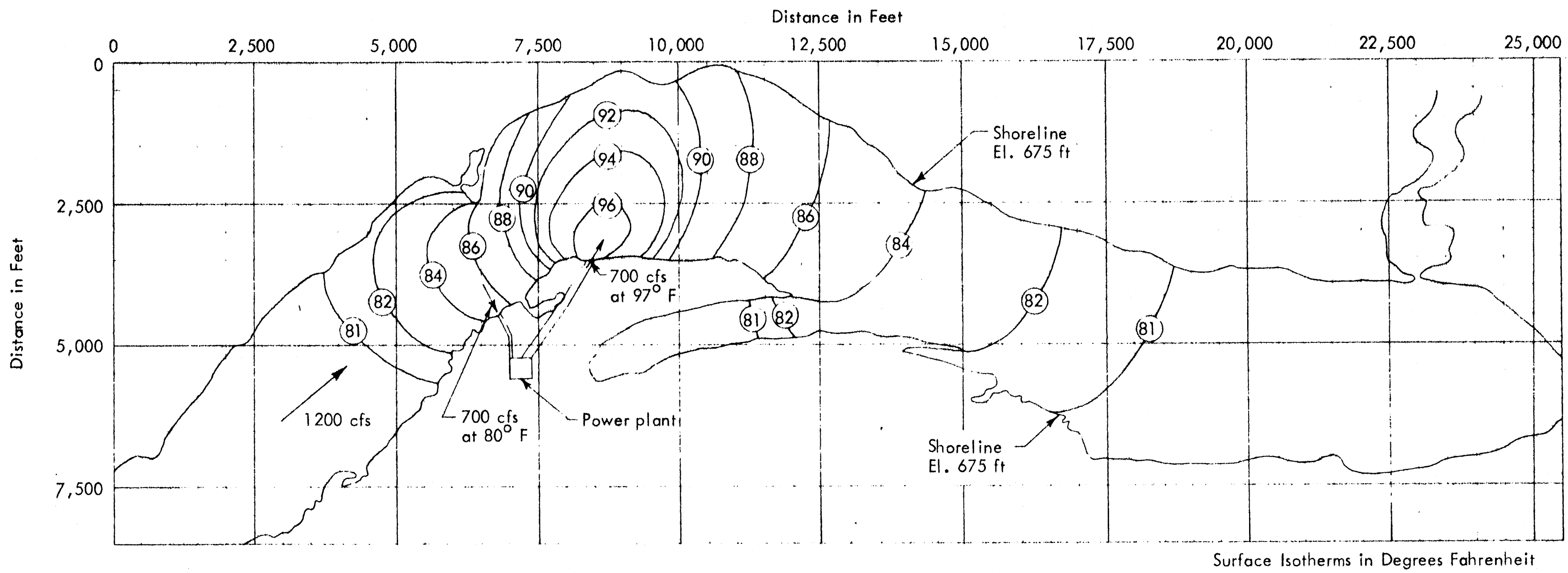
Surface Isotherms in Degrees Fahrenheit

Assumed Meteorological Data:
Wind 6 mph from South
Dew point temperature 80° F

NORTHERN STATES POWER COMPANY
ALLEN S. KING GENERATING PLANT
Predicted Isotherms on Lake St. Croix
During Midsummer

SAINT ANTHONY FALLS HYDRAULIC LABORATORY
UNIVERSITY OF MINNESOTA

DRAWN WQD	CHECKED	APPROVED
SCALE	DATE 12-15-64	NO. 148B443-51

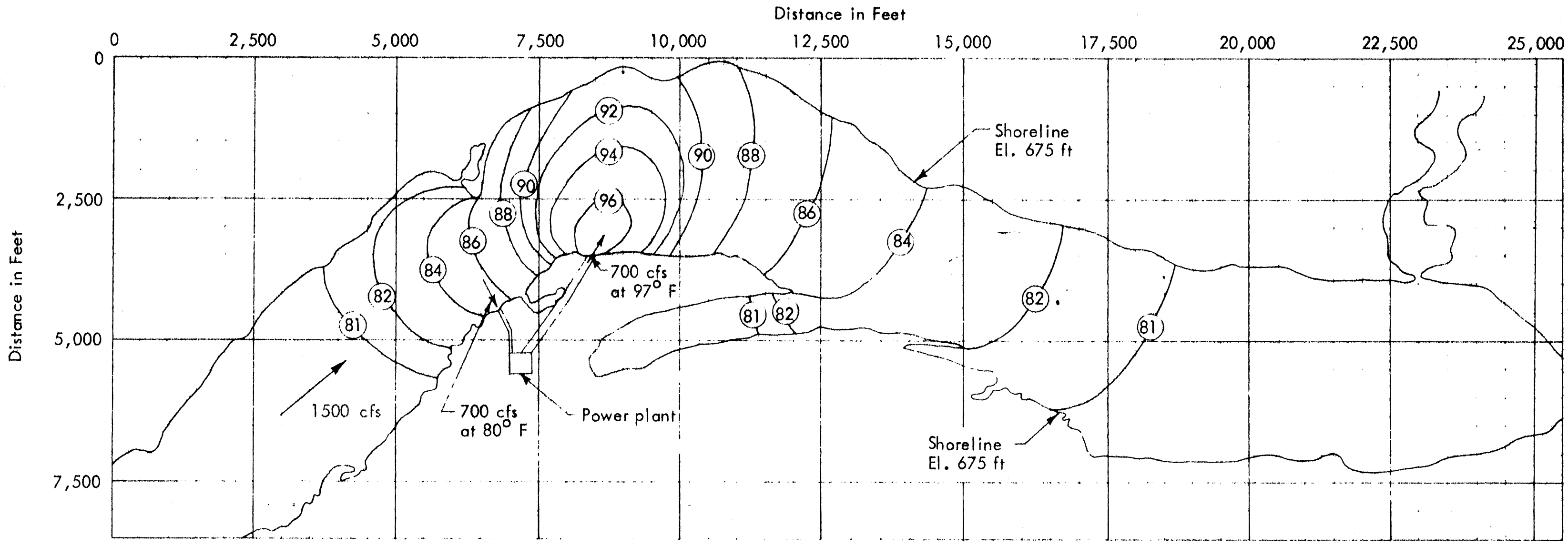


Assumed Meteorological Data:
Wind 6 mph from South
Dew point temperature 80° F

NORTHERN STATES POWER COMPANY
ALLEN S. KING GENERATING PLANT
Predicted Isotherms on Lake St. Croix
During Midsummer

