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# OBSERVATIONS OF THERMAL PLUMES FROM SUBMERGED DISCHARGES IN THE GREAT LAKES AND THEIR IMPLICATIONS FOR MODELING AND MONITORING

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# OBSERVATIONS OF THERMAL PLUMES FROM SUBMERGED DISCHARGES IN THE GREAT LAKES AND THEIR IMPLICATIONS FOR MODELING AND MONITORING

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## ABSTRACT

Measurements of thermal plumes from submerged discharges of power plant cooling waters into the Great Lakes provide the opportunity to view the mixing processes at prototype scales and to observe the effects of the ambient environment on those processes. Examples of thermal plume behavior in Great Lakes' ambient environments are presented to demonstrate the importance of measurements of the detailed structure of the ambient environment, as well as of the plumes, for interpretation of prototype data for modeling and monitoring purposes. The examples are drawn from studies by Argonne National Laboratory (ANL) at the Zion Nuclear Power Station and the D. C. Cook Nuclear Plant on Lake Michigan and at the J. A FitzPatrick Nuclear Power Plant on Lake Ontario. These studies included measurements of water temperatures from a moving boat which provide a quasi-synoptic view of the three-dimensional temperature structure of the thermal plume and ambient water environment. Additional measurements of water velocities, which are made with continuously recording, moored and profiling current meters, and of wind provide data on the detailed structure of the ambient environment.

The detailed structure of the ambient environment, in terms of current, current shear, variable winds, and temperature stratification, often influence greatly thermal plume behavior. Although predictive model techniques and monitoring objectives often ignore the detailed aspects of the ambient environment, useful interpretation of prototype data for model evaluation or calibration and monitoring purposes requires detailed measurement of the ambient environment. Examination of prototype thermal plume data indicates that, in several instances, attention to only the gross characteristics of the ambient environment can be misleading and could result in significant errors in model calibration and extrapolation of data bases gathered in monitoring observations.

## INTRODUCTION

The acquisition of data on thermal-plume behavior at prototype scales requires significant effort and expense. Consequently, there is a paucity of such data, and those available are usually acquired to satisfy a regulatory purpose or to calibrate or evaluate a predictive model at a specific site. On one hand, such data provide the opportunity for insight into the important processes at prototype scales, and, on the other hand, they contain all the complexities of the "real-world" environment and must be interpreted with care. In this paper, we seek to demonstrate both the insightful and potentially misleading aspects of prototype data from studies at submerged discharge sites on the Great Lakes and to suggest their implications for modeling and monitoring.

Argonne National Laboratory (ANL) began measurments of thermal plumes in 1970 at sites on Lake Michigan of surface discharges of once-through cooling waters. Initial measurements were oriented toward understanding surface plume characteristics [1,2,3] and later were directed toward evaluation of mathematical models of surface discharges [4]. More recently, measurements have been focused on submerged discharges at the Zion Nuclear Power Station and the D. C. Cook Nuclear Plant on Lake Michigan and the J. A. FitzPatrick Nuclear Power Plant on Lake Ontario. Plumes have been mapped at surface discharge sites and submerged discharge sites on 60 and 40 occasions, respectively.

The coastal waters of the Great Lakes which receive once-through cooling waters are generally shallow (<10 m), and because of the size discharge structure required, the relative submergence of the submerged discharge is correspondingly small. Relative submergences for the Zion, Cook, and FitzPatrick discharges are 4.2, 8.2, and 11.0, respectively. Near-field mixing is thus influenced by the free surface and bottom boundaries, and, in some instances, discrete buoyant jets give way to well-mixed near-field regimes. While free of the significant periodic variations of depth and salinity of marine coastal waters and estuaries, the coastal waters of the Great Lakes are rarely motionless. They often exhibit important current and temperature variability with time-scales of less than an hour and commonly undergo major changes at 2-3 day intervals. Currents tend to be shore parallel and have magnitudes on the order of 10 cm/s. Both near- and far-field plume regimes can be influenced by this receiving water environment.

## THERMAL-PLUME MEASUREMENT SYSTEMS

Several techniques, ranging from fixed thermistor arrays to aerial infrared imagery, exist for the measurement of thermal plumes. Measurement strategies vary with modeling and monitoring objectives, but the often sought ideal of a synoptic view of the three-dimensional temperature structure is rarely, if ever, achieved. For the purpose of data acquisition for understanding plume behavior and model evaluation, ANL has developed integrated measurement systems which provide a quasi-synoptic view of the three-dimensional water temperature structure and related ambient conditions. The essential requirements for the systems are sufficient horizontal and vertical resolution of temperature measurements to define three-dimensional structure, real-time display of temperature and position to allow for adjustment of the experiment plan to variable conditions, and temperature sensors, all calibrated against a common standard, which are accurate enough to allow determination of the relatively small temperature rises above ambient at submerged discharge sites.

The ANL thermal-plume measurement systems are described only briefly here, and a more detailed discussion of instrumentation, techniques, and data handling procedures is given in Ref. [5]. Plume mapping is carried out from a moving survey boat (Fig. 1) which tows a faired thermistor chain. The dynamics of the chain are such that thermistors are located vertically at about 1-m intervals. The depth to which the chain can be deployed is variable up to a maximum of 10 m. A surface following thermistor is rigged separately and measures the temperature of the upper 2 cm of the water. Boat position data are acquired continuously by means of a microwave range/range system. Temperature data are recorded digitally on paper tape and cassette magnetic tape and are displayed onboard in vertically stacked LED displays. Position data are recorded similarly and are displayed onboard as a "real-time" plot of the boat path by an X-Y plotter. Monitoring of vertical temperature structure and boat location by the experimenters serves to guide the mapping in such a way as to ensure inclusion of important features which might be omitted by "flying blind." Horizontal resolution depends on data acquisition rates and boat speed, but typical operation allows 1000-2000 separate measurement locations in and around a plume to be sampled in 1 to 2 hours.

In addition to the plume mapping system, several continuously recording instruments are employed to sense discharge and ambient conditions. Bendix Q-15R ducted impeller current meters are moored outside the influence of the discharge plume to record ambient current direction and magnitude. One such current meter was employed in early studies, but recently several have been used, including two on a single mooring, to provide time histories of spatial variability of currents. The meters are designed for shallow water environments, and record on cassette tapes typically at eight-minute intervals. The current meter packages include two temperature sensors which can be attached to the mooring and also record on tape at eight-minute intervals. Thermograph packages of similar design, containing four thermistors, are installed in plant discharge conduits to record discharge temperatures. A portable meteorological station is used to record wind speed and direction. Where possible, it is positioned on a breakwater or other structure near the discharge in an attempt to measure over-the-water wind. In some instances, no suitable location for the portable station is found and power plant meteorological records must be used, although those measurements are often from towers on land well above the water surface.

Complementing the continuously recorded measurements of the ambient environment, detailed vertical profiles of current and temperature are made at fixed locations prior to and after plume mapping. These measurements are usually at 0.5- or 1.0-m intervals from the survey boat which is taut-anchored near one of the current-meter moorings. While only a small sample in time of the ambient environment, these measurements provide important information on spatial variability. Additionally, observations of wind speed and direction, surface wave conditions, and other meteorological and limnological parameters are made from the boat at this time.

