INDIANA & MICHIGAN ELECTRIC COMPANY
DONALD C. COOK NUCLEAR PLANT, UNITS 1 AND 2

SUMMARY REPORT COMPARING THE D. C. COOK THERMAL PLUME MEASUREMENTS WITH MODELING PREDICTIONS

ATTACHMENT 1

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Prepared by:

ETA Engineering, Inc.
415 East Plaza Drive
Westmont, Illinois 60559

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1.0 INTRODUCTION

1.1 Technical Specification Requirements

The Environmental Technical Specifications[1] for the Donald C. Cook Nuclear Plant Units 1 and 2 state the following objectives for monitoring the lake water temperature in the region of the plant: (1) determine the thermal characteristics of the lake within the defined study area, (2) determine the size, shape, and location of the thermal plume under different wind and lake current conditions, and (3) determine if the thermal discharge is in compliance with the thermal criteria of the Michigan Water Resources Commission. These Technical Specifications called for monitoring the thermal plume while the two units are operating at, at least, 75% of rated power during four study periods scheduled as follows:

15 February - 15 March
15 April - 15 May
15 June - 15 September
1 November - 1 December

Each study period was to consist of a minimum of five sampling days with two plume resolutions made during each day, dependent upon seasonal weather conditions. The monitoring effort was to determine (1) the area within the Δ3°F isotherm, (2) location of the plume centerline, (3) rate of excess temperature decrease, (4) plume width, (5) thickness of the plume, and (6) depth of the winter sinking plume.

The Technical Specifications required the data to be displayed as isotherm diagrams showing the area enclosed by the Δ3°F isotherm. The data from these studies were to be used to verify the analytic and/or hydraulic models used to predict the size and location of the thermal plumes. The lake current data, as measured by drogues and in-situ current meters, were to be correlated with the meteorological data.

1.2 Objectives of This Report

The primary objective of this report is to provide a comparison of the field data with the analytical and hydraulic models used to predict the thermal

plume characteristics. A second objective is to summarize the monitoring effort and to demonstrate why, even though the winter monitoring period was missed and the spring monitoring effort was delayed until early July 1979, the effort is adequate to validate the model predictions.

wind and the water so that a given wind velocity will create larger waves, and more rapidly, than when the air is warmer than the water. Furthermore, winds out of the north (northwest to northeast) are usually more predominant during the fall and winter. Because of the long fetch for winds from this direction, adverse wave conditions prevail frequently. The east shore of Lake Michigan is more difficult to work than is the west shore because of the predominating wind and wave conditions.

No thermal plume maps were obtained during the winter period because of lake ice. Monitoring attempts were initiated on March 27, 1979, in anticipation of the dissipation of the lake ice. Ice and weather continued to be a problem during this period until Unit 1 was shut down for refueling. On the only day that monitoring could be attempted, the monitoring equipment became erratic because of the extreme cold. No plume maps were obtained during this period.

Both units were down for an extended period for refueling and repairs and did not return to 75% of rated power until July 23, 1979. Ten thermal plumes were mapped during the next five consecutive days to complete the monitoring effort.

2.2 Summary of Monitoring Results

Reference 2 contains the thermal plume maps, a tabulation of the ambient lake data, and a summary of the findings of the thermal plume monitoring with two unit operation. The following summary of the monitoring effort is extracted from that document.

Even though all four seasons were not sampled during the plume mapping periods (due to adverse weather conditions and unit outages), it is believed that a representative collection of varying lake current velocities and directions and of varying ambient lake temperatures were observed. Because of the persistence of lake ice, along with the lake and weather conditions that normally exist during the winter months on the eastern side of Lake Michigan, it is unlikely that sinking plumes, if they are in existence during this time of year, can ever be monitored.

2.2.1 Plume Areas, Widths, and Volumes

The thermal plume areas, widths, and outerlines were determined at a depth of one meter. The Michigan Water Resources Commission concurred in utilizing the one meter data because it eliminated many anomalous results produced by solar heating of the surface water.

Twenty-nine plumes were mapped, and these data are shown in Table 1. The areas within the $\Delta 3^{\circ}F$ isotherm at a depth of 1 meter varied from 21 acres to 740 acres. The average area for all 29 plumes was 290 acres. Three plumes exhibited areas greater than the 570 acres specified in the NPDES permit[3].

The largest plume, 740 acres measured on September 8, 1978, was obviously transitory in nature. It was 35% larger than a plume measured only 3 hours earlier. The increase in the size of this plume, as discussed in reference 2, can be attributed to a change in the ambient temperature during the monitoring period. A comparison of the ambient temperature measured during the ambient run with the in-situ temperatures shows that during the mapping run the natural lake temperature increased about 2°F above the ambient temperature value used in reducing the data. The other two plumes exceeding the NPDES specification had areas of 655 and 634 acres and were measured on November 3, 1978. These plumes were also transitory in nature and can be attributed to variable current directions and low current speeds. There was also evidence that the recirculation of discharge water was greater than during the previous day (probably because of the low current speeds), and this was a contributing factor to the large area.

The maximum width of the plumes within the $\Delta 3^{\circ}F$ isotherm at the 1 meter depth ranged from 984 to 6,724 feet, and the average width for all 29 plumes was 2,765 feet. The average plume width for each of the three monitoring periods is shown in Table 1. In general, the width of the plume increased as the area increased; however, the width for any given plume area varied by a factor of two.

Table 1

Summary of Plume Areas, Widths, and Volumes

August-September, 1978

Date	8/23	8/25	8/25	9/5	9/5	9/6	9/6	9/7	9/7	9/8	9/8
Area (acres)	24	193	311	237	80	287	117	336	568	549	740
Width (feet)	984	2394	2362	2230	1148	2165	1673	4100	4838	5642	4264
Volume (acre-ft)	413	2327	2771	1720	1342	1732	1537	1996	4029	3678	4852

Average area - 313 acres
Average width - 2890 feet
Average volume - 2400+ acre-ft

November-December, 1978

Date	11/1	11/1	11/2	11/2	11/3	11/3	11/7	11/7
Area (acres)	154	389	142	200	655	634	294	515
Width (feet)	1771	2854	2394	1705	3838	4648	2066	6724
Volume (acre-ft)	2414	3747	1105	1520	5197	5615	2883	4103

Average area - 373 acres
Average width - 3250 feet
Average volume - 3323+ acre-ft

July, 1979

Date	7/24	7/24	7/25	7/25	7/26	7/26	7/27	7/27	7/28	7/28
Area (acres)	297	450	109	161	149	269	30	21	171	342
Width (feet)	2034	3182	2296	3116	1804	2821	918	886	2624	2755
Volume (acre-ft)	2363	3295	951	1551	1190	1625	540	173	1494	2412

Average area - 200 acres
Average width - 2244 feet
Average volume - 1559+ acre-ft

The volumes of water within the Δ3°F isotherm regions are also summarized in Table 1 for the three monitoring periods. The volumes of water ranged from 173 acre-feet to more than 5,615 acre-feet. The average volume for all 29 plumes was 2,300+ acre-feet.†

2.2.2 Plume Thickness

Of the 29 plumes monitored, approximately 70% showed no Δ3°F water at depths below 3 meters. The remaining 30% showed relatively small areas of Δ3°F water at the 4 meter depth, with most of these deeper plumes occurring during the November monitoring period. The plumes, in general, were relatively thin, most of the warm water being in the upper one meter of the lake. The majority of the plumes exhibited areas at the one meter depth that were less than half the surface area. In addition, the areas at the two meter depth were usually smaller by a factor of two or more than were the areas at the one meter depth.

2.2.3 Centerline Temperature Decay

Temperature decay along the centerline of the plumes was analyzed by plotting the difference between the plume temperature and the ambient temperature, at a depth of one meter, versus the centerline distance from the discharge structures. These data are shown on Figures 1, 2, and 3, which correspond to the separate monitoring periods.

Comparison of the data in Figures 1 and 3 shows similar trends for the summer periods (August - September, 1978, and July, 1979). The higher excess temperatures decayed quite rapidly until they became 4 to 5°F above the ambient. At that point the temperature decay rate became much more gradual. It can be seen from these figures that the Δ3°F isotherm may terminate anywhere from 1,310 feet to 11,810 feet from the discharge.

†The + implies that the surface areas and volumes were actually larger than the stated value by an amount associated with the surface area that was outside of the monitoring pattern.

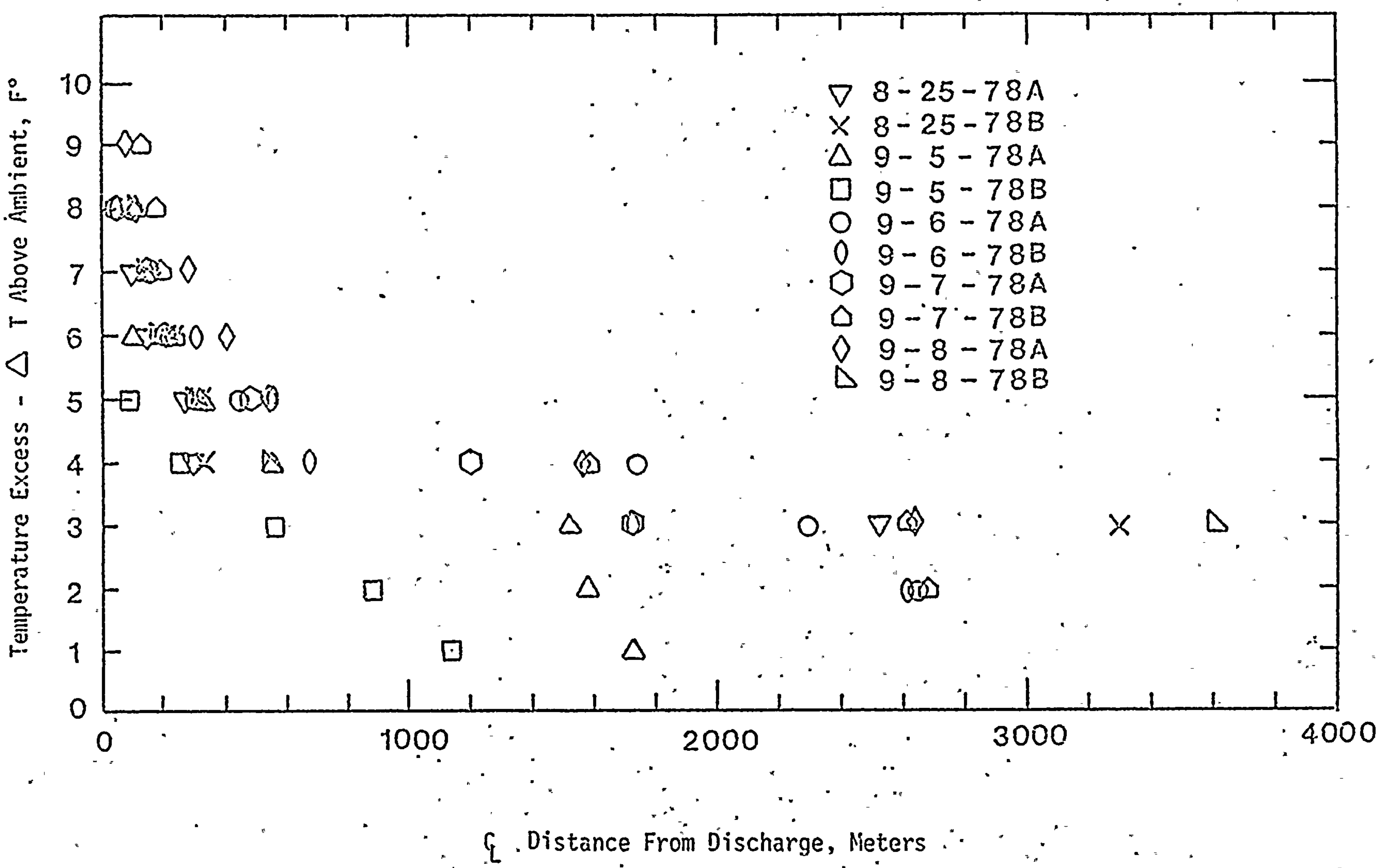


Figure 1. Excess Temperature vs. Distance (August - September, 1978)