SAINT ANTHONY FALLS HYDRAULIC LABORATORY
UNIVERSITY OF MINNESOTA

DRAWN WQD	CHECKED	APPROVED
SCALE	DATE 12-15-64	NO. 148B443-52



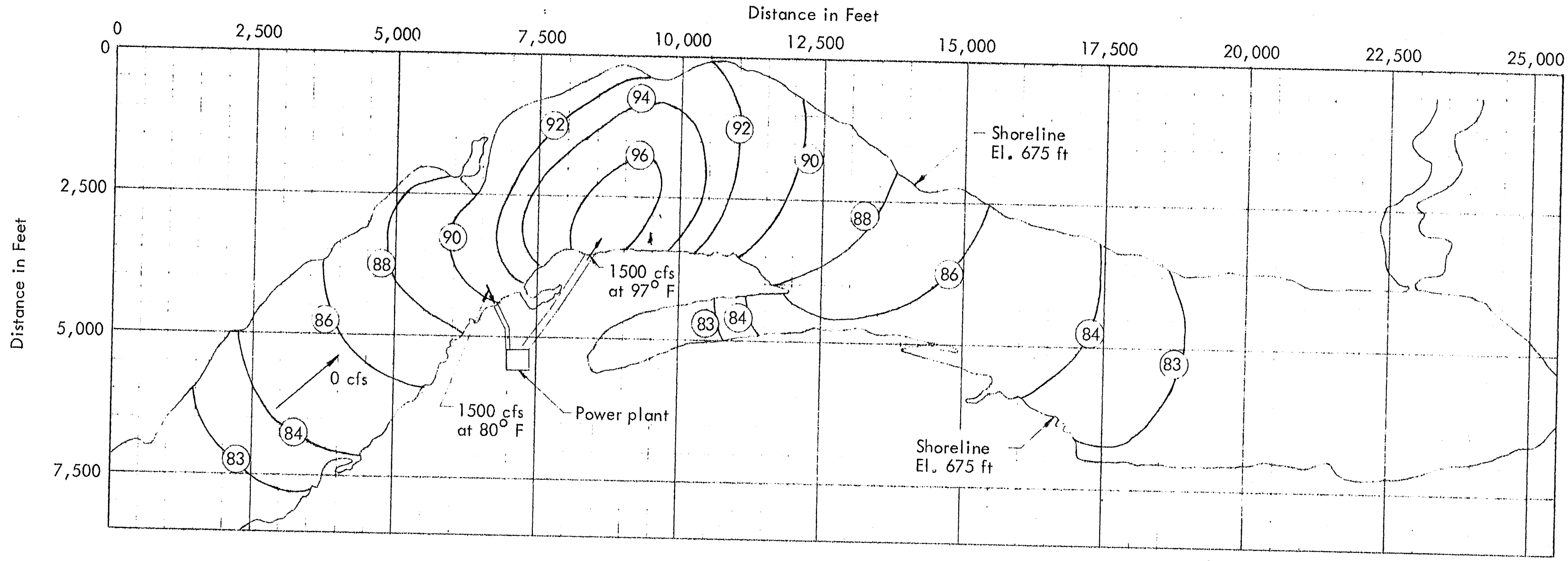
Surface Isotherms in Degrees Fahrenheit

Assumed Meteorological Data:
Wind 6 mph from South
Dew point temperature 80° F

NORTHERN STATES POWER COMPANY
ALLEN S. KING GENERATING PLANT
Predicted Isotherms on Lake St. Croix During Midsummer

SAINT ANTHONY FALLS HYDRAULIC LABORATORY
UNIVERSITY OF MINNESOTA

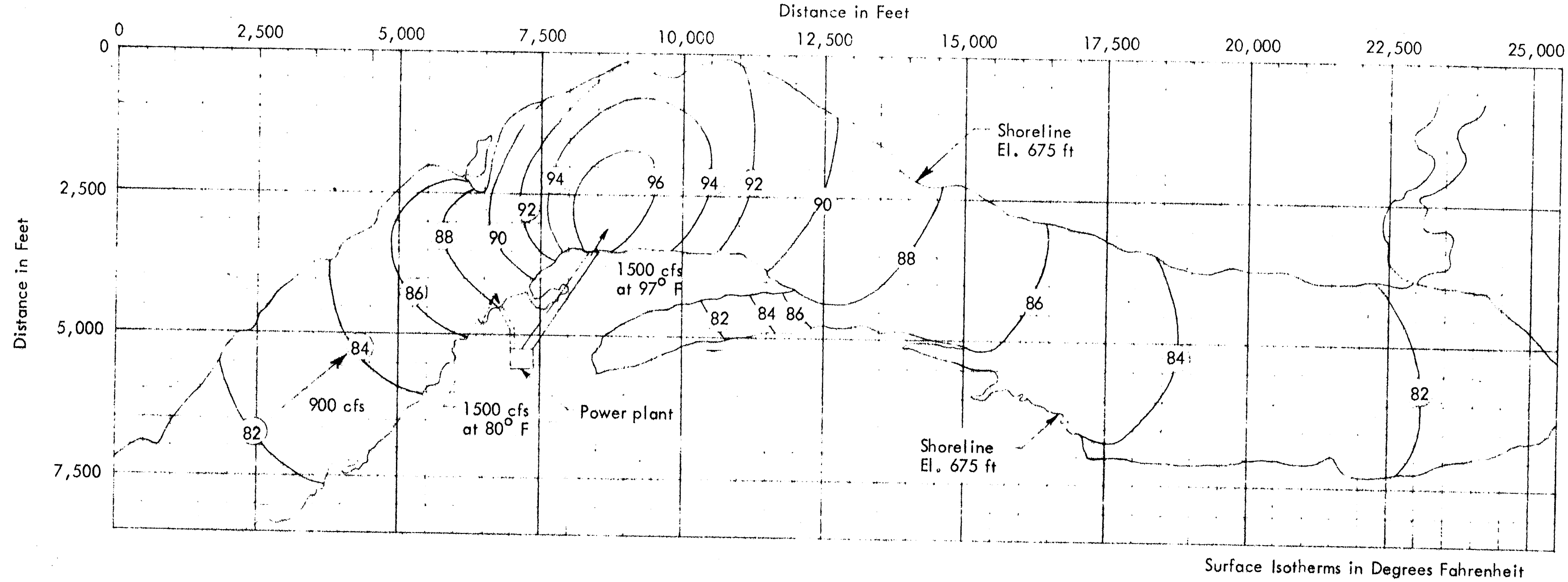
DRAWN WQD	CHECKED	APPROVED
SCALE	DATE 12-15-64	NO. 148B443-53



Surface Isotherms in Degrees Fahrenheit

Assumed Meteorological Data:
Wind 6 mph from South
Dew point temperature 80° F

NORTHERN STATES POWER COMPANY ALLEN S. KING GENERATING PLANT Predicted Isotherms on Lake St. Croix During Midsummer		
SAINT ANTHONY FALLS HYDRAULIC LABORATORY UNIVERSITY OF MINNESOTA		
DRAWN AGY	CHECKED	APPROVED
SCALE	DATE 12-11-64	NO. 148B443-42