## THE AMBIENT ENVIRONMENT

The behavior of thermal plumes from submerged discharges is governed both by the discharge characteristics (velocity, density, and geometry) and by the characteristics of the surrounding or ambient water and atmospheric environment (water velocity and density fields and air temperature, relative humidity, and velocity). Discharge characteristics are generally fixed within certain bounds by the cooling water system design, but characteristics of the ambient environment may vary widely. Preoperational predictions of plume behavior are often made on the basis of estimates of worst-case ambient conditions, e.g. stagnant conditions, strong currents, etc. However, the degree to which both mathematical and physical predictive models can include the characteristics of the ambient environment is limited. For modeling purposes, ambient conditions are often assumed to be steady and spatially uniform, as in the case of a single value for ambient current, or neglected, as in the case of wind stress at the water surface. Prototype measurements of thermal plumes rarely occur in ambient environments with simple characteristics.

The following sections draw upon ANL's measurement experiences at submerged discharges on the Great Lakes to indicate the effects of ambient currents, ambient current shear, variable wind, and ambient stratification on plume behavior. Other aspects of the ambient environment of the Great Lakes are important, but are not discussed here. For example, water depth or submergence of the discharge varies seasonal and on longer cycles in the Great Lakes, but it may also vary daily in response to lake set-up by wind. Also, localized bottom scour by submerged discharges may alter bathymetry enough to affect current patterns, as may other larger scale changes in bathymetry.

### Effects of Ambient Currents

It is well known that ambient currents influence the behavior of thermal plumes, particularly the plume shape in the far-field region. The near-field behavior of plumes from submerged discharges is generally governed, in the absence of stratification, by the discharge densimetric Froude number, the relative submergence, and the ratio of ambient velocity to discharge velocity. Discharges from an individual nuclear power plant on the Great Lakes seldom exhibit substantial variation in Froude number and relative submergence, and velocity ratios, while variable, tend to be small ($<0.1$). Field measurements have provided examples of the important influence ambient current can exert on near-field mixing.

The Zion Nuclear Power Station is located on the western shore of Lake Michigan. It consists of two units, each capable of the gross generation of 1100 MWe and each with its own once-through cooling system discharging about 50 $m^3/s$. The cooling water leaves each unit through separate lines and is discharged into the lake via two submerged structures. Each discharge structure is located 231 m offshore in about 4.5 m of water. The structures are 94 m apart, and each consists of a box 23 m long by 9 m wide with 14 ports approximately 1.6 m wide by 0.9 m high on the offshore end and on the side away from the other discharge structure. The ports are formed by louvers that direct the water at a 45° angle away from shore, and the average discharge velocity at the ports is about 2.4 m/s.

Measurements at the Zion site by ANL included cases of discharge from only one structure, with ambient currents both nominally opposed to and in the same direction as the discharge velocity, and of discharges from both structures. The results of these studies are reported in detail in Refs. [6] and [7]. In general, single unit discharges with discharge direction opposed to that of the ambient lake current resulted in average surface isotherm areas six times larger and average initial (near-field) dilutions at the surface 20% smaller than those cases where the discharge and ambient current were in essentially the same direction.

Of particular interest here is the case of discharges from both of the adjacent structures. Early attempts at prediction of double-discharge plume behavior presumed that the case of zero ambient current would produce the largest isotherm areas. However, that prediction assumed no interaction between plumes, and, in the presence of a current, interaction is possible. In that case, regardless of the north or south orientation of the shore parallel ambient current, one discharge opposes the ambient current and one is in the same direction as the ambient current. Measurements in the presence of a current indicated that two distinct plumes could be observed in the near-field regions (Fig. 2). Closer inspection of the temperature structure indicated larger surface areas associated with the downcurrent plume of the two than those areas associated with the case of a single unit discharge with similar ambient currents. That suggested a shielding by the upcurrent plume of the downcurrent plume from entrainment of water of ambient temperature. Further evidence of interaction between the two plumes is shown in Fig. 3. In this figure, the ratios of the total surface isotherm area measured for double discharges to the sum of isotherm areas measured for single discharges with and against the ambient current are given as a function of excess temperature ratio. For no interaction between the discharges that ratio would be 1.0; yet in the far field (small excess temperature ratios), the ratio is as large as 10. The double plume data are the result of two mappings during which the ambient lake currents were modest, with velocity ratios of 0.022 and 0.026.

An occurrence which demonstrates the variability of Great Lakes coastal waters and the limitations of the quasi-synoptic nature of boat measurements is noted here. In an attempt to gain additional data on double-discharge plume interaction at the Zion site, the plume was again mapped. The surface temperatures measured are shown in Fig. 4. At the crossing of the dotted boat tracks south of the discharges, the temperatures indicated at the large dots reflect measurements made at the beginning and end of the mapping - a time interval of 2 hours 35 minutes. Near the crossing, initial temperatures were about 14.0°C and final temperatures were about 11.6°C. This disparity in ambient temperatures reflected an unusually large temporal gradient in temperature. Examination of the time history of water temperatures at the current meter moored upcurrent of the discharge indicated that a decrease in temperature of about 5.5 C° had occurred there in about 4 hours, just prior to the initiation of plume mapping. Also, current speed and direction at that location indicate that the time-of-travel of a cool water mass northward would be such to cause its intrusion into the thermal plume region during the mapping. Measurements in the near-field region of the plumes were made in a relatively short time (< 1 hour) and did not indicate the variability seen in the complete-field mapping. However, this experiment points out the need, in field experiments, to provide replicate sampling points as a measure of variability and to monitor continuously temperatures and currents in regions not directly influenced by the plumes.

Another example of a submerged discharge site where ambient currents are important is the J. A. FitzPatrick Nuclear Power Plant on the south shore of Lake Ontario. The discharge structure is a multiport diffuser with 12 circular ports, each 0.76 m in diameter, directed horizontally in the offshore direction. The relative submergence of the ports is about 11 and the discharge velocities are about 4.3 m/s. The nominal temperature elevation of the cooling water is about 17.5 C°, but the diffuser system creates dilutions at the surface in the near-field region of 8-10, so that excess temperatures in that region are relatively small. Initial measurments at this site by ANL indicate that currents in the vicinity of the discharge, while shore parallel in a gross sense, are complex in detail. Some interaction between individual discharge jets appears to be present during periods of strong currents normal to the discharge direction. The diffuser, because of its offshore directed momentum, induces some of its entrainment flow over the system from behind the ports. These induced currents, as well as the bottom topography at the site, may be responsible for the apparent complexity of the current structure. Recently, plume mapping experiments at the J. A. FitzPatrick site by ANL included the deployment of ten continuously recording current meters on seven moorings close to the diffuser and in regions thought to be out of the influence of the plumes. Preliminary study of the results of these measurements indicates that entrainment flow induced by the diffuser does appear to influence near-bottom currents at locations 300 m either side of the diffuser in the alongshore direction. Additional studies of these measurements are required, but it is clear that the selection of locations for ambient current measurements for modeling and monitoring purposes in the vicinity of such diffusers requires care.