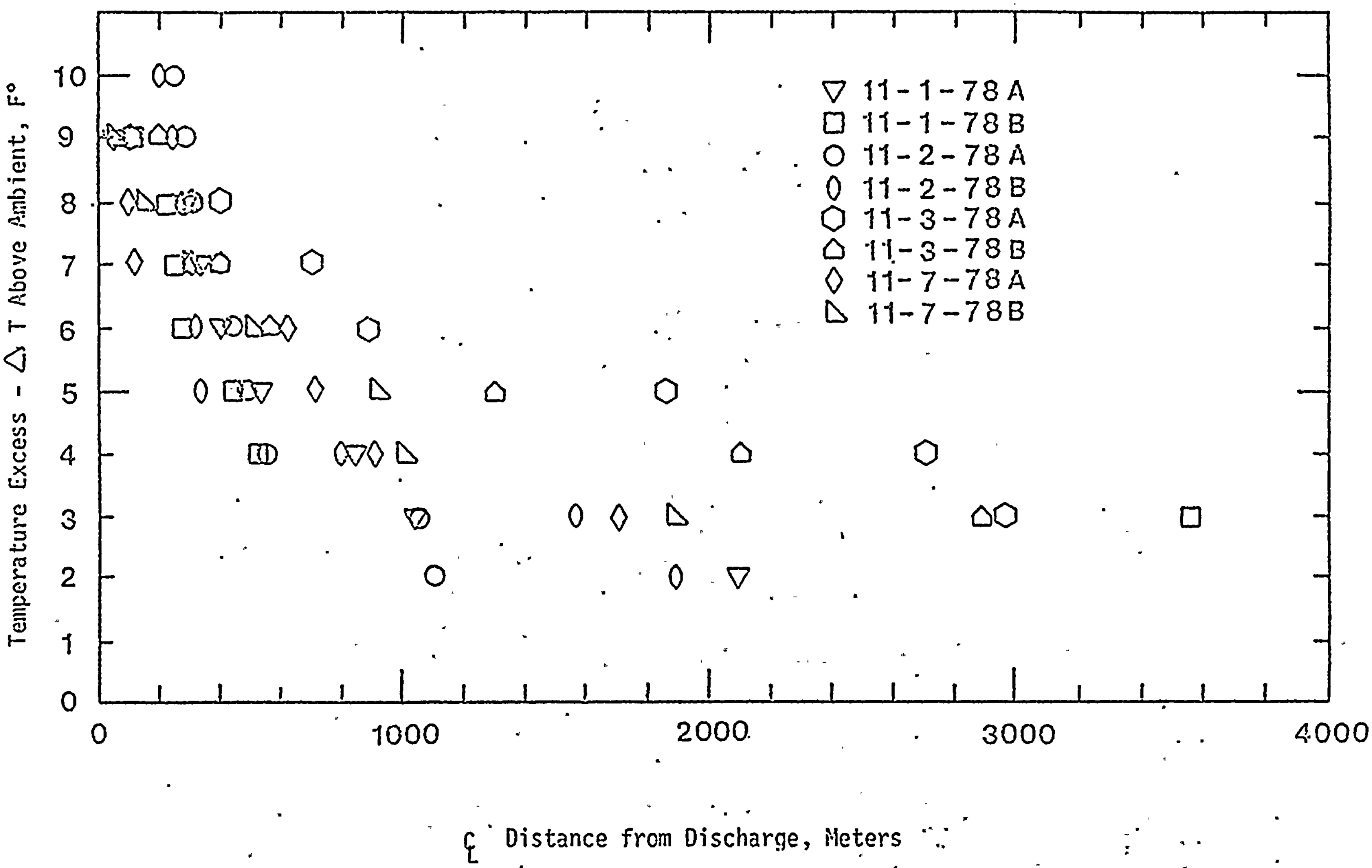


Figure 2. Excess Temperature vs. Distance (November, 1978)

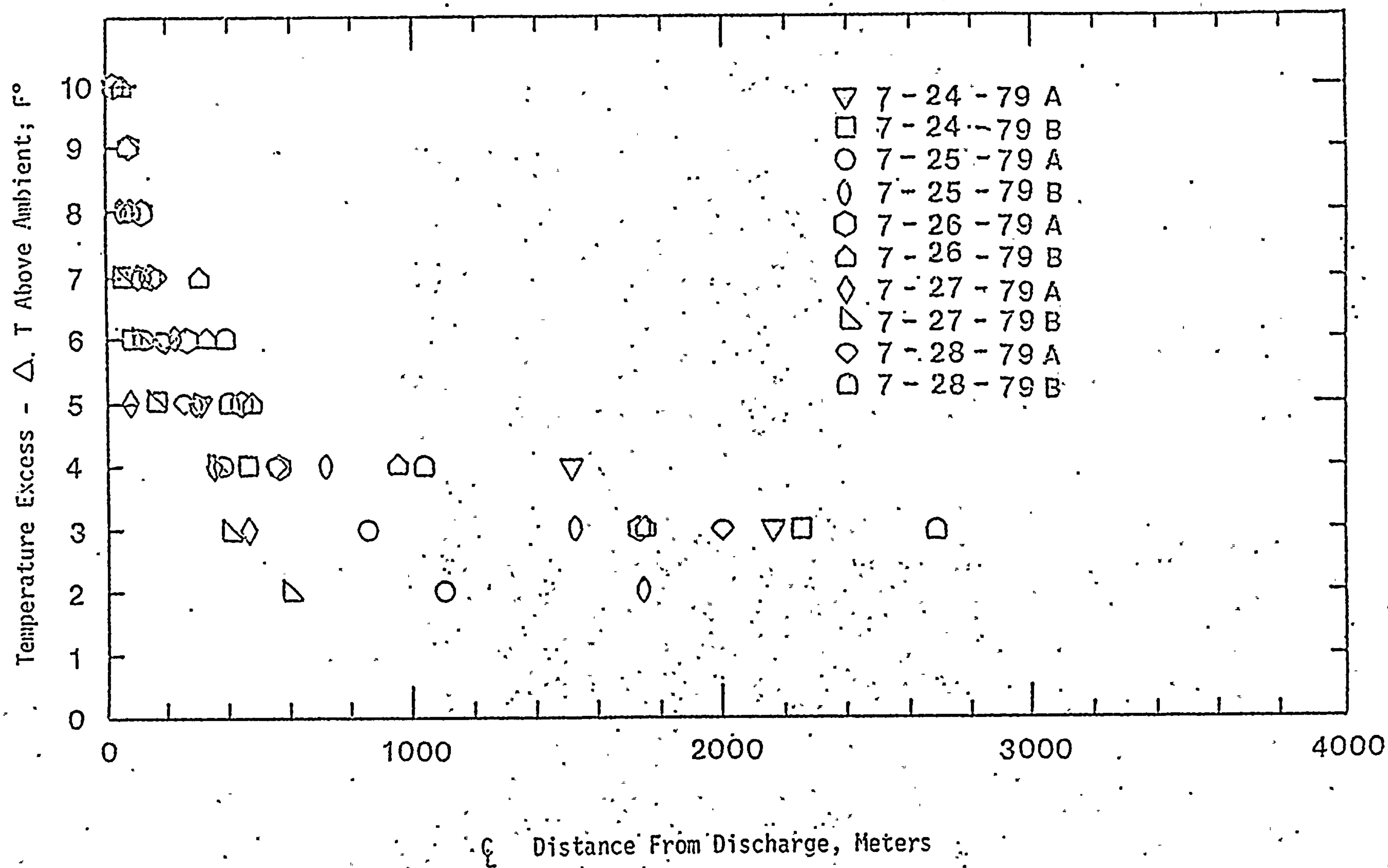


Figure 3. Excess Temperature vs. Distance (July, 1979)

The initial rapid decay rate during these two periods can be attributed to the relatively high discharge velocities that entrained the adjacent lake water. Because of stratification, the entrained water temperature was normally lower than the ambient temperature at one meter. The resulting mixing caused the rapid cooling. As higher velocities and resulting turbulence dissipated, the discharge waters began to stratify, and the rate of temperature decay became more a function of the ambient lake turbulence and the atmospheric heat dissipation.

The gravitational forces associated with buoyant warm water tend to inhibit vertical mixing with cooler, less buoyant ambient water. The amount of ambient lake turbulence, which is a result of energy imparted to the lake by the sun, wind forces, and Coriolis forces associated with the earth's rotation, determines just how fast this warmer water will mix with the cooler water. The turbulence is a major factor in determining the horizontal rate of mixing and spreading of the plume. And when the turbulence level is sufficient to overcome the buoyant forces, it promotes vertical mixing with the cooler water below. The warm water on the surface also gives up some of its thermal energy to the atmosphere by convective, evaporative, and radiant heat transfer.

The data shown in Figure 2 represent that obtained during the November 1978 monitoring period. In this case, it may be seen that the higher temperatures decayed over a greater distance than during the earlier seasons. This is attributable to the lake having been well mixed; i.e., it had a more uniform temperature vertically than during the earlier seasons. During this time of year, when there are no stratification efforts, the water leaving the discharge structure is mixed with water having essentially the same temperature as the ambient temperature at the one meter level. During earlier seasons, however, the stratification process allows water that is colder than the ambient temperature at the one meter level to be mixed with the discharge water, thereby cooling it more rapidly.

When compared with the data obtained from Unit 1 operation alone[4], the maximum excess temperatures observed at the one meter level were 3-4°F higher during the two unit operation. The pattern of higher temperatures being observed at a given distance from the discharge during the fall and winter months, when the lake was well mixed, was also observed in the data from Unit 1 operation[4].

2.2.4 Seasonal Variations

The data for the 29 plumes indicate that the average areas, widths, and volumes did show some seasonal variation. This was true even through there was considerable variation in plumes from day to day, and even during the same day, for any given monitoring period. It may be seen from Table 1 that the parameters listed increase from the early summer period to the late summer period to the fall period. A similar effect was observed in the Unit 1 monitoring effort[4]. It is believed this effect can be attributed to the seasonal differences in the stratification characteristics of the lake.

With stratified conditions existing, the temperature of water entering the circulating water intake structures is normally lower than the ambient water temperature at the one meter level. This results in the condenser discharge water being cooler, with respect to the one meter depth ambient temperature, than it is in the unstratified condition. The plume size is therefore smaller than in the unstratified situation. This effect was fairly evident during the Unit 1 studies[4].

The plume sizes during the monitoring of the two units were occasionally influenced by the apparent recirculation of discharge water, which was seldom observed during the Unit 1 operation alone. The recirculation of warmer water into the intakes raised the condenser discharge temperatures, relative to the one meter ambient temperatures, and created larger plumes than when there was no recirculation. It is felt that the combination of stratification effects with variable and transitory recirculation was responsible for the wide range in plume sizes observed in any given period.

It must be noted that the data collected during this monitoring effort were obtained on relatively calm days, days during which the wind and waves were not severe enough to prevent use of the boat and monitoring equipment. During days when lake conditions were severe, the sizes of the thermal plumes would be expected to be smaller, on the average, than those reported in this study. This is because the increased turbulence in the lake, produced by the intensified wave action, would promote mixing and dissipate the plume more rapidly.

2.2.5 Areas of Influence

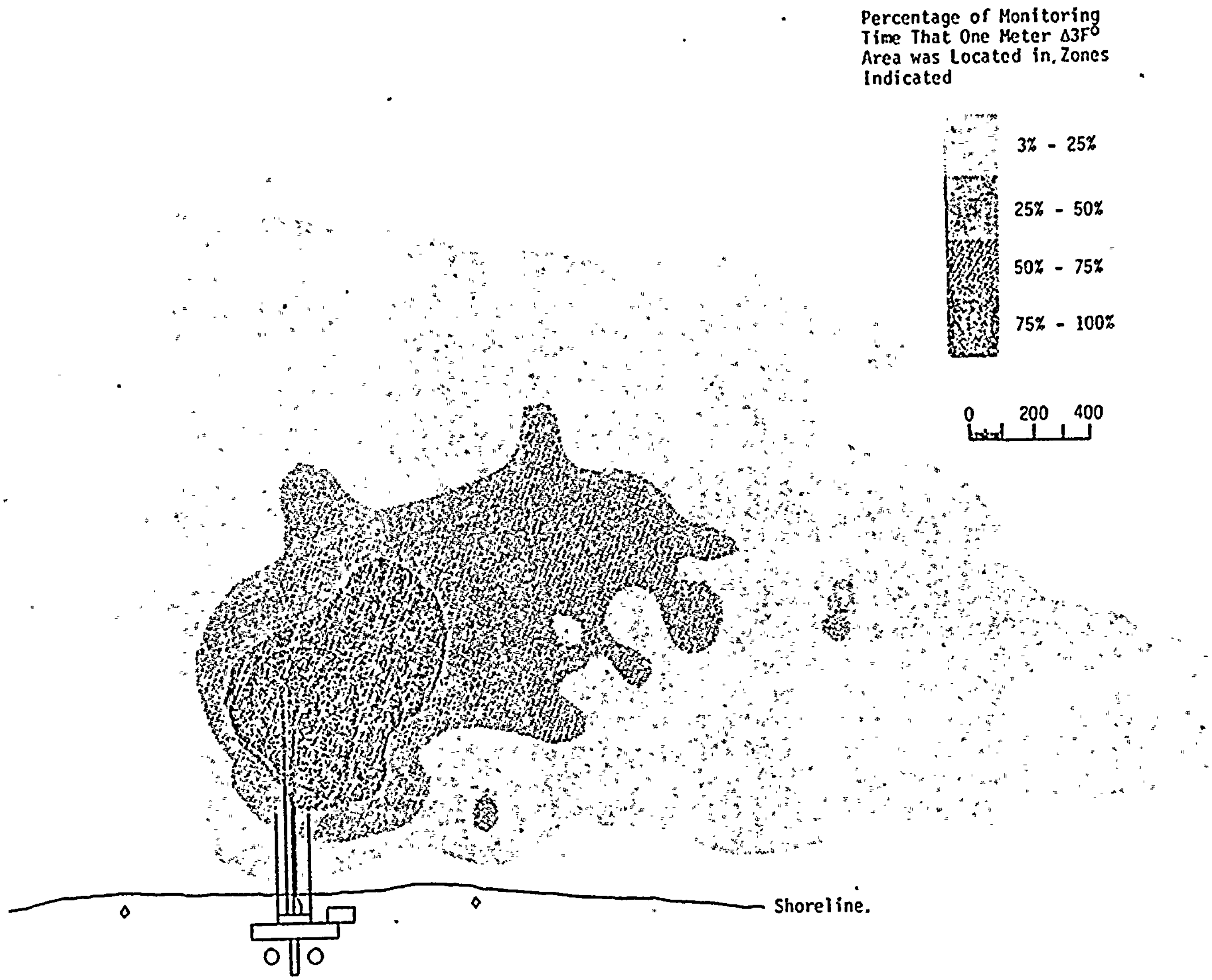
The plume maps obtained during this monitoring effort were utilized to define the region of the lake, at the one meter depth, that was occupied at one time or another by water with a temperature more than 3°F above the ambient water temperature. This region is shown in Figure 4. Areas have been shaded to portray the percentage of plume maps having specific locations influenced by the Δ3°F water when Units 1 and 2 were both operating at 75% full power or more. The skewing of the shaded areas to the north of the plant is the result of the predominantly north-flowing currents observed during the monitoring periods.

2.3 Ambient Conditions

The ambient lake temperatures and currents were observed to be extremely variable and apparently had significant effects on the thermal plume behavior. Ambient lake stratification had a definite impact on the plume size.