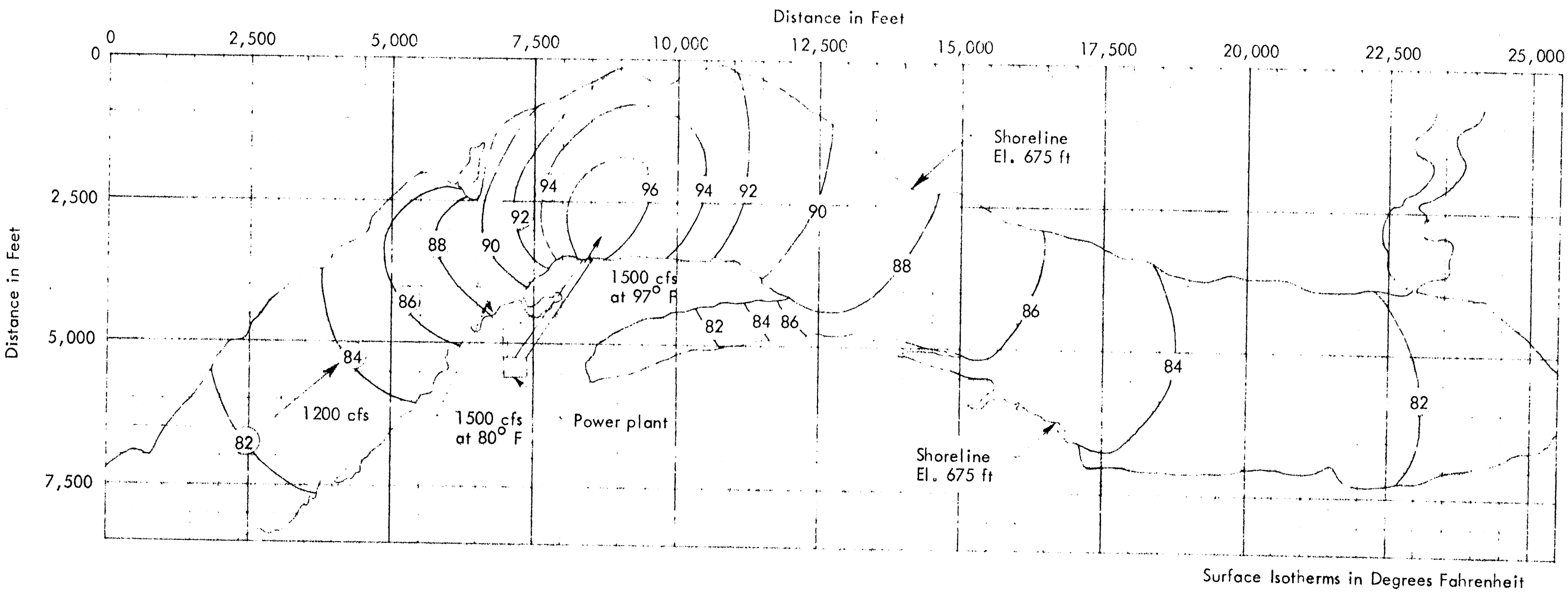


Assumed Meteorological Data:
Wind 6 mph from South
Dew point temperature 80° F

NORTHERN STATES POWER COMPANY
ALLEN S. KING GENERATING PLANT
Predicted Isotherms on Lake St. Croix
During Midsummer

SAINT ANTHONY FALLS HYDRAULIC LABORATORY
UNIVERSITY OF MINNESOTA

DRAWN HC	CHECKED	APPROVED
SCALE	DATE 12-9-64	NO. 148B443-55

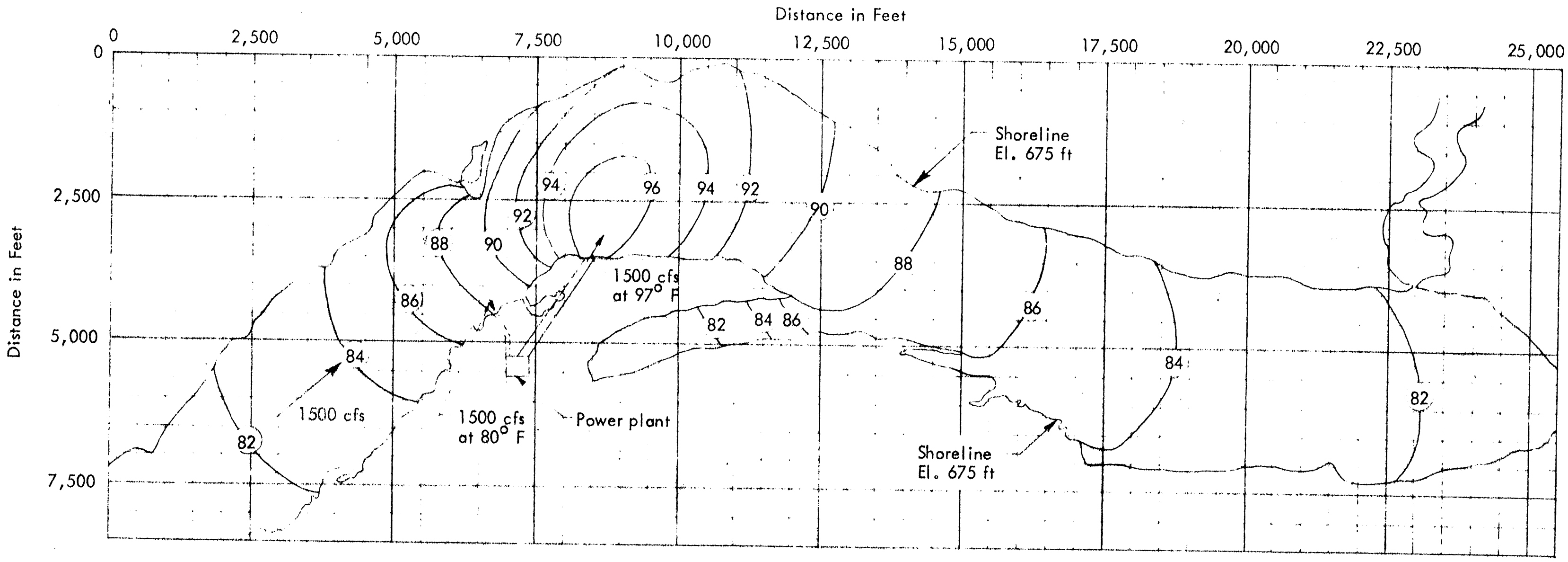


Assumed Meteorological Data:
Wind 6 mph from South
Dew point temperature 80° F

NORTHERN STATES POWER COMPANY
ALLEN S. KING GENERATING PLANT
Predicted Isotherms on Lake St. Croix
During Midsummer