## Effects of Ambient Current Shear

Nonuniformity of the ambient velocity field clearly can influence thermal plume mixing and geometry. The scales of horizontal gradients of ambient velocity are such that, typically, the influence of these gradients is more pronounced in the far-field than in the near-field regions of the plume. They can enhance lateral spreading by differential convection and sometimes produce strange plume shapes. Vertical velocity gradients are associated with smaller length scales, and, while undoubtedly having some influence on near-field submerged plume behavior, can also influence significantly far-field mixing. An example from ANL studies at the D. C. Cook Nuclear Plant is presented to indicate the effects of vertical velocity shear.

The D. C. Cook plant is located on the southeastern shore of Lake Michigan. The gross generating power of Unit 1 (only unit operational in 1975) is 1090 MWe, and its 45.8 $m^3/s$ of cooling water are discharged about 365 m offshore from a submerged structure containing two slots in about 5.7 m of water. Each slot discharges horizontally, one directly perpendicular to shore and one at 75° to the north; and each slot is 9.1 m wide by 0.6 m high and is about 0.5 m above the lake bottom. Thus, the nominal relative submergence is 8.2; the discharge velocity is 4.1 m/s; and the nominal discharge temperature elevation is 12.1 C°. Additional information regarding the characteristics of the Cook plant and ANL's measurements there are given in Refs. [8] and [9].

The results from two plume surveys on consecutive days in October, 1975, indicate the influence of vertical velocity shear on plume behavior. For the surveys of October 7, 1975 (1110-1425 hr EDT) and October 8, 1975 (1017-1253 hr EDT), the gross parameters governing plume behavior were almost identical, as indicated in Table 1. Maps of the surface isotherms of the plumes on these two occasions are shown in Figs. 5 and 6. Note that both drawings are not to be same scale. The appearance of the two plumes at the surface is different, the Oct. 7 plume looking larger, and experimental values of surface areas for several excess temperature ratios confirm that observation. Table 2 includes areas enclosed within the isotherms with excess temperature ratios of 0.2 (approximately the 1.6 C° (3 F°) excess temperature value) and 0.1 at the water surface, 0.2 m below the surface, and 3.2 m below the surface. Also, distances along the plume centerline to the 0.2 and 0.1 excess temperature ratio isotherms are given. In the surface regions, the areal extent of the plume of Oct. 7, 1975 (1110-1425 hr) is about three times larger than that of Oct. 8, 1975 (1017-1253 hr). Also, distances along the centerline from the discharge to comparable isotherms are at least one and a half times larger for the Oct. 7, 1978 (1110-1425 hr) plume. However, at the level 3.2 m below the surface, the isotherm areas and centerline distances are almost the same for both plumes.

The disparity in these characteristics of plume behavior in two situations for which the gross measures of discharge and ambient conditions are nearly identical appears to be due to differences in vertical velocity shear. Although records from the current meter moored in the upper 2-m of the water column, averaged for each plume mapping period, indicate speeds and directions of 34 mm/s and 199° from N and 30 mm/s and 194° from N for the Oct. 7, 1975 (1110-1425 hr) and Oct. 8, 1975 (1017-1253 hr) plumes, respectively, vertical velocity profiles prior to each plume mapping reveal significant differences. On Oct. 7, 1975, prior to plume mapping the velocity profile indicated that in the upper 2 m of water, velocities were about 34 mm/s and 240° from N, while below 2 m the magnitudes were about 60 mm/s and 200° from N. Thus, the surface waters had an offshore component and, at depth, the flow was essentially shore parallel. However, on Oct. 8, 1975, the velocity profile measured prior to plume mapping indicated no gradient in magnitude, and directions, though somewhat variable, were shore parallel at the surface and only slightly offshore with depth. Also, examination of the continuous records from the moored current meter and meteorological station indicated strong offshore currents and winds on Oct. 6, 1975, of which the shear on Oct. 7, 1975, is likely a vestige. The large plume mapped on Oct. 7, 1975 (1110-1425 hr) is probably the result of the offshore component of ambient current revealed in the vertical velocity profile.

## Effects of Variable Wind

The current shear responsible for the large plume areas near the surface in the example above appears to be due to wind. During the Oct. 7, 1975 (1110-1425 hr) plume mapping at the D. C. Cook site (Fig. 5), the wind direction remained nearly constant from the SE. Constant wind direction during an experiment is not always the case, and large variations in wind direction may influence greatly the spreading of plumes near the water surface due to sharp velocity gradients created there. However, flow over all of the water column may not respond immediately to that change in forcing. The coupling between wind and lake currents and current shear is complex, and even simple models of that relationship account for a time lag. Current meters moored to record ambient currents are usually not located close to the water surface. Consequently, the development of surface currents and shear in response to wind variation may not be sensed by such instruments during the period of plume measurement.

The plume mapped at the D. C. Cook site on Oct. 9, 1975 (1057-1423 hr) is an example of that situation. The gross discharge and ambient conditions prevailing during that mapping are given in Table 1 and do not differ vastly from the other two D. C. Cook plumes given there and discussed above - except that the wind direction changed rapidly during the mapping. At the initiation of the mapping, the wind was from the east and shifted through south to the west by the end of the mapping. In this instance, a vertical velocity profile was taken only prior to the mapping and wind shift, and it revealed no vertical shear. The current meter moored at 1.5 m below the surface recorded a small magnitude and constant direction of about 154° from N (small onshore component) during the mapping period. However, the plume (surface isotherms shown in Fig. 7) had the largest areal extent of any measured by ANL at the D. C. Cook site. The area enclosed by the 0.2 excess temperature ratio isotherm was $5 \times 10^5$ $m^2$. Further examination of the current meter records shows that, although the current was small in magnitude and relatively constant in direction during the period of mapping, the ambient current reversed direction in the next six hours. Apparently, then, the large size of the plume was a result of both relatively stagnant conditions over most of the water column and the likely near-surface velocity shear due to shifting wind directions.

### Effects of Ambient Stratification

The effects of ambient temperature stratification on attempts to determine submerged plume behavior from temperature measurements are readily apparent. If the ambient receiving water is isothermal, comparisons among sets of plume characteristics for different occasions can be made in terms of excess temperature ratios. If the ambient water is temperature stratified, there is no single value of ambient temperature. And, it is difficult to find a few parameters to characterize ambient temperature stratification in the Great Lakes coastal waters as variability of ambient thermal structure seems to make each situation nearly unique.

Vertical temperature stratification is often the result of surface heating. For example, for the plume mapped at the D. C. Cook site on Oct. 7, 1975 (1110-1425 hr) and discussed above (Fig. 5), ambient water temperatures were nearly uniform, vertically and horizontally, at 14.9°C. Ambient water temperatures associated with a plume mapped later that day between 1609 and 1821 hr indicated that ambient water temperatures in the upper 2 m had increased to 15.5-16.0°C, while temperatures at the 5.3-m depth remained near 14.9°C. Both vertical and horizontal temperature stratification of the ambient waters is often the result of upwelling and downwelling associated with wind. A local upwelling event may have been the source of the cool water mass which intruded into the double plume at Zion that was discussed above (Fig. 4).