2.3.1 Ambient Lake Temperature

Lake temperatures were measured in the vicinity of the D. C. Cook Nuclear Plant by means of vertical arrays of thermistors and in-situ temperature recorders anchored on the lake bottom. Three temperature recorders were utilized--one north, one south, and one west of the discharge area. An example of the lake temperature data is shown graphically in Figures 5 and 6. This representation illustrates the extreme variability of the natural lake temperatures as a function of depth. The plots show the daily maximum, minimum, and average temperatures, and the dashed lines show plus and minus one standard deviation. These variations, measured in the vicinty of the Donald C. Cook Nuclear Plant, showed magnitudes of temperature changes that exceeded temperatures associated with the Cook Plant's thermal discharges. For instance, changes of more than 20°F were seen occurring from one day to the next over the region of the lake monitored by the recorders. This represented a rate of change of the energy content of the water in this same region that far exceeded anything that the Donald C. Cook Nuclear Plant could produce. Individual temperature sensors regularly recorded daily temperature variations of more than 10°F.



Region of Lake Influence by D. C. Cook Units 1 & 2 Discharge (Power Levels Greater than 75%)

Figure 4

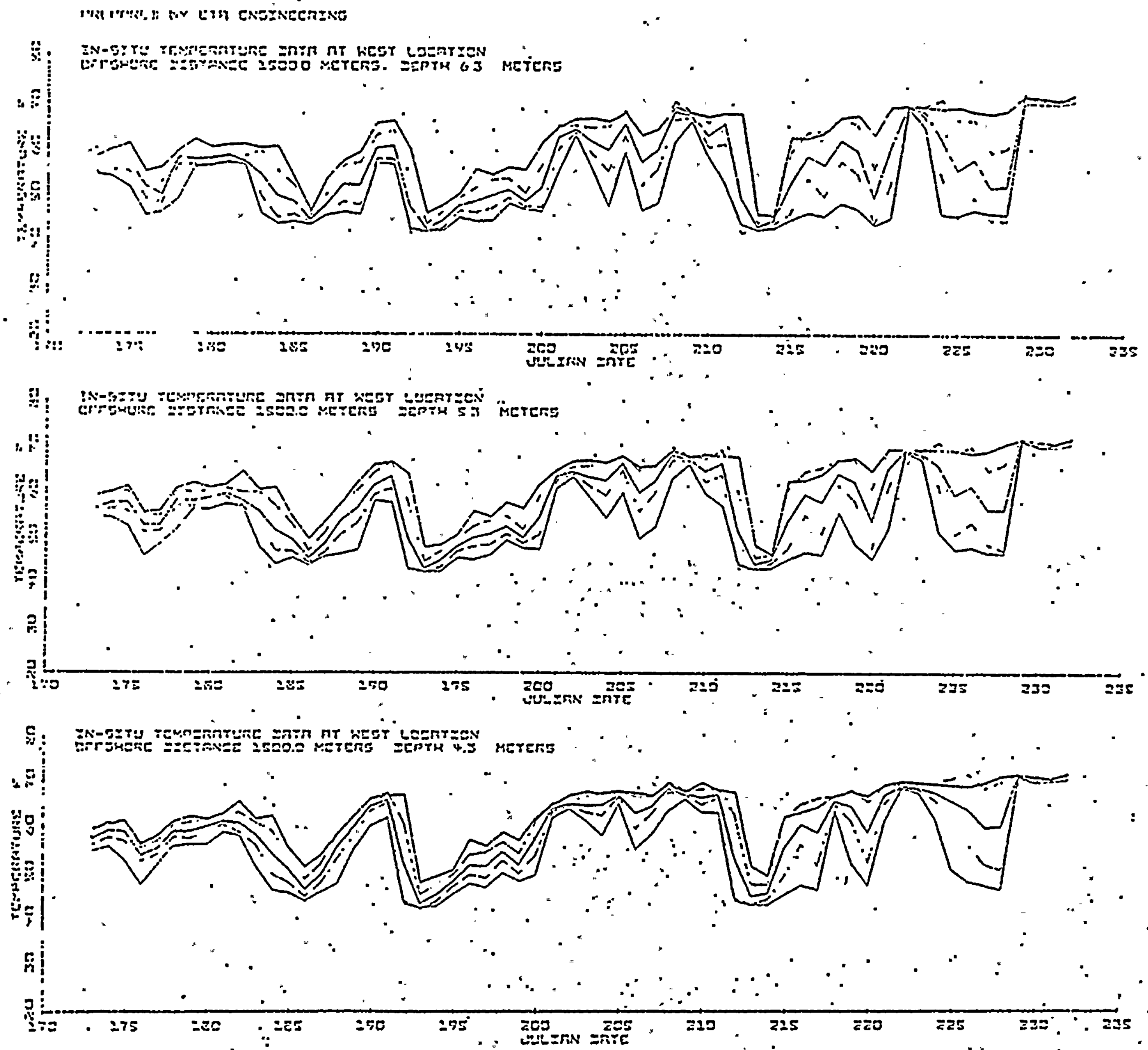


Figure 5.

Lake Temperature Data (6/22/78-8/20/78)

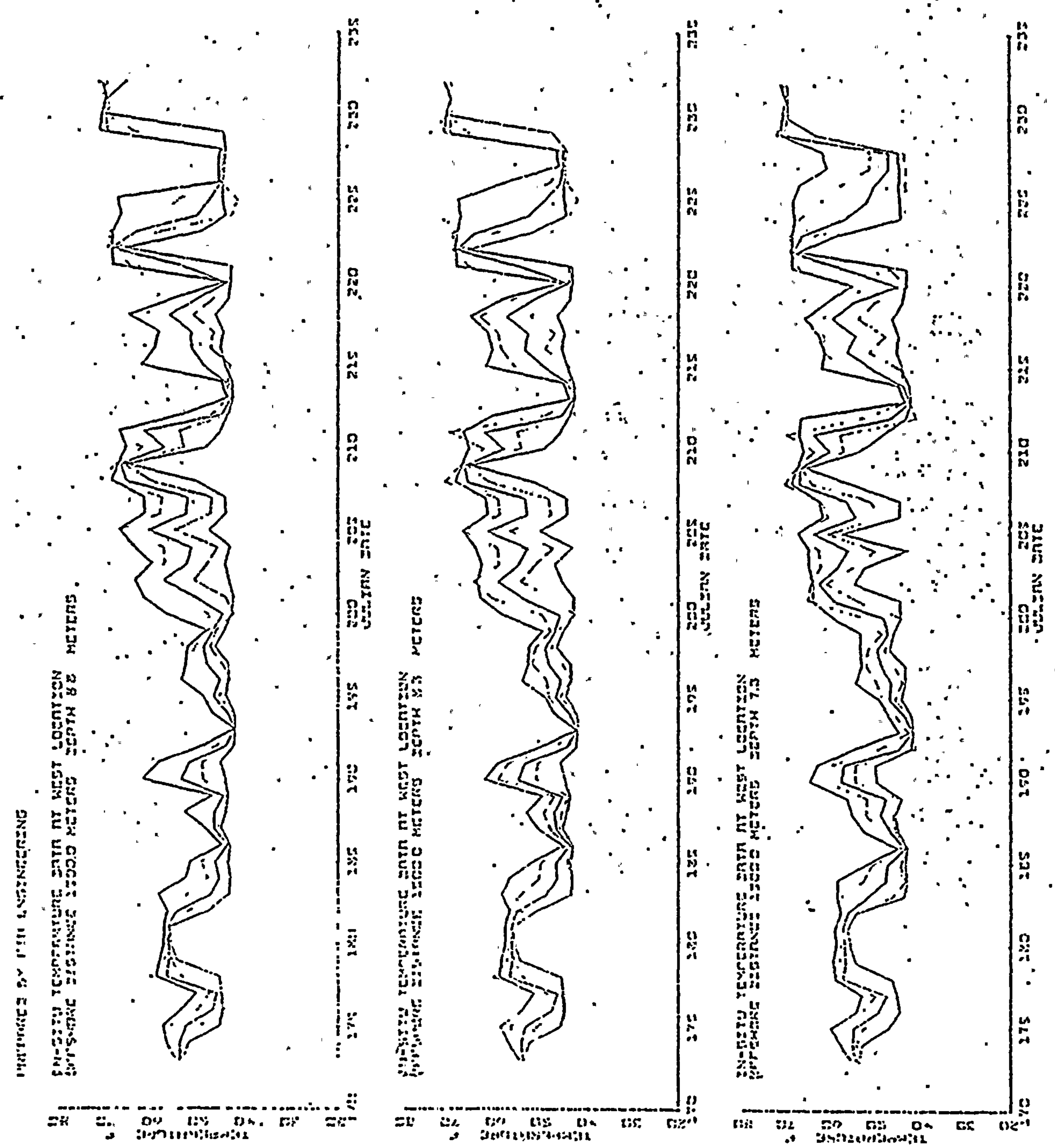


Figure 6.

Lake Temperature Data (6/22/78-8/20/78)

These natural temperature variations and the spatial and temporal variations in lake currents make it impossible to predict what a plume might do from one day to the next. These natural variations, however, are evidence of the dynamic natural processes that exist in the lake and that can be expected to disperse and dissipate the Cook Plant thermal discharges.

A reality of thermal plume monitoring on a large lake like Lake Michigan is the virtual impossibility of defining a single ambient temperature. As graphically illustrated by the in-situ data (Figures 5 and 6), the natural temperatures vary both spatially and temporally in the area near the power plant. The ambient temperatures used in reducing the data from this study were defined as the average of all temperature readings obtained during the "ambient run." (The "ambient run" consisted of measuring the water temperatures at various depths during a shore-perpendicular transect in the region up-current from the discharge area.) A review of the data in reference 2 shows that at times this involved averaging data with a spread of more than 2°F. This spread in the ambient temperature data represented primarily spatial variations and did not reflect the temporal variations.

The ambient temperature utilized in reducing of the data can have a significant effect on the size of the area within the Δ3°F isotherm, as a review of the data related to the 740 acre thermal plume measured on September 8, 1978, shows. For example, if the ambient temperature were actually 1°F higher than that utilized for reducing the data, the plume area would be reduced from 740 acres to 113 acres. For this particular plume, the data averaged to evaluate the ambient temperature showed a spread of 1°F. In addition, the in-situ temperature recorder on the up-current side of the plume indicated an ambient temperature approximately 1°F higher than that determined by averaging the "ambient run" temperatures. A 0.5°F change in the ambient temperature used to reduce the data would have changed the plume area several hundred acres.

Temporal and spatial variations of the ambient temperature in the near shore waters of Lake Michigan often result from upwellings, from vertical motion of the thermocline produced by internal waves, and from solar heating. Upwellings are produced in a stratified lake when a strong, persistent wind drives

the warm surface water to the downwind side of the lake and "tilts" the thermocline sufficiently to cause the colder water below the thermocline to come to the surface on the upwind side of the lake. This results in measured ambient temperatures that increase with distance offshore. Internal waves (vertical motions of the thermocline produced by gravitational and Coriolis forces) create temperature fluctuations as a function of time at any given measurement location as the thermocline moves above and below the sensing instrument. Solar heating results when solar energy is absorbed by the water mass. Most of the energy is absorbed near the surface, causing the temperature to increase in a relatively thin layer. The remainder of the energy is absorbed in the water column to the depth of penetration, which is a function of the purity of the water. Since the solar energy input is uniform over the surface of the lake, the shallow, inshore, and often more turbid water receives more energy per unit volume and is thereby warmed more rapidly than is the offshore water. In this case, the measured ambient temperature would decrease with distance offshore. Solar heating also results in variations of the temperature with time. Temperature increases of 5°F within a two hour period have been observed in the top one foot of water on a hot, calm summer day. Water warmed by solar heating cannot be differentiated from water heated by the power plant. Thus, when there is significant solar heating of the surface, it becomes very difficult to (1) define an ambient surface temperature because of large temperature variations, and (2) to define the boundaries of the thermal plume at the surface.

These natural phenomena, which result in ambient temperature variations, cannot be modeled in a hydraulic modeling facility. The hydraulic modeling is done with water at a uniform temperature.