SAINT ANTHONY FALLS HYDRAULIC LABORATORY
UNIVERSITY OF MINNESOTA

DRAWN HC	CHECKED	APPROVED
SCALE	DATE 12-9-64	NO. 148B443-56



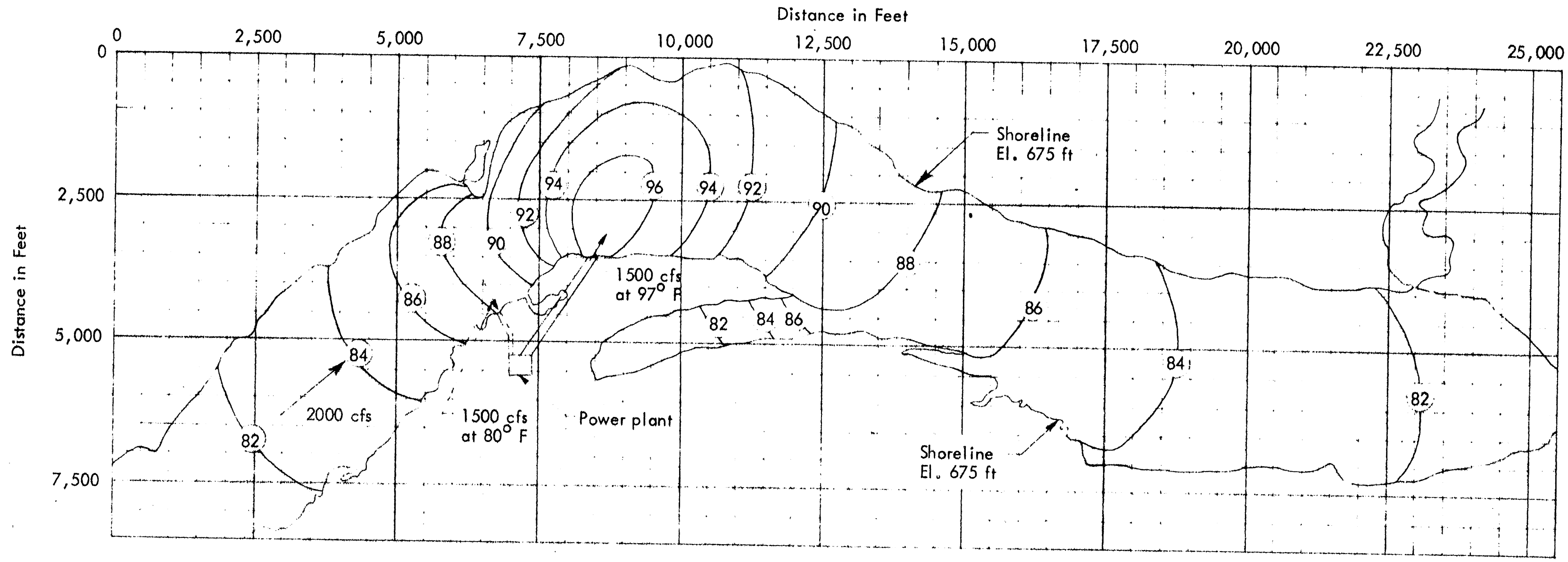
Surface Isotherms in Degrees Fahrenheit

Assumed Meteorological Data:
Wind 6 mph from South
Dew point temperature 80° F

NORTHERN STATES POWER COMPANY
ALLEN S. KING GENERATING PLANT
Predicted Isotherms on Lake St. Croix
During Midsummer

SAINT ANTHONY FALLS HYDRAULIC LABORATORY
UNIVERSITY OF MINNESOTA

DRAWN HC	CHECKED [illegible]	APPROVED
SCALE	DATE 12-9-64	NO. 148B443-57



Surface Isotherms in Degrees Fahrenheit

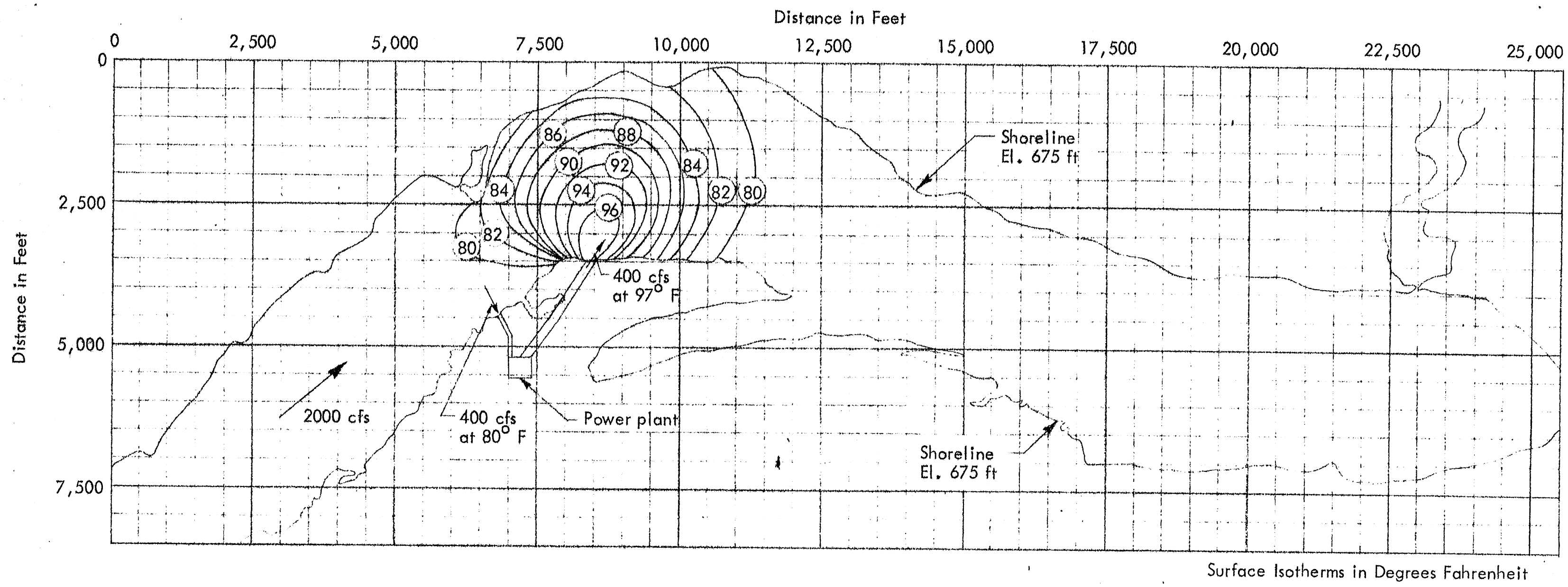
Assumed Meteorological Data:
Wind 6 mph from South
Dew point temperature 80° F

NORTHERN STATES POWER COMPANY
ALLEN S. KING GENERATING PLANT
Predicted Isotherms on Lake St. Croix
During Midsummer