For submerged discharges of heated waters, the obvious effect of vertical stratification is that, at the surface, the plume may have temperatures very near ambient surface temperatures. Extreme vertical stratification and large subsurface entrainment by the plume may even result in a plume cooler at the surface than ambient water. This situation is evident from the surface isotherm map at the D. C. Cook site for May 13, 1975 (1529-1700 hr EDT) shown in Fig. 8. Ambient surface water temperatures ranged between 10-11°C and the discharge temperature was 16.2°C. Near-bottom ambient temperatures in the vicinity of the discharge were about 8.5°C. Consequently, the water surface temperatures in the discharge plume were between 9.4-10.0°C.

Most attempts at three-dimensional mapping of the plume and/or vertical temperature profiles of the ambient water will reveal the stratification. However, measurements of only the near-surface temperatures from boats or remotely from planes may prove difficult to interpret and result in erroneous conclusions about the submerged plume behavior.

## CONCLUSIONS

The examples presented here regarding the variability of ambient environments at submerged discharge sites on the Great Lakes are not given to disparage the value of prototype measurements in understanding plume behavior. Indeed, while not providing the simple environments needed for exact correspondence to some predictive model assumptions, these examples provide other useful information. Many other plume mappings, not presented here, provide situations where less complex ambient conditons prevail and where prototype measurements are particularly useful for the evaluation of predictive models. In addition to revealing some of the limitations of prototype-scale measurements in "uncontrolled" ambient environments, these studies have made apparent a general conclusion regarding modeling and monitoring of submerged discharges in the Great Lakes. The measurement of the detailed structure of the ambient environment is important, even when that detailed structure is not required as input to or produced as output by a model or when it is not the primary objective of a monitoring operation. The absence of such data makes difficult the interpretation of the results of prototype plume measurements in terms of model predictions and monitoring objectives.

It is gratuitous to recommend that predictive models for submerged discharges in the shallow coastal waters of the Great Lakes, or similar water bodies, include more details of the spatial and temporal variability of the ambient environment. There is, however, the necessity to exercise caution in the use of prototype data to calibrate mathematical models for near- and far-field behavior. Since such models often treat the ambient environment as steady and spatially uniform, fitting model predictions to prototype data for which measurements of ambient conditions are sparse or have been averaged to provide single values can be misleading. The example of the two plumes at the D. C. Cook site, for which gross discharge and ambient condition parameters were nearly identical, demonstrates this point. A model calibrated on the basis of only gross ambient characteristics with data from one of the plumes could hardly be expected to provide reasonable predictions of the behavior of the other plume. The substantial differences in plume behavior were the result of difference in ambient current shear. A similar point can be made with regard to modeling which attempts to include the effects of wind shear stress on the water surface. Simply including in such a model a steady wind stress at the water surface corresponding to the average wind during the time of plume mapping may result in predictions of ambient current fields quite unlike those measured because of the transient nature of the interaction between winds and nearshore coastal circulation. As in the modeling of longitudinal dispersion in streams and the modeling of estuarine circulation averaged over tidal periods, averaging in space and time in the modeling of thermal plumes does not do away with the details of the mixing processes it only lumps them in the coefficients. Consequently, modeling efforts require information on the details of the ambient environment so that the sensitivity of model predictions to changes in them can be assessed.

Although the purposes for monitoring vary, measurements of the details of the ambient environment are probably important for most thermal plume-monitoring operations. If one is concerned with only an instantaneous or quasi-instantaneous view of the surface extent of a plume from a submerged discharge to judge compliance or noncompliance with a regulatory standard simply obtaining temperature measurements without particular regard to other ambient environment characteristics may be satisfactory. However, if the purpose is to establish a data base by monitoring, the statistics of which are then to be used to estimate the probability of plume behavior in the future, the details of the ambient environment are important. Even with data on the details of ambient conditions, meaningful statistical information on plume behavior may be difficult to extract; but without data concerning those details, the task is practically impossible.

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TABLE 1

## DISCHARGE AND AMBIENT ENVIRONMENT CHARACTERISTICS AT THE D.C. COOK SITE DURING THERMAL PLUME MAPPING PERIODS

| | Oct. 7, 1975 (1110-1425 hr) | Oct. 8, 1975 (1017-1253 hr) | Oct. 9, 1975 (1057-1423 |
|---|---|---|---|
| Plant Load, MWe | 880 | 870 | 880 |
| Flow Rate, $m^3/s$ | 48.4 | 48.6 | 48.6 |
| Intake Temp., °C | 15.8 | 15.5 | 15.8 |
| Discharge Temp., °C | 24.0 | 23.6 | 23.9 |
| Ambient Current | | | |
| Speed, mm/s | 34 | 30 | 27 |
| Direction, ° from N | 199 | 194 | 154 |
| Discharge Densimetric Froude No. | 42 | 43 | 42 |
| Velocity Ratio (Ambient : Discharge) | 0.0078 | 0.0069 | 0.0062 |
| Wind | | | |
| Speed, m/s | 3.0 | 4.2 | 2.5 |
| Direction | SE | ESE | Variab |

## TABLE 2

### ISOTHERM AREAS AND CENTERLINE DISTANCES AS FUNCTIONS OF EXCESS TEMPERATURE RATIO AT THE D. C. COOK SITE

| | Oct. 7, 1975 (1110-1425 hr) | Oct. 8, 1975 (1017-1253 hr) |
|---|---|---|
| Surface | | |
| Areas, $m^2$ | | |
| $\theta/\theta_o = 0.2$ | $9.5 \times 10^4$ | $3.3 \times 10^4$ |
| $\theta/\theta_o = 0.1$ | $> 3.3 \times 10^6$ (open isotherm) | $1.0 \times 10^6$ |
| Distance along Centerline, m | | |
| $\theta/\theta_o = 0.2$ | 1080 | 790 |
| $\theta/\theta_o = 0.1$ | >4000 | 2100 |
| 0.2 m Below Surface | | |
| Areas, $m^2$ | | |
| $\theta/\theta_o = 0.2$ | $4.6 \times 10^4$ | $2.6 \times 10^4$ |
| $\theta/\theta_o = 0.1$ | $> 2.7 \times 10^6$ (open isotherm) | $5.7 \times 10^5$ |
| 3.2 m Below Surface | | |
| Areas, $m^2$ | | |
| $\theta/\theta_o = 0.2$ | $1.3 \times 10^4$ | $1.2 \times 10^4$ |
| $\theta/\theta_o = 0.1$ | $2.6 \times 10^5$ | $2.8 \times 10^5$ |
| Distance along Centerline , m | | |
| $\theta/\theta_o = 0.2$ | 320 | 370 |
| $\theta/\theta_o = 0.1$ | 1400 | 1620 |

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where:

$\theta/\theta_o$ = excess temperature ratio,

$\theta_o$ = discharge temperature minus ambient water temperature, and

$\theta$ = water temperature at any point minus ambient water temperature.