2.3.2 Ambient Lake Currents

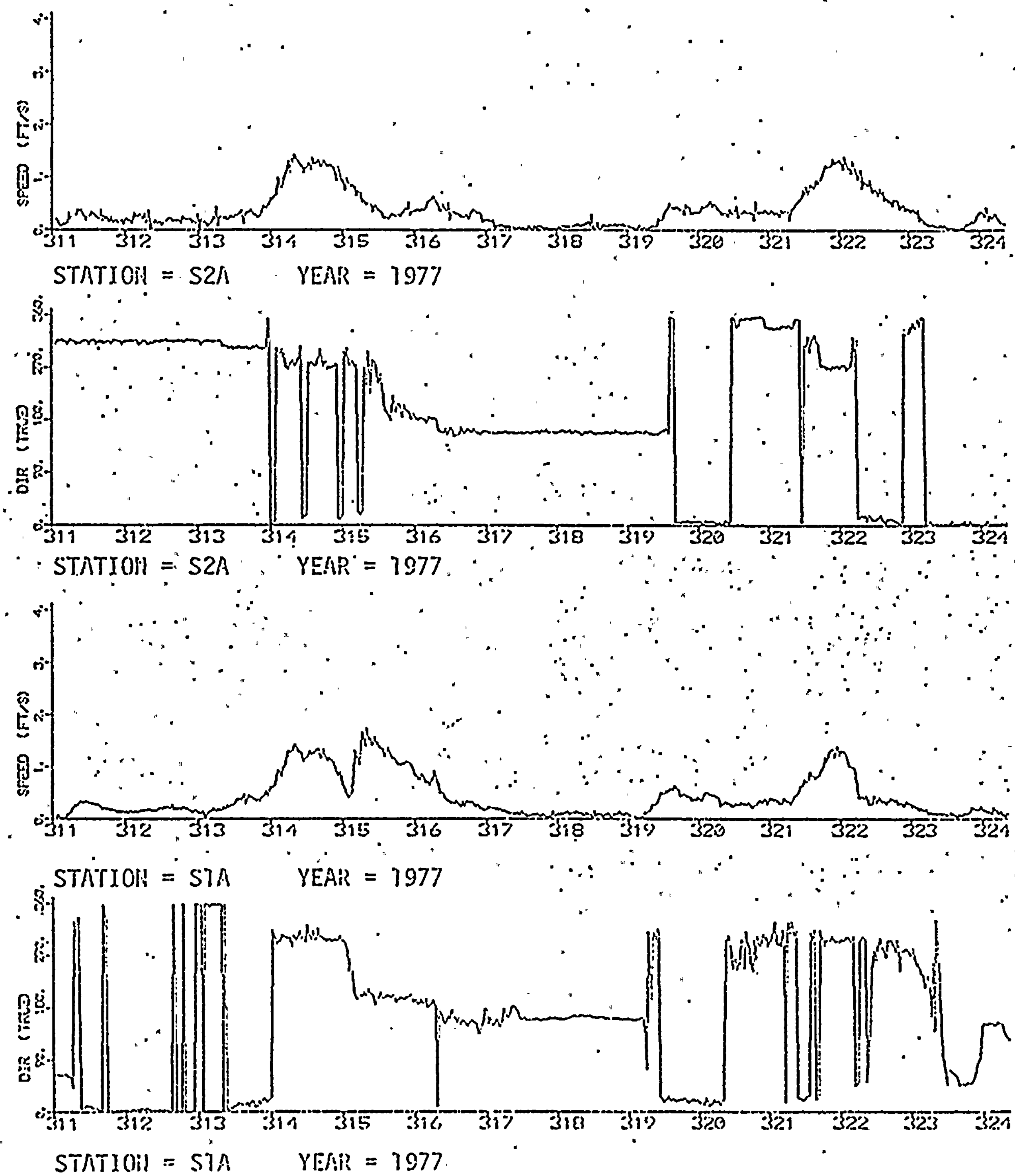
The single most important physical parameter affecting the position and trajectory of the thermal discharge is the ambient lake current in the vicinity of the discharge. The current also affects the size of the discharge plume, but this effect was masked by size variations induced by stratification and recirculation. Four current meters were used for this study of ambient lake currents--two near shore and two offshore.

The graphical representations of current speed and direction (Figures 7 and 8) were used to compare current speed and direction for the various meters. Usually, the current speed plots exhibit the same general trends for all four meters. Even better correlation exists between the current speed trends for the two inshore meters and for the two offshore meters. While the overall trends agree, significant differences in current speeds often occurred at any given time. In other words, long-term trends in current speed show some consistency at the four monitoring locations, but short-term local current speeds show considerable variation.

The plots of current direction show very poor correlation from one current meter to another. For instance, for the period November 17-19, 1977 (Julian dates 321 to 323), the northern offshore meter indicated north-northeast flowing currents; the northern inshore meter showed currents flowing to the southwest; the southern offshore meter recorded current directions varying from the northwest to the north-northeast; and the southern inshore meter indicated northwest flowing currents that occasionally shifted to the northeast. For the period November 29, 1977, to December 19, 1977, the northern inshore and offshore current meters recorded current directions that differed by 105 degrees or more over 50 % of the time.

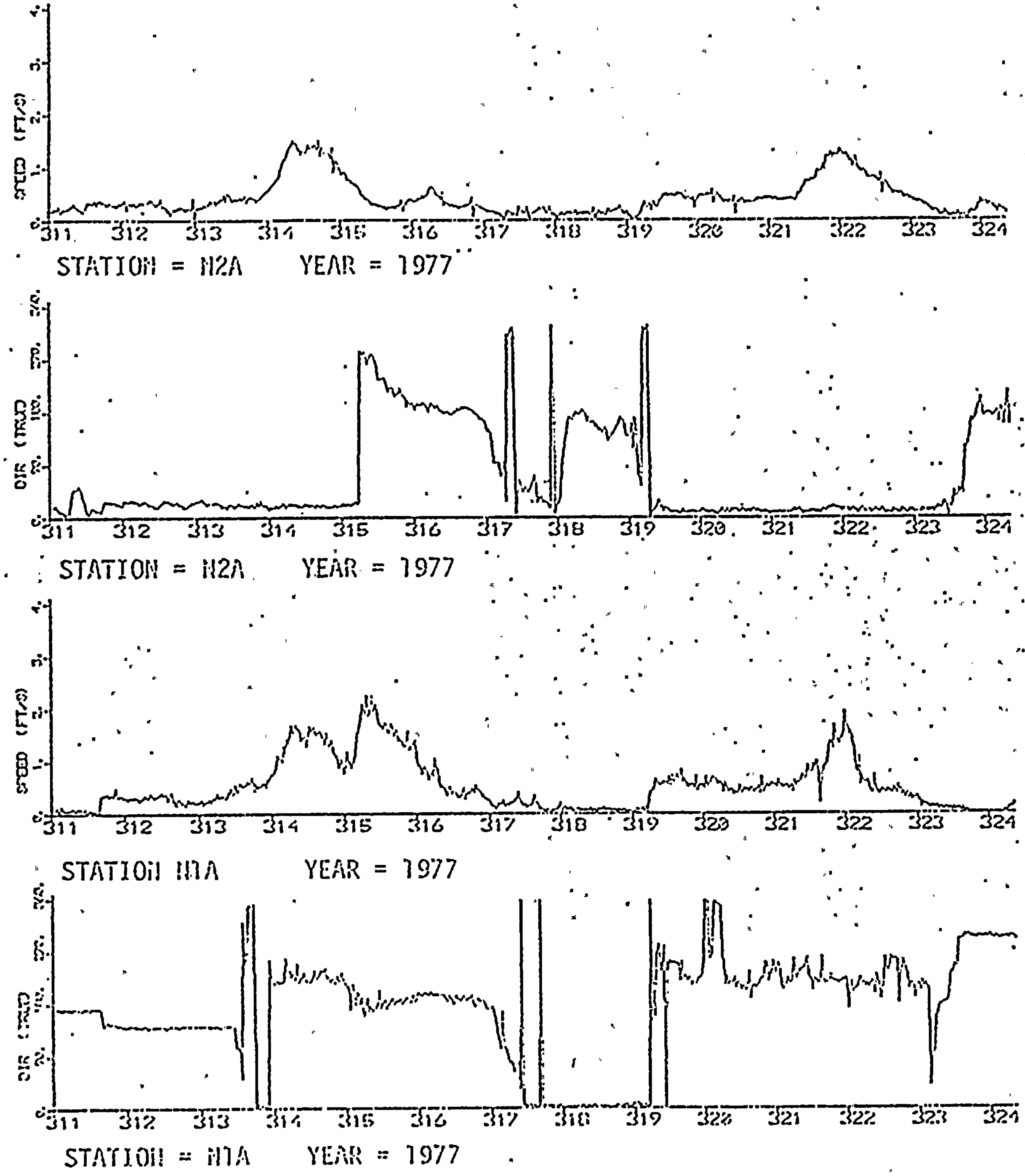
Not shown on these plots is the correlation between the surface currents, as measured by drogues, and the currents measured by these meters at depths of 11 and 22 feet. As discussed in the descriptions of the various plumes[2], there were many instances when the surface currents and bottom currents were flowing in different directions. The two drogues also exhibited differences in the near shore and offshore surface current direction, once showing the two surface currents flowing in opposite directions.

These variations and differences in the currents, both temporal and spatial, serve to highlight the complex and unpredictable flow regimes that exist in the near shore waters of Lake Michigan. Attempts to obtain meaningful correlations with the meteorological data were unsuccessful, since there was often no correlation between the various current measuring devices.



Note: S1A = Southern nearshore meter
S2A = Southern offshore meter

Figure 7. Lake Current Data Plots



Note: N1A = Northern nearshore meter
Northern offshore meter

Figure 8. Lake Current Data Plots

The plots of current direction, similar to that shown in Figures 7 and 8, were used to determine current directional persistence data for the three years that the currents were measured. An example of these data (see Figure 9) shows the percentage of time (based upon recorded data) the lake currents flow in a given direction for a given number of days.

Figure 9 also shows that the directional persistence of less than one day occurred under 28% of the time for all but the northern inshore location, where it occurred 55% of the time. Persistence of more than two days occurred 77% of the time at the north offshore locations, 53% of the time at the south offshore location, and 21 and 47% of the time at the northern and southern inshore locations, respectively. The north flowing currents were only slightly more persistent than the south flowing currents at the southern locations, and the probability of north or south flowing currents was about equal at the northern locations. The data for 1979 generally showed more persistence than did the data from the previous two years.

The surface currents during this monitoring effort indicated north flowing currents for 67% of the measurements, south flowing currents for 29% of the measurements, and east flowing currents for 5% of the measurements. This sample of surface currents was probably biased by winds from the northwest through the northeast, because these winds, which produced south flowing surface currents, also produced larger waves that might well have prevented the boat from going to the plant to make the measurements.

The temporal and spatial variations in lake currents measured near the D. C. Cook site are the result of complex eddying motions, covering a wide "spectrum of eddies." Such motions are associated with the turbulent flow conditions that almost always exist in large lakes. The state-of-the-art of mathematical modeling is not adequate to allow prediction of the micro-effect of eddies at a given location. Similarly, hydraulic models, although designed to produce turbulent flow in the simulated lake water, cannot adequately model the spectrum of eddies observed in the lake.

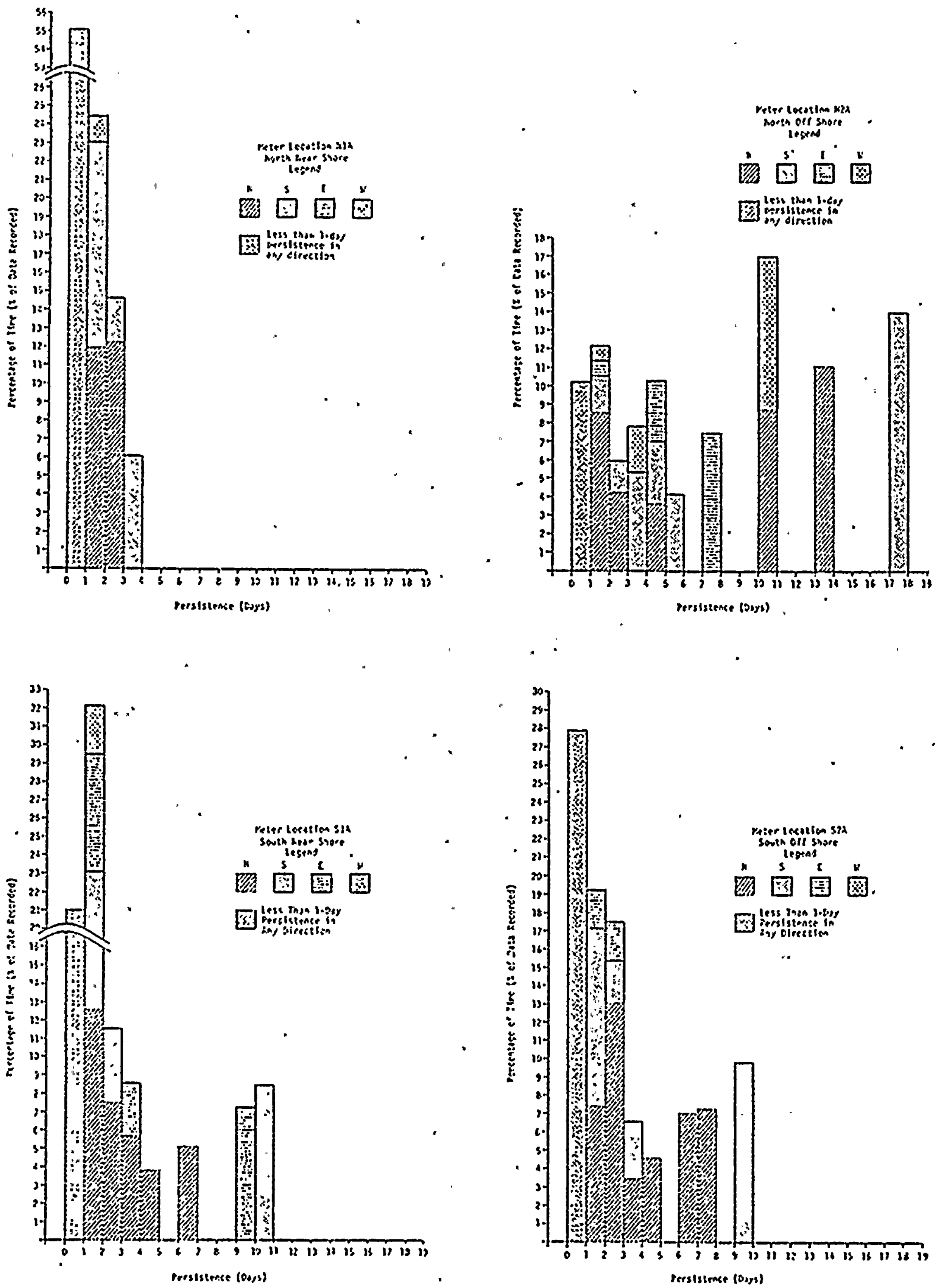


Figure 9. Current Directional Persistence (1979)

2.3.3 Stratification

The effect of stratification, as indicated in Section 2.2.4, appears to be the primary factor influencing the plume size. Since stratification is seasonal, this produces the seasonal variations observed during both monitoring efforts (Reference 2 and 4).

The lake begins to stratify in spring as the rate of solar heating begins to increase. During this time, the layer of warm water on the surface is relatively thin, and thus the condenser cooling water, which is discharged near the lake bottom, can entrain more cold water before it reaches the surface than when the thermocline is at greater depths. This results in the smaller plumes that are observed during the spring. "Negative plumes" (plumes in which the water is cooler than the ambient water) were observed during the first monitoring effort[4].