SAINT ANTHONY FALLS HYDRAULIC LABORATORY
UNIVERSITY OF MINNESOTA

DRAWN HC	CHECKED	APPROVED
SCALE	DATE 12-9-64	NO. 148B443-58

CHART 25

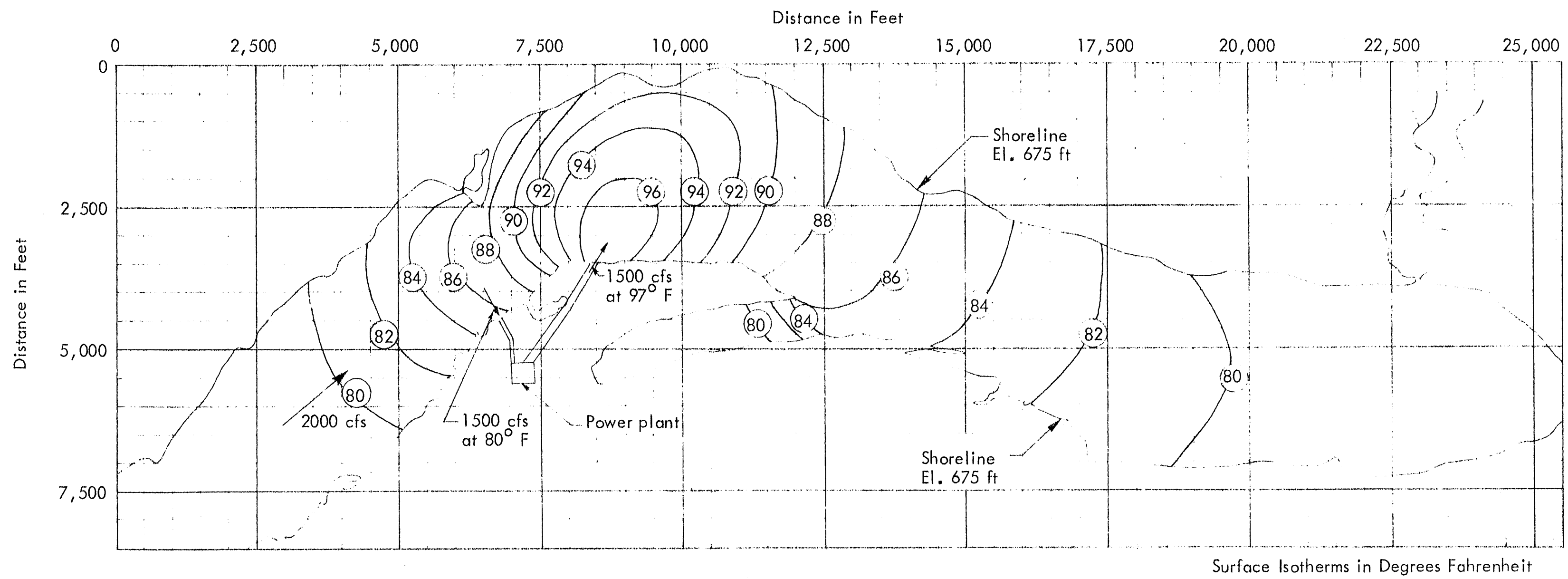


Assumed Meteorological Data:
Wind 6 mph from South
Dew point temperature 75.5° F

NORTHERN STATES POWER COMPANY
ALLEN S. KING GENERATING PLANT
Predicted Isotherms on Lake St. Croix
During Midsummer