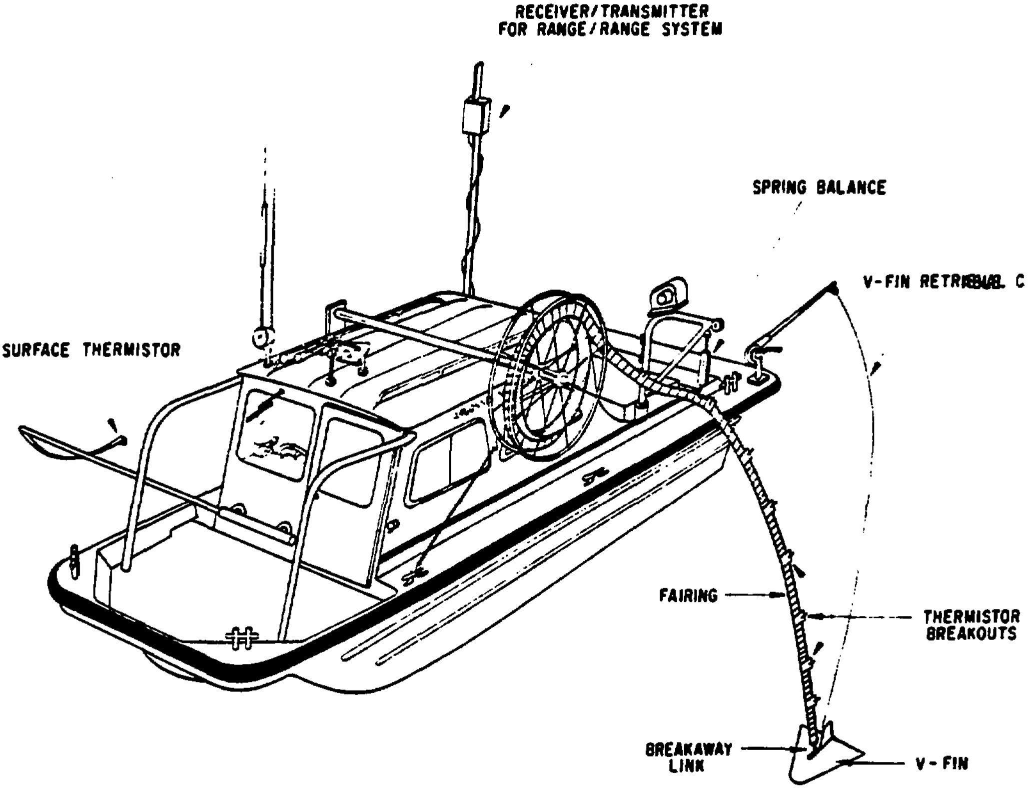


Fig. 1. Argonne National Laboratory Survey Boat Equipped for Therma Plume Measurements.

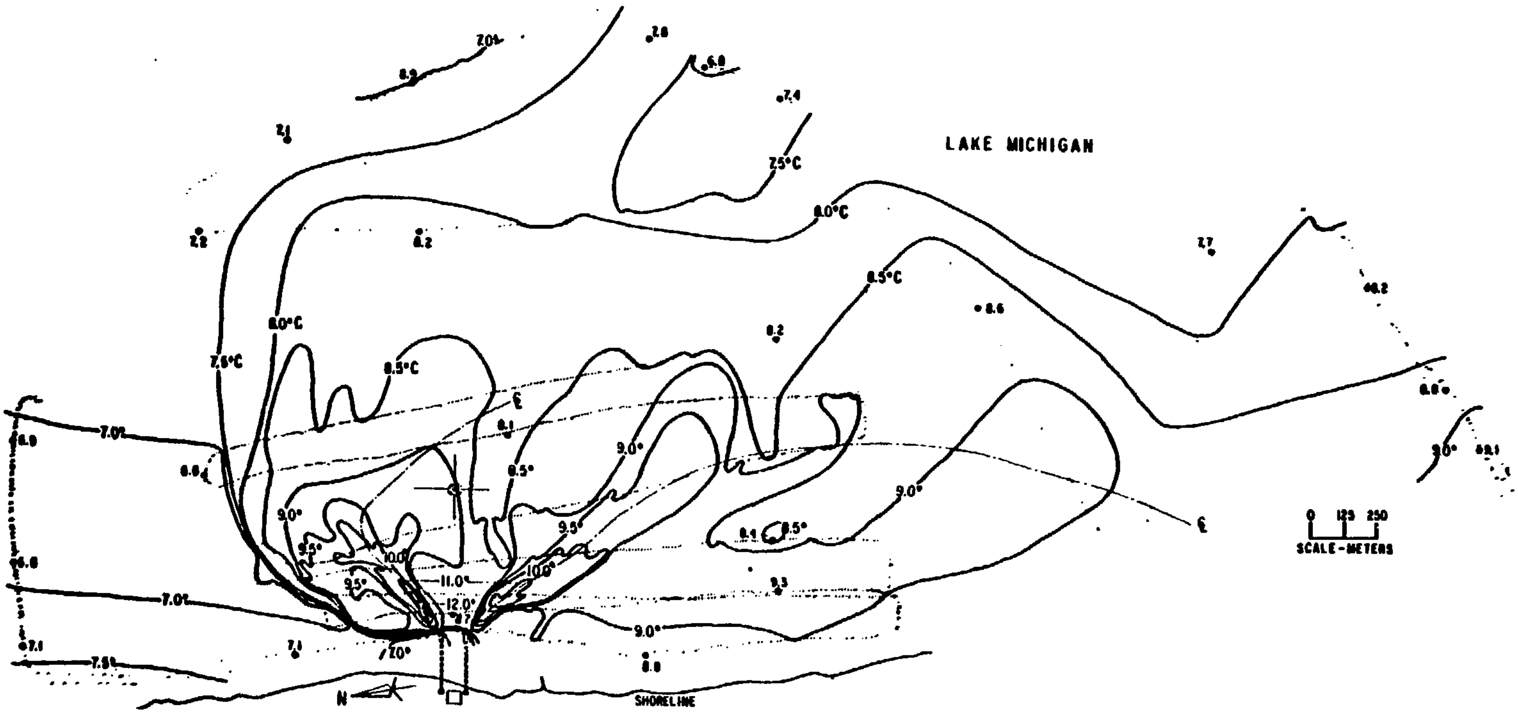


Fig. 2. Thermal Plume at Surface at Zion Site: May 1, 1975, 1010-1300 hr CDT.