As the solar energy input to the lake increases during late spring and summer, the stratified layer of warm water becomes thicker. Under these conditions, the intake water temperature is still considerably cooler than the ambient temperature at the one meter depth. However, the condenser cooling water is now entraining and mixing with more of the warm water in the stratified layer, thereby increasing the size of the area within the $\Delta 3^{\circ}F$ isotherm. When the stratified layer in the lake is deep enough to surround the intake structures, the temperature of the water entering the condensers is consequently warmer, and the differential temperature between the condenser discharge water and the ambient temperature is greater. This condition occurs during the fall and produces the largest plumes. These conditions, i.e., relatively uniform temperatures between the intakes and surface, are the conditions that were simulated in the hydraulic modeling of this discharge.

3.0 SUMMARY OF MODELING EFFORT

The once-through circulating water system for the D. C. Cook Plant utilizes an offshore, submerged, horizontal jet-type discharge structure for each of the two units. The thermal plume which evolves from these discharge structures may be characterized by three flow regimes.

The "near-field" region of the thermal plume is that region where the plume is well defined and the velocity of the water in the plume is still significantly greater than the ambient water body velocity. This velocity difference between the plume and ambient water body produces considerable turbulence and entrainment that results in lateral and vertical spreading of the plume. This induced mixing is enhanced to a lesser degree by the ambient water body turbulence. A "transition region" occurs when the ambient turbulence approaches or exceeds the jet-induced entrainment as an important mechanism in the dilution process. Ultimately, at a sufficient distance from the discharge, i.e., the "far-field," the excess jet velocity is dissipated, and the plume is advected in the direction of the ambient current. Dilution in the far-field is controlled by ambient turbulent dispersion.

3.1 Hydraulic Model

Estimates of the excess temperature distribution within the near-field and the transition region between the near- and far-field were obtained from a hydraulic model study performed by Alden Research Laboratories of Holden, Massachusetts. A large and elaborately detailed hydraulic model was used to simulate the near-field, jet-induced entrainment. This enabled an accurate simulation of the interaction of the discharge plumes from the two multi-jet structures with each other and with the lake boundaries. The hydraulic model was designed on a scale ratio of 1:75 for both the vertical and horizontal dimensions. The model utilized prototypal effluent and ambient water temperatures and simulated the dynamics of the interaction between the discharge jets and the ambient lake current. The model basin was approximately 100 by 47 feet, thus representing a portion of Lake Michigan measuring 7500 feet along the shoreline and 3500 feet out into the lake. Lake bottom contours were reproduced in the model with templates having profiles at any section geometrically similar to those at the corresponding section in the lake.

The model had two water flow systems: one for simulating lake flow and the other for simulating power plant flows. For lake flow, water was pumped from a sump through a flow distributor onto one end of the model basin and allowed to flow out at the other. Flow rate to the model was measured by a venturi meter in the supply line to the flow distributor and was controlled by a valve downstream of the venturi meter. Water level in the model basin was controlled by weirs at the downstream end of the basin. The temperature of the water flowing into the basin from the flow distributor was governed by the temperature of the water in the sump. The latter temperature was adjusted by mixing hot and cold water.

The power plant once-through condenser cooling water system was simulated by a system consisting of intake piping and structures, discharge piping, and a mixing tank.

The intake and discharge piping for each unit was fitted with orifice meters and valves for measuring and regulating the flow into and out of the mixing tank. Simulation of power plant operation consisted of setting the discharge flow on each unit equal to the intake flow on each unit and mixing the intake flow with the amount of hot water needed for a given temperature rise. A portion of the mixture equal to the amount of hot water added was allowed to flow to waste.

Temperature measurement and recording in the model was by a network of thermocouples connected to a data logging system. There were 137 thermocouples in the network, plus two thermocouples in each of the intake and discharge structures and three thermocouples immediately downstream of the flow distributor. These thermocouples were for measuring the temperature of the ambient water upstream of the power plant, and there were additional thermocouples for measuring air wet and dry bulb temperatures and pump temperatures.

3.2 Mathematical Models

The excess temperature distributions for the far-field were obtained by the use of the hydraulic model data and analytical models. The results of the hydraulic model study were used to initialize a far-field analytical model to

obtain the excess temperature distribution in the far-field for both stagnant and representative lake current conditions.

In the stagnant lake case, the extrapolation of the near-field excess temperatures to the far-field entailed the use of an empirical correlation by Weigel[5] for plume centerline temperature decay. By trial and error, an imaginary discharge was defined that would yield a match with the temperatures obtained from the hydraulic model results. Once a match was established, the correlation was used to estimate the centerline location of the excess temperature isotherms in the far-field. The widths of the far-field excess temperature isotherms were approximated by increasing the plume width linearly as a function of centerline distance from the discharge, as proposed by Stolzenbach and Harleman.[6] The appropriate linear growth rate was determined from the hydraulic model data.

For modeling situations involving a lake current, an overall centerline trajectory was obtained by averaging the trajectories of Units 1 and 2. The complexity of the discharge jet configuration made this necessary. The centerline trajectories determined by this process compared favorably with the hydraulic model data. A second step involved the derivation of a model that would simulate the decay of excess temperature in the far-field under the condition of an ambient current. The analysis used the Sundaram[7] model, which assumed the plume in the far-field to be moving along with the same velocity as the ambient lake current. The width of the thermal plume was estimated by assuming the far-field excess temperature to be distributed normally about the plume centerline. The mathematical far-field model was then coupled to the near-field and transition regions, as modeled in the hydraulic tests, by assuming that the far end of the last closed excess temperature isotherm was an imaginary outfall whose location dimensions, temperature, and flow were obtained directly from the hydraulic model data.

The results of this analytic technique were fully reported in references 8 and 9 and are summarized below. It was noted that because the ambient lake turbulence and heat transfer to the atmosphere were not adequately represented by the mathematical models, the results of these analytic extrapolations of the hydraulic model data would conservatively overestimate the size of the plume within the Δ3°F isotherm in the far-field region.

3.3 Modeling Results

Hydraulic model plume data were generated for two units operating at full power, for one unit operating at full power, and for one unit operating at 81% of full power. The effects of a range of ambient lake currents were studied in each case. A comparison of the data for one unit operation with the field measurements was reported in the 316(a) Demonstration Report[10] submitted to the MWRC in January, 1977.

Figures 10-13 illustrate the results of the combined hydraulic and mathematical modeling predictions of the plume behavior with both Units 1 and 2 operating at full power. The figures represent the effect of ambient lake current speeds of 0, 0.2, 0.5, and 1.0 fps, respectively.

The results from these studies are tabulated in Table 2 and show that the maximum plume area of 570 acres was observed at a lake current speed of 0.2 fps. It is postulated that this effect is the result of the interference the two discharge structures exert upon each other due to the warm water discharged from the upstream structure being entrained by the plume discharged from the downstream structure. At higher lake current speeds, the ambient lake momentum would suppress the effect of this entrainment by increasing the amount of cooler lake water available for dilution of the plume. The zero-current lake condition resulted in some re-entrainment of warmer water but to a lesser extent than in the 0.2 fps current speed test, thereby producing a smaller plume area as compared with the 0.2 fps case.

Table 3 summarizes the predictions of the plume temperature and velocity as a function of plume centerline distance from the discharges. The predicted plume areas, depths, and volume for a lake current speed of 0.2 fps are shown in Table 4. An estimte[9] of the dimensions of the lake region that would, at one time or another during the plume's meandering, contain plume water with an excess temperature of 3°F or more is summarized in Table 5.

Table 2

Predicted Plume Areas vs. Lake Current Speeds

Current Speed (fps)	Area Within Given Isotherms (acres)		
	Δ5°F	Δ4°F	Δ3°F
0	15	135	530
0.2	110	225	570
0.5	95	220	460
1.0	45	85	190

Table 3

Predicted Plume Temperature and Velocity vs. Distance

C_L Distance (ft)	Excess Temperature (Δ°F)	Velocity (fps)
0	19.5	13.0
125	10.0	6.2
400	8.0	2.4
650	7.0	2.2
1275	6.0	1.6
3000	5.0	1.0
4410	4.0	0.65
6600	3.0	0.2
12350	2.0	0.2

Table 4

Predicted Plume Areas, Depths, and Volumes

Excess Temperature Isotherms (°F)	Area Between Excess Temperature Isotherms (acres)	Plume Depth (summer) (feet)	Plume Depth (winter) (feet)	Volume (avg. summer and winter) (cubic feet)
10 and 7	6.6	11.0	16.5	3.9×10^6
7 and 5	128.0	14.0	28.5	5.32×10^7
5 and 4	148.0	12.0	30.0	6.62×10^7
4 and 3	289.0	10.5	27.5	1.41×10^8
TOTALS	571.6			2.64×10^8

Table 5

Predicted Maximum Extent of Plume
(derived from a variety of current conditions)

Excess Temperature (°F)	Distance from Discharge Structures (ft)		
	North & South	East	West
2	9400	1200	7400
3	6200	1200	5200
5	2100	1200	2600
7	500	00	600

4.0 COMPARISON OF FIELD DATA WITH PREDICTIONS

Comparison of field data with one unit operation, as reported in reference 10, indicated that the modeling technique described in Section 3.0 was conservative in predicting the plume size and shape. Twenty-eight of the thirty plumes measured had areas considerably smaller than the predicted area. The two plumes with areas larger than that predicted by the models appeared to be influenced by transient conditions in the lake, plant operating difficulties (higher condenser ΔT's because of two pump operation), and some possible recirculation effects.

4.1 Plume Areas

Similar results were observed during the monitoring of two unit operation in that 26 of the 29 plumes measured had areas smaller than the 570 acres predicted by the models. As discussed in Section 2.1 and in reference 2, the three plumes larger than the predicted maximum were transitory in nature. That is, they appeared to result from changes in the ambient lake temperature during the monitoring period and from transient and variable lake currents that probably created some recirculation of discharge water. The average area for all 29 plumes was 290 acres, approximately one-half of that predicted by the models.

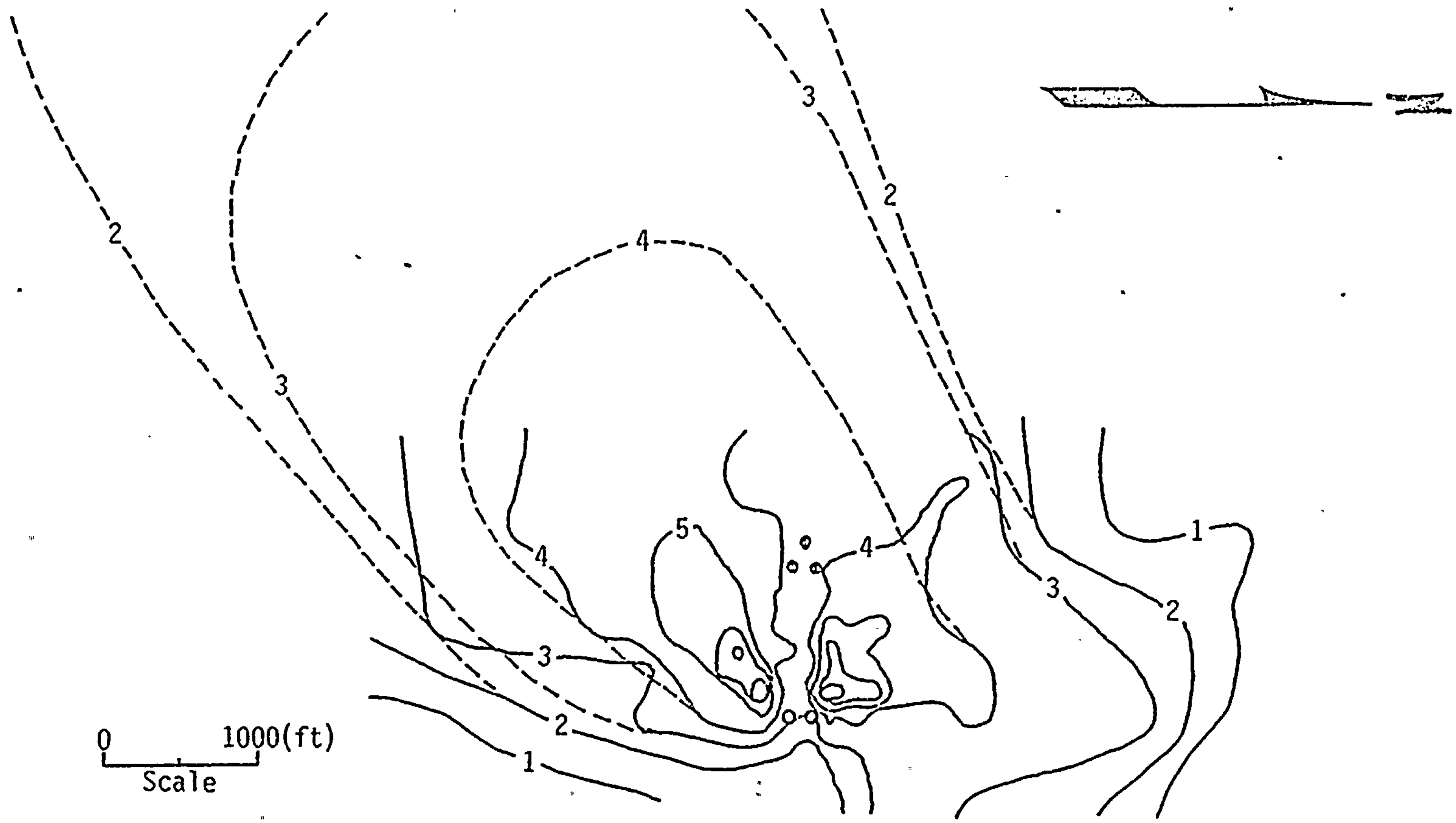
A review of Table 1 will show that the average area of the plumes measured during July (1979) was 200 acres. The average area for plumes measured in August-September (1978) was 313 acres, and the average area was 372 acres for the plumes measured in November-December (1978). This trend, i.e., the plume area increasing as the year progressed, was also observed during the monitoring of one unit. As discussed in Section 2.4, this effect is believed to result from seasonal changes in the stratification characteristics of the lake: As the thermocline goes deeper, the plumes become larger. The limit to this effect would be when the lake, or the area of the lake affecting the thermal discharge, achieves a uniform temperature. A review of the ambient temperature data in reference 2 shows that this condition existed during the November-December monitoring period.