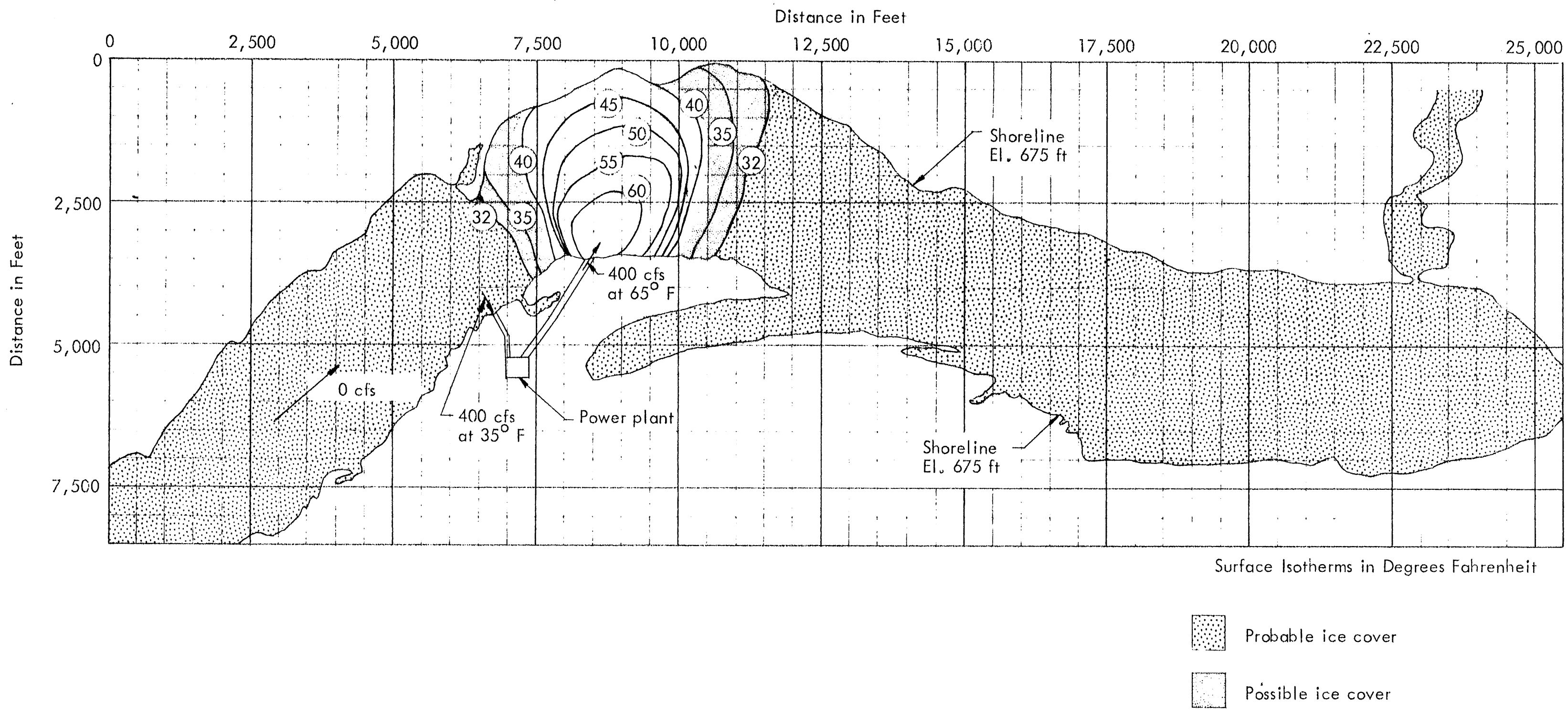
SAINT ANTHONY FALLS HYDRAULIC LABORATORY
UNIVERSITY OF MINNESOTA

DRAWN HC	CHECKED [signature]	APPROVED
SCALE	DATE 12-11-64	NO. 148B443-39



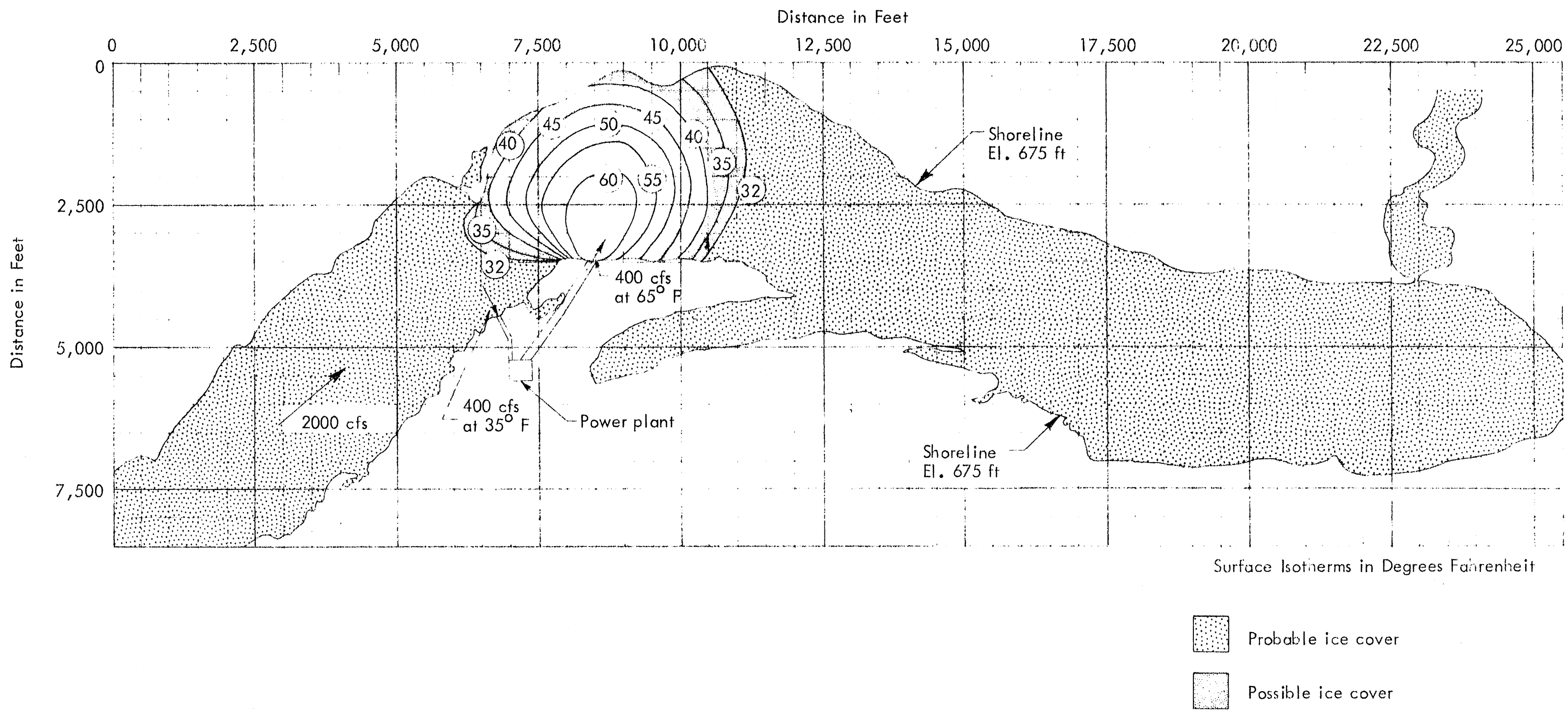
Assumed Meteorological Data:
Wind 6 mph from South
Dew point temperature 75.5° F

NORTHERN STATES POWER COMPANY ALLEN S. KING GENERATING PLANT Predicted Isotherms on Lake St. Croix During Midsummer	
SAINT ANTHONY FALLS HYDRAULIC LABORATORY UNIVERSITY OF MINNESOTA	
DRAWN HC	CHECKED	APPROVED
SCALE	DATE 12-11-64	NO. 148B443-41



Assumed Meteorological Data:
Wind 10 mph from Northwest
Dew point temperature 9° F

NORTHERN STATES POWER COMPANY ALLEN S. KING GENERATING PLANT Predicted Isotherms and Limits of Ice Cover on Lake St. Croix During Midwinter		
SAINT ANTHONY FALLS HYDRAULIC LABORATORY UNIVERSITY OF MINNESOTA		
DRAWN ACY	CHECKED	APPROVED
SCALE	DATE 12-8-64	NO. 148B443-35

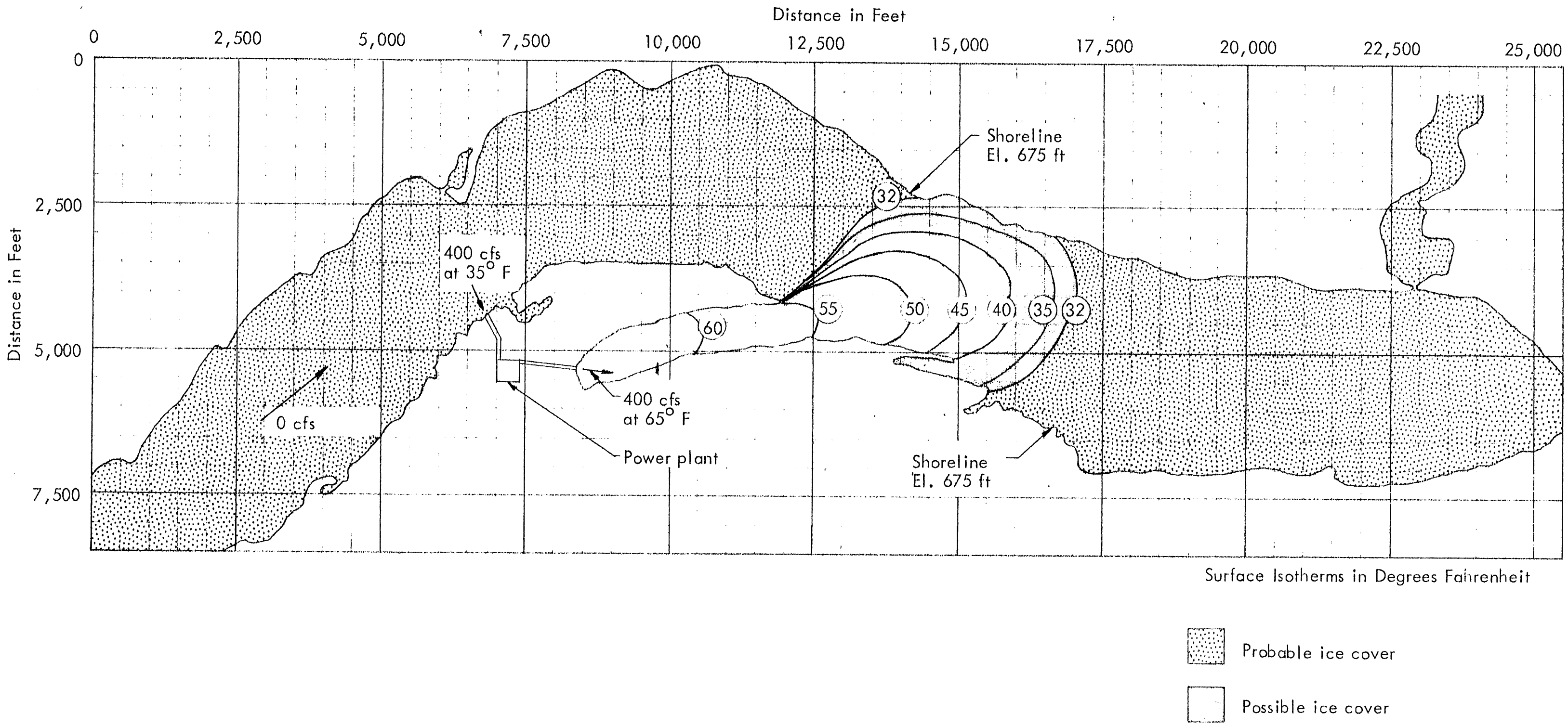


Assumed Meteorological Data:
Wind 10 mph from Northwest
Dew point temperature 9° F

NORTHERN STATES POWER COMPANY
ALLEN S. KING GENERATING PLANT
Predicted Isotherms and Limits of
Ice Cover on Lake St. Croix During Midwinter