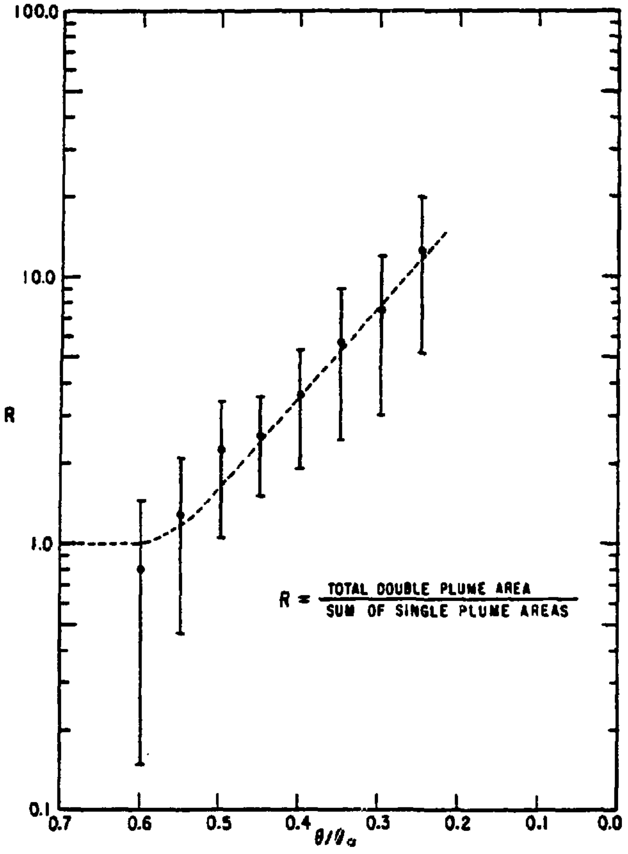


Fig. 3. Ratio of Double-Plume Isotherm Areas to the Sum of Single-Plume Areas as a Function of Excess Temperature Ratio. The Excess Temperature Ratio, $\theta/\theta_o$ is Defined as the Ratio of the Difference between Plume and Ambient Water Temperatures to the Difference between Discharge and Ambient Water Temperatures.

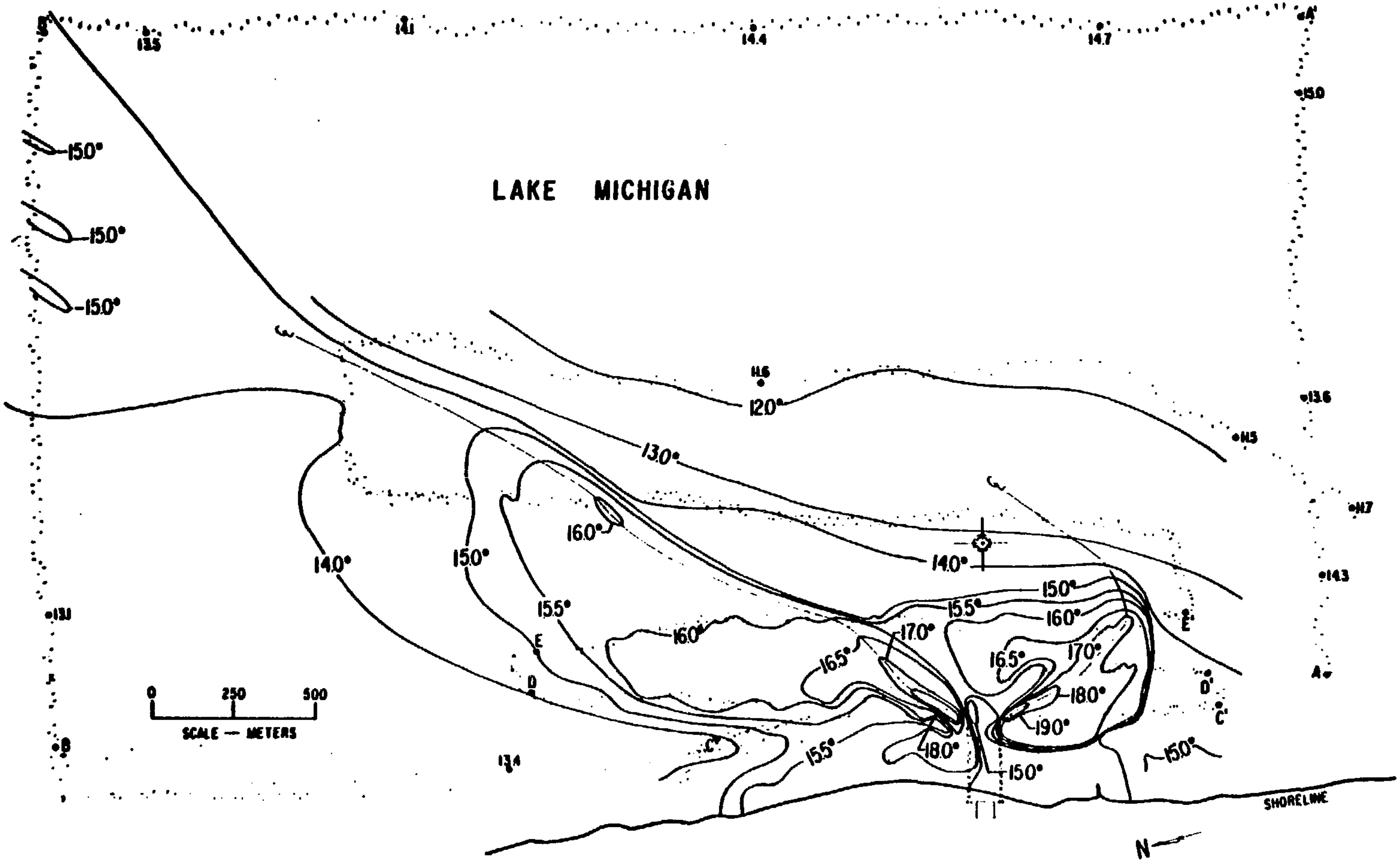


Fig. 4. Thermal Plume at Surface at Zion Site: September 3, 1976, 1149-1415 hr CDT.