The hydraulic scale model used to predict the thermal plumes utilized uniform temperature water to simulate the ambient lake. It could be expected, therefore, that the modeling represented the worst-case situation. Since the real lake does not achieve a uniform temperature until late fall, it may be concluded that data taken then would provide the most realistic comparison with the models.

It may be seen from Table 2 that there is an apparent effect of the current speed on the plume size. However, close examination of the data listed on Figures 10-13 suggest another potential explanation of the variation in plume area. It may be seen that for current speeds of 0 and 0.2 fps the intake temperatures are 1.5 to 2°F higher than the ambient temperature, probably because of recirculation. Thus, the larger plumes observed in the models at the lower current speeds may have been more the result of the recirculation effect than of the current speed effect. If this were the case, the modeling results could be said to have produced a more realistic simulation of the actual conditions than one would conclude by assuming that the current speed effect was the major parameter.

4.2 Centerline Temperature Decay Rate

Table 3 shows the predicted centerline distances from the discharge of the various excess temperature isotherms. These data are plotted on Figures 14, 15, and 16 to show the comparison between the field data and the predictions. It may be seen on Figure 14 that the model predictions tend to over estimate the distances that the various isotherms would exist from the discharge. In other words, the plume temperatures tend to decay more rapidly during this period than predicted by the models. Figure 15 shows that the model predictions similarly predict greater centerline distances for the isotherms than were observed by the field measurements, though not to the same degree as those measured earlier in the year. It is interesting to note that the large 740 acre plume, measured on September 8, 1978, (designated by the arrowhead) exhibited a temperature decay rate that was greater than the predictions, except at the $\Delta 3°F$ isotherm. In other words, the area between the $\Delta 3°$ and $\Delta 4°F$ isotherms was inordinately large compared to the rest of the plume. Figure 16 shows that the centerline temperature profile for the November period was predicted fairly well by the models. The higher excess temper-



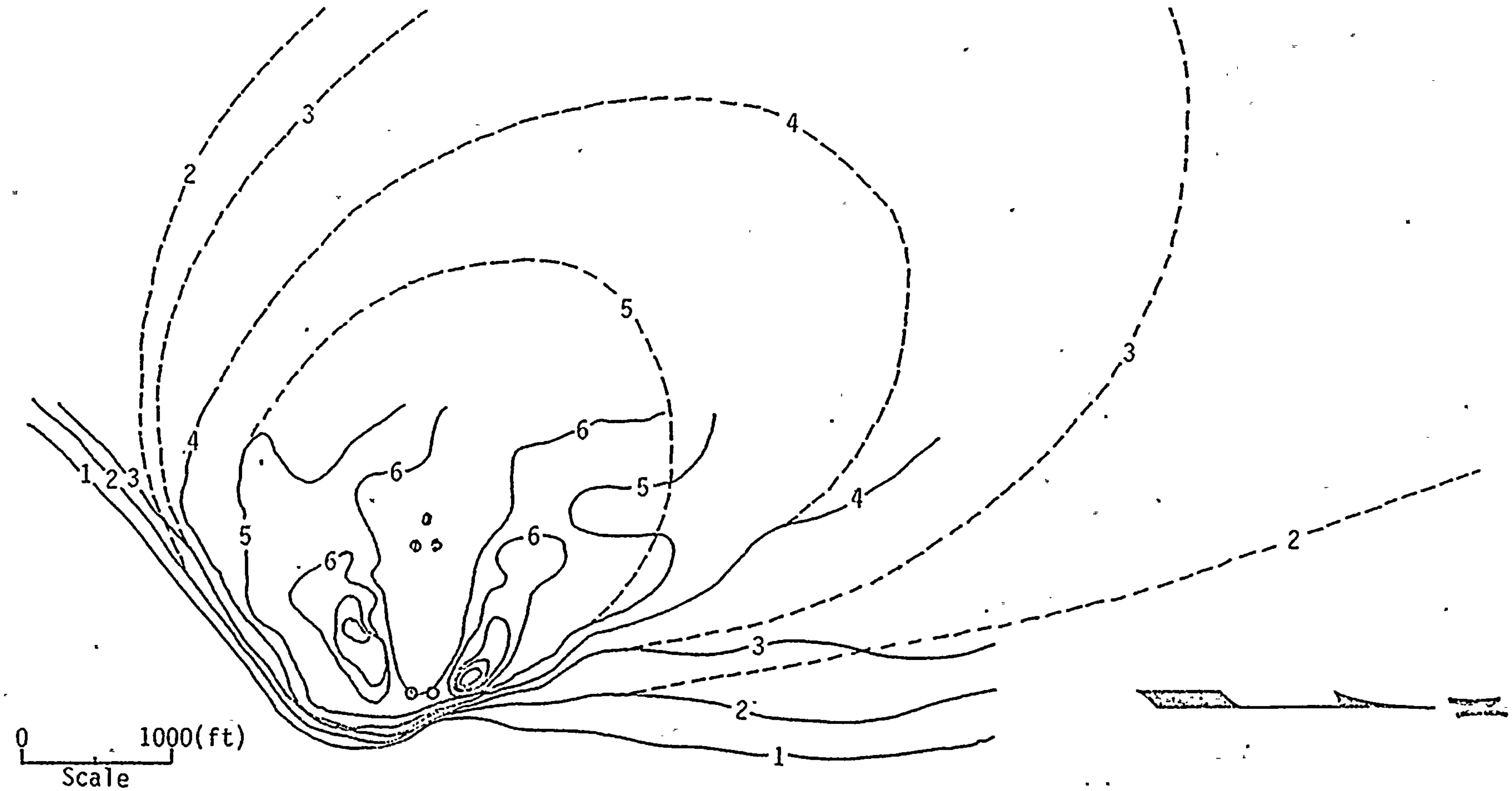
Shoreline

Donald C. Cook Nuclear Plant Units 1 & 2
Isotherm Depth - Surface
Lake Current - 0.0 fps
TEMPERATURES (^{O}F)

Intake	Discharge ΔT	ΔT Ambient Water	Ambient Air
South - 69.0	Unit 1 - 21.6	67.6	Wet Bulb - 68.1
Middle - 69.3	Unit 2 - 17.2		Dry Bulb - 71.2
North - 68.4			

Hydraulic Test Data (9/2/72, 9/22/72, 10/2/72, 10/11/72)

Figure 10



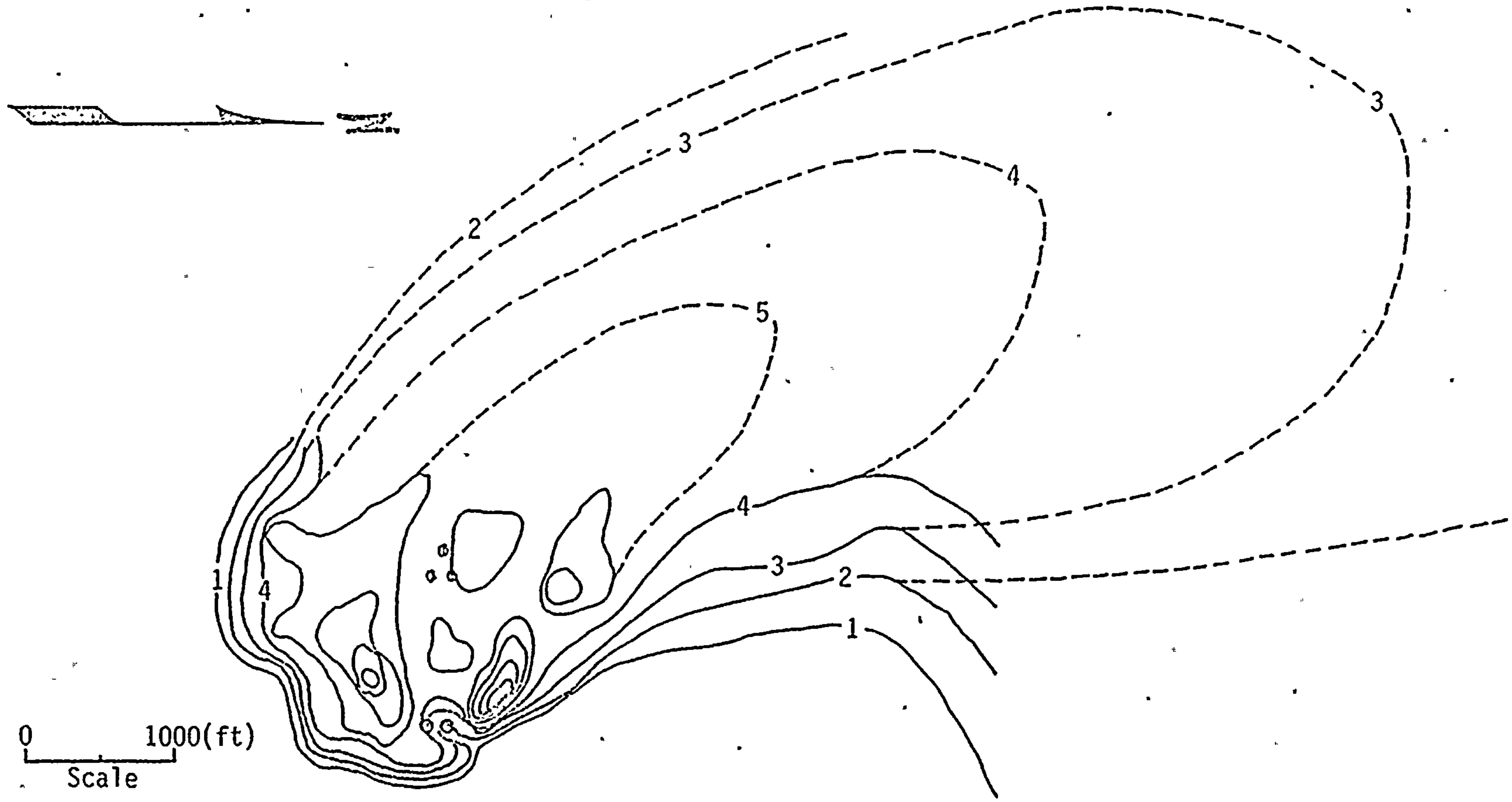
Donald C. Cook Nuclear Plant Units 1 & 2
Isotherm Depth - Surface
Lake Current - 0.2 fps
TEMPERATURES (°F)

Shoreline

Intake	Discharge ΔT	ΔT Ambient Water	Ambient Air
South - 67.3	Unit 1 - 21.6	65.8	Wet Bulb - 65.3
Middle - 68.0	Unit 2 - 17.2		Dry Bulb - 69.0
North - 69.1			

Hydraulic Test Data (11/16/72, 11/20/72)

Figure 11



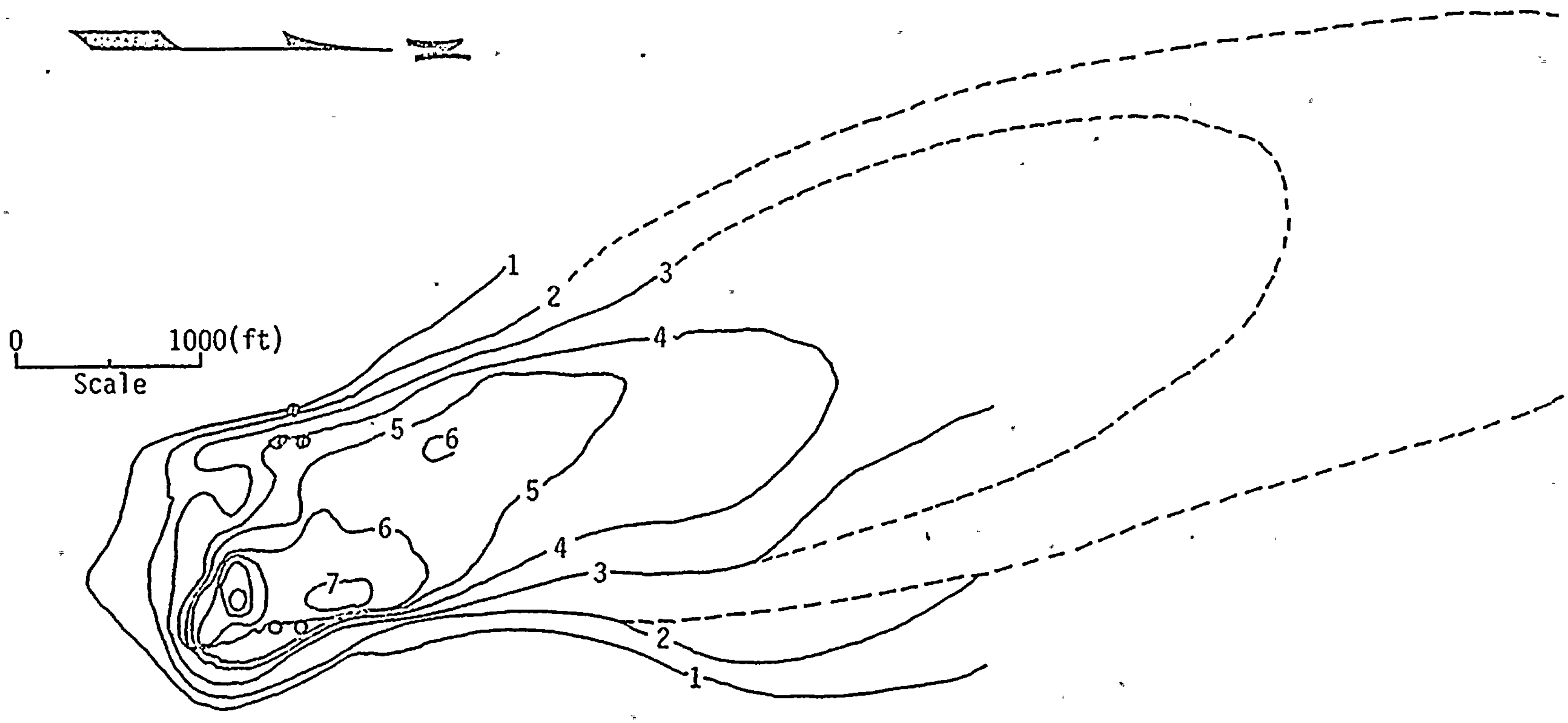
Shoreline

Donald C. Cook Nuclear Plant Units 1 & 2
Isotherm Depth - Surface
Lake Current - 0.5 fps
TEMPERATURES (^{o}F)