SAINT ANTHONY FALLS HYDRAULIC LABORATORY
UNIVERSITY OF MINNESOTA

DRAWN HC	CHECKED	APPROVED
SCALE	DATE 12-11-64	NO. 148B443-40

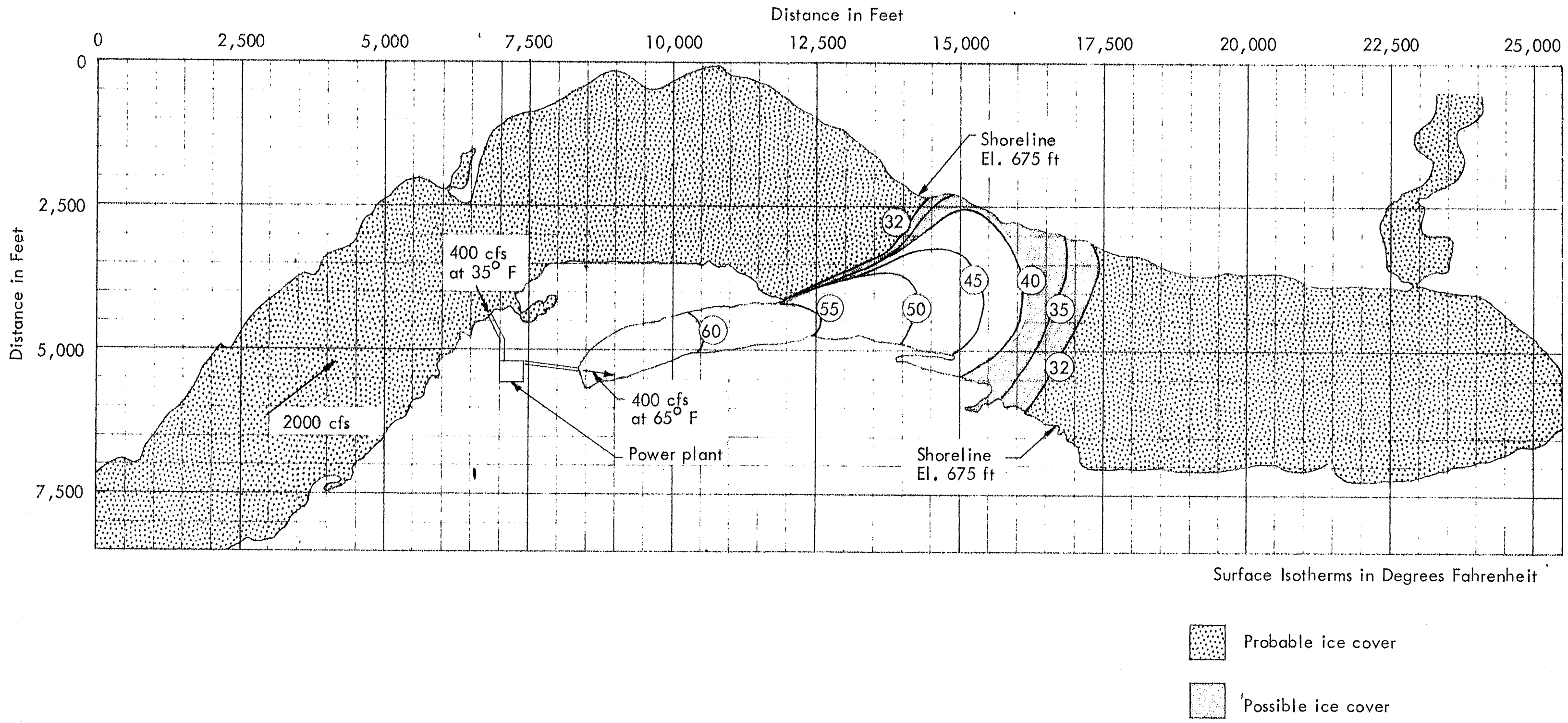


Assumed Meteorological Data:
Wind 10 mph from Northwest
Dew point temperature 9° F

NORTHERN STATES POWER COMPANY
ALLEN S. KING GENERATING PLANT
Predicted Isotherms and Limits of
Ice Cover on Lake St. Croix During Midwinter

SAINT ANTHONY FALLS HYDRAULIC LABORATORY
UNIVERSITY OF MINNESOTA

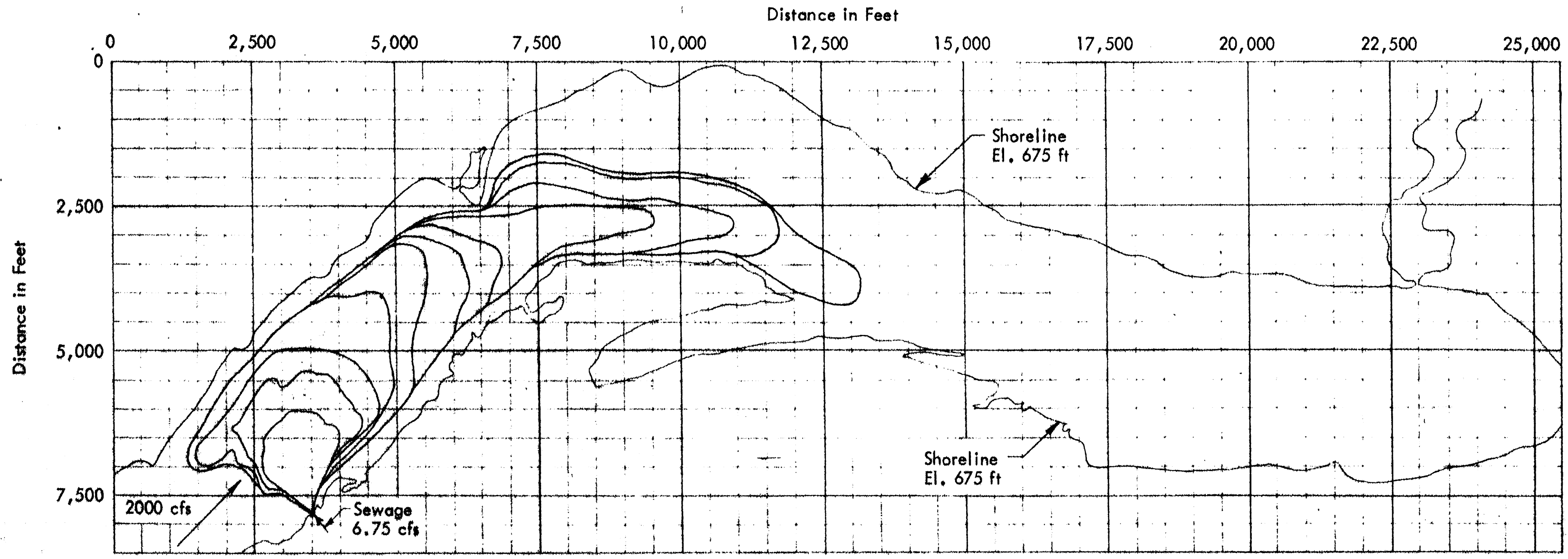
DRAWN ACY	CHECKED HS	APPROVED
SCALE	DATE 11-27-64	NO. 148B443-32



Assumed Meteorological Data:
Wind 10 mph from Northwest
Dew point temperature 9° F

NORTHERN STATES POWER COMPANY ALLEN S. KING GENERATING PLANT Predicted Isotherms and Limits of Ice Cover on Lake St. Croix During Midwinter
SAINT ANTHONY FALLS HYDRAULIC LABORATORY UNIVERSITY OF MINNESOTA