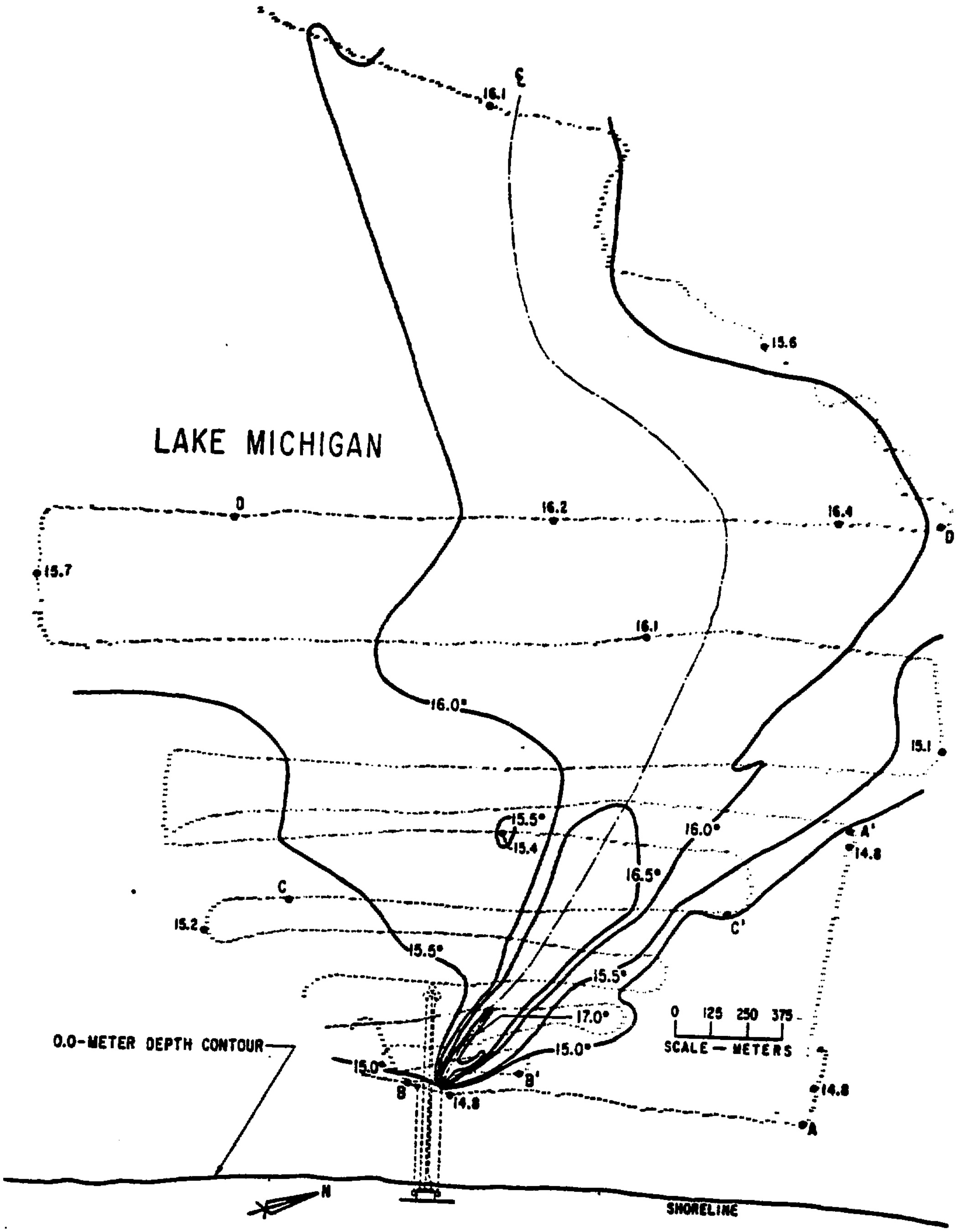
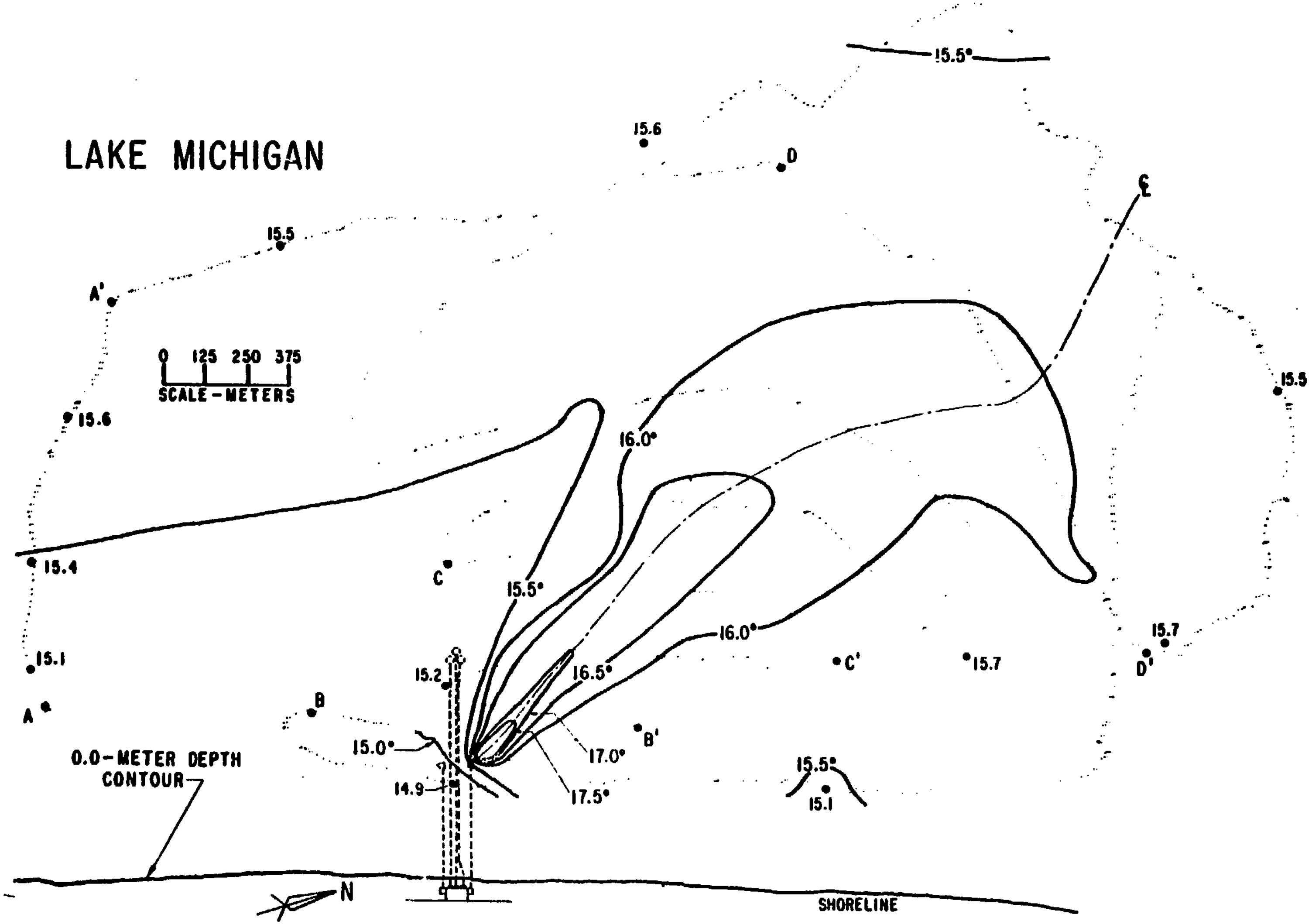


Fig. 5. Thermal Plume at Surface at D. C. Cook Site: October 7, 1975, 1110-1425 hr EDT.



October 8, 1975, 1017-1253 hr EDT.