Intake	Discharge ΔT	ΔT Ambient Water	Ambient Air
South - 66.7	Unit 1 - 22.4	66.2	Wet Bulb - 65.3
Middle - 66.6	Unit 2 - 16.8		Dry Bulb - 67.3
North - 67.5			

Hydraulic Test Data (11/17/72, 11/21/72)

Figure 12



Shoreline

Donald C. Cook Nuclear Plant Units 1 & 2
Isotherm Depth - Surface
Lake Current - 1.0 fps
TEMPERATURES (°F)

Intake	Discharge ΔT	ΔT Ambient Water	Ambient Air
South - 67.5	Unit 1 - 20.9	67.2	Wet Bulb - 66.2
Middle - 67.4	Unit 2 - 16.2		Dry Bulb - 69.8
North - 67.7			

Hydraulic Test Data (9/8/72, 9/15/72, 11/15/72, 11/22/72)

Figure 13

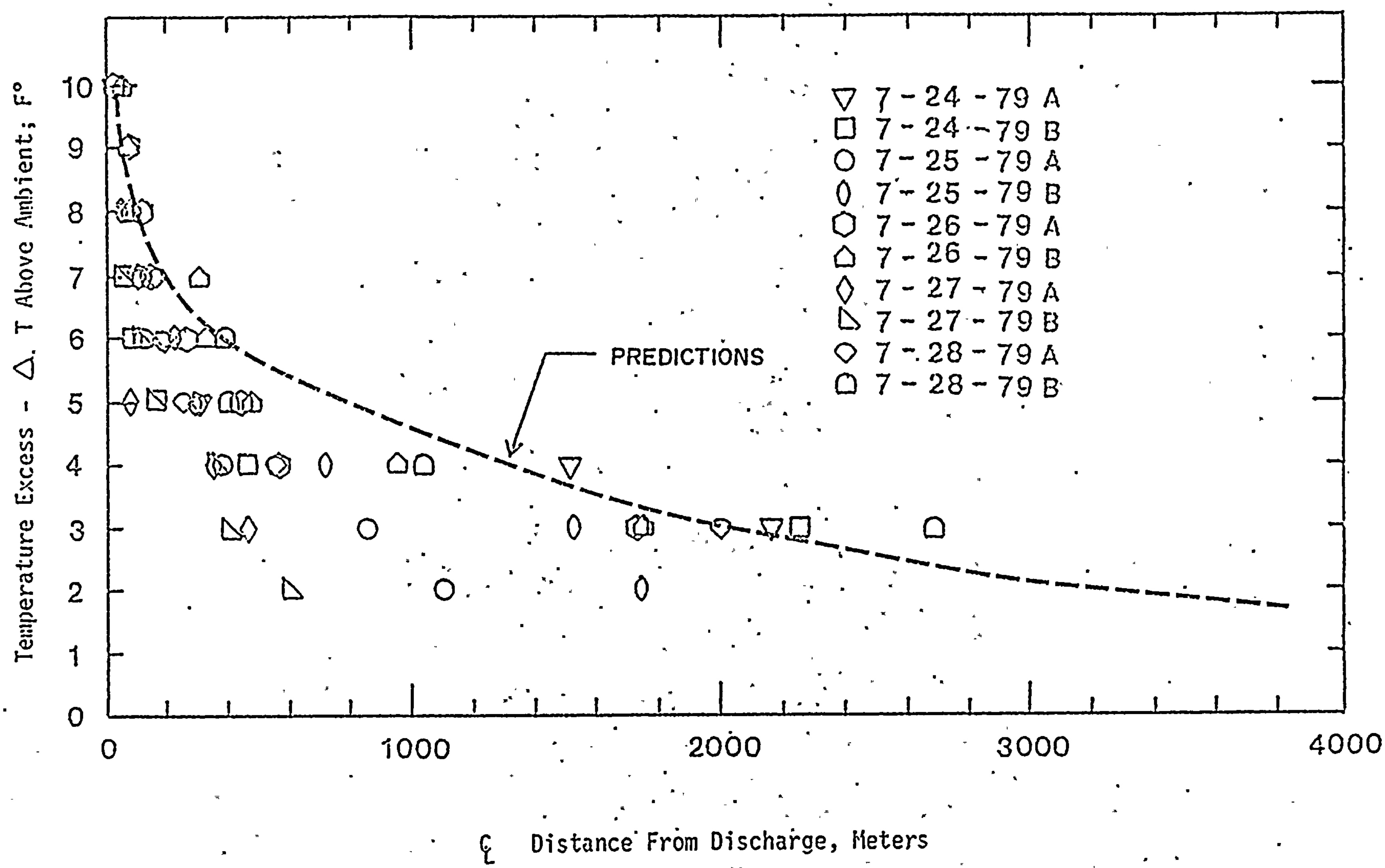


Figure 14. Excess Temperature vs. Distance (July, 1979)

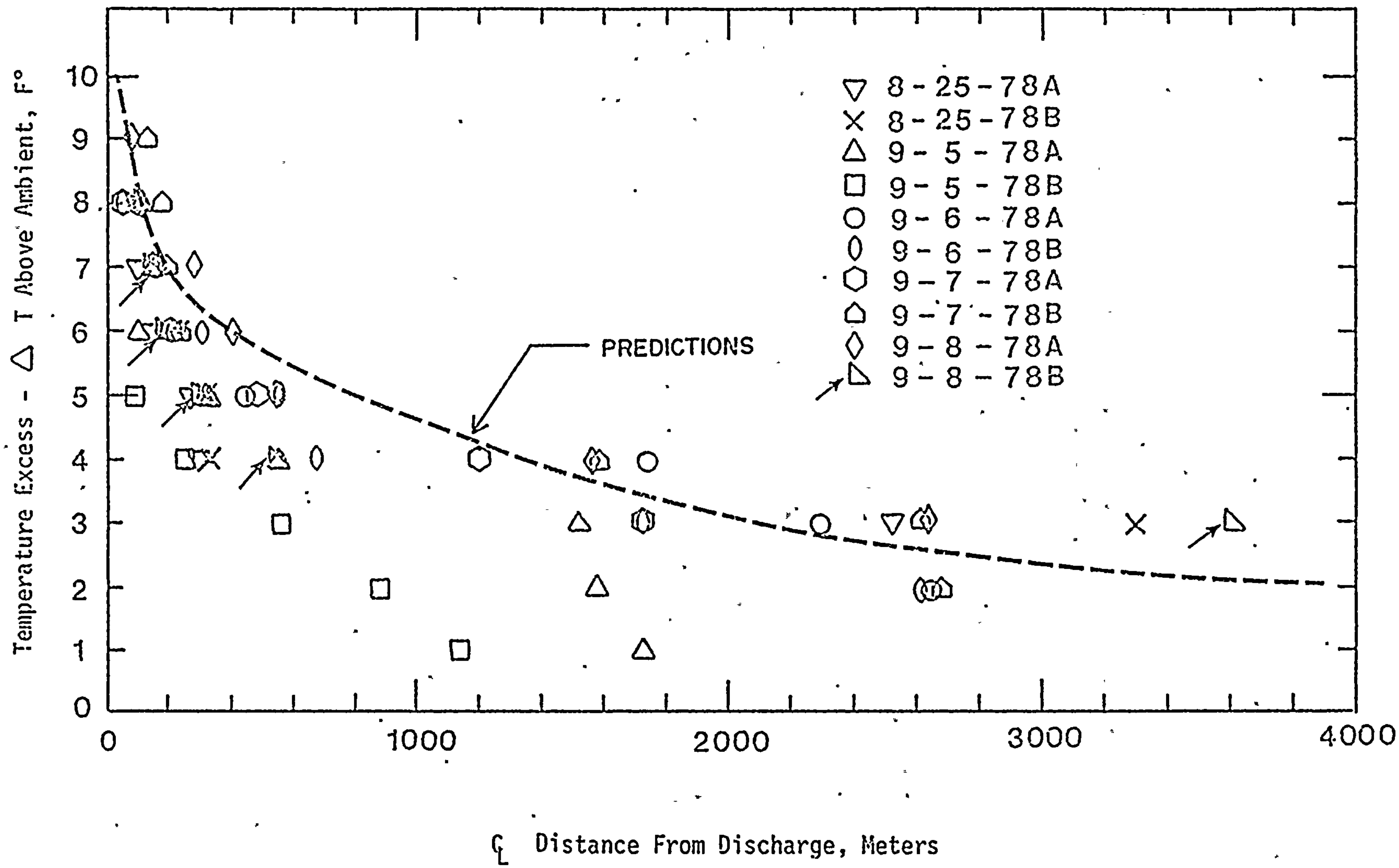


Figure 15. Excess Temperature vs. Distance (August - September, 1978)

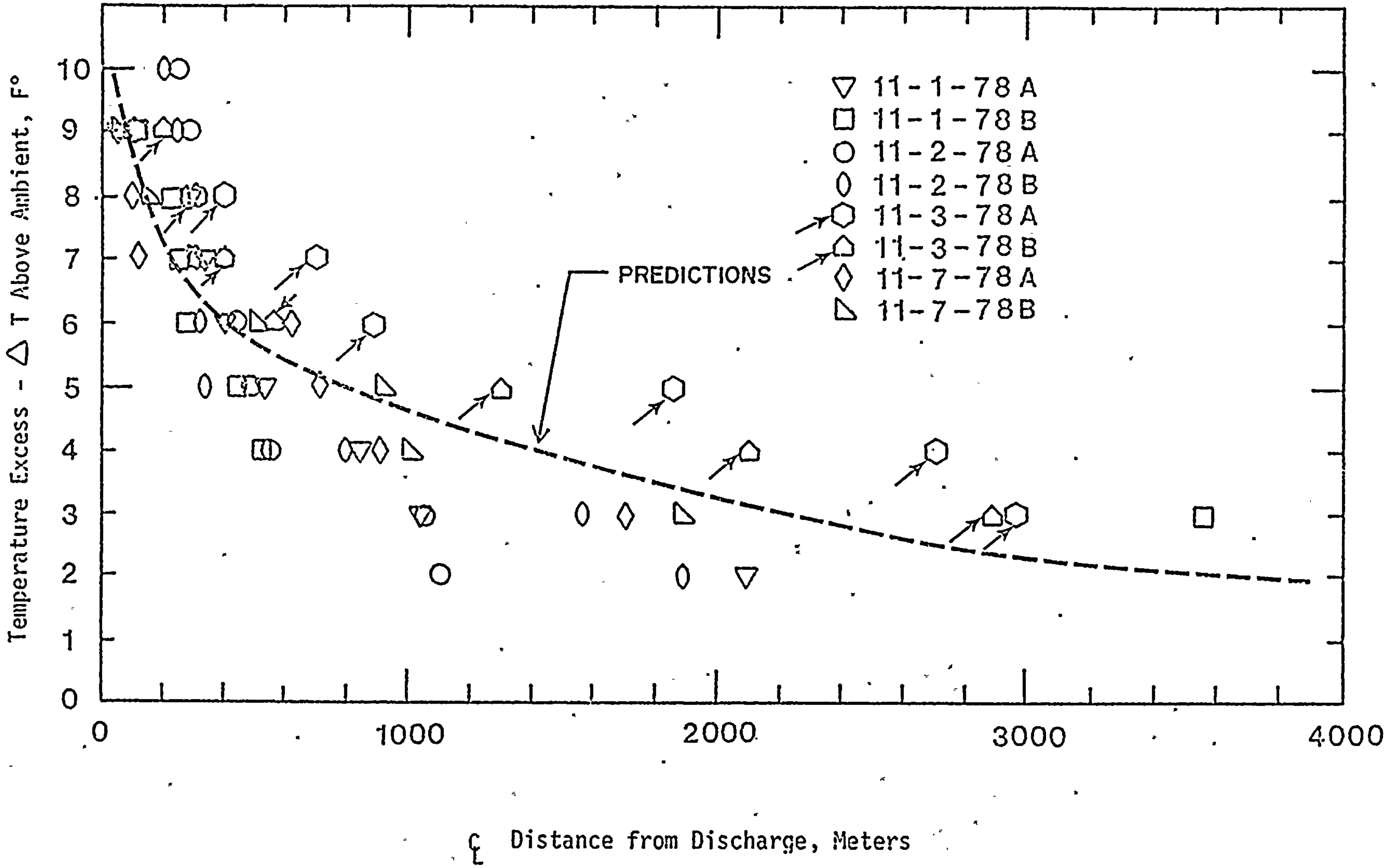


Figure 16. Excess Temperature vs. Distance (November, 1978)

atures persisted somewhat farther than the model predicted, while the lower excess temperatures did not persist quite as far as the model predicted. This is particularly true if the two 600+ acre plumes believed to be transitory in nature, measured on November 3, are discounted.

Again, in view of the fact that the lake conditions existing during the plume monitoring in November 1978 most closely approximated the hydraulic model conditions, it may be concluded that the modeling results were confirmed quite well by these data.