DRAWN ACY	CHECKED HS	APPROVED
SCALE	DATE 11-27-64	NO. 148B443-33

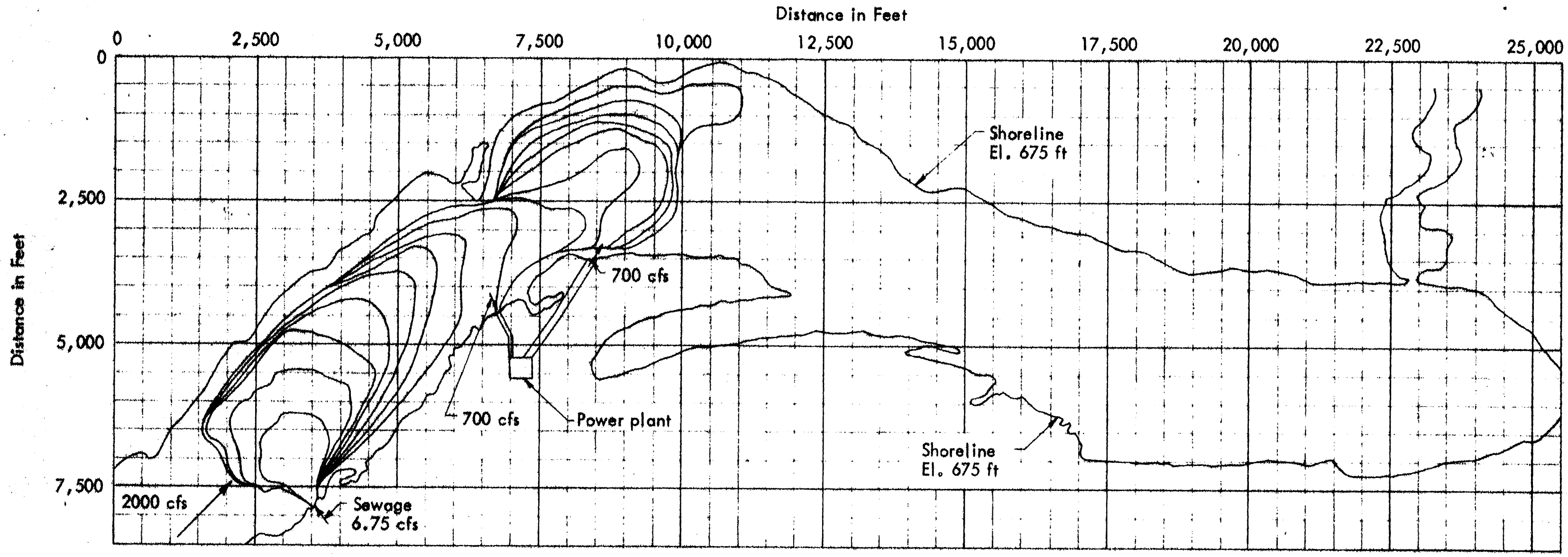


Contours at equal time intervals show movement of Stillwater sewage along river bottom before construction of power plant, sewage heavier than river water

NORTHERN STATES POWER COMPANY
ALLEN S. KING GENERATING PLANT
Predicted Flow Pattern of Stillwater Sewage Entering Lake St. Croix

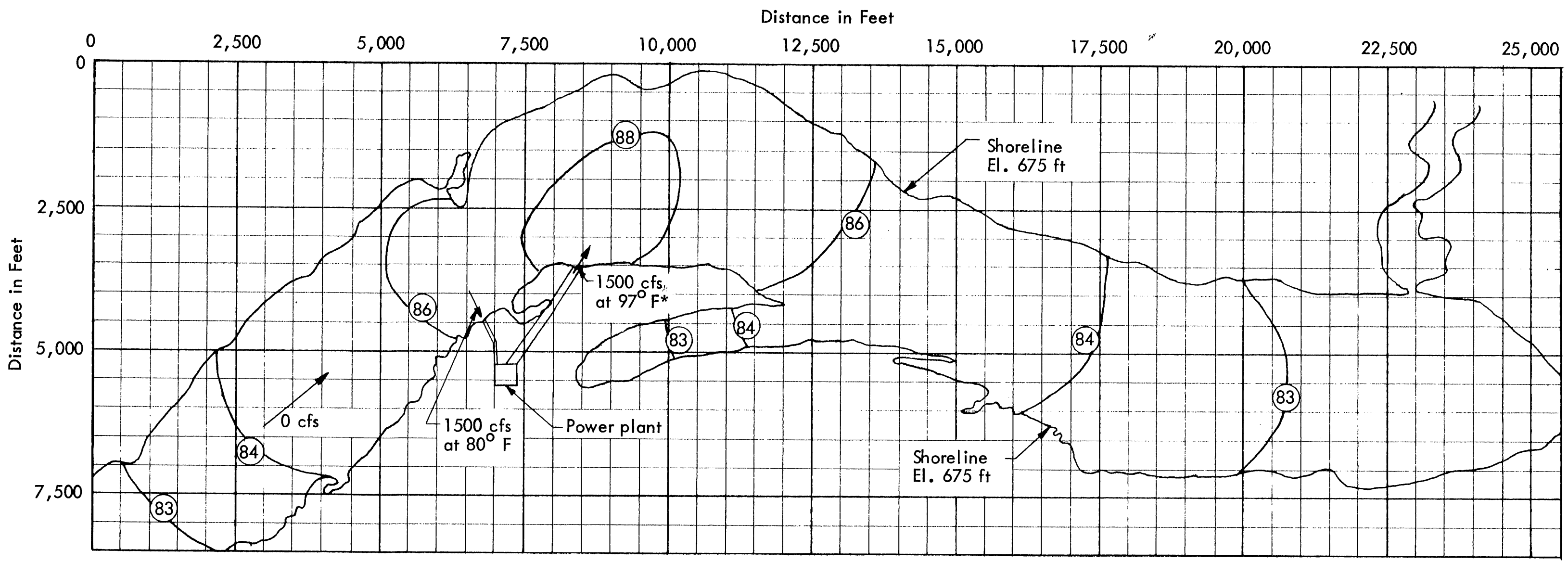
SAINT ANTHONY FALLS HYDRAULIC LABORATORY
UNIVERSITY OF MINNESOTA

DRAWN WQD	CHECKED	APPROVED
SCALE	DATE 12-14-64	NO. 148B443-44



Contours at equal time intervals show movement of Stillwater sewage along river bottom with power plant in operation, sewage heavier than river water

NORTHERN STATES POWER COMPANY ALLEN S. KING GENERATING PLANT Predicted Flow Pattern of Stillwater Sewage Entering Lake St. Croix		
SAINT ANTHONY FALLS HYDRAULIC LABORATORY UNIVERSITY OF MINNESOTA		
DRAWN WQD	CHECKED	APPROVED
SCALE	DATE 12-14-64	NO. 148B443-45



Surface Isotherms in Degrees Fahrenheit

*Isotherms are computed for a virtual discharge of 3000 cfs at 88.5° F which is obtained by assumed intermixing of plant discharge at outlet with 1500 cfs of lake water at 80° F.

Assumed Meteorological Data:
Wind 6 mph from South
Dew point temperature 80° F

NORTHERN STATES POWER COMPANY
ALLEN S. KING GENERATING PLANT
Predicted Isotherms on Lake St. Croix
During Midsummer

SAINT ANTHONY FALLS HYDRAULIC LABORATORY
UNIVERSITY OF MINNESOTA

DRAWN ACY	CHECKED	APPROVED
SCALE	DATE 12-31-64	NO. 148B443-60