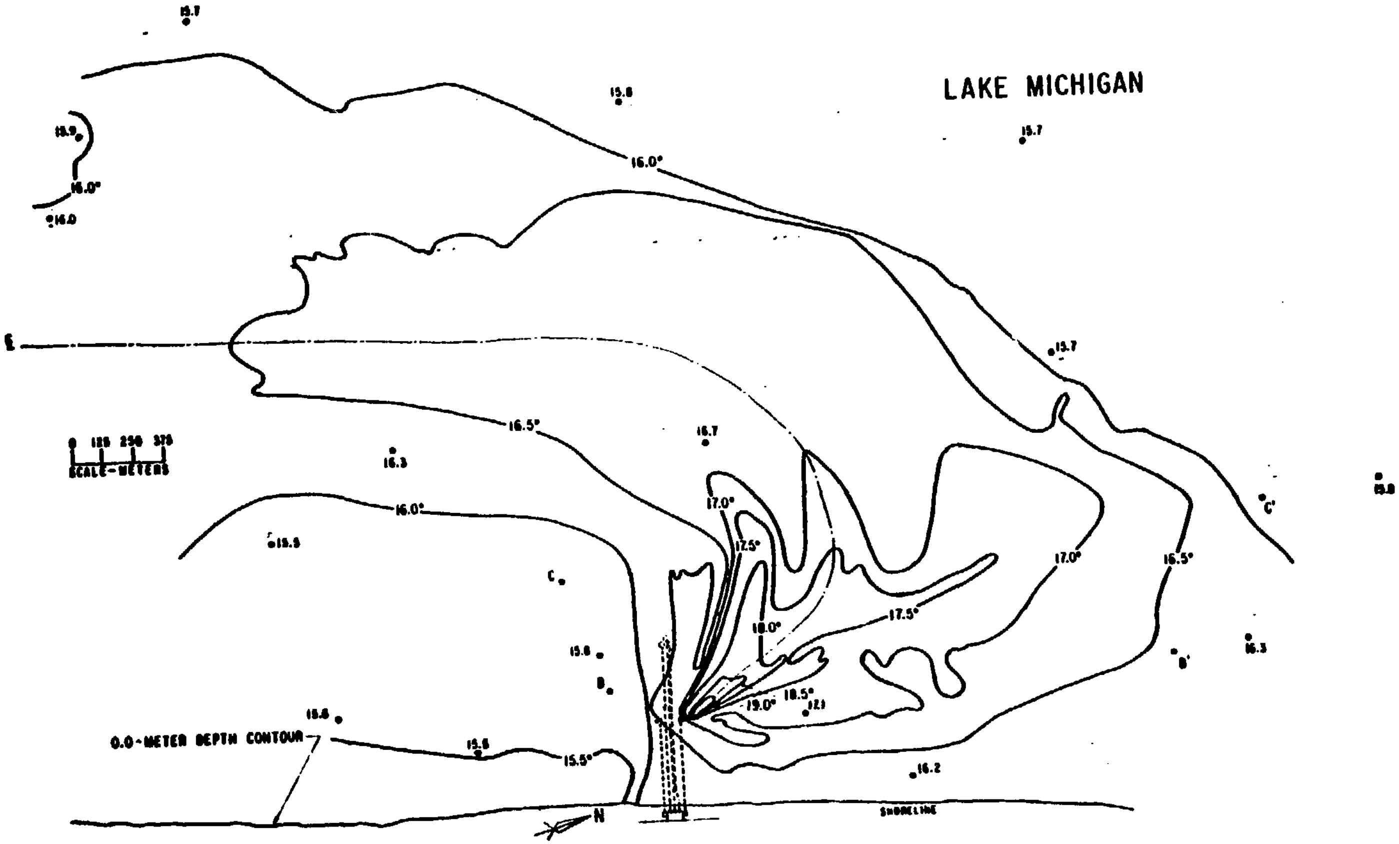


Fig. 7. Thermal Plume at Surface at D. C. Cook Site: October 9, 1975, 1057-1423 hr EDT.

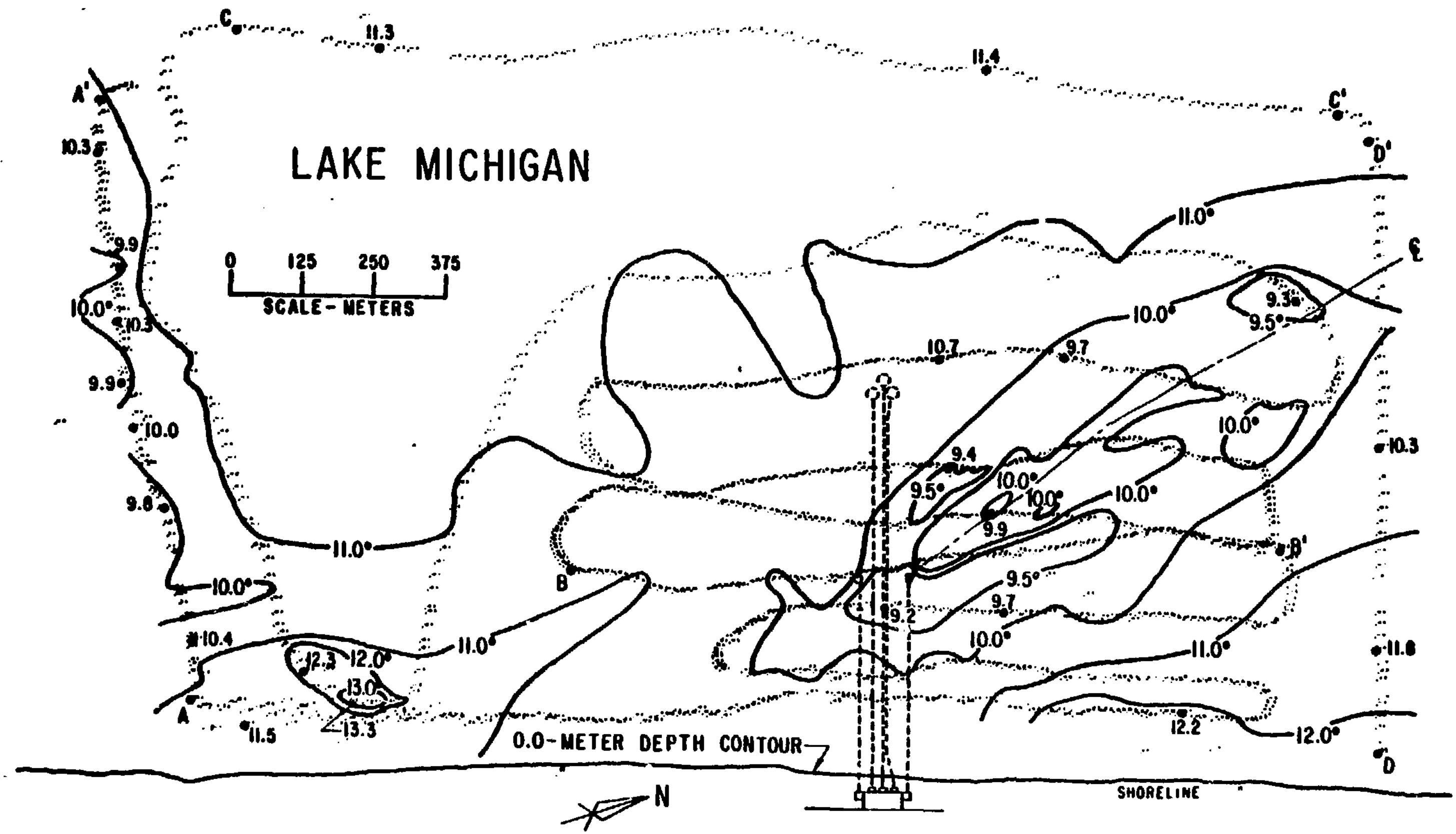


Fig. 8. Thermal Plume at Surface at D. C. Cook Site: May 13, 1975, 1529-1700 hr EDT.