4.3 Plume Depths

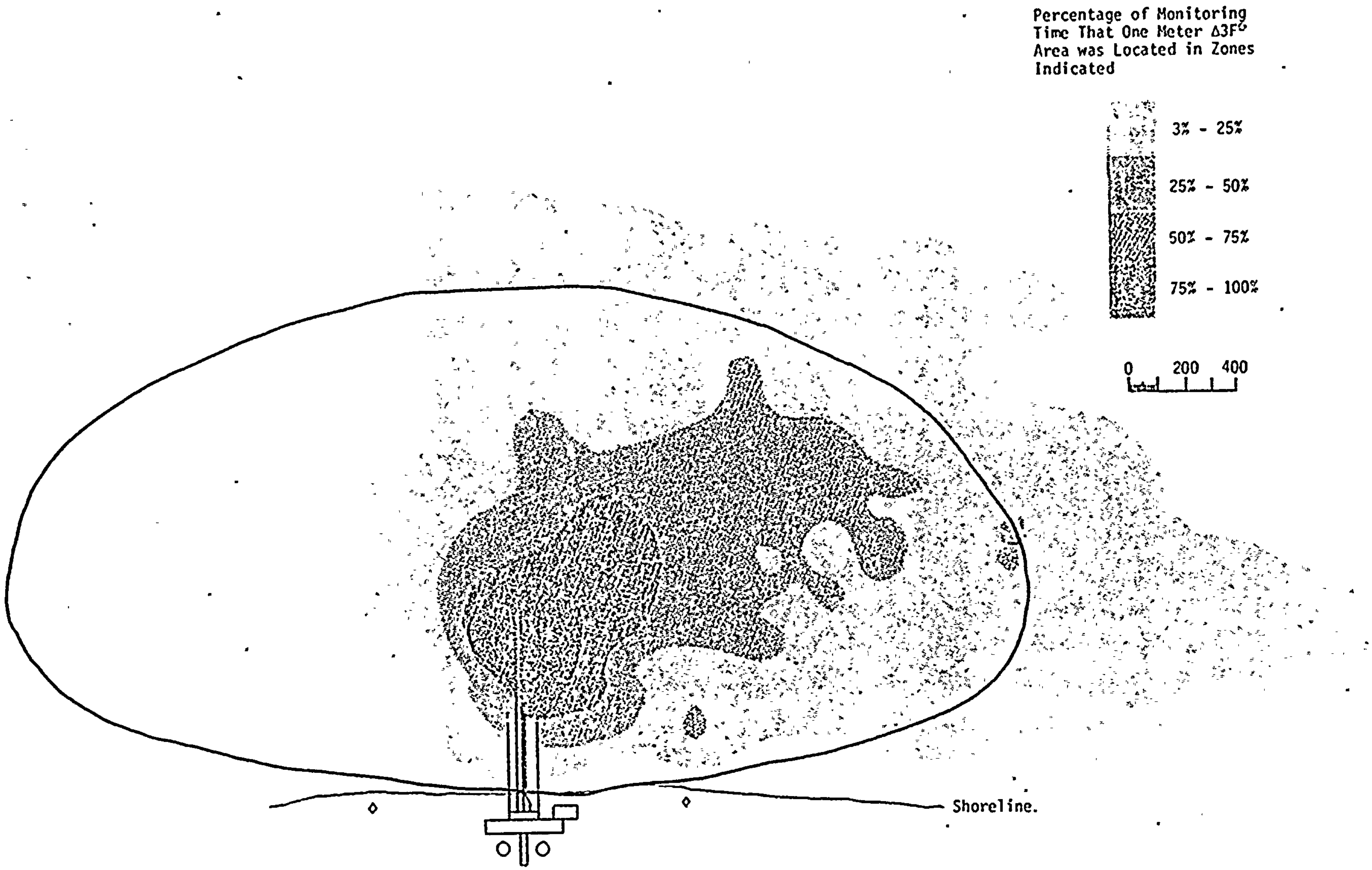
The modeling results shown in Table 4 indicate a predicted plume depth ranging from 10½ to 14 feet in depth during the summer months and 16½ to 30 feet deep during the winter. Approximately 70% of the field data showed little or no $\Delta 3°F$ water below the 10 foot depth. Most of the plumes exhibiting the $\Delta 3°F$ water at the 13 foot depth were measured during the November monitoring period. Since the November conditions most closely approximated the conditions in the hydraulic model, it may be concluded that the model did a good job in predicting the plume depth. Earlier in the year, however, the field data indicated plumes that were not quite as deep as predicted by the model. No data were obtained to allow comparison with the predicted winter plume thickness.

4.4 Plume Volume

Table 4 shows that the models predicted an average volume of 2.64×10^8 cubic feet (or 6,060 acre-ft) for the plume. This volume was calculated assuming a plume depth of 10 feet and also assuming a constant plume area at all depths. The average volume of the plumes measured in the field during November was 3323+ acre-ft, little over half of the predicted volume. The discrepancy between the prediction and the field data could be explained by the fact that the predictions assumed a constant plume area as a function of depth. The field data indicated that the area decreased with depth, and an allowance for this factor would have reduced the predicted volume.

4.5 Region of Influence

The modeling and analytical results were used to estimate an area of influence of the thermal discharge. The data tabulated in Table 5 were used to calculate an oval-shaped envelope representing the area of the lake that would be influenced at one time or another by the $\Delta 3°F$ water during the plume's meandering and fluctuation. An approximate oval of these dimensions was superimposed on Figure 2 to compare it with the region of influence observed during the field studies. This is shown in Figure 17 for the one meter depth. The measured area of influence extended further offshore and to the north than predicted by the modeling. This result was also observed in the monitoring of the one unit operation.



Region of Lake Influence by D. C. Cook Units 1 & 2
Discharge (Power Levels Greater than 75%)

Figure 17

5.0 SUMMARY

Data from the in-situ temperature and current recorders showed a large variability in the natural temperatures and currents in the lake near the Donald C. Cook site. The natural temperature changes represent a rate of change in the energy content of the water that far exceeds anything the Donald C. Cook Nuclear Plant could produce. The variability in the currents are the result of complex eddying motions that, along with the natural temperature variations, are practically impossible to simulate in a hydraulic model.

A comparison of the predictions of plume size and location with the data obtained during the monitoring program showed that, with the exception of the three transitory plumes, the models predicted areas larger than were observed in the field. The prediction of the excess temperature profile along the plume centerline showed relatively good agreement for the plumes measured in November (when the lake temperature was relatively uniform). However, the models over-predicted the excess temperature as a function of distance from the discharge during the earlier monitoring periods. The prediction of the plume depth agreed well with the data, but the predicted volume was almost twice as great as the observed volume. Although the observed volume was smaller than the prediction, the observed region of influence of the $\Delta 3°F$ water was somewhat larger than the predictions.

Conditions in the lake during the late fall monitoring periods most closely approximated the uniform temperature conditions utilized in modeling the thermal plume. The conditions during late fall also produced the largest plume areas because the intake water temperature is essentially the same as the ambient water temperature used to define the excess temperature isotherms. (Stratification effects that occur earlier in the year cause the intake water to be cooler than the ambient water temperature. This results in a smaller temperature difference between the discharge water and the ambient temperature and therefore produces a smaller plume.) This same condition of relatively uniform lake temperatures persists during the winter and until the spring warming--and the beginning of stratification--starts in late March or early April. Therefore, it is felt that this monitoring effort, even though it was unable to monitor plumes during the February-March period and during the

April-May period, has provided adequate data for validating the modeling techniques utilized for the D. C. Cook plant. And it has provided plume data during the time when the plume would be expected to be the largest.

It is highly unlikely that measurements of the thermal discharge during the winter months can be made at the Donald C. Cook plant. The adverse weather and lake conditions existing during the winter, the accumulation of ice, the unavailability of boats during that time of year, along with general safety considerations, render it virtually impossible to obtain winter plume data. Plume measurements during the spring season will also be almost impossible to obtain, since planned maintenance schedules will have one or both of the units down during this period. It is further felt that data obtained during this time of year are of little significance with respect to comparison with the modeling data because of the stratification effects. As the smallest plumes occur during this time of year, the data are also of little significance with respect to validating the allowable area specified in the NPDES permit.

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9. Indiana & Michigan Power Co. (1975), "Plan of Study and Demonstration Concerning Thermal Discharges at the Donald C. Cook Nuclear Plant," submitted to the Michigan Water Resources Commission, April 7, 1975) (pp. E 88-120).

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APPENDIX

SUMMARY OF THE MONITORING PERIODS

The log of the monitoring effort involved in this study is summarized below. It recounts some of the difficulties encountered in performing this monitoring effort on Lake Michigan, particularly during the colder months.

<u>August 21 - September 8, 1978</u>

Monitoring of the thermal discharges from both Unit 1 and Unit 2, with both units operating at greater than 75% full power, was initiated on August 21, 1978. Eleven plumes were mapped on six different days.

Aug. 21 -	Installed monitoring equipment on the boat. Boat generator failed and required repair. Serviced current meters and temperature recorders.
Aug. 22 -	No monitoring. Unit 1 at 40% power, Unit 2 down. Calibrated intake and discharge thermocouples at the plant.
Aug. 23 -	Mapped 1 plume. Sky clear and sunny. Lake changed from light chop to glassy.
Aug. 24 -	No monitoring. Plant was down for the day. Worked on equipment.
Aug. 25 -	Mapped 2 plumes. Sky overcast, foggy in the morning; light wind, 1-3 foot swells.
Aug. 26 -	Plume mapping attempt aborted after Unit 1 tripped early in the run.
Aug. 26 - Sept. 4 -	Unit 1 down.
Sept. 5 -	Mapped 2 plumes. Sky clear and sunny, light wind, lake calm.
Sept. 6 -	Mapped 2 plumes. Sky partly cloudy then clearing, moderate breeze, 2-4 foot swells.
Sept. 7 -	Mapped 2 plumes. Sky sunny with haze, light wind, 1-2 foot swells with chop.
Sept. 8 -	Mapped 2 plumes. Sky sunny and clear, light wind, 2-3 foot swells with chop.

October 30 - December 15, 1978

Monitoring of the thermal discharge during the fall season was begun on October 30, 1978. Eight plumes were mapped on four days early in November. Weather conditions or plant operating conditions prevented additional plume mapping until the effort was terminated on December 15.

Oct. 30 -	Installed equipment on boat and checked its operation. Gale warning prevented monitoring attempt. Serviced current meters and temperature recordings.
Oct. 31 -	Aborted monitoring attempt because of high winds and waves and failure of the generator on the way to the plant. Calibrated intake and discharge water thermocouples at the plant.
Nov. 1 -	Mapped 2 plumes. Sky sunny and hazy, light wind, 1-2 foot waves.
Nov. 2 -	Mapped 2 plumes. Sky sunny with haze, 1-3 foot waves with whitecaps.
Nov. 3 -	Mapped 2 plumes. Sky sunny with some haze, light wind, 1-2 foot waves.
Nov. 4 -	No monitoring. Unit 2 at 60% power.
Nov. 5-6 -	Unit 2 at less than 75% power.
Nov. 7 -	Mapped 2 plumes. Sky had scattered clouds, no wind, lake flat.
Nov. 8 -	No monitoring. Wind blowing at 25 - 30 mph, 4 foot waves.
Nov. 9 -	No monitoring. Lake too rough--4 foot waves with whitecaps.
Nov. 10 -	No monitoring. Unit 2 shut down for scheduled maintenance.
Nov. 27 -	No monitoring. Boat had engine problems. Unit 2 at 60% power. Lake was rough.
Nov. 28 -	Moved equipment to another boat. No monitoring. Wind 17 - 25 mph, 4-6 foot waves.
Nov. 29 - Nov. 30 -	Bad weather. On standby.

Dec. 1 - Monitoring attempt aborted because of high wind and waves.

Dec. 2-6 - Bad weather. On standby.

Dec. 7 - Monitoring attempt aborted after Coast Guard warning of high winds.

Dec. 8-15 - Bad weather. On standby. Monitoring effort aborted.

March 27 - April 6

The winter season monitoring effort was delayed until March 27, 1979, because of heavy lake ice and a frozen St. Joseph River. No plume mappings were obtained because of bad weather prior to an extended shutdown of Unit 1.

Mar. 27 - Lake and mouth of river blocked by ice.

Mar. 28 - Large quantities of lake ice.

Mar. 29 - No monitoring. Lake ice. Boat engines being repaired.

Mar. 30 - Monitoring effort aborted because of ice floes at river mouth.

Mar. 31 -
Apr. 3 - On standby, waiting for ice to clear.

Apr. 4 - Monitoring attempt aborted at the plant after data system became erratic because of the cold.

Apr. 5 - Monitoring effort aborted on way to plant because of increasing winds and waves. Winds gusting to 80 mph that night, 15 foot waves on lake.

Apr. 6 - Winds still gusting to 30 knots. Unit 1 tripped, would be down for refueling until May 30. Monitoring effort terminated.

July 23 - July 28, 1979

No monitoring was performed during the April 15 - May 15 period because the two units were down for refueling and repairs for an extended period. Both units were not at 75% power until July 23, 1979. Eleven plumes were subsequently mapped during six consecutive days.

July 23 - Mapped 1 plume (practice run). Unit 2 at 60% power.

July 24 - Mapped 2 plumes. Sky was cloudy. Lake had 2 foot waves.

July 25 - Mapped 2 plumes. Sky was cloudy. Wind 12-20 mph, 1-2 foot waves.

July 26 - Mapped 2 plumes. Sky sunny and clear, NW wind, 2-5 foot waves.

July 27 - Mapped 2 plumes. Sky sunny with light haze, light wind, 1-2 foot waves.

July 28 - Mapped 2 plumes. Sky cloudy, slight drizzle, light wind, 1-2 foot waves. Appeared to be strong current to north.